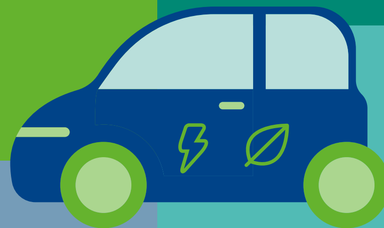
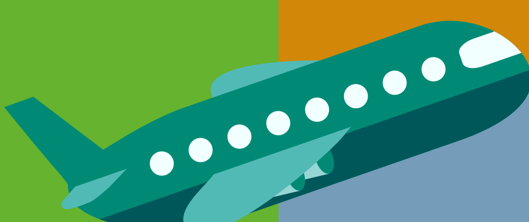


BIOETHANOL

FAST TRACK TO MOBILITY DECARBONIZATION

Summary for policy makers



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G20 BRASIL 2024
BUILDING A JUST WORLD AND A SUSTAINABLE PLANET

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Introduction

The production of sustainable biofuels globally is not in line with net zero goals by 2050 and developing countries hold the greatest potential for expansion in the consumption of renewable energy. However, there is a global need for technology, public policy, experience and knowledge to adequately expand production and distribution at a sufficient rate to collect significant benefits. Over the last five decades, Brazil has accumulated significant experience in this field, which can be – and has already been – shared with several other countries through technical cooperation and capacity-building.

The transport sector is responsible for 20% of energy-related global greenhouse gas emissions and most of these emissions come from road transport, which makes decarbonizing the sector one of the main challenges on the environmental agenda. With increasingly sustainable production and great potential for reducing emissions, bioethanol has one of the smallest carbon footprints in the world, with the capacity to reduce emissions by up to 90% when compared to gasoline. It is also a drop-in technology that can be implemented comparatively quickly, using existing infrastructure. The world has over two billion combustion engine vehicles that could pollute a lot less if they ran on biofuels.

Today, more than 70 countries already promote blending different percentages of ethanol into gasoline; some, notably India, are increasing blending levels to reduce emissions and improve air quality. In Brazil, gasoline contains 27% ethanol, and the blend level is expected to reach 30%. Additionally, the development of flex-fuel engines has allowed for the use of pure bioethanol (E100). 85% of the Brazilian fleet, equivalent to 33.7 million cars, can use both pure bioethanol and gasoline blended with bioethanol.

The energy transitions the world urgently needs can only happen in a fair and equitable manner if we strive to maintain and value an agnostic and neutral approach towards technology. Each country and each region face its own circumstances. Countries should be able to adopt solutions based on their domestic realities and available resources. In other words, we cannot and must not discriminate between alternatives. When choosing options for the generation of clean energy, it is fundamental to take local conditions into account and fulfill sustainability premises, with low emissions and accessible prices. This principle should also apply to the decarbonization of the transport sector.

The transition to a sustainable low-carbon economy worldwide must be an inclusive process that considers the need for job creation, respects diversity and contributes to social development, leaving no one behind. At the same time, it must be an opportunity for the development of new industries, through technological innovations and investment attraction. Creating these opportunities, particularly in developing countries, will contribute to the reduction of global inequalities.

The 2024 Joint Statement on Sustainable bioenergy for climate and development goals[1] sustains that sustainable bioenergy can contribute to energy security, clean energy access, rural development, increased agricultural productivity, improved farmer incomes, job creation, gender equality, responsible industrial

1 This statement was developed by a Cross-Initiative coordination group on bioenergy convened by the Global Bioenergy Partnership (GBEP). The Statement was issued by: Clean Energy Ministerial Biofuture Platform Initiative; Food and Agriculture Organization of the United Nations (FAO); Global Bioenergy Partnership (GBEP); International Energy Agency (IEA); IEA Bioenergy Technology Collaboration Programme; International Renewable Energy Agency (IRENA); United Nations Environment Programme (UNEP); United Nations Economic Commission for Europe (UNECE); and the United Nations Industrial Development Organization (UNIDO).

development, poverty eradication, and climate change mitigation and adaptation strategies. Sustainable biofuels will also be essential to long-term emissions reduction in the aviation and maritime sectors, as well as to the production and transportation of hydrogen.

The Brazilian experience demonstrates how bioenergy is a sustainable, low-cost and competitive solution for decarbonization efforts. Brazil firmly believes that the production and use of sustainable biofuels represent a major contribution from the Global South to global energy transitions. International cooperation — be it bilateral, regional or multilateral — is a key tool for reaching the full potential of biofuels in global decarbonization efforts and the varied benefits biofuels can bring to a diverse array of nations and communities. Through cooperation between experts, legislators, regulators and industry representatives, countries can learn from each other's experiences and best practices, and improve regulation, policy, production, efficiency and sustainability, thereby contributing to a stable biofuels market, both domestically and internationally.

Brazilian diplomacy argues that advocating for the production and use of sustainable bioenergy is not only a means for promoting Brazilian interests and flagship policies, but also for contributing to common international commitments to promoting sustainable development and fostering emissions reduction. This perspective has been one of the main axes of Brazilian energy diplomacy since the beginning of this century.

Initiatives such as the Global Bioenergy Partnership (GBEP), the Biofuture Platform and the Brazilian "Sustainable Mobility: Ethanol Talks" program are examples of how country-led initiatives created by dedicated policy makers can spread their wings in the context of an inevitably growing biofuels market, by fomenting exchange of experiences and identifying avenues for cooperation. India is a paramount example of the positive impact of collaboration between policy makers. Intense bilateral cooperation with Brazil helped boost the production and use of biofuels and flex-fuel vehicles across the country, with the objective of reducing emissions from the transportation sector. On the multilateral level, the Indian G20 Presidency launched the Global Biofuels Alliance (GBA) in 2023, which now gathers 25 countries and 12 international organizations and represents a new avenue for technical cooperation for countries that wish to implement robust and tested biofuel policies.

In 2024, under Brazilian presidency, the discussions taking place in the Energy Transitions Working Group (ETWG) have gained momentum after COP28, in Dubai, where countries made new commitments for the increase of renewable energy and energy efficiency, as well as for the reduction of the dependence on fossil fuels. In this context, the Brazilian Presidency established three priority areas for the ETWG: (i) Accelerating Financing for Energy Transitions, especially in developing countries; (ii) Social Dimension of Energy Transitions; (iii) Innovative Perspectives for Sustainable Fuels.

In face of the perspective of an emerging market of new energy sources, such as hydrogen, and of sustainable fuels, Brazil and its partners have sought to impact international debate on certification and carbon accounting. There have been intense discussions on the margins of the Brazilian G20 presidency in 2024 regarding the need for consistency, common standards and comparability between carbon accounting methodologies based on life-cycle analysis (LCA). These efforts are central to avoiding market distortion, discriminatory measures and to creating a level playing field for all energy sources.

The Summary for Policy Makers embodies this collaborative spirit and helps fulfill the endless potential of international cooperation for the promotion of biofuels. It seeks to provide technical and scientific data to subsidize, provoke and open the minds of policy makers towards a technological pathway that can help the world achieve fast, accessible, inclusive and renewable energy transitions. The Summary is a first view of the discussion contained in the soon to be published Bioethanol – Fast Track to Mobility Decarbonization Book, which brings together authors and specialists from the academia, private sector and Brazilian government to provide detail on the technological, socioeconomic and environmental attributes of bioethanol.

As estimated by the International Energy Agency, expanding the global biofuels market is inevitable for the achievement of global net-zero emissions targets, as a viable, immediate and complementary solution. It is up to international actors and stakeholders to develop regulations, seek standards harmonization, and foment coordination to improve efficiency, production and innovation in this field and accelerate decarbonization in hard-to-abate sectors. International knowledge-sharing and cooperation have already shown significant results and constitute the only path towards achieving our sustainable development goals and fighting climate change.

Joint Statement on Sustainable bioenergy for climate and development goals

In consideration of the persistent debates about what role bioenergy should play in support of climate and sustainable development goals, and acknowledging the most recently available scientific evidence, the undersigned organizations issued the following joint statement:

Sustainable bioenergy is a component of the bioeconomy. It can be produced from biomass resources in multi-functional, integrated agriculture, forestry, fisheries and aquaculture systems, along with food, feed and/or bio-based products, from biogenic waste and residue streams, or as a co-product of ecosystem management.

Sustainable bioenergy can be produced with energy-efficient and low-emission technologies, and is derived from sustainable biomass resources.

Sustainable bioenergy can make a crucial contribution to keep global warming below 1.5 °C by the end of the century. It plays a unique role in just and inclusive energy transitions, and is especially important for sectors and regions where other decarbonization options are costly or not yet available.

Biomass and its bioenergy derivatives are versatile, storable and dispatchable; they can replace fossil energy and complement variable renewables and other low-carbon options in transport, power and heat production, industrial processes and clean cooking, thereby enhancing resilience in the energy system.

Sustainable bioenergy can contribute to energy security, clean energy access, rural development, increased agricultural productivity, improved farmer incomes, job creation, gender equality, responsible industrial development, poverty eradication, and climate change mitigation and adaptation strategies.

Benefits and trade-offs of bioenergy systems depend on context, scale, and local needs and priorities. Good governance of bioenergy systems is key to maximize opportunities and minimize risks of negative impacts, and to ensure an integrated approach that aligns with the Sustainable Development Goals.

Good governance builds on evidence-based assessment of environmental, economic, social and political factors, and safeguards food and energy security, climate justice, biodiversity stewardship, land and water rights and local development priorities. It follows the principles of nature-based solutions,[2] including local stakeholder engagement, and free, prior and informed consent. Recognized norms for quality and sustainability can facilitate investment, fair trade, monitoring and verification.

Through good governance, sustainable bioenergy addresses the risks related to the land and resources used for its production and the potential impacts on food security, natural ecosystems and carbon stocks,[3] as well as the challenges in managing equity and justice, and achieving economic competitiveness and affordability.

This statement was developed by a Cross-Initiative coordination group on bioenergy convened by the Global Bioenergy Partnership (GBEP). The Statement was issued by:

Clean Energy Ministerial Biofuture Platform Initiative
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International Renewable Energy Agency (IRENA)
United Nations Environment Programme (UNEP)
United Nations Economic Commission for Europe (UNECE)
United Nations Industrial Development Organization (UNIDO)

June 20, 2024.

