BIOFUELS IN BRAZIL:

ALIGNING THE ENERGY TRANSITION AND LAND USE FOR A CARBON-NEGATIVE COUNTRY

OCTOBER 2025

CONSIDERATIONS FOR EXPANDING BIOENERGY PRODUCTION IN SYNERGY WITH THE CONSERVATION OF NATURAL AREAS AND THE RESTORATION OF DEGRADED LANDS

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Authors
David Shiling Tsai
Felipe Barcellos e Silva
Felipe Betim
Helen Sousa
Ingrid Graces

Technical Review
André Luis Ferreira (Institute for Energy and the Environment – IEMA)
Mirela Coelho (Brazilian Climate Observatory)
Ricardo Junqueira Fujii (WWF Brazil)
Suely Araújo (Brazilian Climate Observatory)

Graphic Design
Mario Kanno

English Version
Edoardo Lobl

Concept and Organization
Institute for Energy and the Environment (IEMA)
energiaeambiente.org.br
energiaeambiente@energiaeambiente.org.br

Through collaborative workshops, the preparation of this work benefited from the valuable contributions of members of the SEEG and OC Energy and Climate Working Group teams: Anton Schwyter (IEMA) | André Ferreira (IEMA) | Bárbara Zimbres (Ipam) | Clauber Leite (E+) | Délcio Rodrigues (ClimaInfo) | Eduardo Avila (Revolusolar) | Elian Aurélio Nascimento (Engajamundo) | Fábio Ishisaki (OC) | Fernanda Tenório (Idec) | Gabriel Quintana (Imaflora) | Hirdan Costa (Arayara) | Isabelle Flávia Dias (Engajamundo) | Isis Rosa (IEMA) | Joice Oliveira (ICLEI) | Kyem Santos (Pólis) | Lourenço Moretto (Idec) | Marta Salomon (Talanoa) | Meiriele Cumplido (IEMA) | Mirela Coelho (OC) | Mónica Banegas (Pólis) | Nicole Dejarmes (IEMA) | Pedro Guedes (E+) | Priscila Alves (Imaflora) | Priscila Pacheco (OC) | Raissa Gomes (IEMA) | Renato Cunha (Gambá) | Ricardo Baitelo (IEMA) | Ricardo Fujii (WWF Brazil) | Samara Santos (WWF Brazil) | Shigueo Watanabe (ClimaInfo) | Sofia Lasmar (Imaflora) | Suely Araújo (OC) | Társia Medeiros (Comida do Amanhã) | Vinícius Oliveira (IEMA) | Wedja Clementino (E+)

Concept and Organization:

Co-organization:

Support:

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Executive Summary

Brazil's strategy to decarbonize its economy can rely on biofuels as key allies, given the country's decades of experience in this sector and in cultivating the necessary feedstocks—such as sugarcane, corn, and soybeans. There is an expectation that Brazil will make even greater use of these fuels, together with a range of other renewable sources, to meet its growing domestic energy demand driven by economic growth, while also containing and reducing emissions.

However, from a socio-environmental perspective, the increased use of biofuels must be approached with caution, since large-scale feedstock production may depend on extensive areas of monoculture. One of the main issues that arises from this assessment, in the Brazilian context, is the need to ensure that the expansion of bioenergy production does not open new planting areas over natural territories, thereby preserving the country's vegetation cover and enabling the achievement of zero deforestation. This could be achieved by converting already degraded pastures into new agricultural areas.

In this context, this study shows that Brazil can **more than double its biofuel production by 2050** to meet an ambitious scenario of a just energy transition—one that combines economic growth, socio-environmental safeguards, and the restoration of natural areas, as proposed by the Brazilian Climate Observatory (OC)—**without creating pressure on food agriculture or causing new deforestation of natural areas and protected territories.**

This would mean increasing feedstock production for biofuels only within part of the **56 million hectares (Mha) of degraded pastures available for the expansion of Brazilian agriculture**, provided that efforts focus on higher-yield crops such as macaúba and on investments in new technologies such as second-generation ethanol.

To reach this conclusion, the study carried out a sensitivity analysis comparing six possible combinations of feedstocks and technologies to **expand biofuel production by 2050**. The estimated additional areas required under these six scenarios would be added to the roughly **31 million hectares already used in 2024 for bioenergy production**.

Assumptions Considered

This comparative analysis was based on the following assumptions:

- Zero deforestation across all biomes by 2030, except for a residual loss of natural areas of at most 100,000 hectares (1,000 km²) per year, as indicated by the Brazilian Climate Observatory (OC) in its proposal for Brazil's second Nationally Determined Contribution (NDC) under the Paris Agreement;
- An existing area of approximately 100 million hectares (Mha) of degraded pasture, according to MapBiomas (2024);
- The allocation of **21 Mha** of degraded pasture for the **restoration of native vegetation**, **22.5 Mha for the formation of high-vigor pasture for livestock**, and **56 Mha for agriculture** (including energy crops), in line with the guidelines proposed by the Brazilian Climate Observatory (OC) for Brazil's second NDC;
- Expansion of energy crops exclusively over areas currently classified as degraded pasture (of low and medium vigor);
- All undesignated public lands must be designated as protected areas, Indigenous territories, quilombola territories, or agrarian-reform settlements, as likewise advocated by the OC in its NDC proposal;
- No area located within conservation units, Indigenous territories, or quilombola lands is considered available for energy crops;
- A target of reducing emissions across all sectors by 92% by 2035 relative to 2005 levels—a far more ambitious figure than those officially presented so far by the federal government;
- An emissions-mitigation scenario for energy use and production alongside average GDP growth of 2.1% per year through 2050, as published in *Future of Energy: the Brazilian Climate Observatory's Vision for a Just Transition in Brazil (Futuro da Energia: visão do Observatório do Clima para uma transição justa no Brasil)*;
- The environmental guidelines and safeguards proposed in the same report;
- Use of agricultural crops and technological pathways identified as the most likely for biofuel production in Brazil, according to the current dynamics of the bioenergy sector and literature on expectations for this activity;
- Energy-demand projections limited to the domestic market;
- Biofuel consumption in Brazil is expected to increase **from 102 million tonnes of oil equivalent (Mtoe) in 2024 to 221 Mtoe by 2050**.

Area Available for Bioenergy Expansion

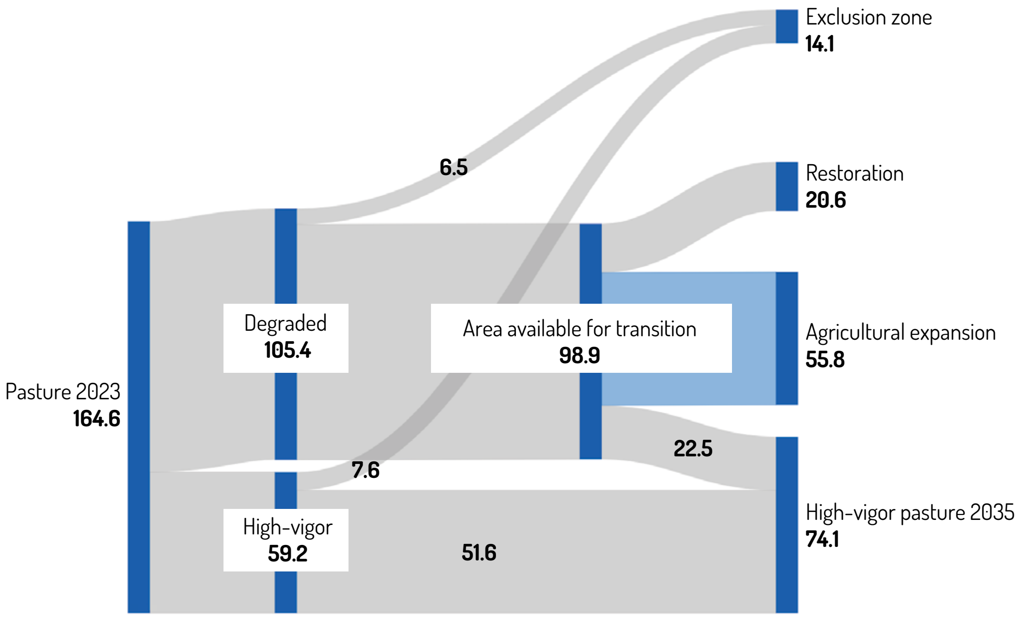
According to the most recent data from MapBiomas, Brazil had 59.2 million hectares (Mha) of high-vigor pastures and another 105.4 Mha of degraded pastures in 2023. Considering that 14.1 Mha of pastures are located within zones that must be protected—conservation units, Indigenous territories, quilombola territories, and undesignated public lands—**Brazil has 98.9 Mha of degraded pastures that should be restored or converted to other uses**.

Although Brazil possesses this significant stock of degraded pastures that can be repurposed, it is important to emphasize that the protection and restoration of natural areas and the production of food must take precedence over biofuel production.

Thus, of the total available area, 21 Mha should be allocated to the restoration of natural areas, in accordance with the Forest Code (Law No. 12,651/2012). In addition, in its NDC proposal, the Brazilian Climate Observatory (OC) calculated—based on existing policies—that 22.5 Mha of degraded pastures must be restored as high-vigor pasture, allowing for increased production and productivity in the livestock industry, as well as greater carbon sequestration in the soil.

Accordingly, **56 Mha remain available for the expansion of agriculture in general**—including areas for planted forests and Integrated Crop-Livestock-Forestry Systems (ICLFS).

Transition of pastures to high-vigor pastures or other uses (million hectares), highlighting the area available for agricultural expansion (including biofuels)



Source: Author's elaboration based on MapBiomas (2024), Forest Code Thermometer (2025), and OC NDC Proposal (2024a).

Scenarios Assessed

The study compared six scenarios for expanding the supply of ethanol, biodiesel, renewable diesel, and sustainable aviation fuel (SAF) through 2050, each featuring different combinations of feedstocks and technologies. Although Brazil's bioenergy matrix is quite diverse, these biofuels were the main focus of the study because of their potential for large-scale use in transport and because they are expected to exert the greatest pressure on land in the coming years.

Of these six scenarios, four fit within the previously proposed limits (56 Mha), requiring an additional 20 to 35 million hectares of cultivated land, approximately:

- **Sugarcane/Macaúba 2050 Scenario – 21 million hectares additional:** 100 % of ethanol, renewable diesel, and SAF produced from sugarcane, and 100 % of biodiesel from macaúba;

- **Macaúba 2050 Scenario – 26 million hectares additional:** 100 % of biodiesel, renewable diesel, and SAF produced from macaúba, and 100 % of ethanol from sugarcane;

- **Sugarcane/Soybean/Macaúba 2050 Scenario – 27 million hectares additional:** 70 % of ethanol produced from sugarcane and 30 % from second-crop corn; biodiesel produced from soybean and macaúba in equal proportions; and 100 % of renewable diesel and SAF produced from sugarcane;

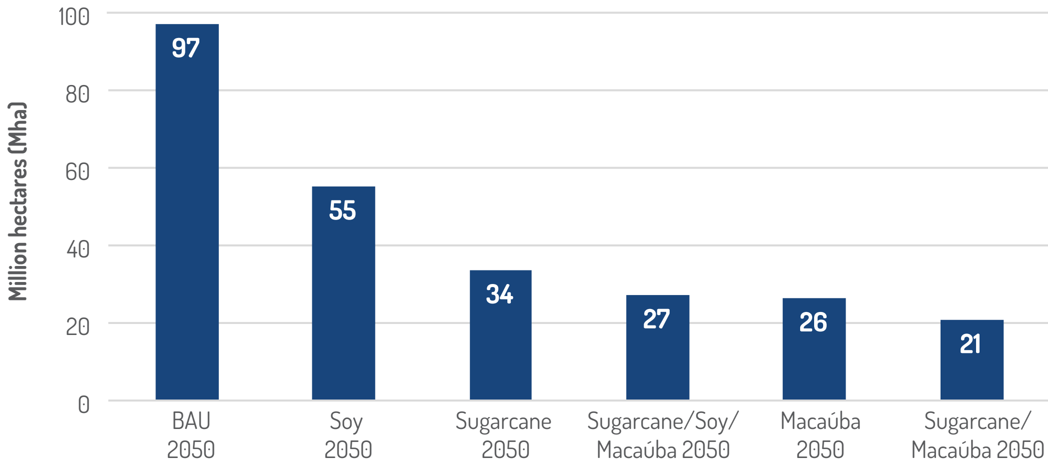
- **Sugarcane-Focused 2050 Scenario – 34 million hectares additional:** 40 % of ethanol produced from sugarcane and 60 % from second-crop corn; 100 % of renewable diesel and SAF from sugarcane; and 100 % of biodiesel produced from soybean oil.

Beyond these four scenarios—in which it is possible to combine bioenergy expansion with Brazil's goals of zero deforestation and natural-area restoration—the study also includes two cases in which those goals become difficult or impossible to achieve.

The **Business-as-Usual (BAU) 2050 Scenario** maintains the current market trend through 2050, assuming 100 % of biodiesel, renewable diesel, and SAF are produced from soybean oil, 20 % of ethanol from corn, and 80 % from first-generation sugarcane technology. As a result, the demand for additional land would reach **97 million hectares**, far exceeding the available stock of degraded land—thereby implying the need to open new natural areas.

In turn, the **Soybean-Focused 2050 Scenario**, which remains centered on soybean but fully exploits the potential to produce ethanol, renewable diesel, and SAF from corn grown in rotation, would require **55 million hectares of additional land** —a figure close to the total stock available for agricultural expansion. However, food production, which must take priority over bioenergy, and the production of raw materials for other industries, such as the textile sector, must also fit within these same limits.

Estimated additional land area required by 2050 to meet biofuel demand



Source: Author's elaboration.

The additional areas required by 2050 across the six scenarios **would be added to the 31 million hectares already used in 2024** for bioenergy production.

It is important to emphasize that these figures also include sugarcane bagasse production and silviculture—that is, planted forests, mainly eucalyptus or pine, which generate firewood, charcoal, or black liquor (a by-product of the pulp and paper industry). The silviculture area is expected to increase from **10.7 million hectares in 2024 to 22 million hectares in 2050** across all six scenarios analyzed.

Results of the sensitivity analysis of land area requirements for feedstock production for biofuels in 2050

	Land use scenarios (Mha)						
Energy crop	**Base – 2024**	**BAU 2050**	**Soy 2050**	**Sugarcane 2050**	**Sugarcane/Soy/ Macaúba 2050**	**Macaúba 2050**	**Sugarcane/Macaúba 2050**
Sugarcane	8.1	11.3	11.3	21.7	24.1	19.6	26.6
Soybean (without second-crop corn)	9.5	87.6	0.0	0.0	0.0	0.0	0.0
Soybean and Corn (Second Crop)	3.0	7.6	53.2	21.3	10.6	0.0	0.0
Macaúba palm	0.0	0.0	0.0	0.0	1.8	16.1	3.6
Silviculture	10.7	22.0	22.0	22.0	22.0	22.0	22.0
TOTAL	31.4	128.5	86.5	64.9	58.5	57.7	52.1
Additional area relative to 2024	–	97.1	55.1	33.5	27.1	26.3	20.7

Source: Author's elaboration.

Recommendations

This study shows that combining more efficient crop and technological-route choices—that is, those requiring less cultivated land per unit of fuel produced—is essential to meet Brazil's energy demand in 2050 under an ambitious decarbonization scenario, while simultaneously fulfilling the commitments to eliminate deforestation, restore environmental liabilities under the Forest Code, and sequester carbon through the rehabilitation of degraded pastures.

