Vol. 63, p. 464-485, jan./jun. 2024. DOI: http://dx.doi.org/10.5380/dma.v63i0.88929 e-ISSN 2176-9109

UFPR
DeMA DESENVOLVIMENTO E MEIO AMBIENTE
BIBLIOTECA DIGITAL DE PERIÓDICOS BDP | UFPR
revistas.ufpr.br

Biogas and biomethane in Brazil: overview and perspectives

Biogás e biometano no Brasil: panorama e perspectivas

Geraldo Lavigne de LEMOS[1*], Maxiane Frank Oliveira CARDOSO[1], Hirdan Katarina de Medeiros COSTA[1]

[1] University of São Paulo (USP), São Paulo, SP, Brazil.

[*] Contact e-mail: geraldolavigne@usp.br

Article received on December 5, 2022, final version accepted on November 1, 2023, published on June 28, 2024.

ABSTRACT: It is estimated that Brazil can currently produce 84.6 billion Nm³/year, the world's largest potential for the production of biogas and, consequently, of biomethane. However, the Brazilian potential is not exploited. Despite a 779% growth between 2011 and 2020, biogas production remains at levels close to 1.5% of the national potential. Federal legislation is insufficient, and state-level legislation is not present in all federative units. The objective of the current study is to understand the regulatory situation of the biogas and biomethane sectors in Brazil and, subsequently, to present the challenges and opportunities of these sectors, in order to suggest development paths for them in the country. The study was developed through bibliographic research with collection of direct and indirect data from the researched industries and from official bodies, current legislation, scientific literature and research institutions. The results indicate that Brazil should include biogas and biomethane in the political agenda of the energy sector, grant economic incentives, promote research, improve the dissemination of technological routes, and use biogas and biomethane as a decarbonization strategy for energy transition, thus becoming a world leader in these sectors. This article aims at serving as reference for researchers and planners in the analyzed area, contributing to enriching the debate.

Keywords: biofuels; biogas; biomethane; energy transition; decarbonization.

RESUMO: Estima-se que o Brasil pode produzir na atualidade 84,6 bilhões de Nm³/ano, o maior potencial do mundo para a produção de biogás e, por consequência, de biometano. Todavia, o potencial brasileiro não é explorado. Apesar do crescimento de 779% na produção de biogás entre 2011 e 2020, a produção permanece em níveis próximos a 1,5% do potencial nacional. A legislação em nível federal é insuficiente e a legislação em nível estadual não ocorre em todas as unidades da federação. O presente estudo tem por objetivo compreender a situação regulatória dos setores de biogás e biometano no Brasil e, em seguida, expor desafios e oportunidades de tais setores, para, ao cabo, sugerir caminhos de desenvolvimento para esses setores no país. O estudo foi desenvolvido mediante pesquisa bibliográfica com a obtenção de dados diretos e indiretos dos setores

pesquisados e oriundos de órgãos oficiais, legislação vigente, literatura científica e instituições de pesquisa. Os resultados apontam que o Brasil deve incluir o biogás e o biometano na agenda política do setor energético, conceder incentivos econômicos, promover a pesquisa, melhorar a divulgação das rotas tecnológicas e utilizar o biogás e o biometano como uma estratégia de descarbonização para a transição energética, tornando-se líder mundial em tais setores. Este artigo tem a pretensão de servir de literatura para pesquisadores e planejadores na área analisada, contribuindo para o enriquecimento do debate.

Palavras-chave: biocombustíveis; biogás; biometano; transição energética; descarbonização.

1. Introduction

The use of fossil fuels and the industrialization of agriculture, among other factors, have destabilized the environment (Rockström et al., 2009). Human influence on planetary harmony is of such magnitude that a new geological era called the Anthropocene is already being suggested, replacing the Holocene (Steffen et al., 2015). Humanity is responsible for global warming, caused by the emission of greenhouse gases, among other significant influences on the biosphere. There is an urgent need to promote energy transition to mitigate the process of climate change (IPCC, 2021).

The international community understands that natural gas will promote integration between fossil fuels and renewable energies on the path to decarbonization (MME & EPE, 2020; IGU, 2021) and there may be a progressive substitution of natural gas by biogas and biomethane. Studies on biogas and biomethane - in cases of supply and consumption - use the unit of measure called Normal Cubic Meter, abbreviated as Nm^3, which corresponds to the amount of gas that occupies one cubic meter under normal temperature and pressure conditions, established as standard conditions. Brazil has the potential to produce 84.6 billion Nm^3/year of biogas, equivalent to about 44.7 billion Nm^3/year of biomethane (ABIOGÁS, 2020). Despite a 779% growth in biogas production between 2011 and 2020, production remains at levels close to 1.5% of the national potential (CIBIOGÁS, 2020; 2021).