Available at:

https://www.fao.org/climate-change/news/news-detail/sustainable-bioenergy-for-climate-and-development-goals/en

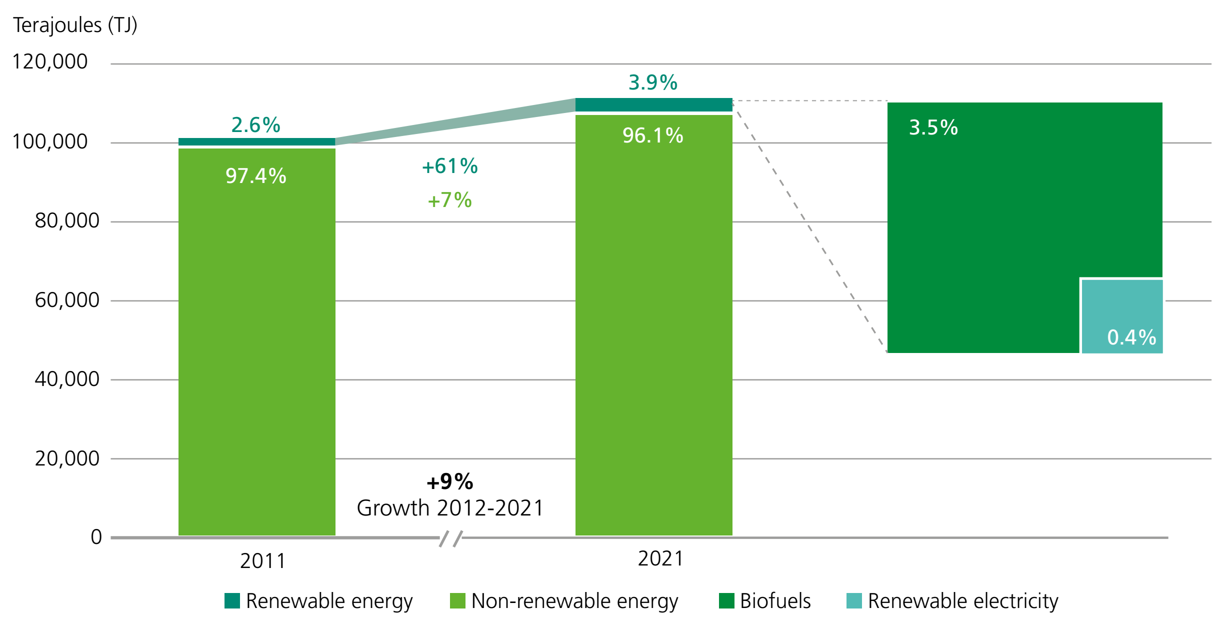
2 United Nations Assembly Resolution on nature-based solutions for supporting sustainable development (UNEP/EA.5/Res.5).

3 As discussed in IPCC, 2019. Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (P.R. Shukla, J. Skea, E. Calvo Buendia, V. *et al.* [eds.]).

Boosting energy transition in mobility

Accelerating the energy transition and decarbonization in mobility is an urgent matter. Replacement of fossil fuels by renewable energy sources has advanced worldwide, in almost all sectors. However, the transportation of people and goods, predominantly by road (77%), remains heavily dependent on fossil fuels. The transport sector consumes nearly 30% of global final energy and is responsible for 20% of energy-related global greenhouse gas (GHG) emissions. In fact, the essential energy transition in transport is even more of an expectation than a reality.

GRAPH 1. Renewable share of total final energy consumption in transport, all modes, 2011 and 2021



Source: REN21 (2024).

The difficulties in promoting energy transition in transportation are well known: a large and growing fleet of vehicles, mostly light vehicles powered by gasoline and still with many years of useful life. In the case of electrification, the most cited alternative, the need for high investments in generation and distribution infrastructure and the dependence on strategic and scarce materials are obstacles that have yet to be sufficiently overcome.

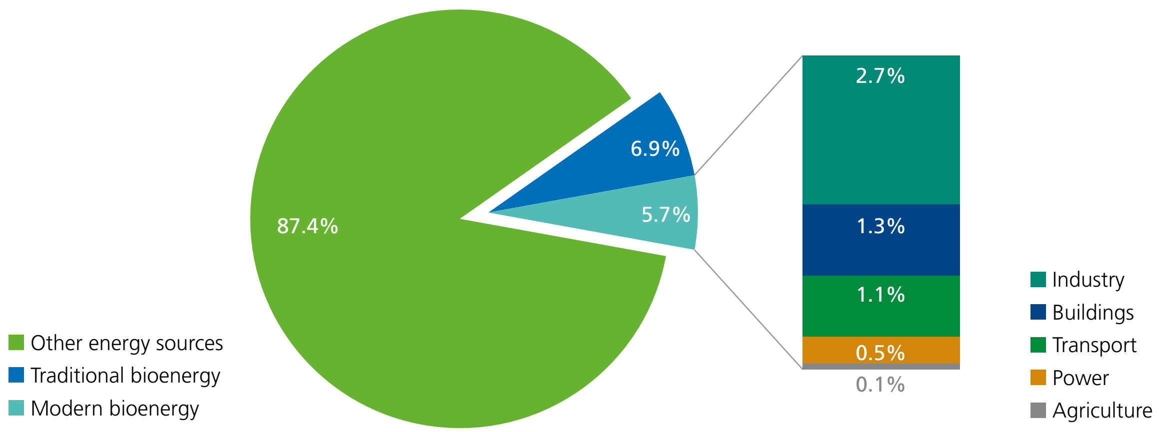
Such a context has been well understood by international energy agencies, which have clearly highlighted the need to increase the production and use of sustainable liquid biofuels. IRENA's World Energy Transitions Outlook indicates that bioenergy could play a major role in the energy transition to limit the rise in global temperatures, expecting the biofuels contribution to transport to increase more than fourfold by 2050 (IRENA, 2023). In turn, International Energy Agency (IEA) points out the need for a "robust growth over the next five years" in biofuels consumption, which can be produced sustainably, with low environment impacts and GHG emissions, blended at high levels with conventional fuels to contribute to achieving climate and energy security goals (IEA, 2023).

Bioenergy is an energy resource used for millennia and can contribute further to the energy transition. Essentially, bioenergy is any kind of energy from biomass, the product of solar radiation, water and atmospheric carbon dioxide (CO_2) by photosynthesis, the fundamental phenomena for life on our planet. From the discovery on how to make fire up to the Industrial Revolution, when fossil fuel exploitation began, mankind used biomass as fuel, recovering solar energy stored as chemical energy in timber.

More recently, after the Oil Shocks during the 1970s, bioenergy came back to the forefront under new meanings and having been technologically developed. Being able to mitigate serious problems in the local and global environment, photosynthetic energy brought a new dynamic to the agro-industrial world and provided an effective alternative to the necessary evolution of modern industrial society toward a more sustainable and rational energy context.

Modern bioenergy has been implemented successfully. Currently, in its various forms, bioenergy covers around 12% of global energy consumption in different sectors, circa 46 EJ in 2020 (REN21, 2024). Approximately half of this consumption occurs in traditional methods, such as cooking on inefficient and potentially harmful stoves. The other half corresponds to the growing use of modern bioenergy by means of efficient and environmentally friendly technologies, such as the production and use of liquid biofuels, biogas and bioelectricity generation, used mainly in industry, buildings and transport.

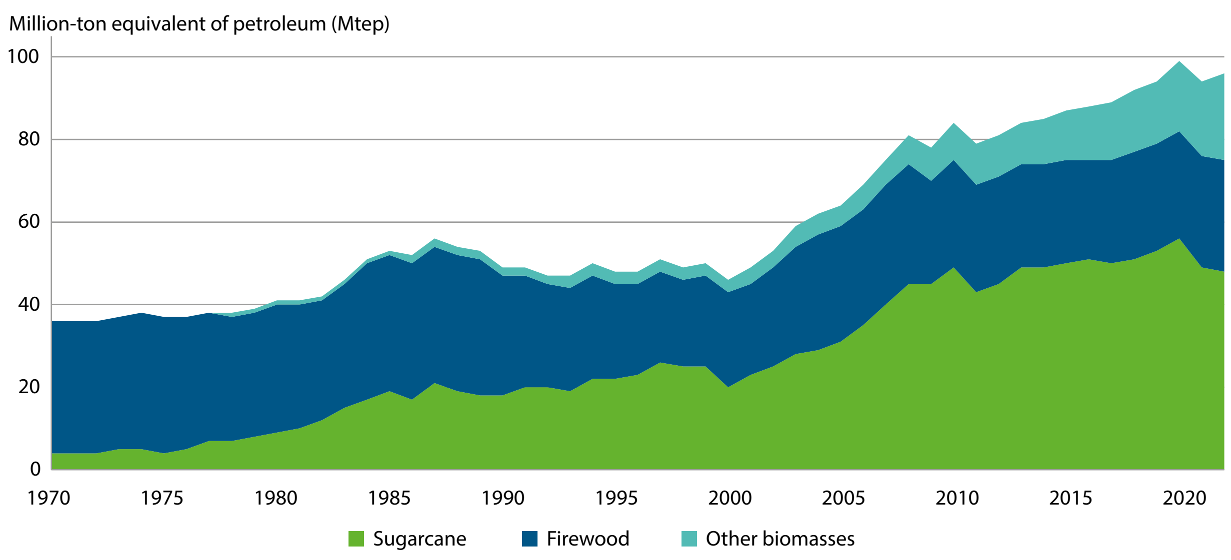
GRAPH 2. Global bioenergy consumption



Source: Prepared by the authors based on REN21 (2023).

Brazil is an example of a tropical country in which bioenergy has always played a prominent role. During the last century the traditional uses of fuelwood were progressively displaced by modern energy vectors, such as bioethanol and biodiesel as vehicular fuel and bioelectricity. In 2022, sugarcane, firewood, corn, and other sources of bioenergy represented 27.2% of the primary energy production in the country, totaling 96 million tons of oil equivalent or 4,0 million TJ, i.e., two thirds of the renewable energy produced that year, being the most important renewable source in the Brazilian energy matrix (EPE, 2023).

GRAPH 3. Bioenergy production by source in Brazil

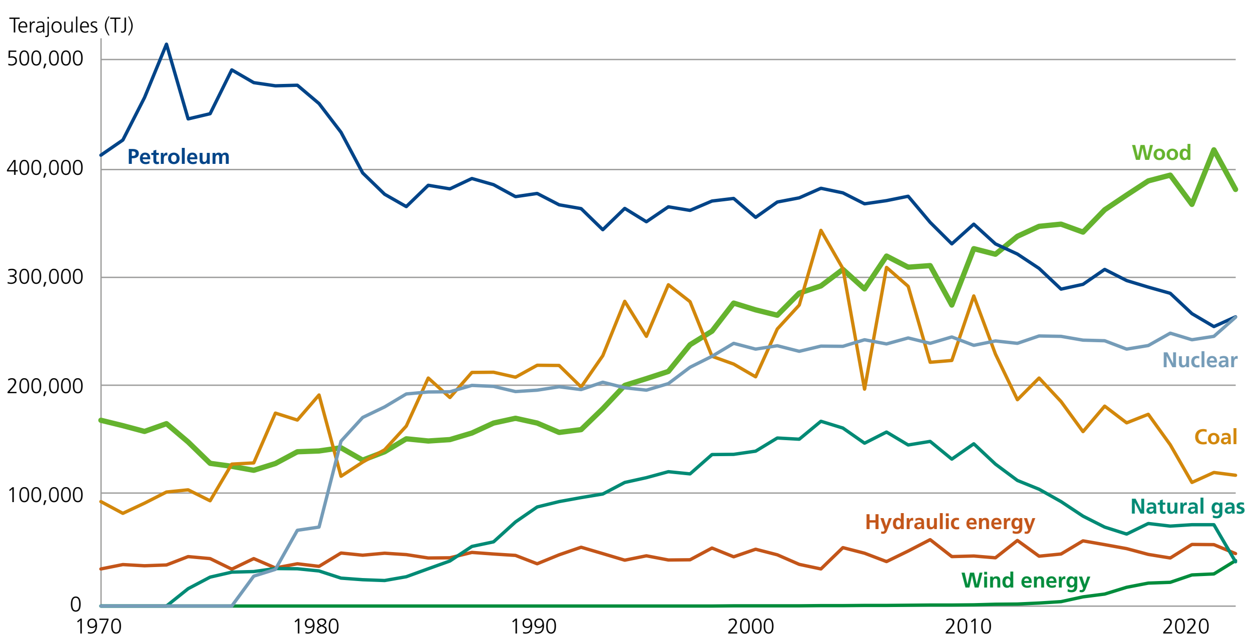


Source: Prepared by the authors based on EPE (2023).