Accordingly, the following public policy recommendations are proposed to advance the understanding and planning of biofuel expansion in Brazil:

1. Define clear biofuel production targets for the domestic market, tied to ambitious greenhouse gas (GHG) mitigation goals;
2. Delineate and monitor cultivation areas and feedstock exclusion zones in alignment with the zero-deforestation commitment and with a strategy for restoring degraded pastures;
3. Develop a feedstock production strategy (e.g., for vegetable oil or ethanol) that reflects the geographical, environmental, and social characteristics of the territories involved;
4. Establish minimum productivity efficiency parameters, measured by the volume of intermediate products (e.g., vegetable oil or ethanol) produced per cultivated area;
5. Promote research and development of new technological routes for biofuel production;
6. Design a strategy for the gradual reduction of petroleum-derived products, while enabling the production of advanced biofuels, assessing the conversion or adaptation of oil refineries into bio-refineries, or the construction of new bioenergy-focused facilities.

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1. Introduction

The *Institute for Energy and the Environment (IEMA)* and the *Brazilian Climate Observatory (OC)* seek to build knowledge to advance Brazil's energy transition, with a view to fulfilling the *Paris Agreement*. As part of this challenge, it is essential to understand the role that different energy sources can play.

Brazil's strategy to decarbonize its economy can rely on biofuels as key allies, given the country's decades of experience in this sector and in cultivating the necessary feedstocks—such as sugarcane, corn, and soybeans. There is an expectation that Brazil will make even greater use of these fuels, together with a range of other renewable sources, to meet its growing domestic energy demand driven by economic growth, without necessarily increasing emissions.

However, given the negative socio-environmental impacts historically associated with feedstock cultivation for biofuels worldwide, the expansion of bioenergy as an alternative to reduce greenhouse gas (GHG) emissions raises concern.

In this context, this study aims to assess the expansion of feedstock production for these biofuels, considering the demand required to achieve a carbon-negative economy by 2050, but relying solely on part of the areas currently occupied by degraded pastures, without any additional deforestation or competition with food production. The goal is thus to understand how the use of bioenergy can align with the preservation of natural areas and the restoration of degraded lands.

To this end, a sensitivity analysis was carried out to estimate the areas needed for the expansion of energy crops[1] based on the following boundary conditions, which take into account concerns about potential negative impacts:

- Zero deforestation across all biomes by 2030, except for a residual loss of natural areas of at most 100 thousand hectares (1,000 km²) per year, as indicated by the OC in its proposal for Brazil's second Nationally Determined Contribution (NDC) under the Paris Agreement (OC, 2024c);
- An existing area of approximately 100 million hectares (Mha) of degraded pasture, according to MapBiomas (2024);

1 *Energy crops* is a term used to refer to agricultural cultivation of plant species capable of providing feedstocks for biofuels, such as sugarcane, soybeans, or eucalyptus plantations.

- Allocation of 21 Mha of degraded pasture for the restoration of native vegetation, 22.5 Mha for the formation of high-vigor pasture for livestock[2], and 56 Mha for agriculture (including energy crops), in line with the guidelines proposed by the Brazilian Climate Observatory (OC) for Brazil's second Nationally Determined Contribution (NDC);

- Expansion of energy crops exclusively over areas currently classified as degraded pasture (of low and medium vigor);

- All undesignated public lands[3] should be designated as protected areas, Indigenous territories, *quilombola* territories, or agrarian-reform settlements, as likewise advocated by the OC in its NDC proposal;

- No area located within conservation units, Indigenous territories, or quilombola lands is considered available for energy crops;

- A target of reducing emissions across all sectors by 92% by 2035 relative to 2005 levels (OC, 2024c);

- An emissions-mitigation scenario for energy use and production alongside average GDP growth of 2.1% per year through 2050, as published in *Future of Energy: the Brazilian Climate Observatory's Vision for a Just Transition in Brazil (Futuro da Energia: visão do Observatório do Clima para uma transição justa no Brasil)* (OC, 2024b);

- The environmental guidelines and safeguards proposed in the same report;

- Use of agricultural crops and technological pathways identified as the most likely for biofuel production in Brazil, according to the current dynamics of the bioenergy sector and literature on expectations for this activity;

- Energy-demand projections limited to the domestic market.

2 *High-vigor pastures* are those with soil in good condition and adequate quantity and growth of grass or other vegetation. This increases cattle-raising productivity while allowing carbon removal from the atmosphere and its storage in the soil. Maintaining this condition through management techniques—such as maintenance fertilization or rotating grazing areas to prevent excessive soil compaction—is considered good agricultural practice.

3 *Undesignated public lands* "are areas that belong to the Federal Government (União), states, municipalities, the Federal District, or entities of indirect administration, but whose use has not yet been defined by those public authorities. For this reason, they are the most unprotected areas across Brazil's biomes and those most affected by land grabbing, deforestation, and illegal mining." — *Public Forests Observatory (Observatório das Florestas Públicas).*

2. Brief Context on Biofuels in Brazil

From a socio-environmental perspective, the expansion of biofuel use must be approached with caution, since its large-scale production depends on extensive areas of monoculture—such as sugarcane, corn, soybeans, and other crops.

One of the main issues that arises from this assessment, in the Brazilian context, is the need to ensure that the expansion of bioenergy production does not open new planting areas over natural territories, thereby preserving the country's vegetation cover and enabling the achievement of zero deforestation. This can be achieved by converting already degraded pastures into new agricultural areas, which also includes energy crops.

The expansion of biomass-based energy use appears to be a natural path for Brazil, given its accumulated experience since the 1970s, when the liquid biofuels sector for large-scale transport use first took shape. At that time, the country—through the National Alcohol Program (Proálcool)—turned to ethanol to navigate global oil crises and meet domestic fuel demand at better prices. Later, in the 2000s, flex-fuel engines, capable of running on both gasoline and ethanol, gave renewed impetus to the bioenergy sector.

According to the *2024 Biofuels Market Outlook (Análise de Conjuntura dos Biocombustíveis 2024)* published by the Energy Research Office (EPE) (2025a), Brazil's vehicle fleet reached 37 million units that year, with approximately 85% featuring flex-fuel technology—an attribute that enhances ethanol use in the Brazilian market.

In Brazil, sugarcane is the main feedstock for ethanol production. However, corn has gained importance, accounting for about 20% of ethanol supply in 2024 (EPE, 2025a). This reflects the fact that corn is cultivated as a second crop in areas primarily dedicated to soybean production, allowing large volumes of the former to be used as feedstock for ethanol. As a result, ethanol production in 2024 reached a record 37.3 billion liters, up 5.7% from the previous year, with 29.7 billion liters from sugarcane and 7.7 billion liters from corn.

In the case of trucks and buses, Brazil has been investing in biodiesel, which relies primarily on soybean oil as a feedstock—72.4% of total output in 2024 came from this source. In August 2025, the proportion of biodiesel blended into commercial diesel was raised to 15%, with a target of 20% in the coming years. Accordingly, national biodiesel production in 2024 reached 9 billion liters, representing over 20% growth compared to 2023 (EPE, 2025c).

In this context, ethanol and biodiesel together accounted for more than 22% and 25% of the energy used in transport in 2023 and 2024, respectively, according to the *National Energy Balance (Balanço Energético Nacional – BEN)* (EPE, 2025c).

In 2023, passenger transport emitted 106.1 million tonnes ($MtCO_2e$), while freight transport emitted 117.7 $MtCO_2e$, according to data from the Greenhouse Gas Emissions and Removals Estimating System (SEEG, 2024). These transport-related emissions—especially from passenger vehicles—would have been significantly higher without biofuels[4]. In 2024, the emissions avoided through the use of ethanol and biodiesel, compared with their fossil equivalents (gasoline and diesel), totaled 92 $MtCO_2e$, according to official data (EPE, 2025a).

Given this predominant role of the transport sector in Brazil's emissions, the debate on bioenergy has increasingly focused not only on ethanol and biodiesel, but also—more recently—on renewable diesel[5] and sustainable aviation fuel (SAF)[6], given the projected growth in the use of these two biofuels over the coming decades. In addition to their potential for large-scale deployment in transport, they are also the most feedstock-intensive, which could drive pressure on land use in the years ahead.

Beyond the biofuels mentioned above, the bioenergy sector also encompasses sugarcane bagasse, biogas and biomethane, charcoal, firewood, black liquor, and other biomass sources used on a smaller scale.

Bioenergy is not only relevant in Brazil. The United States and Europe—especially Germany, the world's third-largest biofuel producer—have been increasing production of advanced biofuels in biorefineries, such as renewable diesel and sustainable aviation fuel (SAF), which are regarded as essential for decarbonizing the aviation sector. Another promising development is the expansion of second-generation ethanol, produced from sugarcane residues, such as straw and bagasse, or other agricultural residues rich in lignocellulosic biomass.

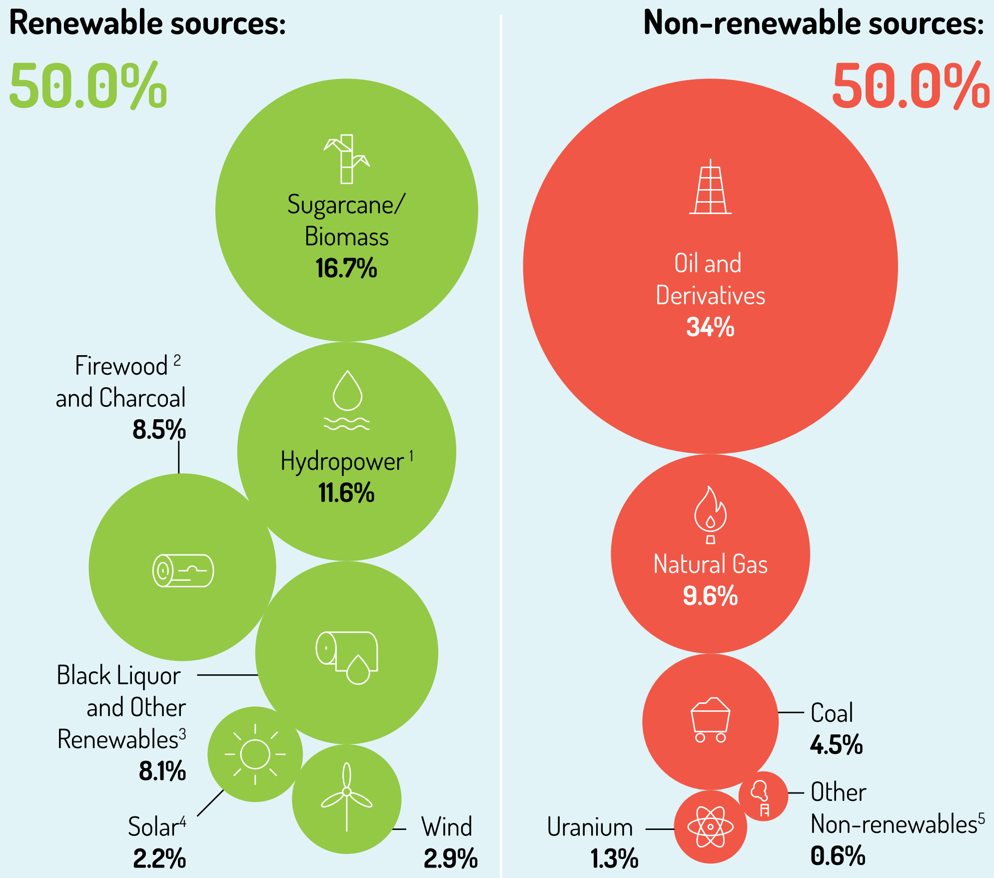
Technological advances in the sector and the potential to reduce greenhouse gas (GHG) emissions place biofuels among the alternatives capable of meeting the growing energy demand of a country seeking to decarbonize its economy. In Brazil, bioenergy already accounts for 33.3% of total energy supply in the national energy matrix, when the different sources presented in Figure 1 are combined.

4 In its guidelines, the Intergovernmental Panel on Climate Change (IPCC) states that biofuels can be considered neutral in terms of direct CO_2 emissions. This is because all CO_2 released during the combustion of these fuels was previously captured from the atmosphere through photosynthesis during the growth cycle of the biomass used as feedstock for biofuel production.

5 Although both biodiesel and renewable diesel are intended to replace fossil diesel in combustion engines, they are different biofuels. The first, more widely used in Brazil, is a fatty acid ester obtained by reacting oils or fats with an alcohol—mainly methanol—in a process known as transesterification. Because it is less stable, biodiesel must be blended with fossil diesel (currently at a 15% proportion). By contrast, renewable diesel is a hydrocarbon with a chemical composition similar to petroleum diesel, produced through hydroprocessing, which removes oxygen from vegetable oils or animal fats. With higher calorific value, it is more stable and can be used in any proportion—even entirely replacing fossil diesel in combustion engines. The most commonly produced renewable diesel worldwide is HVO (Hydrotreated Vegetable Oil), which uses plant-based feedstocks such as soybeans, macaúba, and other palm species. In Brazil, Petrobras currently produces HVO coprocessed with fossil diesel, in a blend branded Diesel R by the company. An increase in renewable diesel production is expected from the next decade onward.

6 Sustainable aviation fuels (SAF) can be produced from vegetable oils, ethanol, organic residues, or recycled fats.

Figure 1 – Breakdown of Brazil's Domestic Energy Supply in 2024



[1] Includes energy imports. [2] Includes wood chips. [3] Includes black liquor, biodiesel, other biomass, biogas, and industrial gas from charcoal. [4] Includes photovoltaic (mini- and micro-distributed generation) and solar thermal sources. [5] Other non-renewables include liquefied natural gas (LNG), blast-furnace gas, steel mill gas, sulfur gas, and others.

Source: National Energy Balance (Balanço Energético Nacional – EPE, 2025c)

This considerable share is not due solely to the inclusion of biofuels in passenger and freight transport. According to the *National Energy Balance (Balanço Energético Nacional – BEN)*, the renewability of industry—the second-largest energy-consuming economic activity in Brazil, after transport—reached 64.4% in 2024, with bioenergy playing a key role in this result.

In the pulp and paper industry, for example, black liquor—a liquid by-product generated from wood digestion in the production process—is used in boilers to produce steam for self-generation of electricity and to meet the plant's thermal needs. The same applies to sugarcane bagasse in the sugar and ethanol industry, where cane residues (from both sugar and ethanol production) are burned for self-generation of electricity used by the industrial unit itself, with the surplus sold to power utilities (*Embrapa, 2016*).

In electricity generation, biomass—including sugarcane bagasse, black liquor, biodiesel, and firewood, among other sources—ranked as the fourth-largest source in

Brazil's power mix in 2024, according to the *BEN*. It trailed other renewable sources—hydropower, wind, and solar—but surpassed emitting sources such as fossil gas and petroleum derivatives.

Charcoal, in turn, comes from planted forests, mainly pine and eucalyptus, and is used in industries such as metallurgy. Firewood, on the other hand, remains largely associated with cooking in low-income households, serving as an indicator of social vulnerability. It is desirable that its use decline as Brazil finds solutions to overcome the energy poverty faced by millions of families lacking access to more appropriate energy sources.