In this context, it is very important to understand the biogas and biomethane sectors in contemporary Brazil, with the identification of barriers and opportunities (CIBIOGÁS, 2020; 2021). Biogas is produced in the anaerobic digestion of organic matter and consists of a gas mixture composed mainly of methane and carbon dioxide. If released into the atmosphere, biogas contributes to the greenhouse effect. However, after the removal of compounds such as water vapor, hydrogen sulfide, ammonia, siloxanes, and particulates through the cleaning process, biogas can be used as fuel in boilers, for example. Biomethane, on the other hand, results from the purification or upgrading of biogas, increasing methane concentrations, comparable to natural gas when it reaches concentrations above 90%. Biomethane can share natural gas pipelines and infrastructure, used in power plants and vehicles, among other residential, commercial, and industrial installations (Coelho *et al*., 2018; 2021).

Biogas and biomethane are two promising renewable fuels for energy transition and can be strategic for national security in the energy matrix. In addition, biogas and biomethane can significantly contribute to achieving the decarbonization goals of the Paris Agreement consolidated in the Brazilian commitment made in the Nationally Determined Contribution, now in its third version (BRAZIL,

2022), submitted to the United Nations Framework Convention on Climate Change on April 7, 2022 (UNFCCC, 2022).

The main objective of this study is to understand the regulatory situation of the biogas and biomethane sectors in Brazil, describing and analyzing the main characteristics of the recent regulatory framework. To achieve this, the specific objectives are to contextualize the biogas and biomethane sectors in Brazil and identify the challenges and opportunities. Based on the previous specific objectives, the research also aims to discuss how the biogas and biomethane sectors can be developed in Brazil. In this context, the study presents the panorama of biogas and biomethane in Brazil, the current context, and the existing Brazilian regulations at the federal and state levels. It then highlights the main barriers and opportunities identified for the biogas and biomethane sectors in Brazil. Finally, it draws conclusions from the conducted study.

2. Materials and methods

The methodology of this research was developed through exploratory and descriptive research, based on bibliographic and documentary research, with the collection of indirect data from official bodies and public and private institutions. Furthermore, it took into account scientific literature research, technical production, sectoral reports, and legal and technical standards, all associated with biofuels and low-carbon economy. The collected data were analyzed qualitatively and quantitatively, with the adoption of the deductive method as the central vector of the work. The data analysis allowed describing the characteristics of the biogas and biomethane sectors, as well as the regulatory framework, the current situation, and projected data. Based on this information and sector projections, the research discussed the barriers and opportunities for the development of biogas and biomethane in Brazil.

3. Biogas and biomethane panorama in Brazil

3.1. Context of the biogas and biomethane sectors

Renewable energies are considered alternative sources to fossil fuels, comprising naturally replenished sources including geothermal, solar, hydro, wind, and those derived from biomass (Ferraz Junior et al., 2022). Biomass is all organic matter of animal or plant origin; it stores chemical energy and, when used for energy purposes, biomass is considered a primary source of non-fossil energy (EPE, 2021). The release of this chemical energy from biomass occurs through various technological routes for bioenergy production (MME & EPE, 2020).

One of the technological routes is anaerobic digestion in an oxygen-free environment for the production of biogas, a mixture of methane, carbon dioxide, and small amounts of other gases (IEA, 2021). Biogas can be used for various purposes, such as steam production, heating, electricity generation, injection into the natural gas grid, and vehicle fuel (Ferraz Junior et al., 2022). The technological route for biogas production can be applied in sanitary sewage, urban, agricultural, and agro-industrial waste, among others. The proper use

of waste and effluents makes any of these activities more sustainable, efficient, and profitable, attracting development and providing job opportunities (Costa, 2021; i17, 2021b).

The immense Brazilian population generates a significant amount of urban solid waste and sanitary sewage (i17, 2021b). It is estimated that in 2019 in Brazil, 79,069,585 tons of urban solid waste were generated, with 72,748,515 tons being collected, which corresponds to 92%. Of the collected urban solid waste, 59.5% was sent to landfills, 23% to controlled landfills, and 17.5% to open dumps (*lixões*) (ABRELPE, 2020). Such waste and effluents have always been a concern for cities regarding proper disposal and reducing environmental impacts. Urban waste and effluents can also be used for energy recovery purposes (Costa, 2021). Biogas is among the top three energy products from urban solid waste, along with electricity (generated from incineration or burning of biogas itself) and heat (MME & EPE, 2020).