Tropical countries are not the only ones that can implement modern bioenergy. In Finland, high levels of energy consumption coexist with less favorable climatic conditions for biomass production. Nevertheless, based on forestry and efficient processes, bioenergy participation in the Finnish energy matrix has evolved remarkably since the 1970s, enabling an effective energy transition.

In 1990, oil consumption represented more than twice the consumption of wood for energy purposes. However, since 2012, due to climate and energy policies, biomass became the main source of energy, reaching 33% of the total energy consumption in 2022, a process associated with a significant reduction in the consumption of coal, oil, and natural gas (OSF, 2024). This remarkable evolution, while maintaining dependence on oil for transportation, highlights the potential of bioenergy even in apparently adverse conditions.

GRAPH 4. Evolution of the consumption of energy sources in Finland



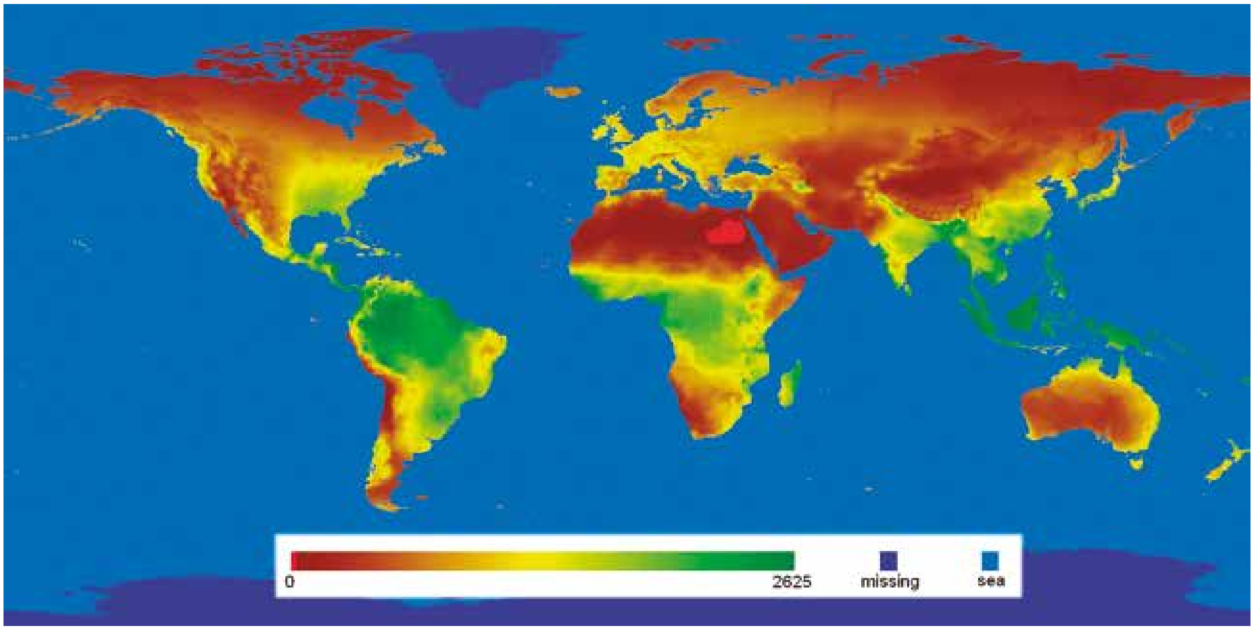
Source: Prepared by the authors based on OSF (2024).

Sustainable bioenergy has a large production potential globally. It is estimated that just 0.1% of the solar radiation incident on Earth is used to produce annually around 114 billion tons of dry biomass, which means in energy 1,920 EJ or 314 trillion barrels of oil, about eight thousand times the current world consumption of this fossil fuel. The average efficiency of solar energy assimilation lies below 1%, although some higher performance plants, such as sugar cane, can reach 2.5% on an annual average. Naturally, these values serve only as a reference for understanding the energetic magnitude of photosynthesis, being pointless regarding imagining bioenergy as a substitute for all forms of energy supply. As seen, such plant growth occurs especially in native tropical formations, and estimates suggest that agricultural activities correspond to about 6% of this total (Smil, 1991).

Water is an essential factor for photosynthesis and the great limiting factor for expanding plant production. Extensive sunny areas in semi-arid regions scarcely contribute as a biomass source without irrigation with significant volumes of water, implying high costs and energy expenditures that often make bioenergy production unfeasible. Irrigation currently consumes almost 70% of the available water resources worldwide and accounts for around 40% of agricultural production, making access to water a topic of enormous priority (UNESCO, 2021). Fortunately, some tropical regions have enough water availability, enabling rain-fed agricultural production with less dependence on irrigation.

Net primary productivity allows us to estimate the theoretical potential of photosynthesis to produce biomass. It represents the maximum possible value for plant production under the local temperature, water availability, and solar radiation, evaluated in grams of dry matter produced during a year per square meter of vegetable leaf exposed to the sun. As depicted in Figure 1, the humid tropical regions of Africa, Asia, and Latin America have the highest theoretical biomass productivity, configuring the most favorable contexts to produce bioenergy to be promoted in harmony with the local lush forests and agriculture.

FIGURE 1. Biomass Net Primary Productivity (dry g/m²/year)



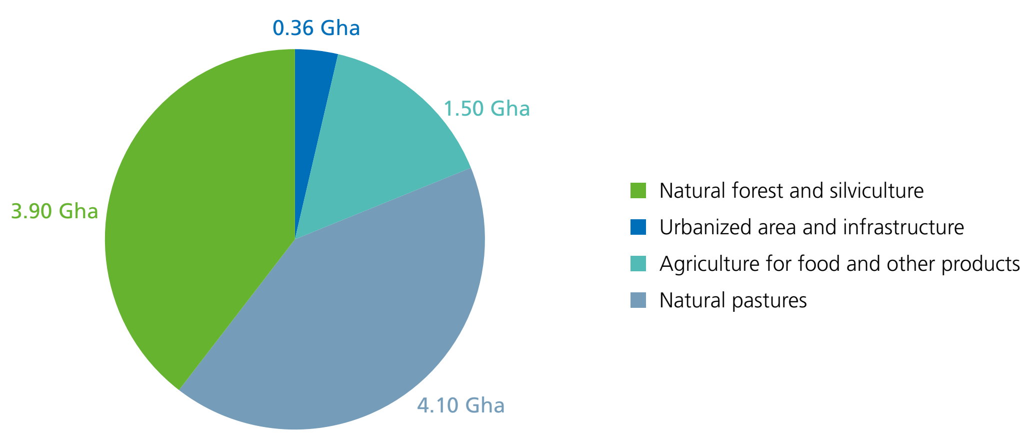
Source: FAO (2006).

Soil fertility and topography are other important factors for sustainable bioenergy production, in addition to the basic requirements for photosynthesis. In general, bioenergy crops require the use of organic and chemical fertilizers to achieve satisfactory levels of productivity and the adoption of sustainable agriculture management practices and mechanization. Joint assessment of all these factors delimits potentially cultivable areas for bioenergy and all other uses.

It is important to properly evaluate the land available for bioenergy production. Considering the entire planet — the total dry area of which is estimated at 14.86 Gha (gigahectares or tens of millions of square kilometers) — and discounting glaciers and deserts, the planet totals 9.86 Gha, covered by urbanized areas; logistical and energy infrastructure (3.7%); areas cultivated for food, fiber, and other agricultural products (15.2%); natural pastures (41.6%); and natural and cultivated forest formations (39.6%), as shown in Graph 5 (UNEP, 2013).

The area currently dedicated to traditional or modern bioenergy production totals less than 60 million hectares and would require another 50 to 200 million hectares, depending on the adopted technology, to achieve a total bioenergy production from 100 to 200 EJ/year (Souza *et al.*, 2015). This total potential demand for land to produce bioenergy in a volume relevant to global energy consumption can be compared with the land available and feasible for agricultural production.

GRAPH 5. Uses of cultivable surface on Earth



Source: UNEP (2013).

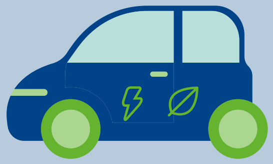
Land availability for expanding agricultural frontiers is high, although unevenly distributed across the regions of the planet, especially in places that are still little explored or used extensively, such as low-productivity pastures. In fact, the highest total potential land demand estimates for bioenergy, 260 million hectares, represents 6% of the land currently occupied by pastures.

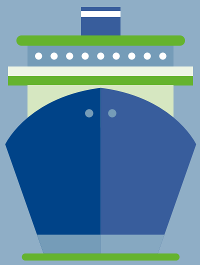
Agroecological zoning can be used for assessing these available areas at a detailed level (FAO and IIASA, 2021).

Ensuring the sustainable development of bioenergy is crucial since connected to the production of food, feed, fibers and livestock, forestry, land use, water, and biodiversity, as mentioned in preceding paragraphs. Bioenergy development must consider food security and ensure the sustainable use of resources available in each specific context, avoiding competition while looking for synergies to provide the needs of a growing global population. Likewise, the sustainable use of water is vital, particularly in water-scarce regions. Assessment campaigns and monitoring of environmental, economic and social aspects of the different value chains should be regularly conducted to inform national policies and to prevent deforestation, ecosystem disruption and biodiversity loss.

It is important to consider bioenergy properly. Despite the notable expansion of other forms of renewable energy in recent times, bioenergy remains the most important source of renewable energy globally. Without claiming to be the exclusive solution, capturing and storing solar energy in plants can play a prominent role in building an energy future for nations. As prophesied by Ignacy Sachs (Consultor..., 2007):

> *Bioenergy is just one part of a broader concept of what is called sustained development, a concept that is based on the tripod biodiversity, biomass and biotechnology and that can serve as a lever for the place that biomass may represent in the coming decades.*




Bioethanol: a qualified vehicular fuel, increasingly adopted worldwide

In the beginning of the automobile age, bioethanol was used as motor fuel. In 1860, Nicolaus Otto, inventor of the spark-ignition internal combustion engine, used bioethanol in one of his engines. With the expansion of motorized cars abroad, several countries such as Angola, Argentina, Australia, Austria, Brazil, Chile, China, Costa Rica, Cuba, France, Germany, India, Italy, Japan, Malaysia, the Philippines, Poland, South Africa, Switzerland, the United Kingdom, the United States, and Vietnam adopted this biofuel either in mixture with gasoline or pure, as a local alternative to reduce gasoline dependence or recognizing its renewable nature (Kovarik, 2006).