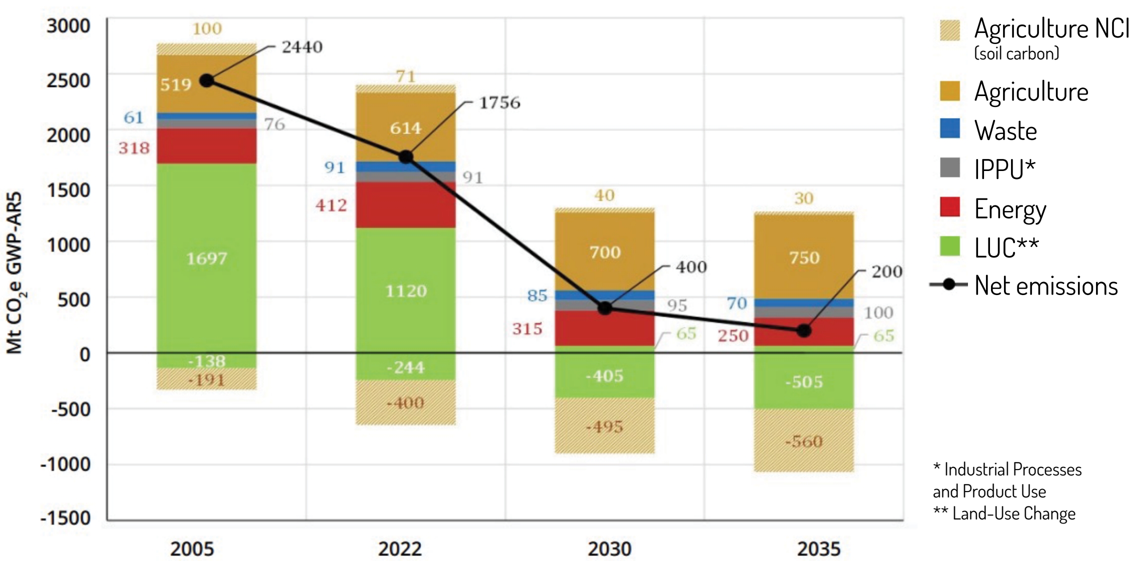
Lastly—but no less importantly—biogas and biomethane are gaseous biofuels with the potential to replace fossil gas, liquefied petroleum gas (LPG), diesel, and other fuels. They originate from the anaerobic decomposition of organic matter in landfills, from sugarcane industry residues, and from livestock waste. As such, there is significant, yet still underutilized, potential for energy generation without changes in land use.

In summary, biofuels are already a reality and part of the strategy adopted by Brazil's main authorities to advance the national energy transition. They are expected to remain relevant through 2050, both in passenger and freight transport and in industry, among other economic activities. This is evidenced by the recent laws and regulations approved in Brazil, such as the *Fuel of the Future Law (Lei do Combustível do Futuro, Law No. 14,993/2024)* and the *National Biofuels Policy (Política Nacional de Biocombustíveis – RenovaBio)*.

3. Brazilian Climate Observatory's Vision for Land Use and Emission Mitigation

This work takes as its starting point the Brazilian Climate Observatory's (OC) proposal for Brazil's second Nationally Determined Contribution (NDC) under the Paris Agreement (OC, 2024c). The document presents a prescriptive mitigation scenario involving a 92% reduction in Brazil's net emissions by 2035 relative to 2005 levels. This figure is consistent with a fair contribution by Brazil toward the global goal of limiting the increase in average temperature to 1.5°C, as established under the Agreement. It represents a commitment to reduce net greenhouse gas (GHG) emissions from 2.44 billion tonnes of CO_2e—the 2005 figure estimated by the Greenhouse Gas Emissions and Removals Estimating System (SEEG)—to around 200 million tonnes of CO_2e (Figure 2), denoting a far more ambitious decarbonization scenario than that presented by the federal government in its most recent official NDC (*Ministry of the Environment and Climate Change – MMA, 2024*).

Figure 2: Emissions and removals in OC's proposal for Brazil's second NDC



Source: Foundations for Brazil's second NDC (2030–35) (OC, 2024a)

To achieve emission reductions from land-use change (LUC) and agriculture and livestock, the OC's 2nd NDC proposal presents a land-use scenario for 2035. In this scenario, annual deforestation in Brazil is limited to 100,000 hectares (1,000 km²) as of 2030. This effectively means bringing deforestation in Brazil close to zero, with only a small number of new vegetation clearances still eligible for licensing. Thus, the deforestation area is expected to decline from current levels to 100,000 hectares by 2030.

As one of the instruments to enable this downward trajectory, Brazil must classify all currently undesignated public lands as protected areas, Indigenous territories, quilombola territories, or agrarian-reform settlements.

Consequently, no major land-use transitions will be permitted to originate from natural areas.

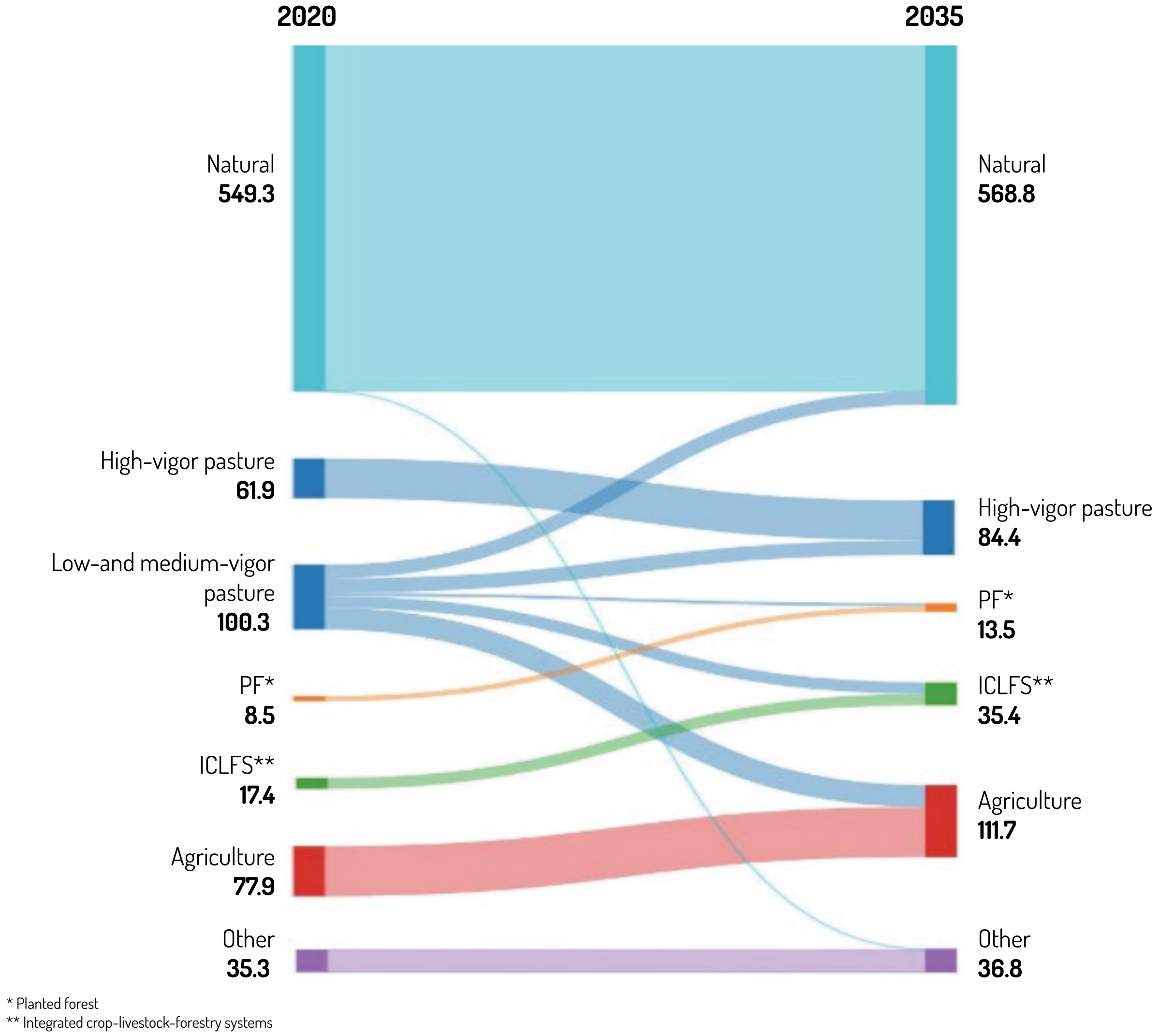
In simplified terms, land use in Brazil can be classified as natural, agricultural/livestock, or other (urban zones, mining, etc.). More specifically, the agricultural/livestock category can be broken down into: (i) high-vigor pasture; (ii) low- and medium-vigor pasture; (iii) planted forest (PF); (iv) integrated crop-livestock-forestry systems (ICLFS); and (v) agriculture.

The OC's NDC proposal establishes that the expansion of agricultural and livestock activities must occur only over areas of low- and medium-vigor pasture, which tend to be less productive, show signs of soil degradation, and lack the capacity to store and remove carbon in the soil (OC, 2024a).

In addition to eliminating deforestation, Brazil must restore approximately 21 million hectares of natural areas. This figure, estimated by the *Forest Code Thermometer (Termômetro do Código Florestal)* (2025), refers to the environmental liabilities of the Forest Code (Law No. 12,651/2012)—that is, areas within rural properties that were converted from their natural state without authorization. "These areas must undergo restoration to ensure the environmental regularization of rural properties" (OC, 2024c). It is assumed that this entire restoration effort will also originate from degraded pastures (low and medium vigor).

Figure 3 illustrates the land-use and land-cover transition dynamics between 2020 and 2035 developed by the OC in its NDC proposal, aiming at emission reductions, environmental preservation, increased livestock productivity, and the expansion of food and agricultural input production. The figure highlights the end of deforestation, accompanied by extensive restoration efforts, resulting in an increase in natural areas and the cessation of their conversion into other land uses. Furthermore, it shows that all land-use changes occur exclusively within existing low- and medium-vigor pasture areas. This implies a reduction in total pasture area nationwide, but also a more than 35% increase in high-vigor pastures, which are more productive and enable the expansion of meat production—in line with the sector's expectations.

Figure 3 – Land Use and Transitions in 2020 and 2035 (million hectares), in line with the emission-reduction scenario proposed by the Brazilian Climate Observatory (OC) for Brazil's 2nd NDC

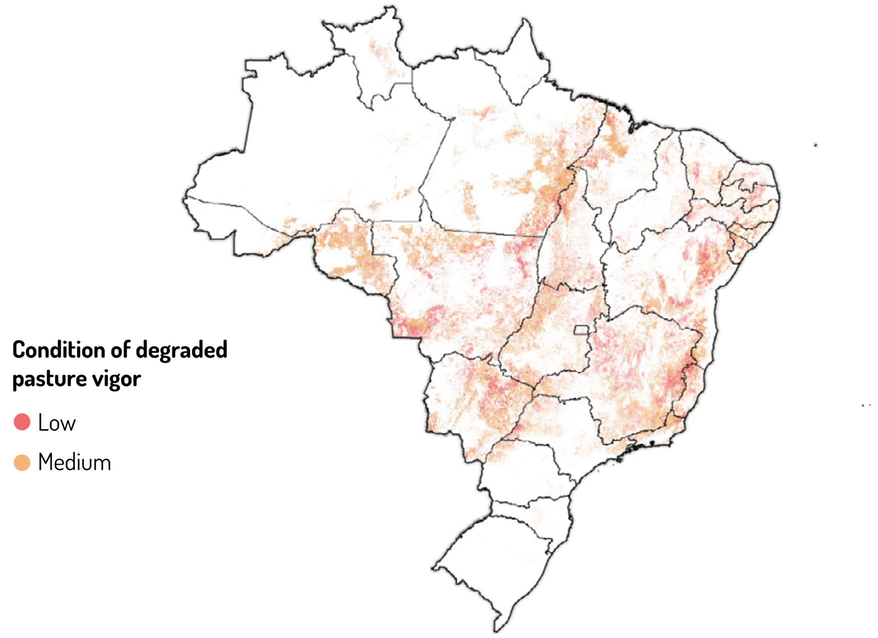


Source: Foundations for Brazil's 2nd NDC (2030–2035) (OC, 2024a).

In addition to the portion of degraded pastures that must be converted into restored pastures or reforested areas, there is another significant share—about 60 million hectares (Mha)—available to become mainly agricultural land.

Figure 4 shows the location of all low- and medium-vigor pastures in Brazil (distribution for 2024), totaling approximately 100 Mha that are expected to receive a new land use by 2035, as described in the previous paragraphs.

Figure 4 – Low- and Medium-Vigor Pastures in Brazil (2024)



*High-vigor pastures are not represented here.
Source: MapBiomas (2025).

This study is based precisely on this land-use framework and on the conversion of degraded pastures, enabling Brazil to pursue a just energy and ecological transition, as advocated by the Brazilian Climate Observatory (OC).

Brazil can therefore transform low- and medium-vigor pastures into agricultural areas, eliminating the need to open new cultivation areas over natural vegetation or protected territories. Priority should be given above all to fair food production. When appropriate, these agricultural areas may also include potential crops for biofuel production, provided that all necessary socio-environmental safeguards are followed.

Initiatives to boost both environmental restoration and agricultural productivity are supported by public policies such as Green Path Brazil (Caminho Verde Brasil), led by the Ministry of Agriculture and Livestock (MAPA), which seeks precisely to restore degraded areas and promote better practices in the field. The program aims to restore up to 40 million hectares of low-productivity pastures over the next ten years, converting these areas into high-yield farmland without the need for deforestation (MAPA, 2025).

The program is supported by Decree No. 11,815/2023 (*Official Gazette – DOU, 2023*), through which the federal government established the National Program for the Conversion of Degraded Pastures into Sustainable Agricultural and Forestry Production Systems (PNCPD), with the purpose of "promoting and coordinating public policies aimed at converting degraded pastures into sustainable agricultural and forestry production systems, in order to foster good agricultural practices that lead to carbon capture at levels higher than those of degraded pastures."

3.1 Updating Land-Use Transition Areas Based on Recent Data

According to the most recent statistics from MapBiomas (2024), the areas of degraded (low- and medium-vigor) pastures and high-vigor pastures are no longer the same as in 2020, which served as a reference for the OC's NDC proposal (2024a). In 2023, Brazil had 59.2 million hectares (Mha) of high-vigor pastures and another 105.4 Mha of degraded pastures.

As discussed earlier, all new land-use transitions must originate from degraded pastures. However, this current analysis excludes pastures located within zones that must be protected—here referred to as exclusion zones—which include conservation units, Indigenous territories, quilombola territories, and undesignated public lands.

Still according to satellite imagery classified by MapBiomas, within these exclusion zones there are 6.5 Mha of degraded pastures and 7.6 Mha of high-vigor pastures, totaling 14.1 Mha that must be restored or preserved.

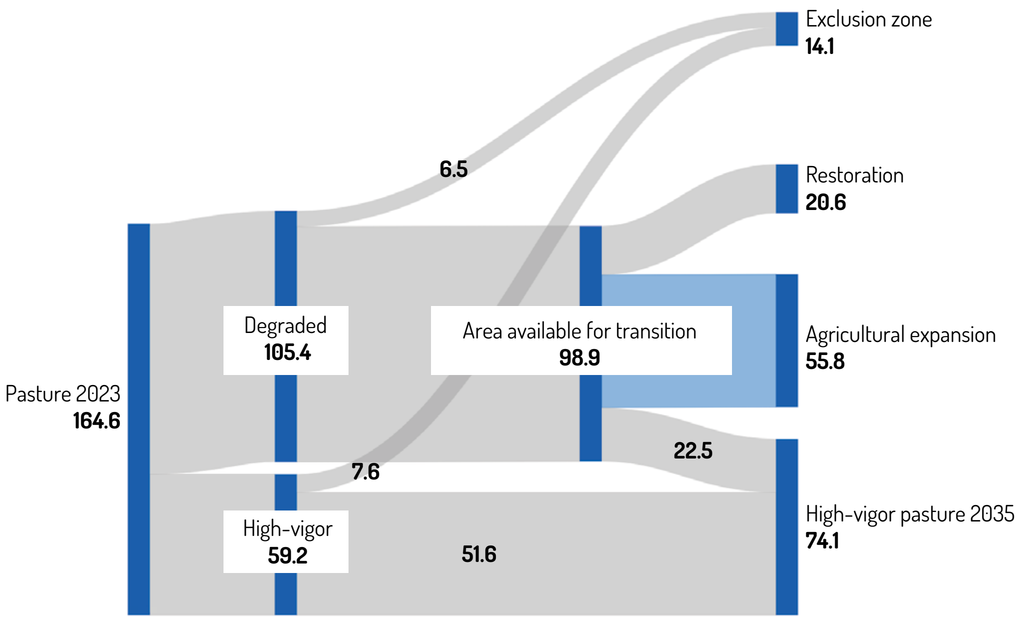
Therefore, after excluding pastures in these protected zones, Brazil has 51.6 Mha of productive (high-vigor) pastures, which should be maintained as such, and 98.9 Mha of degraded pastures, which should be restored or converted to other uses.