In the same context, agricultural and agro-industrial productions represent a significant share of the Brazilian domestic product and have global relevance. The waste and effluents from these activities, previously underutilized, have become the subject of studies for energy recovery purposes, among others. Brazil already utilizes sugarcane bagasse, lye, rice husks, animal fats or greases, but there is still a large supply of sugarcane residues (straw and tops, vinasse, and filter cake), wood chips, soybean and corn straw, coffee husks, coconut residues, beans, peanuts, cassava, cocoa, among others (MME & EPE, 2020). Various studies continue to be conducted in these areas, such as in the case of vinasse (Almeida; Rizzatto, 2022), but there is ample room for research and development in the sector.

Globally, Asia is the main continent producing biogas, which also holds the greatest potential. Currently, about 70% of the biogas produced worldwide is consumed for power and heat, 20% is used for cooking, and 10% is purified into biomethane. Biomethane is a gas almost purely composed of methane and is produced both by biogas purification and gasification (IEA, 2021). The purification or upgrading of biogas is a process of removing carbon dioxide and other gases, raising the methane concentration to values between 80 and 99% (Ferraz Junior et al., 2022). If all the biogas produced worldwide were purified into biomethane, the supply of biomethane would be equivalent to 20% of the current demand for natural gas (IGU, 2021).

However, when countries are analyzed individually, Brazil stands out as having the greatest potential for biogas production in the world (CIBIOGÁS, 2020; IGU, 2021). In 2018, Brazil's biogas production potential was estimated at around 84.6 billion Nm^3/year, and in 2019, only 1.3 billion Nm^3 was produced in Brazil, which is 1.5% of the national potential (CIBIOGÁS, 2020). This potential is evidently underutilized. In the current context, it is estimated that the potential production could supply 36% of the national energy demand or 70% of the diesel demand (IGU, 2021).

The BEP (i17, 2021b) estimated the short-term potential supply of biogas in Brazil for easily collectible residues and effluents in sectors of livestock (finishing swine, laying poultry, and dairy cattle), industry (dairy industries, swine slaughterhouses, poultry slaughterhouses, cattle slaughterhouses, and sugarcane industry), and sanitation (sewage treatment plants and urban solid waste), with data from 2017 to 2021. The result, which BEP considers conservative and achievable within five years,

identified a potential volume of 10.8 billion Nm³/year of biogas, equivalent to 7.3 billion Nm³/year of biomethane.

ABIOGÁS (2020) also estimated the Brazilian biogas potential, but through a more comprehensive methodology, in the sugarcane industry, agro-industry (slaughterhouses, animal waste, dairies, cassava, corn, and soybeans), and sanitation (urban solid waste and sanitary sewage) sectors for the year 2019. The ABIOGÁS result identified a potential volume of 84.6 billion Nm³/year of biogas, equivalent to approximately 44.7 billion Nm³/year of biomethane.

3.2. Biogas and biomethane production in Brazil

According to CIBIOGÁS (2022), Brazil has 811 plants with a productive capacity of 2.82 billion Nm³/year; however, only 755 units are in operation, producing 2.35 billion Nm³/year, with 44 of the remaining 56 units under construction and 12 undergoing renovation or reform. It should be noted that the vast majority of producing plants are small and have little representation in total production. In numbers, approximately 80% of the plants are responsible for only 0.178 billion Nm³/year, about 7% of the total production. On the other hand, large plants have significant representativeness in total production, with only 51 units producing 1.93 billion Nm³/year.

Another highlight in the national biogas production is the imbalance between potential and production. According to BEP (i17, 2021b), the sugarcane industry has the capacity to produce 7.2 billion Nm³/year of biogas, but this fact does not reflect the participation of the sugarcane sector in total biogas production. Data show that 74% (1.74 Nm³/year) of current production comes from the solid urban waste (SUW) and sanitation sector (i17, 2021b). According to data from the Institute of Agricultural Economics (IEA), the state of São Paulo is the largest producer of sugarcane in the country, accounting for about 54% of the 2020/21 harvest and 48% of ethanol production, equivalent to 14.3 billion liters (Nachiluk, 2021). Since each liter of ethanol produced also generates 10 to 12 liters of vinasse, which can be reused for biogas and biomethane production (Coelho *et al*., 2018), the state of São Paulo holds the main potential for biogas production from sugarcane processing effluents. The use of this potential from vinasse depends on a cost-benefit analysis, since vinasse is also used in fertigation (Elia Neto, 2005; 2016).