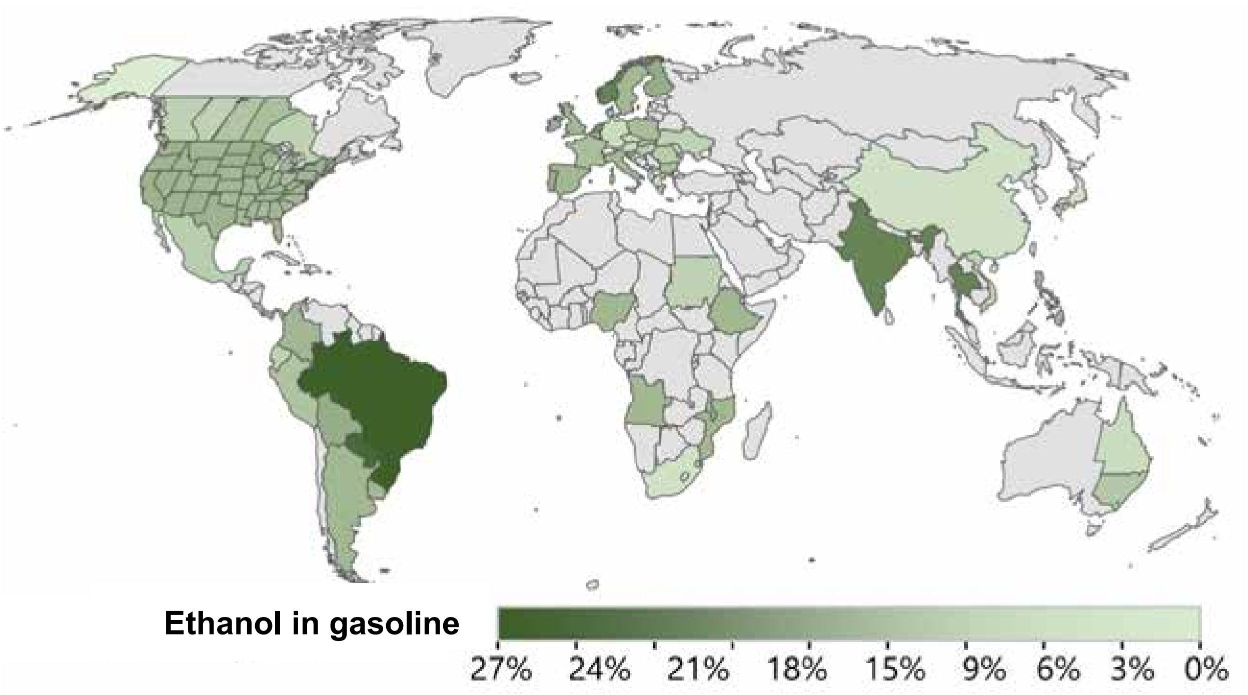
Henry Ford with a Model T Ford using pure ethanol as a fuel.

Ford Motor Company, Public domain, via Wikimedia Commons. Available at: https://commons.wikimedia.org/wiki/File:H.Ford_et_sa_Ford_T.jpg. Access in: Set. 2024.

However, in the early decades of the last century, interest in bioethanol fuel waned. The main disincentive to using bioethanol fuel was the growth of the oil industry, increasing the supply of gasoline at low prices. In addition, in the United States, the Prohibition banned ethanol production and sale between 1920 and 1933. A few exceptions, such as Brazil, United Kingdom and India, kept ethanol use as fuel for longer.

In recent times, the use of bioethanol as a fuel has been revived due to its economic, environmental and strategic advantages. Bioethanol is an eclectic fuel, as benefits the mobility of the future. It is among the few renewable fuels capable of being used efficiently in combustion engines and turbines, as well as being suitable for electrochemical devices such as fuel cell. Bioethanol can be adopted in the short term throughout the current global fleet of cars and motorcycles, in blends with gasoline ranging from 1% to 30%, as has been happening in dozens of countries. Several countries also have fleets of "flex" vehicles, which can be fuelled with pure bioethanol (E100), such as Brazil, Paraguay and India, or with high percentages of bioethanol (E85), such as Canada, the United States and in Europe.

FIGURE 2. Countries that use bioethanol fuel blended with gasoline (Brazil and Paraguay also use pure bioethanol)



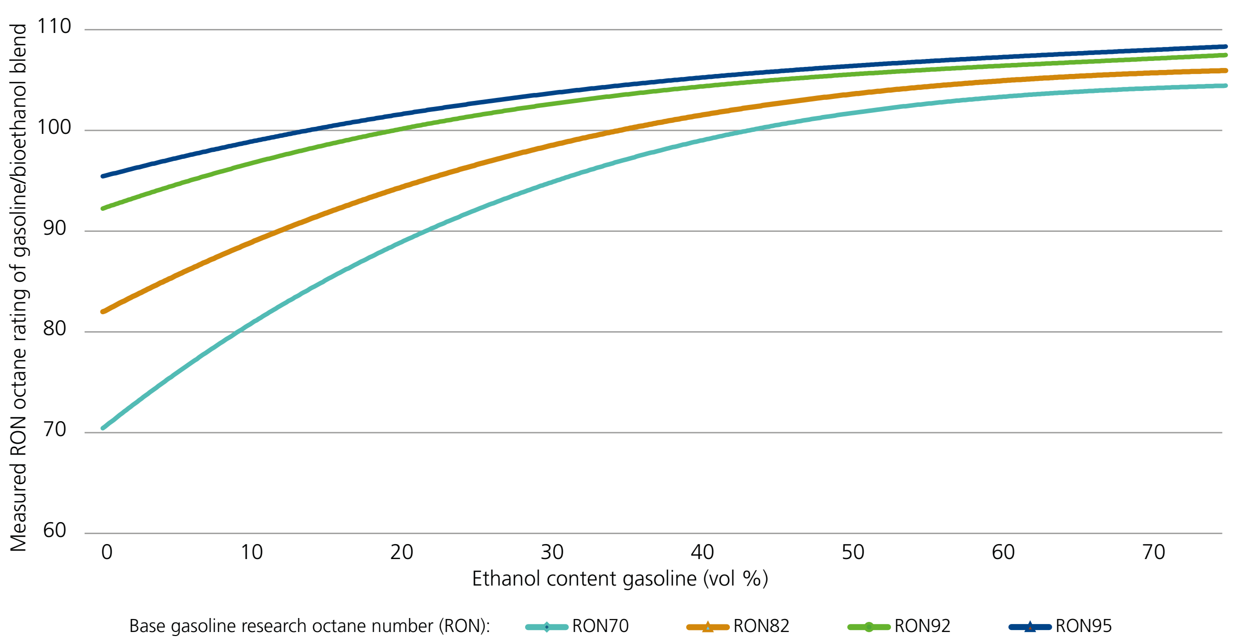
Source: Cantarella *et al*. (2023).

Bioethanol has relevant properties favorable for use as fuel in internal combustion engines. Although it has a lower energy content than gasoline (35% less by mass and 30% by volume), its high oxygen content (around 35% by mass of bioethanol) brings important advantages to bioethanol. Due to its partial oxidation, bioethanol combustion requires 40% less air compared with gasoline, which increases engine torque and power, in addition to reducing pollutant emissions.

Bioethanol oxygen content improves its resistance to detonation, also known as octane rating. Higher octane rating allows for better use of the energy released in combustion and is one of the most important properties of a fuel for Otto cycle engines. Two standardized methods are used to measure the octane rating of fuels: the RON method, with the engine operating under relatively mild conditions, and the MON method, with the engine operating under severe conditions.

When mixed with gasoline, bioethanol behaves like a real additive, an octane booster. Pure gasoline, as produced in oil refineries, always needs to adjust its properties to a specification that ensures good performance. As implemented in several countries, bioethanol added to gasoline has replaced the high-priced carcinogenic hydrocarbons previously used as octane boosters. Bioethanol blending allows the use of lower quality, cheaper base gasolines (reformulated blendstock for oxygenate blending – RBOB).

GRAPH 6. Effect of bioethanol blending on the RON octane rating of gasoline



Source: Prepared by the authors based on Wang *et al*. (2017).

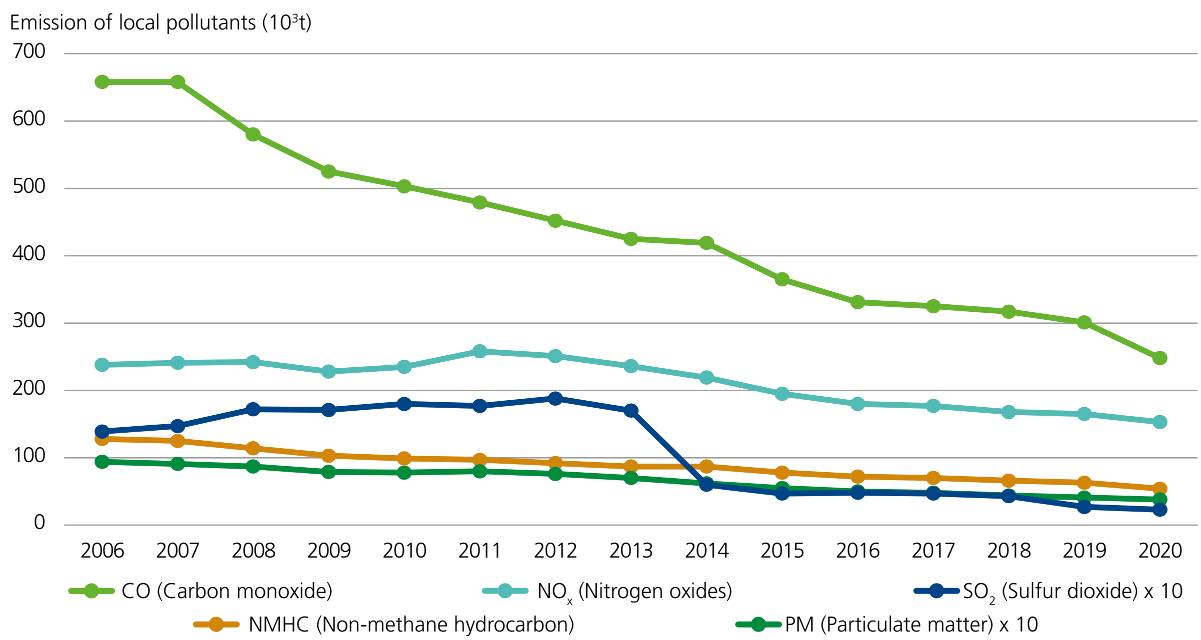
Currently, more than 60 countries blend bioethanol in gasoline, from 5 to 30%, with 10% bioethanol (called E10) being the most widely used blend. The Worldwide Fuel Charter (WWFC), edited by the main motor vehicle manufacturers' associations around the world, expressly accepts the use of gasoline with 10% bioethanol for all gasoline engines (ACEA, 2019).