Of these 98.9 Mha of pastures requiring transition, it is estimated that 20.6 Mha should be allocated to the restoration of natural areas in accordance with the Forest Code (Law No. 12,651/2012)—these are the most up-to-date figures monitored by the *Forest Code Thermometer (2025)*. In addition, in its NDC proposal, the Brazilian Climate Observatory (OC) calculated, based on existing policies, that 22.5 Mha of degraded pastures must be restored as high-vigor pasture, allowing for increased production and productivity in the livestock industry as well as greater carbon sequestration in the soil.

Accordingly, as highlighted in Figure 5, 55.8 million hectares remain available for the expansion of agriculture in general—including areas for Planted Forests (PF) and Integrated Crop-Livestock-Forestry Systems (ICLFS).

Thus, this study adopts as a fundamental premise that only part of these 55.8 million hectares (Mha) may be used by Brazil to expand feedstock production for the biofuels industry.

Figure 5 – Transition of pastures to high-vigor pastures or other uses (million hectares), highlighting the area available for agricultural expansion (including biofuels)



Source: Author's elaboration based on MapBiomas (2024), Forest Code Thermometer (2025), and OC NDC Proposal (2024a).

3.2 Distribution of Available Areas for Agricultural Expansion by State

The areas available for agricultural expansion—according to the premises of this study, which include energy crops—were allocated among the federal units (states) through the following steps:

1. Low- and medium-vigor pasture areas were identified by state, totaling 105.4 million hectares (Mha).

2. For each state, low- and medium-vigor pastures located within exclusion zones (conservation units, Indigenous territories, quilombola territories, and undesignated public lands) were filtered out, leaving 98.9 Mha distributed across Brazil's states.

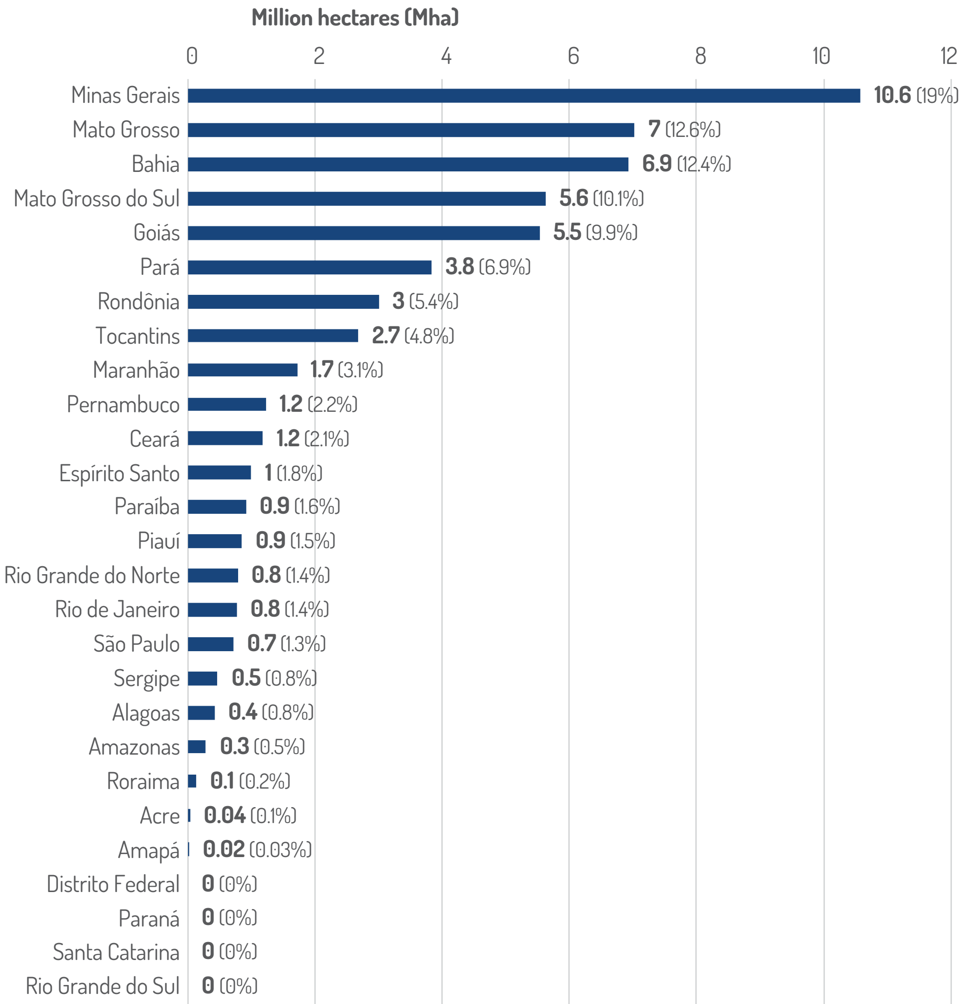
3. Each state's environmental liability—the area to be restored under the *Forest Code (Law No. 12,651/2012)*—was subtracted from the amount of degraded pasture to undergo transition. The environmental liability by state was obtained from the *Forest Code Thermometer (2025)*.

4. The 22.5 Mha of degraded pastures that, according to the Brazilian Climate Observatory (OC) NDC, should be converted into high-vigor pasture were, for simplification, distributed among the states in proportion to the current amount of degraded pasture within each territory relative to the national total. For example, since Minas Gerais contains 16 % of the country's low- and medium-vigor pastures, it was assumed that 3.6 Mha (16 % of 22.5 Mha) of that state's degraded pastures should be converted into productive pasture.

5. From the remaining pasture areas per state available for transition after step **3** (a total of 78.3 Mha), the future high-vigor pasture values determined in step **4** were deducted for each state.

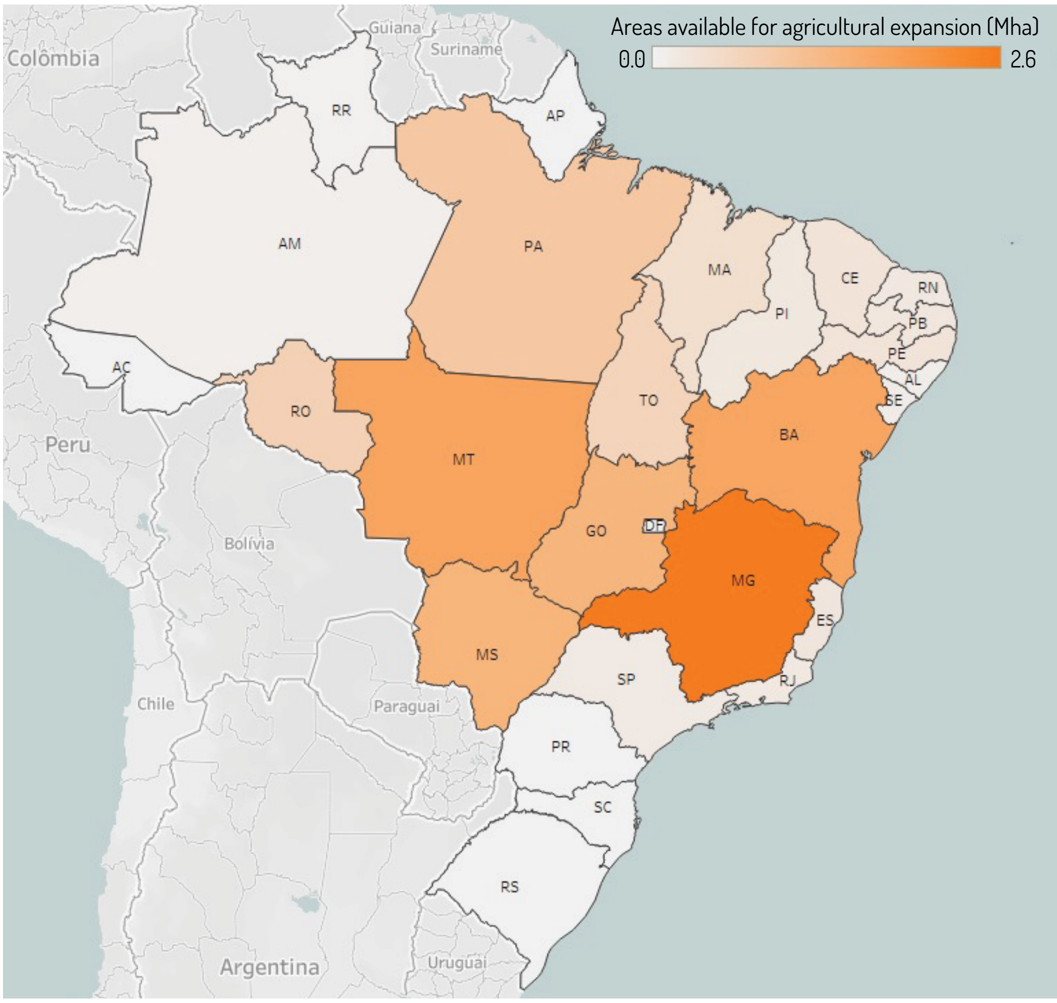
6. The result was 55.8 Mha of areas available for agricultural expansion, distributed among the states, with the majority (64 %) located in five states—Minas Gerais, Mato Grosso, Bahia, Mato Grosso do Sul, and Goiás—as shown in Figures 6 and 7.

Figure 6 – Areas Available for Agricultural Expansion by State



Source: Author's elaboration based on MapBiomas (2024), Forest Code Thermometer (2025), and Brazilian Climate Observatory (OC) NDC Proposal (2024a).

Figure 7 – Areas Available for Agricultural Expansion in Brazil



Source: Author's elaboration based on MapBiomas (2024), Forest Code Thermometer (2025), and Brazilian Climate Observatory (OC) NDC Proposal (2024a).

4. Sensitivity Analysis of Estimates of Feedstock Cultivation Areas for Biofuels: Methodology and Results

To assess land use for increasing the production of feedstocks for biofuels, considering the demand required to achieve a carbon-negative economy by 2050, a sensitivity analysis was conducted to estimate the areas needed for the expansion of energy crops. The following steps were adopted and are detailed in the subsections of this chapter:

1. Projection of biofuel **demand** through 2050 (*Future of Energy*);
2. Definition of **supply** scenarios, considering different feedstocks and technological pathways;
3. Compilation of **productivity** parameters (liters or tonnes per hectare); and
4. Comparative analysis of the **areas** required for energy-crop cultivation against the available-area framework (2035), as outlined in the Brazilian Climate Observatory (OC) NDC proposal.

4.1 Use of Bioenergy as Part of Brazil's Energy Transition: Future Demand for Biofuels

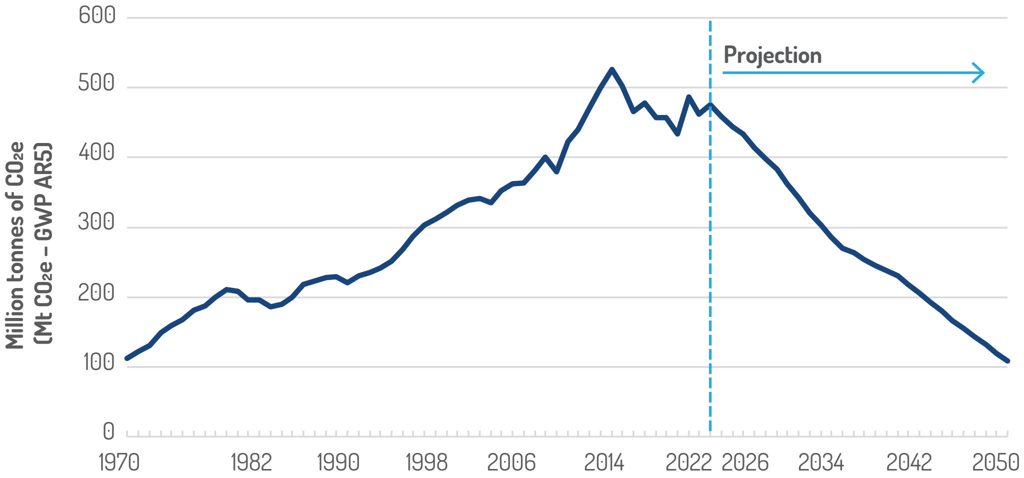
In the second half of 2024, the Brazilian Climate Observatory (OC), through its Climate and Energy Working Group (GT Clima e Energia), released the report *Future of Energy: the Brazilian Climate Observatory's Vision for a Just Transition in Brazil (Futuro da Energia: visão do Observatório do Clima para uma transição justa no Brasil)* (OC, 2024b). The document presents a strategy deemed necessary for Brazil's energy transition. It outlines an ambitious scenario for the deployment of low- or zero-emission technologies, as well as structural changes that increase the systemic efficiency of energy use, aiming to minimize fossil-fuel consumption in the country while assuming continued economic growth.

Historically, energy use tends to rise proportionally with economic growth, represented by Gross Domestic Product (GDP). To meet the projected increase in energy demand, the study anticipates a greater share of non-fossil energy sources, such as electricity from photovoltaic or wind power plants, green hydrogen, and biofuels. In addition, energy-efficiency improvement rates were applied to various economic activities, flattening the projected demand curve.

To test the sensitivity of the developed model, three different average annual GDP growth rates were assumed: 1.3 %, 2.1 %, and 2.8 %—each corresponding to a distinct energy-demand curve through 2050. The same decarbonization solutions were applied across all GDP scenarios; therefore, the higher the economic growth, the greater the persistence of fossil fuels in the energy matrix, resulting in higher emissions.

The GHG-emission-reduction profile obtained in this study—considering the average GDP-growth scenario (2.1 % per year)—is presented in Figure 8. Under the energy--transition pathway advocated by the OC, Brazil's emissions from the energy sector and from the use of reducing agents in metallurgical industrial processes will reach 108.9 million tonnes (Mt) CO_2e by 2050, representing a 77 % decline compared to 2024 levels (475.8 Mt CO_2e).

Figure 8 – Historical emissions (1970–2023) and projections according to the OC's vision (2024–2050) for the energy sector and the use of reducing agents in metallurgical industrial processes[7]



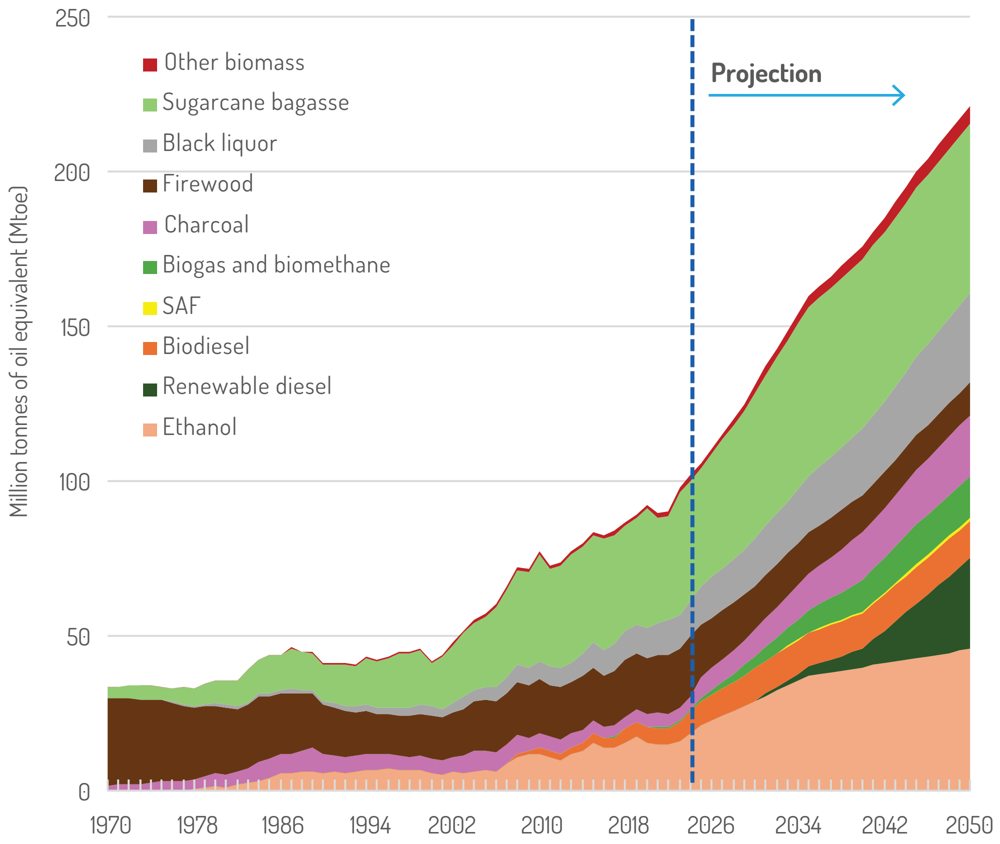
Source: Adapted from Future of Energy (OC, 2024b).