Regarding biomethane, national production follows the global trend, where less than 20% (522 million Nm³/year) of total production is purified, with only 10 producing units. Production is concentrated in the Southeast Region, which houses 6 units, with 4 having SUW and sanitation as the supplying source, 1 agricultural, and 1 industrial (sugarcane). Only 6 units are authorized by National Agency of Petroleum, Natural Gas and Biofuels (ANP) for production and commercialization, as shown in table 1.

New authorization requests to ANP show the possibility of doubling the current biomethane production capacity in the coming years, with the planned construction of 13 more producing units and an estimated production of 420 thousand Nm³/day. The realization of these investments depends on a favorable economic and regulatory environ-

TABLE 1 – Biomethane producing units authorized by the ANP

Social name	Region	State	Authorized Capacity (m³/d)	Processing Capacity (m³/d)	Volume Processed (m³/d)
Gás Verde S.A.	Southeast	Rio de Janeiro	204,000	480,000	397,119
Cocal Energia S.A.	Southeast	São Paulo	27,112	51,600	3
GNR Dois Arcos Valorização de Biogás Ltda.	Southeast	Rio de Janeiro	16,000	30,672	28,635
Engep Ambiental Ltda.	Southeast	São Paulo	30,000	84,000	29,549
GNR Fortaleza Valorização de Biogás Ltda.	Northeast	Ceará	110,000	300,000	146,695
Metagás Biogás e Energia S.A.	Southeast	São Paulo	30,000	60,000	12,930

SOURCE: ANP, Biofuel Producers, 2023.

ment, as well as the availability of the necessary raw material.

Cardoso & Mouette (2022) highlight that biomethane production is still insignificant compared to the natural gas (NG) national supply. According to the Ministry of Mines and Energy (MME), in 2021, an average gas volume of 45.36 million Nm3/day was offered, and only 0.01% of this supply is from biofuels, which are not included in these monitoring data. The same relationship can be made for the generation of electric power through biogas sources, which, according to the Energy Research Company (EPE, 2022), accounts for 1.4% of counted renewable energy production.

3.3. Use of biogas and biomethane in Brazil

Although biomethane is available in Brazil, it still does not have a representative scale in the country. There are signs of increasing demand for this product, mainly due to its sustainable appeal. Companies with public commitments to reducing GHG emissions seek alternative and environmentally sustainable investments for their operations, seeking adaptation of the production chain to this new reality.

Within this context, Scania, a Swedish producer of trucks, buses, and automotive engines, declared its goal of leading the change with the driving of a sustainable transportation system. It established a goal in which vehicles produced in 2025 should have CO_2 emissions 20% lower per kilometer compared to vehicles produced in 2015. This resulted in the development of engines powered by renewable sources of fuel or natural gas, in their different stages - compressed or liquefied - and their different sources - fossil or renewable - for the combustion engine. A vehicle running on biomethane can reduce CO_2 emissions from Well-to-Wheel[1] by up to 80%, compared to an equivalent in fossil diesel.

Major carriers partnered with Scania and immersed in the transport ecosystem work closely with customers, logistics operators, transporters, infrastructure suppliers, fuel suppliers, and other decision-makers. In 2021, negotiations and commercial operations began with trucks powered by CNG and biomethane and. according to the National Federation of Motor Vehicle Distribution (FENABRAVE, 2022), we observed growth in the number of CNG truck registrations, totaling 374 trucks duly regulated to operate. In fact, not all are fueled with biomethane, but part of this production is directed to the market.

L'Oréal Brazil, a cosmetics company ranking third in Brazilian sales, began transporting its products with trailers powered by biomethane in August 2020 (Carletto, 2020). According to director Maya Colombani, the project is aligned with the ambition to create a better future, aiming to achieve the goals set for what they call the "new commitment