Since 2015, Brazil has adopted a mandatory blend of 27% anhydrous ethanol in all regular and additive gasoline sold in the country, based on a detailed and ample testing program, evaluating emissions, economy and engine performance. Currently, this fuel is used in a fleet of around 45 million cars and 21 million motorcycles, mostly with gasoline engines, with positive results.

In general, engines burning pure ethanol or blended with gasoline comply well with vehicle emissions legislation. Even modern direct injection engines have been approved by environmental agencies in their emissions of particulate material and polycyclic aromatic hydrocarbons. Aldehydes are pollutants particularly associated with the burning of ethanol in engines, emitted mainly in the early stages of the vehicle's driving cycle, when the engines are relatively cold. The establishment of strict limits on the emission of organic gases other than methane and aldehydes was important and was well received and met by the automotive industry (Souza *et al.*, 2014).

An example of environmental benefits of using bioethanol and adopting emission limits is the state of São Paulo, which concentrates around 30% of the Brazilian vehicle fleet. Even with the significant and growing consumption of pure ethanol and ethanol mixed with gasoline, and the constant expansion of the fleet, with 31 million vehicles in 2019, pollutant emissions showed some reduction.

GRAPH 7. Evolution of vehicle pollutant emissions in São Paulo state



Source: Cetesb (2022).

In some countries the possibility of aqueous phases separation in blends bioethanol/gasoline is mentioned as a hurdle for adopting bioethanol. In fact, bioethanol acts as a cosolvent between gasoline and water, reducing the risk of phase separation. Other issues regarding bioethanol blending, such as cold start, evaporative losses, drivability and compatibility with automotive materials were fully resolved by proper fuel specification of bioethanol and gasoline. Correct definition and strict observance of the biofuel specification are essential for the success of the bioethanol fuel program, as the positive experience in many countries has confirmed (Abel *et al.*, 2021).

Using advanced air/fuel mixture and ignition control systems, flexfuel engines have been launched, capable of using mixtures of bioethanol and gasoline in any proportion, without any interference from the driver and meeting efficiency and drivability requirements and legal emission limits. Two concepts of flexible vehicles have been adopted. In Brazil, users can choose at the time of refueling, from 100% bioethanol to gasoline with 27% bioethanol, both available at all service stations in the country. The introduction of various models of flexfuel vehicles from 2003 onwards was well received by Brazilian consumers and has since accounted for a significant majority of new vehicle sales. Nowadays, flexfuel vehicles represent 85% of the Brazilian fleet, which means that 33.7 million cars are able to use both pure ethanol and E27.

This concept has been adopted in India, where, following the mandatory adoption of a 10% blend of ethanol in gasoline in 2021, the aim is to reach 20% by 2025, facilitating the introduction of these flexible vehicles (India MTRH, 2022). In the United States, Canada and Europe, flexfuel vehicles operate on a range from pure gasoline, without ethanol, to a blend of 85% anhydrous ethanol and 15% gasoline, marketed under the acronym E85, the gasoline content of which allows cold starts at very low temperatures.

Bioethanol use has allowed for more efficient combustion engines. In recent decades, the technological development of combustion engines, incorporating digital electronic monitoring and control systems, has allowed increases in efficiency, which are reinforced with the use of high level mixtures of ethanol or pure ethanol, the octane rating of which reaches 110 RON (DOE, 2024). Nowadays, compact engines, with small displacement, supercharged and direct fuel injection into the combustion chamber, have predominated in new launches by automakers. This technology allows high torque at low speeds, improving drivability and reducing fuel consumption and exhaust emissions.

The US Department of Energy's Co-optima project was was innovative in assessing and classifying technologies for mobility by jointly optimizing engines and energy inputs (electricity and fuels) (Farrell *et al.*, 2020). This comparative assessment placed bioethanol in first position for short- and medium-term use in modern engine designs, with more efficient thermodynamic cycles adopted in hybrid vehicles, such as the Atkinson or Miller cycles, improvements from the Otto cycles. Contributing for this top ranking of the new bioethanol engines, the high RON, greater sensitivity (the difference between RON and MON values) and high latent heat of vaporization constitute a special set of properties of pure ethanol and its blends, particularly favoring the efficiency of combustion engines (McCormick, 2016).

Bioelectric vehicles, associating electrification with modern combustion engines burning bioethanol at optimized operation achieve high thermal efficiency, as indicated by the Co-optima project. Engines for dedicated use in hybrid vehicles developed from 2022 onwards have evolved so quickly that in 2025 they will be sold with 50% thermal efficiency (Nissan's..., 2021).

These important advances show that there is still potential for relevant technological developments in modern internal combustion engines, which can no longer be considered an end-of-life technology, but essential elements for rational electrification in mobility (Gauto *et al.*, 2023).

The Brazilian experience in combining efficient combustion engines with bioethanol as fuel resulted in effective decarbonization on road mobility. The very reduced carbon footprint of bioethanol and the high efficiency of engines, especially in bioelectric vehicles, have allowed us to reach the lowest specific emissions for road vehicles around 25 gCO_2e/km, a similar range of battery electric vehicles powered with green electricity (Gauto *et al.*, 2023).

Environmental sustainability of bioenergy production

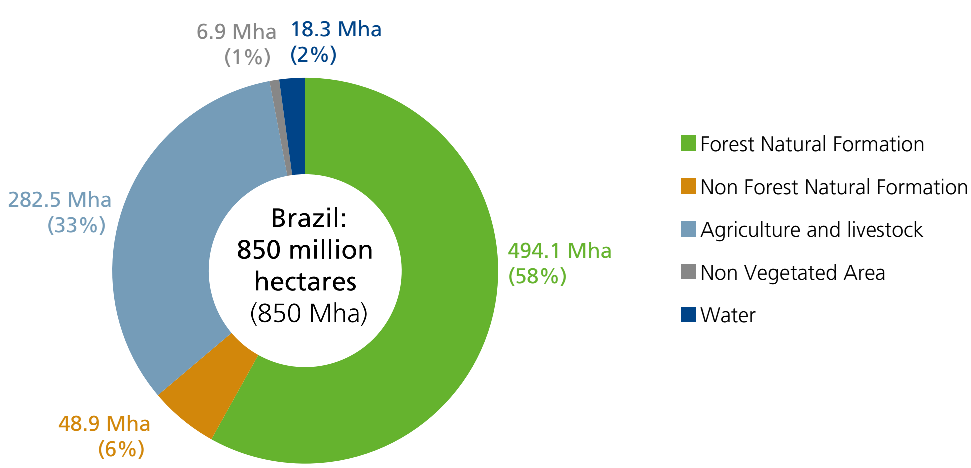
Reducing GHG emissions and achieving harmony between agricultural production and land use are key issues for the effective contribution of biofuels to the energy transition. Using land for growing energy crops can result in synergies or trade-offs between GHG emission reductions and other sustainability effects. The potential impacts will depend on the specific conditions of the context, implementation scale, previous land use, bioenergy crop, soil type, regional climate and agricultural management practices. While positive environmental impacts can be expected, it is essential to regularly monitor/evaluate impacts to take corrective actions to avoid or minimize negative impacts.

The high potential for sustainable bioenergy production in Brazil reflects a natural condition and land use pattern observed in other humid tropical regions of the planet. The topics mentioned here essentially present the panorama of bioenergy in Brazil, but many aspects correspond to similar realities for promoting sustainable bioenergy in other countries in Latin America, Africa and Asia. These regions have significant potential for reducing bioenergy GHG emissions, and the implementation of appropriate policies to stimulate investment, overcome costs and ensure competitive prices are essential.

Brazil has made progress in managing the expansion of land use for bioenergy production. Brazil is home to a significant portion of the tropical forests and global biodiversity, which implies recognition and responsibilities. Approximately 64% of the Brazilian territory is composed of natural vegetation, predominantly forest (58%), and 33% is dedicated to agriculture and livestock, 58% of which is pasture and 22% is arable lands. Land allocation management is complex and challenging, involving command and control measures for the conservation of natural resources, such as national policies and environmental legislation, in addition to investments in resource efficiency, waste utilization and land-saving strategies.

In Brazil, the RenovaBio program (Law No. 13,576/2017), aligned with other land use and environmental protection policies such as the new Forest Code (Law No. 12,651/2012), has been essential in promoting more sustainable bioenergy production. RenovaBio is Brazil's biofuels policy, established in 2017. The program aims to reduce GHG emissions in the production, commercialization and use of biofuels, including Life Cycle Assessment mechanisms as well as promoting the expansion of bioenergy in the national energy matrix and ensuring predictability for the competitive participation of the various biofuels in the national fuel market. Land use management is addressed by risk management mechanisms, through established eligibility criteria, which reaffirm important environmental and land use planning policies.

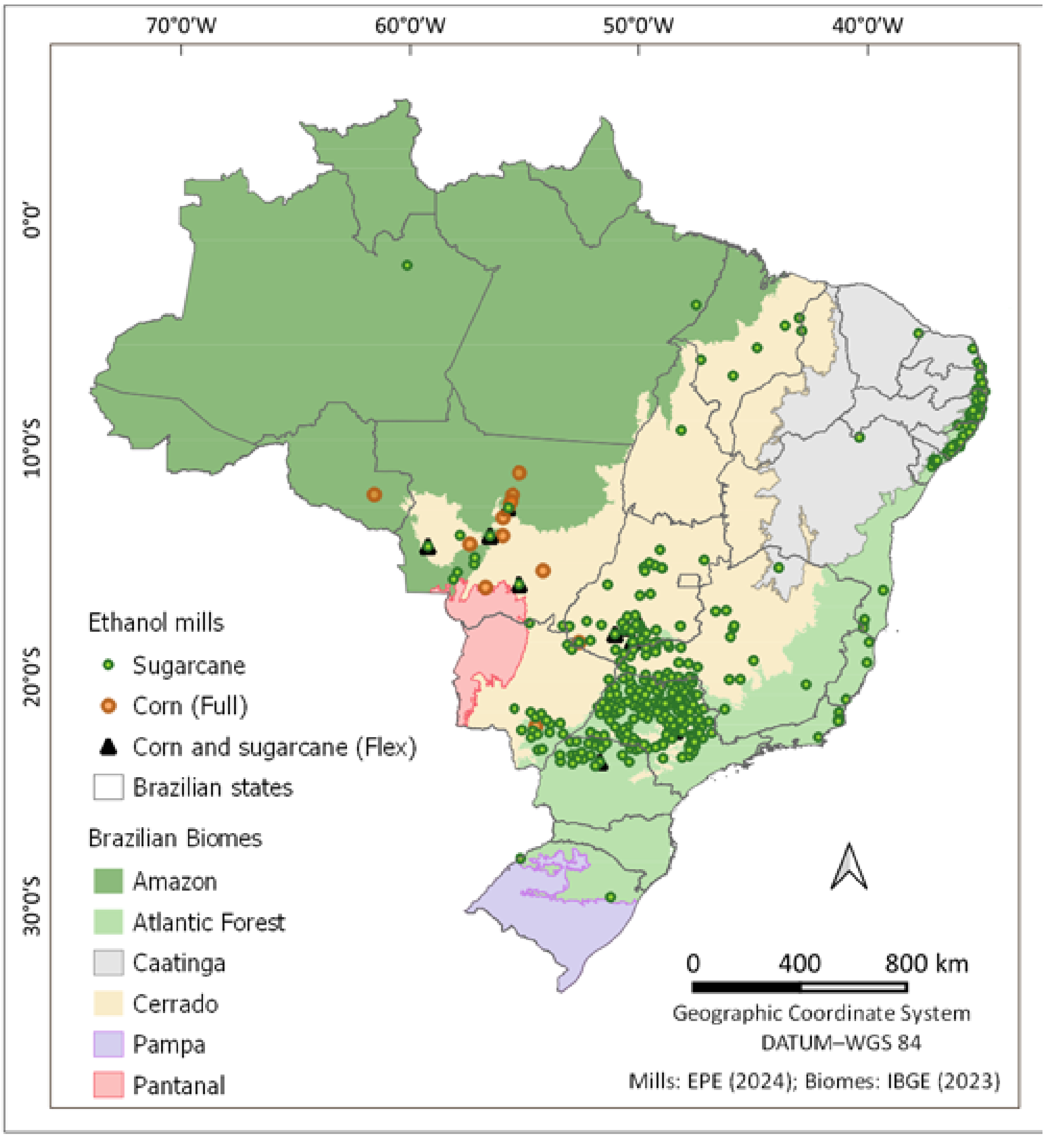
GRAPH 8. Land use and land cover in Brazil in 2022