This subsection aims to detail the bioenergy-use trends presented in the *Future of Energy* study (OC, 2024b), considering here only the scenario of 2.1 % annual GDP growth for Brazil. **In other words, it presents the OC's vision for the role of biofuels as one of the solutions for Brazil's energy transition.**

7 The historical emission results used in the preparation of the *Future of Energy* study (OC, 2024b) were taken from Collection 11 of SEEG – the Greenhouse Gas Emissions and Removals Estimating System, published in 2023, which includes data up to the 2022 base year. In the figure, emissions for the period 1970–2023 were updated using data from Collection 12 of SEEG, released in 2024 with 2023 as the base year (SEEG, 2024). Projections for 2024 onward are the same as those published in the *Future of Energy* report.

In Figure 9, the historical curve of bioenergy use in Brazil is shown, together with the projected increase required. Altogether, considering the various types of biofuels, domestic bioenergy consumption reached 102 million tonnes of oil equivalent (Mtoe) in 2024 (EPE, 2025b), led by sugarcane bagasse, firewood, and ethanol. By 2050, the supply of biomass-based fuels is expected to more than double, reaching 221.1 Mtoe. The biofuels mix will also become more diverse, incorporating new renewable energy sources.

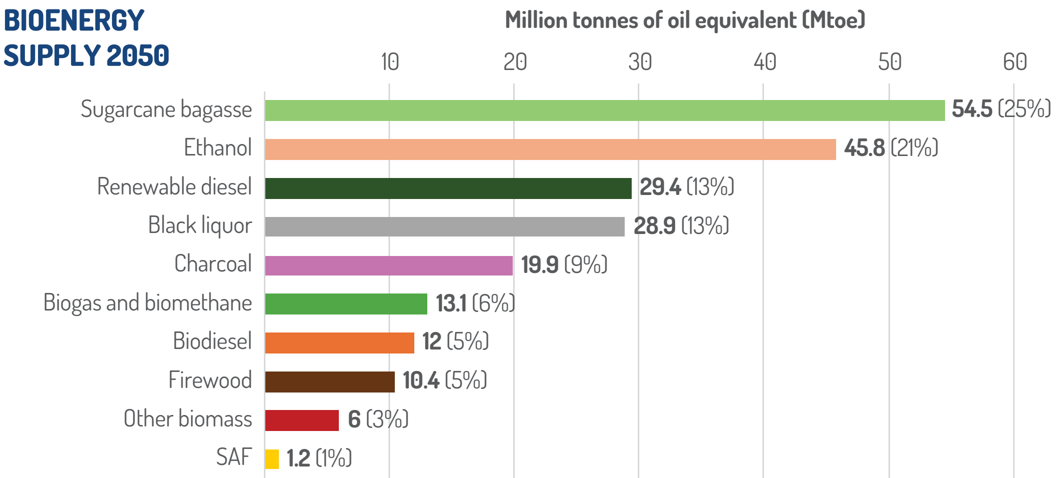
Figure 9 – **Historical bioenergy consumption (1970–2024) and projections according to the OC's vision for Brazil's energy transition (2025–2050)**

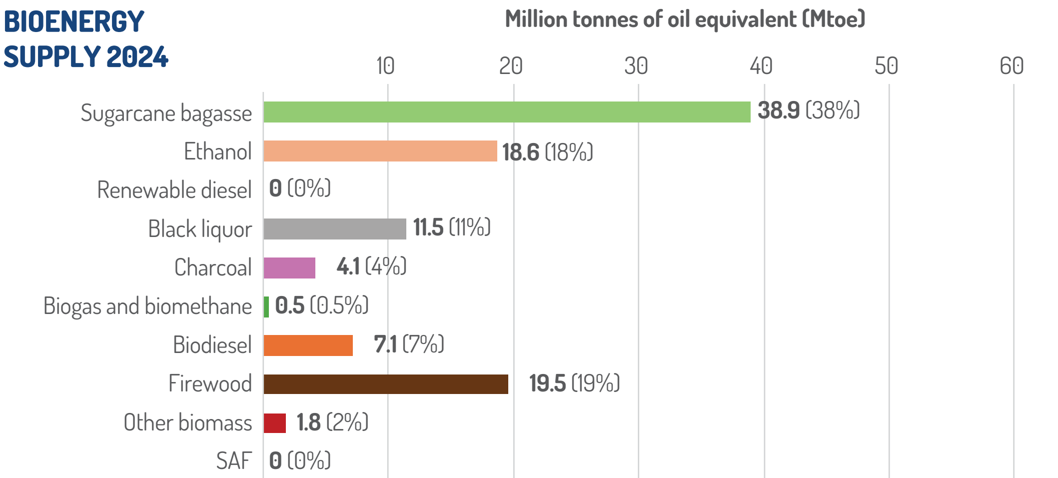


Source: National Energy Balance (EPE, 2025b) and Future of Energy (OC, 2024b).

Figure 10 provides a more detailed comparison between bioenergy supply in 2024, according to the *National Energy Balance (Balanço Energético Nacional – BEN)* (EPE, 2025b), and the Brazilian Climate Observatory's vision for 2050 (OC, 2024b).

Figure 10 – Bioenergy supply and share of each biofuel in total supply for the years 2024 (historical) and 2050 (projection)





Source: National Energy Balance (EPE, 2025b) and Future of Energy (OC, 2024b).

A significant expansion is expected for almost all biofuels, except firewood, which remains widely used for residential cooking. This use of firewood is energetically inefficient, methane-intensive (CH_4 – a greenhouse gas dozens of times more potent than CO_2), and produces local air pollutants harmful to human health, such as particulate matter (PM) and carbon monoxide (CO). In reality, this use of firewood is an indicator of energy poverty rather than an appropriate application of bioenergy, and it should be minimized or eliminated, especially in urban contexts.

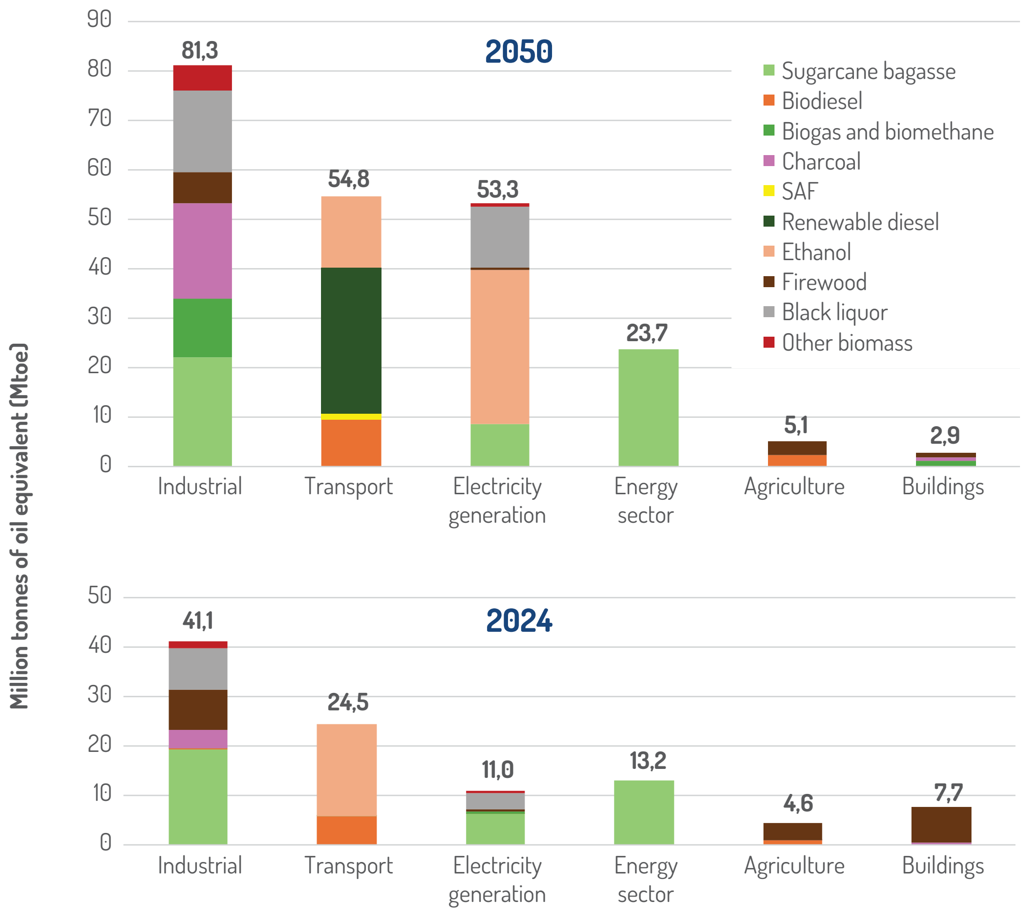
Technologies already well-established today—such as ethanol and charcoal—will need to be scaled up, supporting the decarbonization of transport (mainly light vehicles), electricity generation, and industry (particularly steelmaking). The OC's vision projects that ethanol use will grow by 146 % between 2024 and 2050, while charcoal use will increase by 384 % over the same period.

Also noteworthy is the consolidation of new or currently underdeveloped solutions: biomethane, renewable diesel, and sustainable aviation fuel (SAF). Over the next

25 years, Brazil is expected to produce, for example, 29.4 Mtoe of renewable diesel through biorefineries. This biofuel will be crucial for replacing fossil diesel, which primarily fuels heavy-duty vehicles, since it can be used in existing engines without requiring modifications or new vehicle technologies. This is particularly promising because it enables decarbonization of operations without the need to renew the entire fleet of 2.1 million trucks[8] – vehicles currently in circulation will remain in use for many years — or to modify the existing fuel-distribution infrastructure.

Figure 11 illustrates the importance of renewable diesel for transport by 2050, as well as the use of different biofuels across various energy-consuming activities.

Figure 11 – Biofuel demand by sector for the years 2024 (historical value) and 2050 (projection)



Source: National Energy Balance (EPE, 2025b) and Future of Energy (OC, 2024b).

8 Values for the year 2024 were calculated based on the methodology of the *National Inventory of Atmospheric Emissions from Road Motor Vehicles*, published in 2014 by the Ministry of the Environment (MMA) in partnership with the Institute for Energy and the Environment (IEMA) and other organizations (MMA, 2014).

4.2 Definition of Biofuel Supply Scenarios

4.2.1 Technological Pathways and Feedstocks Considered

After modeling future biofuel demand for decarbonizing energy use under a scenario of average GDP growth of 2.1 % per year, this study seeks to estimate the magnitude of the land area required to cultivate the feedstocks that will support the expansion of bioenergy supply in Brazil.

This enables the evaluation of how the strategy proposed by the Brazilian Climate Observatory (OC) in the *Future of Energy* report (OC, 2024b) aligns with its land-use transition, restoration, and conservation premises set out in the organization's NDC proposal (2024a).

The model developed for *Future of Energy* identified the demand for various biofuels through 2050, but did not determine the corresponding technological pathways and feedstocks to be used. Distributing biofuels across their respective production routes is a necessary step to estimate the cultivated area required for energy crops, since each combination of technology and feedstock features a different productivity rate (the amount of energy delivered by a biofuel relative to the area required to cultivate its agricultural feedstock).

Ethanol, biodiesel, renewable diesel, and sustainable aviation fuel (SAF) exhibit significant diversity in both production technologies and feedstocks that can be employed. A single agricultural crop may serve as input for different biofuels, depending on the chosen technological pathway.

The pathways considered in this study for each energy crop, used later for estimating the land-area demand scenarios, are described below.

Sugarcane cultivation:

- The juice extracted from sugarcane can be used to produce first-generation ethanol.
- The milling of sugarcane to obtain juice also generates bagasse, which can be burned for energy recovery (electricity and heat generation).
- Instead of being burned, bagasse can also be used to produce second-generation ethanol, a process so named because it does not require food-grade feedstocks. In this process, a portion of the bagasse remains that can no longer yield ethanol but can still be used directly as fuel (combustion).
- Both first- and second-generation ethanol can be used directly as fuel or as feedstock for renewable diesel and sustainable aviation fuel (SAF) production through a technological pathway known as ATJ (Alcohol-to-Jet).

Soybean cultivation:

- The oil extracted from soybean grains can, through the transesterification process, be converted into biodiesel (FAME – Fatty Acid Methyl Ester).
- Alternatively, soybean oil can be directed to produce renewable diesel[9] and sustainable aviation fuel (SAF) via the HEFA route (Hydroprocessed Esters and Fatty Acids), both of which are co-produced in a biorefinery.

Soybean cultivation in crop rotation with corn as a second crop:

- As noted above, soybean oil can be used to produce biodiesel (FAME) or renewable diesel and SAF (HEFA).
- From corn, starch can be extracted and then converted into first-generation ethanol.
- Corn ethanol can be used directly for energy consumption or as feedstock in biorefineries producing renewable diesel and SAF via the ATJ (Alcohol-to-Jet) pathway.

Macaúba cultivation:

- Macaúba is a palm species native to the Americas, whose fruit yields a highly productive vegetable oil, similar to that of oil palm. This oil can be used to produce biodiesel (FAME) or renewable diesel and SAF (HEFA).

Silviculture:

- From planted forests, mainly eucalyptus or pine, it is possible to obtain firewood, charcoal, or black liquor (a by-product of the pulp and paper industry).

Other biofuel sources:

- Biogas results from the anaerobic decomposition (in the absence of oxygen) of organic matter and can be collected in a controlled manner—for example, from landfills or biodigesters fed with agro-industrial residues, such as animal waste or vinasse (generated during ethanol production). Hence, this biofuel is not considered a direct driver of new land occupation.
- Biomethane is obtained by purifying biogas, removing impurities so that the resulting gas consists almost entirely of methane.
- The *National Energy Balance (EPE, 2025b)*—and consequently the projections from *Future of Energy*—still include an aggregate bioenergy category called "other biomass," which covers lesser-used biofuels such as

9 The renewable diesel resulting from the HEFA biorefining process is of the HVO type (Hydrotreated Vegetable Oil).

elephant grass. The land area required to produce these "other biomass" sources is not estimated here, since demand for such biofuels is minimal compared with the others and, above all, because there is no specific information on the actual composition of this aggregated category.

The soybean, corn, and sugarcane crops were selected here as the feedstock sources for ethanol, biodiesel, renewable diesel, and SAF, since they currently account for the major share of ethanol production (sugarcane and corn) and biodiesel production (soybean). Although other products such as wheat, castor bean, and sugar beet could also be used, it is highly likely that the dominant use of soybean, corn, and sugarcane will continue—both for the production of ethanol and biodiesel, which are already established in Brazil's energy matrix, and for the production of renewable diesel and sustainable aviation fuel (SAF), which are still practically non-existent in Brazil[10].