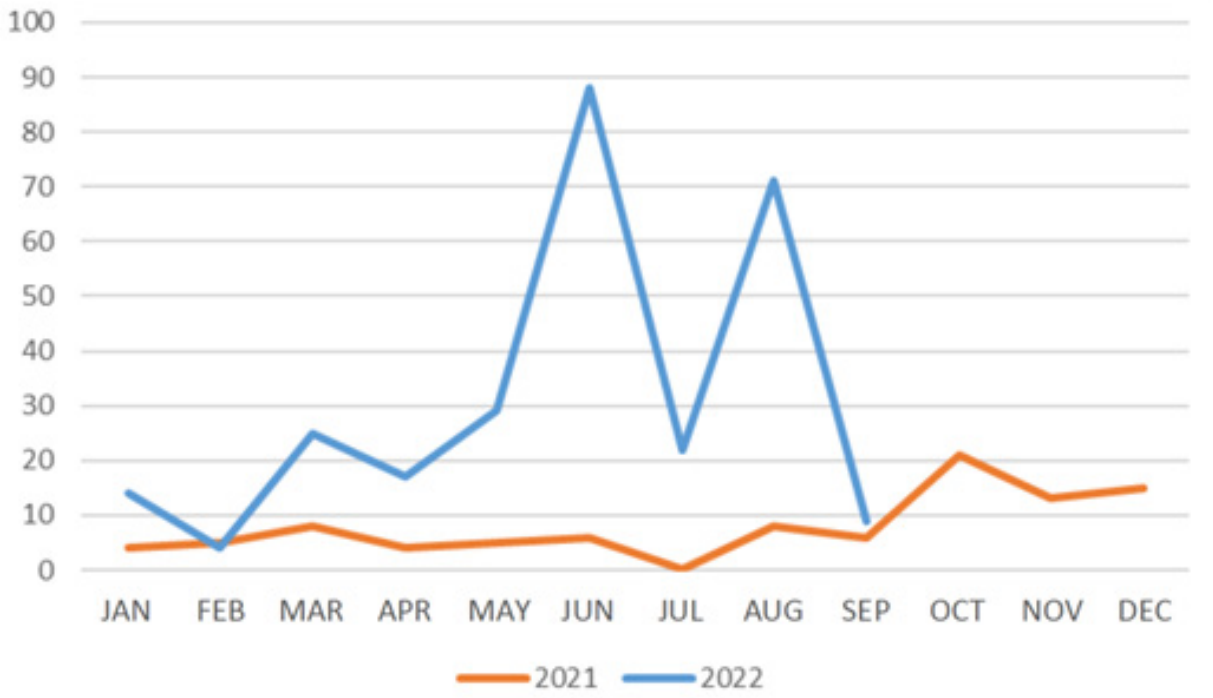

FIGURE 1 - Registration of CNG trucks.

SOURCE: Prepared by the authors based on FENABRAVE registration data, 2022.

[1] Well-to-Wheel represents a life cycle assessment that includes emissions from the source of the raw material for biofuel production to its final disposal or total utilization. Such concept allows evaluating and comparing the balance of greenhouse gases of various fuels to define preferences and strategies.

to sustainability", with business transformation goals, empowerment of the business ecosystem, and contribution to urgent social and environmental challenges by 2030 (Carletto, 2020). Thus, we see the path of socio-environmental governance expanding (Carletto, 2020).

Ambev also uses biogas from the treatment plant of its effluents to drive turbines and generate electricity. This renewable energy reduces GHG emissions and avoids overloading the electrical grid. According to Anderson Carneiro de Souza, Energy and Fluids Specialist at Ambev, the company has sustainability goals and has committed to reducing carbon emissions by 25% along the value chain by 2025 (AMBEV 2020).

There is a growing use of biogas and biomethane in Brazil, along with an opportunity for them to serve as alternative fuels for energy transition and decarbonization. There is even the possibility of biogas and biomethane replacing significant portions of the natural gas market itself, leveraging all the existing infrastructure. Biogas and biomethane are promising fuels for the Brazilian reality, given the significant national production potential.

4. Brazilian standards on biogas and biomethane

Brazilian standards on biogas and biomethane are constantly being updated, given the contemporaneity of the topic. The similarities between biogas, biomethane, and natural gas allow some standards to be shared among these fuels. See case by case.

4.1. Federal constitution and federal regulations applicable to the biogas and biomethane sectors

Biogas and biomethane are alternative fuels to natural gas and petroleum-derived fuels. However, such fuels are not the same. While biogas and biomethane are fuels obtained from biomass, a renewable source, natural gas and petroleum-derived fuels are from non-renewable, fossil sources. Therefore, Article 177 of the 1988 Federal Constitution, which imposes the Union's monopoly on oil and natural gas, does not apply to biogas and biomethane, even though the possibility of contracting with state or private companies to carry out the activities inherent to the Union's monopoly on oil and natural gas was later introduced by Constitutional Amendment No. 9, of 1995, which gave new wording to paragraph 1 of Article 177 and included paragraph 2 in the same article.