Source: Prepared and provided by Agroicone (https://agroicone.com.br/) based on MAPBIOMAS (2023).

Sugarcane production in Brazil has expanded predominantly over degraded pastures. Sugarcane and bioethanol production is concentrated mainly in the Center-South and Northeast regions of Brazil, in the Cerrado and Atlantic Forest biomes. Over the last two decades, approximately 98% of sugarcane expansion has occurred over areas already in agricultural use, mainly over degraded pastures, and less than 1.6% of the entire area currently occupied by sugarcane was occupied by natural vegetation in 2000 (Guarenghi *et al.*, 2023). After 2008, there was also an increase in the recovery of areas of natural vegetation and a reduction in the suppression of natural vegetation on sugarcane-producing properties. This demonstrates the concern with the environmental adequacy of producers to control mechanisms such as zoning and vegetation protection mechanisms, and national policies on biofuel production.

FIGURE 3. Location operational bioethanol plants in Brazil



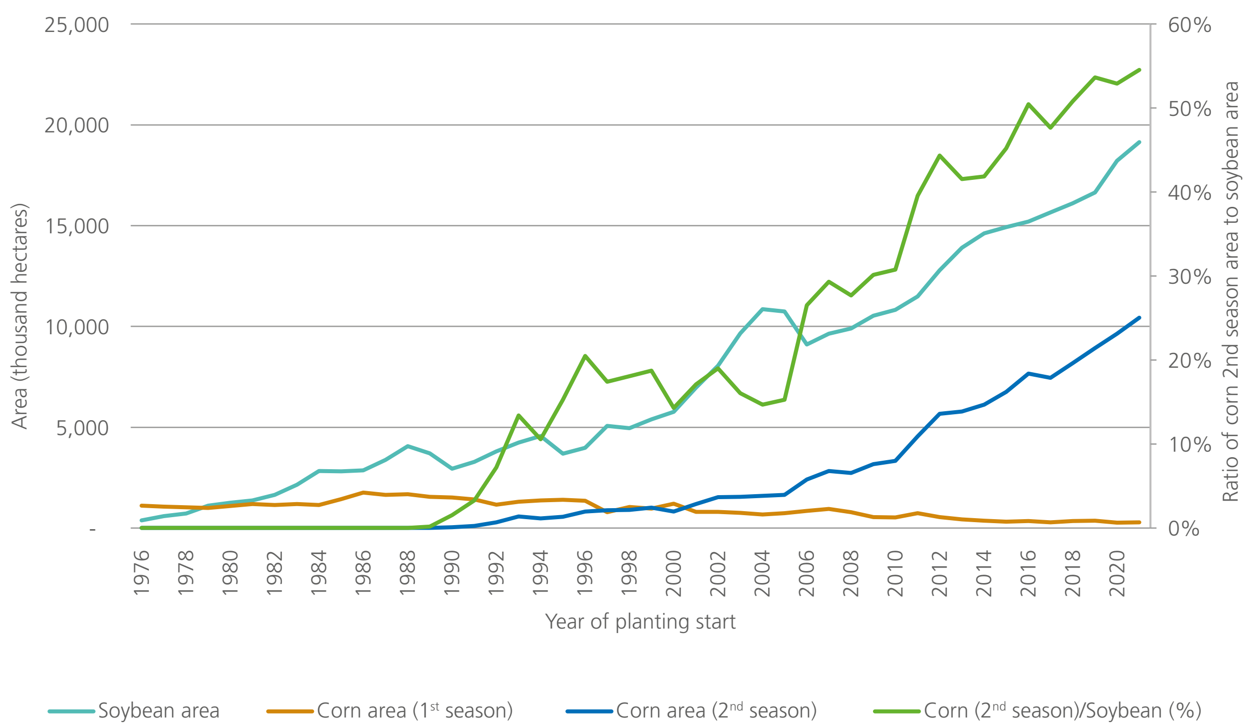
Source: Prepared and provided by Agroicone (https://agroicone.com.br/) based on EPE (2024).

RenovaBio encourages the use of areas already used for cultivation, not allowing raw materials from areas of native vegetation deforested after 2018 to be eligible for the program. Rural properties are also monitored through the Rural Environmental Registry (CAR), which allows monitoring of the Forest Code, which contains the boundaries and environmental information of these properties. The Forest Code is the main legal instrument for protecting native vegetation in the country, with rules for the preservation of permanent protection areas and native vegetation. Thus, bioenergy producers have increasingly adopted sustainable agricultural practices, in the efficient use of already degraded areas and in the conservation of natural vegetation areas.

Bioethanol from corn as a secondary crop is an innovation in traditional agricultural systems, as it does not require additional land for its expansion. In Brazil, corn bioethanol is produced mainly from corn cultivated as secondary crop, in the same location and year, after the main soybean crop is harvested. The production and significant expansion of secondary-crop corn, used in bioethanol production, occurs mainly in Brazil's Central-West region and the state of Paraná. The system adopted is direct seeding, with corn sown directly after and on top of soybean residues.

This production model ensures the best agro-environmental management of the soil, eliminates competition for land with other first-crop crops, and contributes to reducing the number of inputs used in production. In traditional systems, corn is produced only in the first crop, and increasing corn production for bioethanol requires additional land.

GRAPH 9. Soybean and corn area (1st and 2nd harvest) and participation of second-harvest corn area in soybean areas in the Central-West region



Source: Prepared and provided by Agroicone (https://agroicone.com.br/) based on CONAB (2023).

The adoption of good agricultural practices is essential to produce sustainable low-carbon bioenergy, and Brazil has made progress in this regard. Bioenergy production must consider agricultural practices that minimize negative impacts and maximize environmental benefits. Techniques such as crop rotation, adequate waste management, intensification of livestock farming, use of degraded areas, and Integrated Crop-Livestock Systems are among the strategies adopted to promote sustainable Brazilian bioenergy production. Such practices contribute to reducing GHG emissions, minimizing impacts on biodiversity and soil quality, and increasing agricultural productivity.

Bioethanol plays a fundamental role in reducing GHG emissions in Brazil. To achieve the goals established in the country's Nationally Determined Contribution (NDC), Brazil intends to increase the share of biofuels and renewable energies in its energy matrix to around 18% and 45%, respectively, by 2030. Since the introduction of flexfuel engines in 2003, the demand for bioethanol has increased and it is estimated that bioethanol has prevented the emission of approximately 600 million tons of CO_2 in Brazil (UNICA, 2020).

Brazilian sugarcane and secondary-crop corn bioethanol has one of the best carbon footprints in the world. The carbon footprint of Brazilian bioethanol is around 20 to 25 gCO2e/MJ, which represents a reduction of 70% to 82% compared to gasoline and can reach up to 90% reduction in the best cases. These values are lower than those found for corn bioethanol, as well as for bioethanol produced from other raw materials, such as sugar beet and wheat in temperate climate regions. The characteristics of the crops, the adopted cultivation practices, the dynamics of raw material production expansion, the use of agro-industrial waste and the use of biomass for cogeneration contribute to the low carbon footprint values of sugarcane and corn bioethanol in Brazil (Cherubin *et al.*, 2021; Moreira *et al.*, 2020).

The expansion of sugarcane and secondary-crop corn presents low risks of deforestation, related to direct change (dLUC)[4] and low risks of indirect change (iLUC)[5]. Large-scale production of energy crops raises concerns about land use change (LUC) and its impact on estimates of the carbon footprint of biofuels. However, recent literature shows that the expansion of sugarcane and second-crop corn in Brazil, and their derived biofuels, has protected areas of natural vegetation (Guarenghi *et al.* 2023; Canabarro *et al.*, 2023), and presents a low risk of iLUC and induced effect[6] (Moreira *et al.*, 2020; Fiorini *et al.*, 2023). Models that estimate iLUC for second-crop corn bioethanol, in fact, indicate values close to zero and negative

4 dLUC refers to the direct conversion of a land use to the cultivation of biofuel feedstocks.

5 iLUC occurs when bioenergy production displaces cultivation from productive areas to other locations.