In addition, these crops are tied to other productive chains that further strengthen their role as the main feedstocks for biofuel production. These include sugar production (sugarcane) and grain, meal, and soybean oil production (soybean and corn in second-crop systems)—all of which are highly relevant products in both the domestic and export markets.

As a representative of alternative oil-producing feedstocks, this study simplistically considers only macaúba cultivation. This oil-bearing palm stands at the opposite extreme from soybean in terms of oil productivity (kg/ha): while macaúba can yield 4,000 kg of oil per hectare, soybean yields around 400 kg/ha (*Embrapa*). Moreover, macaúba is native to Brazil and occurs across much of the national territory (especially in the Cerrado biome) (*BiodieselBR, 2023*), making it suitable for production systems that adopt sustainable agricultural practices, such as agroforestry, which integrates agricultural and forestry species.

Regarding the production processes for renewable diesel and SAF, the sensitivity analysis of the areas required for the manufacture of these fuels will consider only the HEFA and ATJ pathways, even though others exist, such as gasification/Fischer–Tropsch. This is because HEFA and ATJ are the two most commercially viable routes to date.

The HEFA technology has become dominant (EPE, 2025a), with average international costs tending to be lower than those of other alternatives (ICCT, 2019). The ATJ route has also been gaining commercial traction (EPE, 2025a) and fits well with Brazil's context, given its well-established ethanol industry, which provides a key input for this pathway. Consequently, production costs for renewable diesel and SAF via ATJ technology in Brazil could be even lower than via HEFA (*MIT, 2024*).

Furthermore, companies—including Petrobras—have already announced projects for the construction of HEFA and ATJ biorefineries in Brazil (EPE, 2025a).

Finally, it is worth noting that this study considers the use of sugarcane bagasse

10 Petrobras is already capable of producing renewable diesel through coprocessing with fossil diesel, resulting in a blend containing 5 % renewable diesel and 95 % petroleum diesel, marketed as Diesel R (Petrobras, 2025).

only for the production of second-generation ethanol, that is, ethanol derived from lignocellulosic feedstock that is not used for food purposes. Bagasse (and sugarcane straw) has already been employed for this purpose in the few operational plants currently running in Brazil and will likely see this application expand and become more predominant in the near future.

4.2.2 Participation of Different Feedstocks and Technologies in the Supply of Each Biofuel

Table 1 presents the projected demand from the *Future of Energy* study (OC, 2024b) for each of the biofuels considered in the sensitivity analysis of the total area of energy crops required for their production.

In this exercise, the feedstocks and technologies used to supply the values shown in Table 1 vary only for biodiesel, ethanol, renewable diesel, and SAF.

In 2024, 80 % of ethanol was produced from sugarcane and 20 % from corn (EPE, 2025b), both through first-generation routes. Although 72.4 % of the biodiesel produced in Brazil in 2024 used soybean oil as feedstock[11] (EPE, 2025a), for the sake of simplicity **this study assumes that 100 % of biodiesel came from soybean oil**.

This distribution of feedstock and technology for ethanol and biodiesel production in 2024 is therefore considered the **baseline scenario** for the analysis.

Table 1: Bioenergy demand in commercial units for the years 2024 (historical value), 2035, 2045, and 2050 (projection)

	2024	2035	2045	2050	Additional demand (2050 vs. 2024)
Billions of liters					
Biodiesel	**9.0**	**13.8**	**14.9**	**15.2**	**6.2**
Ethanol	**36.0**	**72.6**	**84.0**	**89.7**	**53.8**
Renewable diesel	**0.0**	**3.5**	**20.8**	**34.6**	**34.6**
SAF	**0.0**	**0.4**	**1.0**	**1.4**	**1.4**
Millions of tonnes					
Sugarcane bagasse	**182.6**	**256.6**	**256.5**	**255.8**	**73.2**
Charcoal	**6.4**	**18.3**	**26.8**	**30.8**	**24.5**
Firewood	**63.0**	**42.7**	**36.2**	**33.7**	**–29.3**
Black liquor	**40.0**	**63.3**	**88.0**	**100.9**	**60.9**

Source: National Energy Balance (EPE, 2025b) and Future of Energy (OC, 2024b).

To understand the order of magnitude of land areas required for energy

11 The remaining 27.6 % were produced using beef tallow (5.6 %), palm oil (0.7 %), and other fatty materials (21.3 %), such as used cooking oil (EPE, 2025a).

crops under different technological pathway and feedstock combinations detailed earlier (Section 4.2.1), six supply scenarios for 2050 were defined (Figure 12) and applied to the values presented in Table 1.

Figure 12: Scenarios of feedstock and technology participation in the supply of biodiesel, ethanol, renewable diesel, and SAF in 2050

BASE SCENARIO – 2024
Ethanol: 80% from sugarcane (1G) + 20% from second-crop corn (1G)
Biodiesel: 100% from soybean (FAME)
Renewable diesel and SAF: no production

(same shares as in 2024)
BUSINESS AS USUAL (BAU) 2050:
Ethanol: 80% from sugarcane (1G) + 20% from second-crop corn (1G)
Biodiesel: 100% from soybean (FAME)
Renewable diesel and SAF: 100% from soybean (HEFA)

SUGARCANE/SOYBEAN/MACAÚBA 2050
Ethanol: 70% from sugarcane (1G + 2G) + 30% from second-crop corn (1G)
Biodiesel: 50% from soybean (FAME) + 50% from macaúba (FAME)
Renewable diesel and SAF: 100% from sugarcane (1G + 2G + ATJ)

FOCUS ON SOYBEAN 2050:
Ethanol: 100% from second-crop corn (1G)
Biodiesel: 100% from soybean (FAME)
Renewable diesel and SAF: 45% from soybean (HEFA) + 55% from corn (1G + ATJ)

FOCUS ON MACAÚBA 2050:
Ethanol: 100% from sugarcane (1G + 2G)
Biodiesel: 100% from macaúba (FAME)
Renewable diesel and SAF: 100% from macaúba (HEFA)

FOCUS ON SUGARCANE 2050:
Ethanol: 40% from sugarcane (1G + 2G) + 60% from second-crop corn (1G)
Biodiesel: 100% from soybean (FAME)
Renewable diesel and SAF: 100% from sugarcane (1G + 2G + ATJ)

SUGARCANE/MACAÚBA 2050:
Ethanol: 100% from sugarcane (1G + 2G)
Biodiesel: 100% from macaúba (FAME)
Renewable diesel and SAF: 100% from sugarcane (1G + 2G + ATJ)

The following considerations apply to Figure 12:

- Since it is currently the most common production route (EPE, 2025a), it was assumed that renewable diesel and SAF will be produced using HEFA technology in the BAU 2050 scenario. Moreover, the only feedstock used for these fuels in that scenario will be soybean, given that it is presently Brazil's main source of vegetable oil for biofuel production.

- Except for the BAU 2050 scenario, it was assumed that all soybean-planted areas for biofuel production in 2050 will also produce corn as a second crop. The corn will be used primarily for ethanol production (for direct consumption) and, if there is surplus, for renewable diesel and SAF production via the ATJ (Alcohol-to-Jet) route.

- The participation of second-crop corn in the production of ethanol and renewable diesel/SAF in the "*Soybean-Focused 2050,*" "*Sugarcane-Focused 2050,*" and "*Sugarcane/Soybean/Macaúba 2050*" scenarios was calculated based on the previous premise, along with the biofuel productivity levels (L/ha) derived from corn and soybean by-products (see Table 2).

- The production of sugarcane bagasse, charcoal, firewood, and black liquor is included in the sensitivity analysis of total agricultural areas required but is not represented here, as these sources do not vary by technological route or feedstock.

- "1G" refers to the first generation, and "1G+2G" refers to the combined first and second generations.

4.3 Productivity: Biofuel Production per Hectare of Cultivated Feedstock

To convert the quantities of biofuels demanded in 2024 and 2050 (see Table 1) into land-use estimates under the different scenarios of technological routes and feedstocks (see Figure 12), it was necessary to determine productivity values expressed in liters or kilograms of biofuel produced per hectare of agricultural feedstock cultivated. The figures obtained, along with their respective references, are shown in Table 2.

For example, **by multiplying 15,200,000,000 liters** (15.2 billion liters)—the projected demand for biodiesel in 2050—**by 50 %**, which represents the share of macaúba in biodiesel (FAME) production under the "*Sugarcane/Soybean/Macaúba 2050*" scenario, **and then dividing the partial result by 4,210 L/ha/year, we obtain the cultivated area** of macaúba required in that scenario: **1.8 million hectares per year.**

It is important to note that, as mentioned in Section 4.2.1, some cropping systems can supply different feedstocks and, consequently, yield different biofuels. This is the case of soybean grown in rotation with corn, which, within the same area, supplies both corn for ethanol production and soybean oil for biodiesel production.

A similar situation occurs with sugarcane cultivation, where the same crop—and therefore the same area—produces juice for ethanol and bagasse used for electricity or heat generation.

In such cases, cultivated areas were counted only once in the analysis, thereby eliminating any double counting.

Table 2: Biofuel productivity by technological route/feedstock

Biofuel	Feedstock	Technology	Productivity	Parameters and references used
thousand liters per hectare per year (thousand L/ha/year)				
Ethanol	**Sugarcane**	First Generation (1G)	**6.88**	80.9 tonnes of sugarcane/ha/year (EPE, 2024); 85.0 liters of 1G ethanol per tonne of sugarcane (Socicana, 2020)
		Second Generation (2G)	**1.73**	80.9 tonnes of sugarcane/ha/year (EPE, 2024); 0.28 tonnes of bagasse per tonne of milled sugarcane (NovaCana); 50% moisture per tonne of bagasse (NovaCana); 153 liters of 2G ethanol per tonne of dry bagasse (Pinheiro et al., 2025)
	Corn	First Generation (1G)	**2.48**	6.1 tonnes of corn/ha/year (Conab, 2025); 407 liters of 1G ethanol per tonne of corn (Senar, 2023)
Biodiesel	**Soybean**	FAME	**0.71**	3.56 tonnes of soy/ha/year (Embrapa, 2025); 19% oil per tonne of soybean grain (StoneX, 2022); 926.1 g of soy oil/liter of soy oil (Costa, 2021); 0.975 liters of biodiesel per liter of vegetable oil (Ferrari; Oliveira; Scabio, 2005)
	Macaúba	FAME	**4.21**	4,000 kg of oil/ha/year (Embrapa); 926 g of oil/liter of oil (Moura et al., 2019); 0.975 liters of biodiesel per liter of vegetable oil (Ferrari; Oliveira; Scabio, 2005)
Renewable diesel	**Soybean**	HEFA (optimized for renewable diesel process)	**0.47**	3.56 tonnes of soy/ha/year (Embrapa, 2025); 19% oil per tonne of soybean grain (StoneX, 2022); 926.1 g of soy oil/liter of oil (Costa, 2021); 0.83 liters of refined fuel/liter of vegetable oil (Yeh; Goh, 2022); 0.77 liters of renewable diesel/liter of refined fuel (ICCT, 2019)
	Macaúba	HEFA (optimized for renewable diesel process)	**2.77**	4,000 kg of oil/ha/year (Embrapa); 926 g of oil/liter of oil (Moura et al., 2019); 0.83 liters of refined fuel/liter of vegetable oil (Yeh; Goh, 2022); 0.77 liters of renewable diesel/liter of refined fuel (ICCT, 2019)
	Sugarcane	ATJ (with 1G and 2G ethanol) (optimized for renewable diesel process)	**3.99**	80.9 tonnes of sugarcane/ha/year (EPE, 2024); 85.0 L 1G ethanol/t sugarcane (Socicana, 2020); 0.28 t bagasse/t milled sugarcane (NovaCana); 50% moisture per tonne of bagasse (NovaCana); 153 L 2G ethanol/t dry bagasse (Pinheiro et al., 2025); 0.56 liters SAF/liter ethanol (Copersucar, 2025); 90% SAF yield optimized process; 75% renewable diesel yield optimized process (LanzaJet, 2025)
	Corn	ATJ (with 1G ethanol) (optimized for renewable diesel process)	**1.15**	6.1 tonnes of corn/ha/year (Conab, 2025); 407 L 1G ethanol/t corn (Senar, 2023); 0.56 L SAF/L ethanol (Copersucar, 2025); 90% SAF yield optimized process; 75% renewable diesel yield optimized process (LanzaJet, 2025)

Biofuel	Feedstock	Technology	Producti-vity	Parameters and references used
SAF	Soybean	HEFA (optimized for renewable diesel process)	0.09	3.56 t soy/ha/year (Embrapa, 2025); 19% oil/t soybean (StoneX, 2022); 926.1 g soy oil/L oil (Costa, 2021); 0.83 L refined fuel/L vegetable oil (Yeh; Goh, 2022); 0.135 L SAF/L refined fuel (ICCT, 2019)
	Macaúba	HEFA (optimized for renewable diesel process)	0.47	4,000 kg oil/ha (Embrapa); 926 g oil/L oil (Moura et al., 2019); 0.83 L refined fuel/L vegetable oil (Yeh; Goh, 2022); 0.135 L SAF/L refined fuel (ICCT, 2019)
	Sugarcane	ATJ (with 1G and 2G ethanol) (optimized for renewable diesel process)	1.33	80.9 t sugarcane/ha (EPE, 2024); 85.0 L 1G ethanol/t sugarcane (Socicana, 2020); 0.28 t bagasse/t sugarcane (NovaCana); 50% moisture/t bagasse (NovaCana); 153 L 2G ethanol/t dry bagasse (Pinheiro et al., 2025); 0.56 L SAF/L ethanol (Copersucar, 2025); 90% SAF yield optimized; 25% SAF yield for renewable diesel process (LanzaJet, 2025)
	Corn	ATJ (with 1G ethanol) (optimized for renewable diesel process)	0.38	6.1 t corn/ha (Conab, 2025); 407 L 1G ethanol/t corn (Senar, 2023); 0.56 L SAF/L ethanol (Copersucar, 2025); 90% SAF yield optimized process; 25% SAF yield for renewable diesel process (LanzaJet, 2025)
thousand kilograms per hectare per year (thousand kg/ha/year)				
Sugarcane bagasse	Sugarcane	Post-milling	22.65	80.9 t sugarcane/ha/year (EPE, 2024); 0.28 t bagasse/t milled sugarcane (NovaCana)
		Sugarcane	4.55	80.9 t sugarcane/ha/year (EPE, 2024); 0.28 t bagasse/t milled sugarcane (NovaCana); 50% moisture/t bagasse (NovaCana); 30% lignin and ash content post-milling (Antunes et al., 2022); 10% losses in 2G ethanol process (Melo, 2020)
Firewood	Eucalyptus	Silviculture	13.14	33.7 m^3 wood/ha/year (Ibá, 2024); 90 kg wood/m^3 wood (EPE, 2022)
Charcoal	Eucalyptus	Silviculture	3.36	33.7 m^3 wood/ha/year (Ibá, 2024); 390 kg wood/m^3 wood (EPE, 2022); 25% of firewood mass converted to charcoal in kilns (EPE, 2025b)
Black liquor	Eucalyptus	Silviculture	9.86	33.7 m^3 wood/ha/year (Ibá, 2024); 390 kg wood/m^3 wood (EPE, 2022); 0.5 t pulp/t wood (Gominho et al., 2015); 1.5 t black liquor/t pulp (Tran; Vakkilainen, 2016)

4.4 Results: Allocation of Biofuel Demand by Area

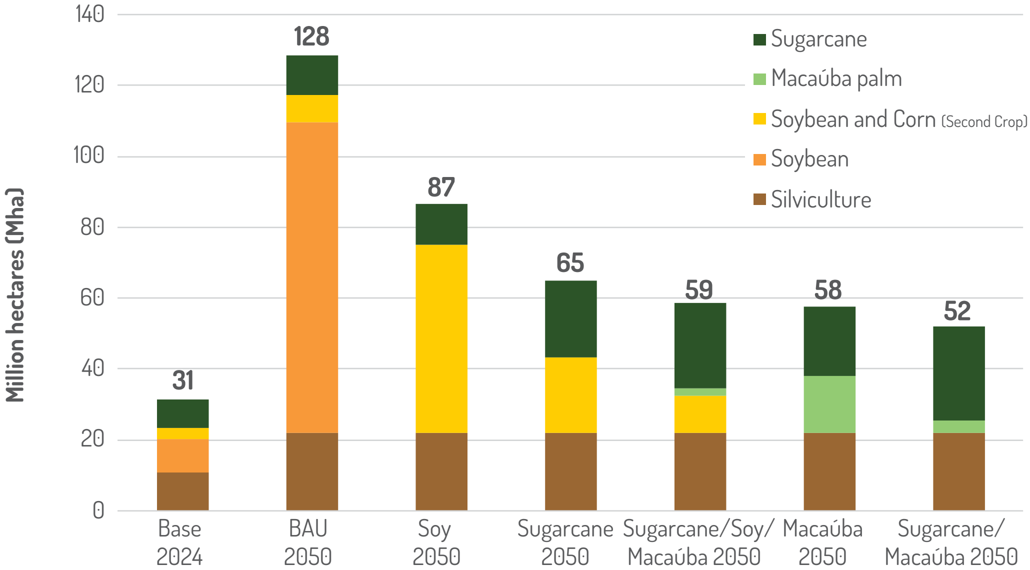
Table 3 and Figure 13 present the estimated land areas required for the production of feedstocks for biofuels, in order to meet the demand projected by the Brazilian Climate Observatory (OC) in its vision for a just energy transition. The figures, expressed in million hectares (Mha), are organized by energy crop and supply scenario. Below, for each scenario analyzed, both the total area estimates and the additional area relative to the year 2024 are presented.