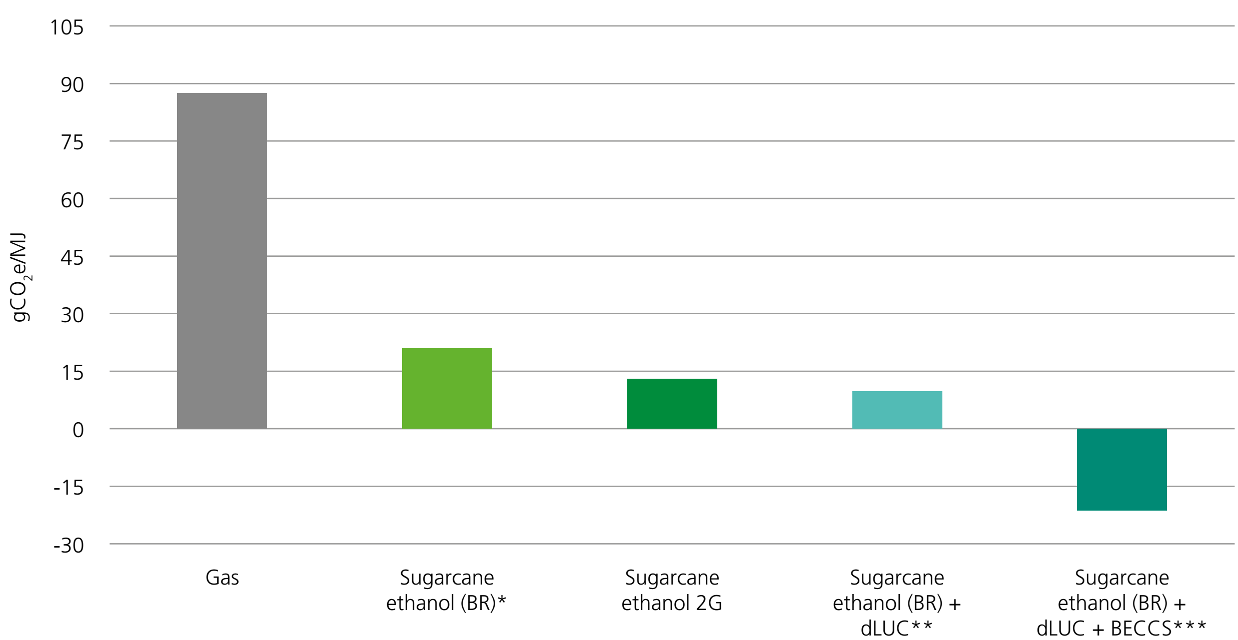
6 Induced land use change includes dLUC and iLUC.

(Moreira *et al.*, 2020; Fiorini *et al.*, 2023). For sugarcane, the estimated iLUC values are lower than those of other biofuels based on different raw materials.

The potential for mitigating bioethanol emissions could be even greater, reaching near-zero or even negative emissions. Technological advances, the adoption of better agricultural practices, and the consequent increase in biomass production, in addition to the greater use of waste such as straw for the production of 2G bioethanol, and the use of biomethane produced from co-products of sugarcane processing, replacing the diesel used in agricultural machinery, will play an important role in mitigating GHG emissions for 1G and 2G bioethanol (Nogueira *et al.*, 2023). These new and more efficient technologies, diversifying products in biomass processing and promoting the circular economy, have expanded significantly during the last decade in Brazil, adopted in several plants that are operating normally.

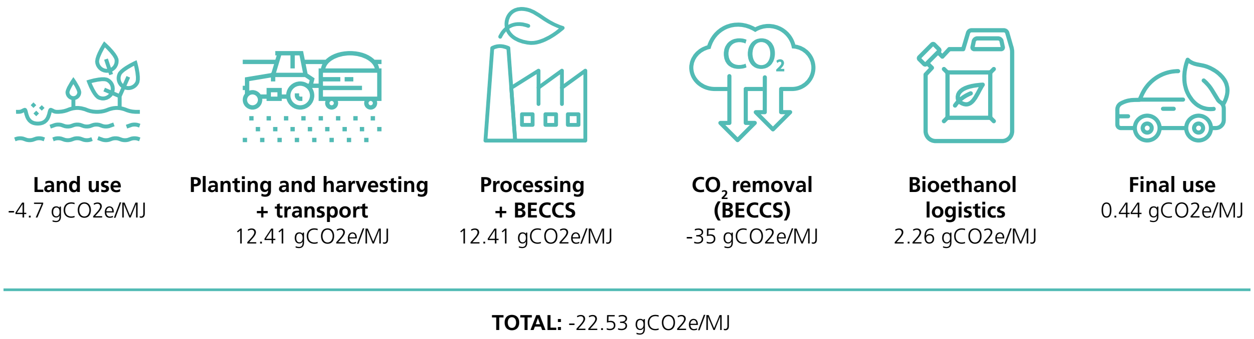
Implementation of Bioenergy with Carbon Capture and Storage (BECCS) technology, which captures and stores CO_2 during the bioethanol production process, can also enable a negative carbon footprint for Brazilian bioethanol, contributing to further mitigate GHG emissions to values close to 30 gCO2e/MJ (Moreira *et al.*, 2016; Chagas *et al.*, 2016). With the recent Bill for the Fuel of the Future Program, Brazil intends to advance in the regulation of carbon capture and storage.

GRAPH 10. Estimated carbon footprint of sugarcane bioethanol incorporating different mitigation strategies (approximate values)



Source: Prepared and provided by Agroicone (https://agroicone.com.br/) based on ANP (2024), Guarenghi *et al*. (2023), and Chagas *et al*. (2016).
*Produced in Brazil (BR)
**Direct Land Use Change (dLUC)
***Bioenergy with carbon capture and storage (BECCS)

FIGURE 4. Stages of the life cycle assessment of corn bioethanol from one of the main corn bioethanol production units in Brazil*



Source: Prepared and provided by Agroicone (https://agroicone.com.br/) based on Moreira *et al*. (2020) and ANP (2024).
*Considering corn grown as a second crop in rotation with soybeans, using eucalyptus chips supplemented with agricultural and agro-industrial waste as a source of energy for the process, and taking into account a production of approximately 425 liters of bioethanol per ton of processed corn.

Socioeconomic sustainability of biofuel production

Biofuels have more inclusive socioeconomic indicators than fossil fuels. In countries where modern bioenergy production accounts for a significant portion of their respective domestic energy supplies, evidence presented in several studies shows that the socioeconomic impacts of these activities have advantageous characteristics compared to fossil energy production chains in terms of, for example, job creation, impact on income (gross domestic product – GDP) and income distribution.

In Brazil, the bioenergy agroindustry has an important role in job creation and income, either through direct effects – in the production and processing of raw materials (mostly sugar cane, corn and soybeans) to produce biofuels – or through indirect effects with the demand for services and inputs in this sector.

Using the input-output analysis (which considers the propagation of all direct and indirect effects along the production chain of the economic sector of interest), Table 1 presents the results of the comparison between the activities of (i) biofuel production and (ii) oil refining in Brazil (production of diesel oil and gasoline) in 2021 per thousand tons of oil equivalent for each of these sectors.

TABLE 1. Comparison of socioeconomic aspects between the biofuels and oil refining sectors (production of diesel oil and gasoline) in Brazil in 2021

Item	Mineral diesel oil and pure gasoline (a)	Biofuels (b)	Comparison (b)/(a)
Jobs by thousand tons of oil equivalent	10.3	60.1	5.86
Sectorial GDP in thousand R$ by ton of oil equivalent	3.3	5.4	1.62
Monthly average income in thousand R$ per job	4.8	3.3	0.69
Monthly average income in R$ by ton of oil equivalent	49.6	199.5	4.02
Share of income over the sectorial GDP	17.9%	44.4%	2.49

Source: Prepared by the authors based on information from IBGE (2023).

Even with the high degree of mechanization in sugarcane, corn and soybean crops in Brazil, biofuel production generates 5.86 times the number of jobs per energy output compared to oil refining. For an energy transition associated with the need to generate employment and income in countries located in the intertropical belt and with edaphoclimatic potential to produce modern bioenergy, this characteristic deserves attention for the formulation of policies that encourage this industry as an inclusive vector of sustainable economic development. It is also noted that each energy output from the production of biofuels has an impact on the sectoral GDP that is 62% of that of the production of fossil energy (mineral diesel oil and gasoline).

The functional distribution of income in the biofuel production chain values labor more than capital, when compared to the fossil fuel production chain. In the Brazilian context, for biofuels, 44.4% of the impacts on the sectoral GDP are concentrated in the remuneration of the labor factor and gross mixed income (the income earned by self-employed workers where it is not possible to distinguish the portion related to the labor factor and that related to the capital factor), while in fossil fuels this portion is only 17.9%. This aspect reinforces, once again, the importance of biofuels as an alternative for the energy transition that prioritizes the generation of income associated with the labor factor, also accompanied by the generation of more jobs.

Mechanization of the agricultural sector contributes to improving working conditions. A determining factor in the quantity and quality of jobs generated in the bioenergy production chain is the increased use of capital in the agricultural sector. In the production of bioethanol from sugarcane in Brazil, the adoption of mechanized sugarcane harvesting was motivated by (i) economic (cost reduction); (ii) social (elimination of stressful working conditions during sugarcane harvesting); and (iii) environmental (laws, protocols and incentive programs to eliminate burning before harvesting) factors.

Currently (2023/2024 harvest), 92% of sugarcane harvesting in Brazil is done mechanically, maintaining the trend of increasing mechanization in the sector in recent decades. In the Center-South region, responsible for more than 90% of sugarcane production in Brazil, with predominately flat areas, favorable to harvesting with machines, mechanization of the harvest already represents about 99% of the total. Thus, there is an intensification of the capital factor, that is, an increase in investment in equipment, technologies and infrastructure to improve economic efficiency. With harvest mechanization, there is a greater demand for qualified labor and better pay; however, the total number of jobs in the sector is reduced.

The economic efficiency promoted by mechanization – producing more with the same use of resources, such as energy and labor – can be beneficial to society, since workers laid off from one activity can be reallocated to other roles, if they have the qualifications required. However, workers with low levels of education, especially in manual agricultural operations, face difficulties to take on other roles, whether in the sugar-energy sector or in other sectors of the economy. Therefore, it is necessary to intensify actions aimed at these low-skilled workers, providing opportunities for qualification so that they can operate machinery or even take on activities in other areas of the bioenergy sector or other sectors of the economy.

Biofuel production can boost regional development. The biofuel production chain encompasses all agricultural activities related to the production of raw materials, transportation to processing units and distribution to the end consumer. In addition to the direct jobs generated in the sector, there is great potential for generating indirect jobs – those linked to the demand for inputs and services from other sectors of the economy – and induced jobs, since it boosts the consumption of goods and services in the local and regional economy due to the increase in income from direct and indirect jobs.

In addition to jobs, the development of the biofuel production chain strengthens regional infrastructure, diversifying the local economy, promoting the construction and/or maintenance of roads for the flow of production, as well as investments in research and professional training. It is also worth remembering that social indicators – such as life expectancy, infant mortality rate and illiteracy rate – are strongly related to the availability of energy and increased income, factors essential for local development, allowing other industrial and service sectors to establish themselves in the region.

Brazil's five decades of experience in formulating and establishing policies to promote bioenergy production and usage highlight the critical role of public-private partnerships. These collaborations can accelerate the progress of less developed regions, providing investments in more efficient technologies and practices in the sector's production chain (including the agricultural sector) and, thus, reducing inequality in regional development levels. In this sense, it is essential to understand that the adoption of sustainable development strategies must include the generation of jobs and income that result in the eradication of poverty and also seek to achieve the conditions so that the current generation can meet its own needs, especially the portion of the population that is poor and below the poverty line.