Table 3: Results of the sensitivity analysis of land area requirements for feedstock production for biofuels in 2050

Energy crop	Land use scenarios (Mha)						
	Base – 2024	BAU 2050	Soy 2050	Sugarcane 2050	Sugarcane/Soy/ Macaúba 2050	Macaúba 2050	Sugarcane/Ma-caúba 2050
Sugarcane	8.1	11.3	11.3	21.7	24.1	19.6	26.6
Soybean (without second-crop corn)	9.5	87.6	0.0	0.0	0.0	0.0	0.0
Soybean and Corn (Second Crop)	3.0	7.6	53.2	21.3	10.6	0.0	0.0
Macaúba palm	0.0	0.0	0.0	0.0	1.8	16.1	3.6
Silviculture	10.7	22.0	22.0	22.0	22.0	22.0	22.0
TOTAL	31.4	128.5	86.5	64.9	58.5	57.7	52.1
Additional area relative to 2024	–	97.1	55.1	33.5	27.1	26.3	20.7

Source: Own elaboration.

Figure 13: Estimated total land areas for feedstock cultivation required to meet biofuel demand (see Table 1), according to the proposed supply scenarios (see Figure 12)



Source: Own elaboration.

It is important to emphasize that these figures do not represent land exclusively dedicated to biofuels. In the Base Scenario, it is estimated that 4.1 Mha of sugarcane plantations were required to obtain the sugarcane juice used to produce

28.8 billion liters of ethanol. The 8 Mha occupied by sugarcane fields in 2024 also include 3.9 Mha used to produce juice destined for sugar production. The milling of sugarcane for ethanol or sugar always generates bagasse as a by-product, which can be used for energy recovery. In other words, in approximately 50 % of sugarcane areas, there is an overlap between food production (sugar) and bioenergy (bagasse).

A similar overlap occurs in 100 % of the areas used for soybean cultivation. All 12.5 Mha estimated in this analysis as soybean area were utilized both for oil extraction—directed to the biodiesel industry—and for the production of food by-products, especially soybean meal, which is mainly used as animal feed for meat, milk, egg, and dairy production. Thus, animal feed remains the primary economic driver of soybean cultivation. Soybean meal, subsequently used in livestock production, is obtained through soybean crushing, which also yields oil as a co-product, enabling biofuel manufacturing.

Even in silviculture, multiple uses of feedstocks—and consequently, of land—can be observed. In the pulp and paper industry, for example, wood is used as the main raw material for these products, while black liquor, generated as a by-product of industrial processing, is used as an energy source/biofuel.

These potential overlaps in land use must therefore be taken into account when interpreting the projected results for 2050. Overall, as shown in Figure 13, the estimates range from 50 to 130 million hectares, highlighting the high sensitivity of land-use requirements for biofuel feedstock production, whether wholly or partially dedicated, depending on the crop mix adopted.

Scenarios with greater participation of soybean-based biofuels result in higher total land demands by 2050, even though this crop simultaneously serves other industries (notably the food sector) and allows for second-crop corn production.

The highest land requirement corresponds to the Business-as-Usual (BAU) Scenario, in which 100 % of biodiesel, renewable diesel, and SAF are produced from soybean oil, 20 % of ethanol from corn grown as a second crop on land also used for soybean cultivation in the same year, and 80 % of ethanol from sugarcane. Without using soybean-cultivated areas to also produce second-crop corn for ethanol or renewable diesel/SAF, the land demand in the BAU scenario skyrockets, reaching 128 million hectares needed for bioenergy production.

This number drops to 87 Mha in the "*Soybean-Focused 2050*" scenario, which remains centered on soybean but fully exploits the potential for producing ethanol, renewable diesel, and SAF from corn grown in crop rotation with soybean—a good practice that helps "save" land.

In scenarios with greater participation of sugarcane and macaúba, the demand for land dedicated to energy crops remains high but begins to decline, suggesting the feasibility of producing biofuels in Brazil while simultaneously producing food and restoring and protecting natural areas.

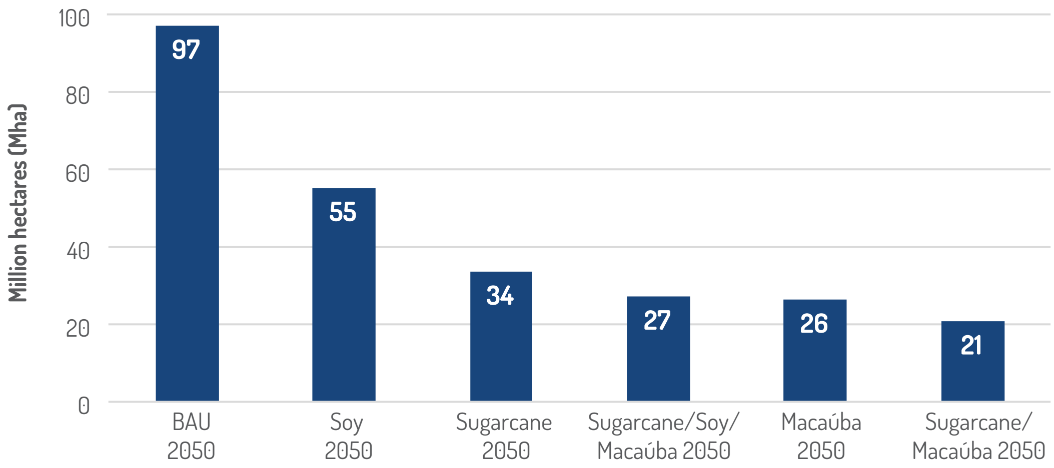
Thus, when analyzing these results, the central question arises once again:

Is it possible to expand biofuel feedstock production exclusively within the approximately 56 million hectares (Mha) of degraded pastures to be converted into new agricultural areas?

Even with simplifications, the results suggest that the answer tends to be yes, provided that the production of biodiesel, renewable diesel, and sustainable aviation fuel (SAF) is not centered exclusively on soybean cultivation. It should be reaffirmed, however, that within this agricultural expansion area, food production must take precedence over biofuel production.

By subtracting the 31 Mha currently used for biofuel production from the total land requirements projected across the various 2050 scenarios, the following figures for additional area needs were obtained (Figure 14): 97, 55, 34, 27, 26, and 21 Mha. These numbers represent, under different supply scenarios (combinations of feedstocks and technological routes), the additional areas required to meet the biofuel demand projected under OC's vision.

Figure 14: Estimated additional land area required by 2050 to meet biofuel demand



Source: Own elaboration.

The two scenarios requiring the addition of 97 Mha or 55 Mha of energy crops exceed the available "stock" of 56 Mha suitable for agricultural use—especially considering that, by 2050, food production and feedstock cultivation for other industries (such as textiles) must also be accommodated within the same 56 Mha.

However, the remaining scenarios would occupy between 60 % and 37.5 % of the areas currently classified as degraded pastures, which, according to the OC's vision presented in Chapter 3, are expected to be converted specifically to agriculture.

Accordingly, energy crops could require approximately 20 to 35 million additional hectares by 2050. Any expansion beyond that range would be inconsistent with the available land stock. This variation reflects the different pathways the bioenergy industry could take by mid-century:

- "Sugarcane/Macaúba 2050" scenario: ethanol, renewable diesel, and SAF would be produced exclusively from sugarcane, while biodiesel would come solely from macaúba.
- "Macaúba 2050" scenario: 100 % of biodiesel, renewable diesel, and SAF would be produced from macaúba, while ethanol would come entirely from sugarcane.
- "Sugarcane/Soybean/Macaúba 2050" scenario: ethanol would be produced from sugarcane and corn, biodiesel from soybean and macaúba, and 100 % of renewable diesel and SAF from sugarcane.
- "Sugarcane 2050" scenario: ethanol would come from sugarcane and corn, renewable diesel and SAF would also come from sugarcane, and 100 % of biodiesel would be derived from soybean oil.

Therefore, the results indicate that it is indeed possible, even with highly ambitious decarbonization goals for Brazil's economy, to increase biofuel feedstock production entirely within existing low- and medium-vigor pasture areas, without causing new deforestation, and while respecting the allocation of part of these degraded lands for forest restoration and food production, as illustrated in Figure 5.

However, for this to effectively occur, soybean—one of the least productive feedstocks for biofuel production—cannot remain the flagship of Brazil's bioenergy expansion. It will be essential to promote the development of new technological routes, such as second-generation ethanol, and to encourage the cultivation of feedstocks like macaúba, which require less land per hectare to produce biodiesel, renewable diesel, and SAF.

Moreover, it must be acknowledged that the magnitude of land areas potentially required for biofuel production by 2050 is considerable. Therefore, to ensure that energy-crop areas do not compete with essential land uses—such as forests and food production—Brazil will need to implement public policies for planning, monitoring, and controlling the expansion of the biofuel industry.

Limits of the Analysis and Potential for Future Studies

This study does not aim to exhaust the discussion on how Brazil can expand its biofuel supply to decarbonize its economy in an ambitious and equitable way—without causing further deforestation. In fact, it should be seen as a starting point. It is expected that, based on the limitations of this analysis, other studies will be developed to further refine the debate and understanding of this subject.

This work relied on highly aggregated land-use data and on the current productivity levels of crops cultivated in monoculture systems for biofuel feedstock supply. Based on this information, the study mapped both the available and required areas for expanding feedstock production, outlining pathways to achieve this expansion without new deforestation and in compliance with a range of socio-environmental safeguards.

Among the factors that could serve as directions for future research, and which were not addressed in this study, the following stand out:

- An assessment of land prices and ownership structures for degraded areas;
- A land suitability map (soil and climate) for various energy crops;
- The potential productivity gains of these crops by 2050;
- The possibilities of producing feedstocks through more sustainable models, such as Integrated Crop-Livestock-Forestry Systems (ICLFS) and agroforestry;
- A topographic characterization of areas with potential for feedstock production expansion;
- An evaluation of water availability in these areas and of the water demand that feedstock production may generate;
- Climate change scenarios that could affect agriculture;
- An expansion of feedstock and technological-route scenarios for biofuel manufacturing;
- An analysis of international bioenergy demand, particularly for sustainable aviation fuel (SAF);
- The impacts of using genetically modified crops and agrochemicals, as well as the identification of alternative management solutions;
- The potential of bioenergy in terms of job quality and quantity;
- An integrated assessment of the land areas required for other forms of energy generation and use, especially electricity, since wind and solar plants also require physical space for installation.

5. The Need for Socio-environmental Safeguards

Betting on biofuels also means that Brazil will continue to produce agricultural feedstocks on a large scale, which currently rely on intensive pesticide use[12] and monocultures that affect soil, water, and local ecosystems. The risk is that this expansion could intensify a range of socio-environmental impacts, such as increased deforestation, rural exodus, land concentration, labor exploitation, and contamination of water bodies. Combined with concerns about competition for land with food production, these are the main factors that generate resistance to bioenergy as a pathway for Brazil's energy transition.

There is also apprehension that using land for commodity production may compromise food security itself. Without minimum safeguards, the pursuit and acquisition of more fertile land for biofuel feedstock production could not only increase land concentration, but also exacerbate land conflicts, population displacement, and biodiversity loss.

This dynamic has already been observed in Brazil's Center-South region, where sugarcane expansion has displaced rice, beans, corn, coffee, and other crops into new areas (*Aguiar; Souza, 2014*). Moreover, although biodiesel can be produced from a diverse range of plant and animal feedstocks—such as macaúba, sunflower, oil palm, peanut, castor bean, or beef tallow—more than 70 % is produced from soybean oil, grown primarily for export markets.

In turn, the production of charcoal and firewood is linked to energy forests, which are planted, harvested, and replanted in cycles designed to reduce pressure on natural forests. Eucalyptus and pine are the main species used for this purpose

12 Brazil is considered the world's largest user of pesticides, according to the Food and Agriculture Organization of the United Nations (FAO). More than 800 tonnes of pesticides were applied to Brazilian crops in 2023—more than the combined use of the United States and Indonesia, the world's second- and third-largest consumers, respectively. A 2024 study by the consultancy Kynetec Brasil showed that soybean, corn, and sugarcane rank first, second, and fifth, respectively, among the crops that use the most pesticides in the country. Experts warn that large-scale monocultures make crops more vulnerable to pests and diseases, increasing dependence on pesticides to maintain high productivity. More information can be found in the following sources:

JORNAL DA USP, 2025. *Monoculture, the foundation of agribusiness, depends on pesticide use*. Available at: https://jornal.usp.br/radio-usp/monocultura-alicerce-do-agronegocio-e-dependente-do-uso-de-agrotoxicos/. Accessed on: 12 Sept. 2025.

GLOBO RURAL, 2024. *Area treated with pesticides increases by more than 10% in Brazil*. Available at: https://globorural.globo.com/insumos/noticia/2024/11/area-tratada-com-defensivos-aumenta-mais-de-10percent-no-brasil.ghtml. Accessed on: 12 Sept. 2025.

FAO, 2025. FAOSTAT – *Pesticides Use*. Available at: https://www.fao.org/faostat/en/#data/RP. Accessed on: 12 Sept. 2025.

due to their high energy content and rapid growth, but they are not native species in Brazil. Depending on the region, biome, previous land-use conditions, and management practices adopted, they may cause local ecosystem impacts, such as soil drying and degradation, reduced biodiversity, and lowering of the water table (*Repórter Brasil, 2011*).

Indonesia provides an example of what Brazil must avoid if it is to pursue a just energy transition without causing new socio-environmental harm. The Southeast Asian country expanded oil palm cultivation (a species similar to Brazil's macaúba) over its primary tropical forests to produce oil used mainly by the food industry, but also by cosmetics, detergent, and biofuel manufacturers.

According to a study on the subject (*Gaveau et al., 2022*), the area dedicated to oil palm cultivation in Indonesia is estimated to have doubled between 2001 and 2019, reaching 16.2 million hectares—64 % of which are industrial-scale operations and 36 % managed by smallholders. During the same period, natural forest area decreased by 9.8 million hectares, representing an 11 % reduction in forest cover.

A report by the European Union (European Parliament, 2020)—which identifies Indonesia and Malaysia as the world's leading palm oil producers, accounting for 42 % and 36 % of global production, respectively—states that monoculture production of this commodity has endangered tropical forests, threatened biodiversity, and, paradoxically, increased GHG emissions associated with deforestation.

"It is claimed that the sector provides direct employment to nearly 1 million people in Malaysia and 4 million in Indonesia, often in remote rural areas where alternative employment is scarce. However, not everyone has benefited; in Indonesia, Indigenous communities often lack legal documentation proving their land ownership, and numerous legal disputes exist between companies holding government concessions in forest areas and the people who have used the land for centuries. In some cases, this has resulted in local populations losing access to land and resources," the report states.

"Deforestation is the main reason palm oil remains controversial. Expanding production requires more land for new plantations. This does not necessarily lead to further deforestation, as oil palms can be planted on degraded or previously cultivated land. However, scientific studies suggest that 45 % of the area covered by new plantations was previously natural forest," it adds.

The EU document also notes that Indonesia has adopted a series of measures to make palm oil production more sustainable. For example, since 2011, the country has ceased granting new concessions for clearing primary forests to open new production frontiers. Despite this, the report highlights that Indonesia lost more than 10,000 km² of forest per year between 2017 and 2019, largely due to palm oil production. "The good news is that this is still less than half the record deforestation rate of 24,000 km² in 2016. Deforestation has also slowed in neighboring Malaysia, another major producer, which has committed to maintaining at least half of its land area under natural forest cover."

It is worth noting that Indonesia and Malaysia are major suppliers of palm oil for the international market, a context that—at least for now—differs from Brazil, which is the world's leading soybean supplier, whose oil can also be used for biofuel production. These examples are part of a global context in which agricultural commodity-producing countries are often not the primary consumers of the final products.

Nonetheless, the facts and concerns described above are the same ones addressed in the report *Future of Energy: the Brazilian Climate Observatory's Vision for a Just Transition in Brazil*. Despite the importance of biofuels, it is therefore essential to reaffirm the need for socio-environmental safeguards, including controls on the areas and resources used to produce bioenergy, as well as the definition and regulation of exclusion zones, such as the Amazon Forest.

The document also outlines general measures to mitigate the socio-environmental impacts of renewable energy, under the premise that the energy transition must be just, ensure broad participation by affected communities, and be guided by a robust regulatory framework capable of addressing current challenges.

Among such measures, the following stand out:

- Environmental licensing processes must be better structured and carefully conducted, prioritizing conservation and the mitigation of impacts caused by new projects;
- Socio-environmental and territorial safeguards should be established beyond licensing, including risk-control and monitoring mechanisms and guarantees for the enforcement of rights;
- Public authorities must map socially and environmentally sensitive areas for the implementation of renewable energy projects, establishing exclusion zones and buffer zones around protected or inhabited areas;
- To ensure the rights of local communities, land tenure regularization should be accelerated for territories undergoing lengthy processes of recognition, demarcation, and protection by public institutions.

An example of a public policy to be followed is Decree No. 6,961/2009, which established the Agroecological Zoning of Sugarcane (ZAE Cana) and, among other measures, prohibited sugarcane cultivation in the Amazon, the Pantanal, and the Upper Paraguay Basin[13].

By contrast, the recently enacted General Environmental Licensing Law (Lei Geral do Licenciamento Ambiental, Law No. 15,190/2025)[14], which aims to create a unified framework for environmental licensing, takes the opposite direction—dismantling existing safeguards for permit issuance. It is important to note that environmental

13 BRAZIL. *Office of the Chief of Staff of the Presidency of the Republic*. Decree No. 6,961, of 17 September 2009. Available at: https://www.planalto.gov.br/ccivil_03/_ato2007-2010/2009/decreto/d6961.htm. Accessed on: 12 Sept. 2025.

14 BRAZIL. *Federal Senate*. Bill No. 2,159, of 2021. Available at: https://www25.senado.leg.br/web/atividade/materias/-/materia/148785. Accessed on: 15 July 2025..

licensing in rural areas was already fragile even before the law's approval, as the agricultural sector is governed by state-level regulations that often exempt or fail to monitor a range of activities.

Yet, at a time when Brazil needs stronger environmental regulations—to consolidate itself as both an environmental and energy power—the new legislation goes further, exempting from environmental licensing, nationwide, the following activities:

- Cultivation of agricultural species, whether temporary, semi-perennial, or perennial;
- Extensive and semi-intensive livestock farming;
- Small-scale intensive livestock farming; and
- Agricultural research activities that do not pose biological risks, among others.

Consequently, the agricultural activities that sustain the biofuel sector will now be exempt from environmental licensing—precisely the opposite of what is required to promote an expansion of bioenergy alongside environmental protection.

It should be noted, however, that exemption from environmental licensing does not exempt producers from complying with the Forest Code, including the obligation to maintain Permanent Preservation Areas (APPs) and Legal Reserves (RLs). Thus, native vegetation removal, water use, and other forms of natural-resource utilization will still require authorization from the relevant agencies, as stated in the text of the law. Moreover, even if exempt from licensing, activities will remain subject to inspection by environmental authorities and to applicable penalties in the event of violations.

Finally, it should be stressed that no energy source is free from socio-environmental impacts. Large hydropower projects have displaced populations and caused negative effects on local ecosystems; wind and solar power plants have led to psychosocial disruptions and territorial conflicts in socially sensitive areas, such as quilombola territories; and electric-vehicle batteries require strategic metal mining in equally sensitive regions.

Therefore, the risks associated with biofuels do not disappear when other energy sources are adopted. Nonetheless, there is a broad understanding that, when socio-environmental safeguards are respected, bioenergy can play a strategic role in enabling Brazil to advance its energy transition now, as part of a diverse portfolio of renewable solutions that includes electrification and other clean technologies.

6. Conclusions, Recommendations, and Final Considerations

This study shows, first and foremost, that Brazil can expand biofuel production while eliminating deforestation of natural vegetation for the conversion of new agricultural areas. This conclusion, it should be emphasized, assumes an expansion of bioenergy production at a scale and pace consistent with the urgent need to decarbonize the Brazilian economy, in a scenario aligned with the country's fair contribution toward achieving the Paris Agreement goals — as outlined in the study *Future of Energy: the Brazilian Climate Observatory's Vision for a Just Transition in Brazil* (OC, 2024b).

However, the realization of this potential will depend on how the production of these energy sources is guided — namely, which crops are transformed into feedstocks, which technological routes are adopted, and, crucially, on the planning and territorial management strategies used to allocate part of the areas currently classified as degraded pastures for this purpose.

To meet the country's growing energy demand by 2050, in parallel with a rapid trajectory of emission reductions, biofuel supply must more than double, particularly through the use of low-emission drop-in fuels — those that can be used directly in existing equipment (especially motor vehicles), without requiring new technologies. This expansion must occur alongside other equally essential measures, such as electrification and systemic efficiency gains.

It is important to note that meeting this demand using the current mix of feedstocks and technological routes would require an agricultural expansion incompatible with the decarbonization scenario proposed by the Brazilian Climate Observatory (OC). Therefore, it is not feasible for soybean to remain the primary source of vegetable oil, given its low oil yield per hectare.

Although there is potential to add value to soybean production by exporting soybean meal and using the oil domestically for biofuel production, the only way to meet future bioenergy demand without new deforestation is to incorporate alternative, higher-yield crops, such as macaúba.

The sensitivity analysis conducted in this study demonstrates that a combination of more efficient crop choices and technological routes — that is, those requiring less cultivated land per unit of fuel produced — appears promising for simultaneously meeting Brazil's energy needs and aligning land use with the country's commitments to end deforestation, restore environmental liabilities under the Forest Code, and sequester carbon by rehabilitating degraded pastures.

Even though Brazil possesses a significant stock of degraded pastures suitable for cultivation, the potential land demand remains non-negligible. It is also crucial to emphasize that natural area protection and restoration, as well as food production — which must not be confused with commodity crop exports, such as soybean — should take precedence over biofuel production.

In addition, areas theoretically available for biofuel production are often located near the Amazon, requiring extra caution to ensure compliance with the safeguards advocated by the Brazilian Climate Observatory.

For all these reasons, as well as other safeguards discussed previously, land-use monitoring and regulatory policies become even more essential.

At the same time, it must be considered that part of the additional area needed for biofuel production overlaps with degraded land already slated for soybean production, a crop cultivated regardless of biofuel demand — since, in this case, biofuel feedstock is a by-product.

It is also worth noting that biofuels offer opportunities for Brazil's reindustrialization, driven by a new bioenergy value chain. Petrobras itself, with its extensive experience, investment capacity, and long-standing contribution to Brazil's economic development, can be a key player in accelerating the development of new technological routes and in transforming the oil refining industry into a bio-refining industry.

Based on the findings of this study, the following public policy recommendations are proposed to advance the understanding and planning of biofuel expansion in Brazil:

1. Define clear biofuel production targets for the domestic market, tied to ambitious greenhouse gas (GHG) mitigation goals;

2. Delineate and monitor cultivation areas and feedstock exclusion zones in alignment with the zero-deforestation commitment and with a strategy for restoring degraded pastures;

3. Develop a feedstock production strategy (e.g., for vegetable oil or ethanol) that reflects the geographical, environmental, and social characteristics of the territories involved;

4. Establish minimum productivity efficiency parameters, measured by the volume of intermediate products (e.g., vegetable oil or ethanol) produced per cultivated area;

5. Promote research and development of new technological routes for biofuel production;

6. Design a strategy for the gradual reduction of petroleum-derived products, while enabling the production of advanced biofuels, assessing the conversion or adaptation of oil refineries into bio-refineries, or the construction of new bioenergy-focused facilities.

Finally, it is important to emphasize that biofuel production in Brazil, while essential for decarbonizing the transport and industrial sectors, does not replace ecological restoration as a strategic alternative for carbon sequestration, as discussed in Chapter 3 (OC's Vision for Land Use and Emission Mitigation).

Brazil possesses an extensive area of degraded and low-productivity pastures that can be restored over the coming decades without jeopardizing food security or bioenergy production.

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ANNEX: Current Laws, Policies, and Regulations on Biofuels in Brazil

A key piece of Brazilian legislation on bioenergy is Law No. 13,576/2017, which established the National Biofuels Policy (RenovaBio)[15]. This law seeks to expand the production and use of biofuels within Brazil's energy matrix through three main pillars:

1. The creation of mandatory, individual targets for all fuel distributors to reduce GHG emissions linked to fuel commercialization;
2. The certification of efficient biofuel production or importation, under which producers and importers receive an energy-environmental efficiency score reflecting their individual contribution to GHG mitigation; and
3. The issuance of Decarbonization Credits (CBIOs) by producers and importers—each equivalent to one metric ton of CO_2e avoided—to be purchased by fuel distributors as an environmental offset mechanism.

The GHG reduction targets and the CBIO issuance targets are defined annually, covering a 10-year horizon, by the National Energy Policy Council (CNPE). The latest targets were established by Resolution No. 14, of December 10, 2024[16], which set the goal of reducing the carbon intensity of Brazil's fuel matrix from 71.7 gCO_2/MJ in 2025 to 65 gCO_2/MJ in 2034, and increasing CBIO issuance from 40.39 million in 2025 to 72.54 million in 2034.

Complementing RenovaBio, Law No. 14,993/2024, known as the Fuel of the Future Law[17], created the National Sustainable Aviation Fuel Program (ProBioQAV), the National Renewable Diesel Program (PNDV), and the National Program to Promote Biomethane.

15 BRAZIL. *Presidency of the Republic*. Law No. 13,576, of 26 December 2017. Available at: https://www.planalto.gov.br/ccivil_03/_Ato2015-2018/2017/Lei/L13576.htm. Accessed on: 14 July 2025.

16 *Ministry of Mines and Energy (MME)*. Resolution No. 14, of 10 December 2024. Available at: https://www.in.gov.br/web/dou/-/despacho-do-presidente-da-republica-602955102. Accessed on: 12 July 2025.

17 BRAZIL. *Presidency of the Republic*. Law No. 14,993, of 8 October 2024. Available at: https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2024/lei/L14993.htm. Accessed on: 14 July 2025.

Regarding the aviation sector, the law mandates that airlines reduce their emissions through the use of sustainable aviation fuel (SAF) beginning in 2027, with SAF blending requirements ranging from 1% to 10% of total commercial jet fuel volume by 2037. The National Civil Aviation Agency (ANAC) is responsible for oversight and emission verification methodologies, in alignment with the goals of the International Civil Aviation Organization (ICAO) to achieve carbon neutrality by 2050, under the *Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA)*[18].

In addition, the law stipulates that the ethanol blend in gasoline must be no less than 22% of total volume, with potential increases of up to 35% by federal decree. In July 2025, the government officially announced that, starting in August, gasoline would contain 30% ethanol.

For biodiesel, the legislation requires a mandatory 15% blend with fossil diesel beginning in 2025, with an annual 1 percentage point increase until reaching 20% in 2030. From that point onward, the CNPE may raise the blend level to up to 25%, provided technical feasibility is demonstrated.

With respect to biomethane, the law mandates that the CNPE define annual GHG reduction targets for the fossil gas market (produced or imported), to be achieved through biomethane's share in total consumption. This obligation will take effect on January 1, 2026, with an initial reduction target of at least 1%, not exceeding 10%.

In parallel, the federal government enacted Law No. 14,902/2024, which created the Green Mobility and Innovation Program (Programa Mover)[19]. The program aims to stimulate investments in new vehicle technologies and energy efficiency, while raising decarbonization requirements for Brazil's vehicle fleet, including passenger cars, buses, and trucks. It also sets minimum recycling standards in vehicle manufacturing and establishes the Green IPI—a taxation system under which less-polluting vehicles pay lower taxes.

The law explicitly states that one of its guiding principles is the "promotion of biofuels, other low-carbon fuels, and alternative propulsion systems, reinforcing the value of Brazil's energy matrix." It also provides for R$19.3 billion in financial credits between 2024 and 2028, to be used by companies for federal tax deductions in exchange for investments in research, development (R&D), and new production projects.

Considering all these policies, both the National Energy Plan 2050 (PNE 2050) (EPE, 2020) and the Decennial Energy Expansion Plan 2034 (PDE 2034) (EPE, 2024)—which outline the Ministry of Mines and Energy's (MME) projections for sectoral expansion—anticipate continued growth in biofuel supply and demand for the transport sector in the coming years, particularly for ethanol and biodiesel.

18 *Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).*

19 BRAZIL. *Presidency of the Republic*. Law No. 14,902, of 27 June 2024. Available at: https://www.planalto.gov.br/ccivil_03/_ato2023-2026/2024/lei/l14902.htm. Accessed on: 14 July 2025.

For the 2025–2034 period, the PDE projects a freight transport network still dominated by road transport, with increasing energy demand and a high dependence on fossil diesel. The technological and cost barriers to electrifying heavy trucks that travel long distances remain significant, underscoring the importance of biodiesel and renewable diesel during the transition.

Finally, Brazil is developing its National Mitigation Strategy (ENM), which integrates the Climate Plan (Plano Clima) alongside the National Adaptation Strategy. The ENM comprises seven sectoral plans, including those for energy and transportation. Its objectives include expanding sustainable biofuel production, promoting technological innovation, and developing value chains related to bioenergy. It also aims to encourage the replacement of fossil fuels, fostering the development and efficient use of sustainable biofuels, electrification, and low-carbon hydrogen solutions.

BIOFUELS IN BRAZIL:

ALIGNING THE ENERGY TRANSITION AND LAND USE FOR A CARBON-NEGATIVE COUNTRY