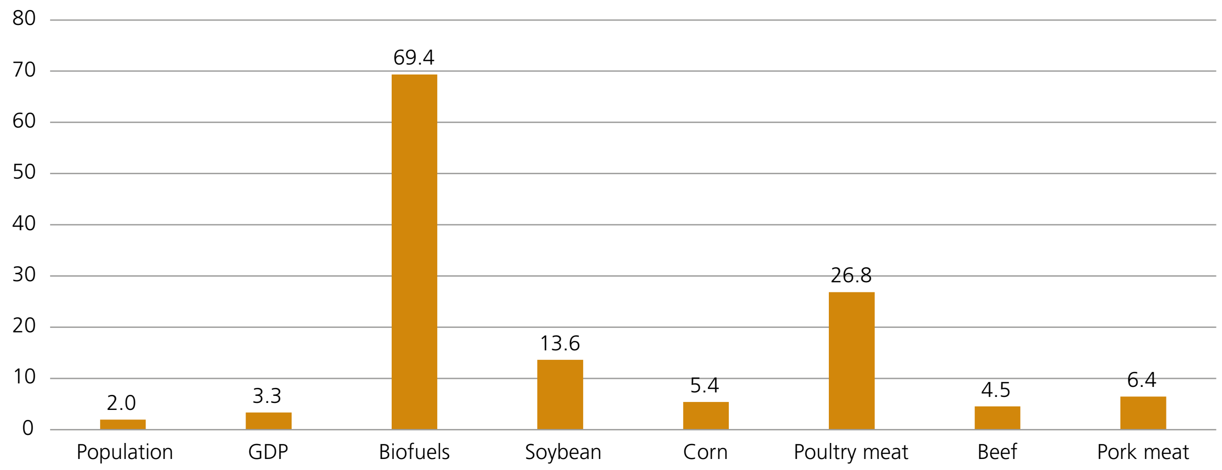
Biofuels need a fair economic playing field to be competitive with fossil fuels. As a good example, the Brazilian production and use of liquid biofuels, mainly ethanol, accompanied by technological improvements in the agricultural and industrial phases, followed a learning curve over several decades, with significant cost reductions, reaching levels like those of conventional fuels. Nevertheless, the competitiveness of biofuels is often distorted by inadequate pricing of fossil fuels. In this sense, balanced taxation by useful energy content and incorporation of negative externalities in the consumer price of each fuel are essential.

In this direction, the recent National Biofuels Policy (RenovaBio) has been in operation in Brazil since 2019. It seeks to promote incentives for the production and consumption of biofuels, with one of its main instruments being the creation of CBIO (decarbonization credit), a financial asset traded on the Stock Exchange that represents the contribution of the reduction in greenhouse gas emissions promoted by biofuels replacing fossil fuels. RenovaBio creates a carbon market in which producers and importers of biofuels can issue and sell their credits (CBIOs) to fossil fuel distributors for increasing the supply of biofuels, making the energy matrix cleaner and contributing to the commitment to the Paris Agreement (Ribeiro and Cunha, 2021). In addition to emissions, the policy inhibits deforestation and seeks positive impacts in job creation and better income distribution in the country, providing greater predictability for the competitive participation of biofuels in the Brazilian market (Brasil, 2017).

Increased biofuel production may be accompanied by increased per capita food production. Coordinated actions between the public and private sectors, supported by effective policies that seek to obtain productivity gains and associated with instruments aimed at maintaining sustainability (in its environmental, social and economic tripod), can result in a significant increase in the production of biofuels and food.

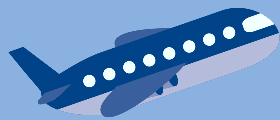
A concrete example of this possibility can be seen in Graph 11, which presents the multipliers of population, gross domestic product (GDP), biofuel production (on an energy basis) and agricultural production – soybeans, corn, beef, chicken and pork. The data refer to the period from 1975 (the year in which the Proálcool, the Brazilian federal program that increased ethanol blending in gasoline and promoted the use of pure ethanol as vehicle fuel, was established) to 2021 – a period of almost five decades.

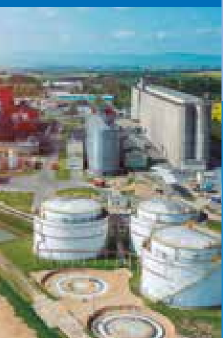
GRAPH 11. Multiplication of Brazilian population, GDP, and agricultural production from 1975 to 2021

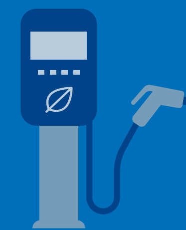


Source: Prepared by the authors based on data from EPE (2023), FAO (2024) and IBGE (2024).

From 1975 to 2021, the real GDP of the country was multiplied by 3.33, whereas the population by 1.97 – resulting in a GDP per capita multiplication of 1.69. It is worth noting that biofuel production has increased by a factor of almost 70, but this has not prevented food production from lagging behind GDP growth and, even less so, population growth. The facts show that, in Brazil, the scale of bioenergy production has been accompanied by an increase in per capita food production that is greater than the gains in per capita GDP over the last five decades.







Bioethanol for a FAIR – Fast, Accessible, Inclusive, and Renewable – energy transition: takeaway messages

The energy transition in mobility is crucial for reducing greenhouse gas emissions and combating climate change. Despite significant advancements in the adoption of renewable energy across various sectors, the transport sector remains heavily reliant on oil. This sector contributes approximately 30% of global energy consumption and a significant portion of CO_2 emissions. However, the transition in transport energy is more of an expectation than a reality due to the large fleet of gasoline-powered vehicles, the need for substantial investments in electrification infrastructure, and the dependence on strategic and scarce materials.

International energy agencies stress the need to increase the production and use of sustainable biofuels to achieve climate and energy security goals. The International Renewable Energy Agency (IRENA) projects that bioenergy could play a major role in limiting global temperature increases, with the contribution of biofuel to transport expected to increase more than fourfold by 2050. The International Energy Agency (IEA) also calls for robust growth in biofuel consumption over the next five years to meet these objectives. Besides decarbonization, implementing bioenergy promotes sustainability in a broad sense and the global trade.

Bioethanol is a qualified vehicular fuel that has seen increasing global adoption due to its economic, environmental, and strategic advantages. Bioethanol is versatile and can be used efficiently in combustion engines and turbines, as well as can be seamlessly integrated into existing logistics, storage, and distribution systems. It also enhances energy security by diversifying energy sources, reducing dependence on fuel imports and promoting domestic production. Many countries, including Brazil, the United States, and various European nations, blend bioethanol with gasoline or use it in pure form in flexible fuel vehicles (flex-fuel).

Bioethanol improves combustion efficiency and reduces pollutant emissions due to its high oxygen content and octane rating, making it a valuable additive and octane booster for gasoline. Moreover, the substantial reductions in specific emissions that can be achieved through the combination of its low carbon intensity with the high efficiency of modern engines, especially in bioelectric vehicles (e.g., hybrid EV fueled by bioethanol), corroborate bioethanol as not only a short-term but also as a long-term mitigation strategy. Further reductions on bioethanol carbon intensity are also expected with the progressive deployment of practices such as second-generation technologies, energy cane, biomethane from vinasse, and carbon capture and storage or utilization.

Bioethanol can serve as a decarbonization mechanism in various sectors. In addition to its significant potential for decarbonization in road transportation, bioethanol can also be utilized in hard-to-abate sectors. It can be adopted as a platform for drop-in solutions, such as through the alcohol-to-jet (ATJ) pathway for producing sustainable aviation fuels (SAF). Further, it can also be used as an alternative feedstock for plastics, among other Chemical, as well as synergically integrated into hydrogen production and carbon capture and storage or utilization.

There is a vast potential to produce bioethanol with competitive sustainability indicators. Bioenergy contributes significantly to a fair energy transition, especially in tropical countries, in which bioenergy has always played a prominent role. Modern bioenergy, covering around 12% of global energy consumption, is produced through efficient and environmentally friendly technologies. Brazil, for instance, uses sugarcane, corn, and other forms of bioenergy, which represented 67% of its renewable energy production in 2023.

The expansion of bioethanol using low carbon stocks areas can lead to important environmental benefits. This approach reduces the environmental impact and supports biodiversity conservation. For example, the expansion of bioethanol in Brazil has been primarily based on using degraded pastures and existing agricultural lands, which has frequently led to higher carbon stocks in the soil while minimizing indirect land use changes. Innovations like the production of bioethanol from secondary crops, like corn, further enhance the sustainability of the sector, without additional land requirements. Other practices such as proper agricultural residue management (e.g., vinasse and filtercake mud recycling) and integrated livestock-crop systems also helped to recycle carbon, nutrients, and water, therefore reducing negative impacts and maximizing environmental benefits.

The socioeconomic impacts of bioenergy production are advantageous compared to fossil fuels. Evidence from various studies shows that the bioenergy sector generates significantly more employment per energy output than petroleum refining. This job creation is crucial for countries in the intertropical region, which have significant potential for modern bioenergy production and need to generate employment and income to support sustainable development.

Bioenergy production also promotes income distribution, favoring labor over capital, contributing to equitable economic development. The production of biofuels channels a larger share of the gross domestic product (GDP) toward labor remuneration compared to fossil fuels. This redistribution of income supports broader economic development and social equity, particularly in regions with high bioenergy production potential.

Mechanization in bioenergy production, especially in agriculture, has significantly transformed the sector. In Brazil, the mechanized harvesting of sugarcane has increased efficiency, reduced labor intensity, and minimized environmental impacts. While mechanization reduces the total number of jobs, it increases the demand for skilled labor and offers better remuneration. This shift requires policies focused on worker reatraining and education to ensure that the economic benefits of mechanization are widely shared.

Bioenergy can drive domestic regional development, particularly in the poorest regions, by generating employment and stimulating local economies. The biofuel production chain includes agricultural activities, processing, and distribution, creating direct and indirect jobs. Additionally, bioenergy infrastructure investments, such as roads and professional training, further support regional development. Social indicators like life expectancy, infant mortality, and literacy rates improve with increased energy availability and income, contributing to overall development.

The production of biofuels complements food production. In Brazil, the evolution of biofuel production has not adversely affected food prices or availability. Instead, it highlights the potential for productivity gains and complementarities across biofuel and food production, among other coproducts. Public policies, such as those promoting integrated agriculture-forestry systems, support this synergy and enhance the sustainability of both sectors.

The economic competitiveness of bioethanol is higher than it seems to be. Distortions in the pricing of gasoline, defined frequently with subsidies, without a balanced taxation by useful energy content and incorporation of negative externalities, affects the consumer price of bioethanol. Policies like the Low Carbon Fuel Standard in California (USA) and RenovaBio in Brazil, which focuses on incentivizing low carbon intensity biofuels, are crucial for maintaining the competitiveness of bioethanol. From 2020 to 2023, RenovaBio has avoided the emission of 100 million tons of CO_2 while enabling an estimated revenue close to 2 billion dollars to the biofuels industry.

The environmental and socioeconomic benefits of bioethanol make it strategic for achieving sustainable development goals.

Robust policies, international collaboration, and continuous innovation are key to achieving the full potential of biofuels and ensuring a fair and inclusive energy transition. By promoting a fair energy transition that prioritizes both environmental sustainability and socioeconomic development, bioethanol (and bioenergy) can significantly contribute to a sustainable low-carbon future in different parts of the globe.

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