The sections of Law No. 9,478 dated August 6, 1997, on the exercise of monopoly, with emphasis on Section I, also do not apply to biogas and biomethane. At the federal level, the aforementioned Law No. 9,478/1997 deals with the National Energy Policy and activities related to the oil monopoly, establishing the National Energy Policy Council (CNPE) and the National Agency of Petroleum, Natural Gas, and Biofuels (ANP). Considering that the economic activities of the biofuels industry are not reserved for state monopoly, Law No. 9,478/1997, with modifications included by Law No. 12,490/2011, ensures that any company or consortium of companies incorporated under Brazilian laws with headquarters and administration in the country may obtain authorization from ANP to carry

out such activities, for the purpose of exploration in a regime of free initiative and broad competition.

Law No. 9,478/1997 contains the current concepts of natural gas, biofuel, biodiesel, ethanol, and bio-kerosene. It should be noted that Law No. 9,478/1997 was in force without any mention of biofuels until the advent of Law No. 11,097/2005, the first amending law. Thus, Law No. 9,478/1997 applies to biogas and biomethane in everything that regulates biofuels. However, even after the modifications introduced by Laws No. 11,097/2005, 11,909/2009, 12,490/2011, and 13,033/2014, it remains silent on the concepts of biogas and biomethane.

A long period of time elapsed until the advent of the next federal law on biofuels. This is Law No. 13,576 of December 26, 2017, which establishes the National Biofuels Policy (RenovaBio), an integral part of the National Energy Policy provided for in Law No. 9,478/1997. Law No. 13,576/2017 aims, in summary:

(i) to contribute to the fulfillment of Brazilian commitments under the Paris Agreement;

(ii) to improve energy efficiency and reduce greenhouse gas emissions in the biofuels sector;

(iii) to expand the production and use of biofuels in the national energy matrix; and

(iv) to enhance the participation and competitiveness of biofuels in the domestic market.

However, Law No. 13,576/2017 does not introduce new concepts because, as an integral part of the National Energy Policy, it adopts the concepts contained in Law No. 9,478/1997. Thus, biogas and biomethane were also not expressly addressed. According to the MME and EPE (2020), RenovaBio adopts anhydrous and hydrated ethanol, first and second-generation, biodiesel, biomethane, aviation bio-kerosene (bioQAV), and alternative biofuels.

Similarly, Law No. 14,134/2021, called the New Gas Law, exclusively deals with matters and concepts of natural gas, relegating biogas and biomethane to a brief passage, stating that, for the purposes of Law No. 14,134/2021, gas that does not fit the definition of natural gas provided therein may receive equivalent treatment, as long as it adheres to the specifications established by ANP. Thus, biomethane, as well as other gases that may be considered equivalent in the regulated sector, may benefit from the application of natural gas premises. However, although Law No. 14,134/2021 has been seen as a modernization of the previous Gas Law, namely Law No. 11,909/2009, it is certain that Law No. 14,134/2021 did not adequately regulate biogas and biomethane, biofuels that are so important for the low-carbon economy and energy transition.

The importance of biogas and biomethane only gained greater prominence with the advent of Decree No. 11,003/2022, which established the federal strategy to promote the sustainable use of these gases. Aimed at addressing climate change, the regulation seeks to contribute to fulfilling the commitments made by Brazil under the United Nations Framework Convention on Climate Change, the Glasgow Climate Pact, and the Global Methane Pledge. Finally, Decree No. 11,003/2022 defined biogas and biomethane as follows:

(i) biogas is the raw gas whose composition contains methane obtained from renewable raw materials or organic waste; and

(ii) biomethane is the gaseous biofuel consisting essentially of methane, derived from the

purification of biogas, subject to the specifications established by the National Agency of Petroleum, Natural Gas, and Biofuels – ANP.

Decree No. 11,003/2022 consolidated the known sources of biogas and biomethane, citing waste disposed of in landfills, waste generated in sewage treatment plants, waste from the sugarcane energy chain, and waste from pig farming, poultry farming, and others, without excluding future discoveries of sources, in a non-exhaustive list. Decree No. 11,003/2022 brought important regulations for the development of biogas and biomethane in the country, and among the innovations, it is worth noting the incentive to the carbon market, with the creation of methane credits, a financial, environmental, transferable asset, similar to carbon credits. Furthermore, it was from Decree No. 11,003/2022 that the Ministry of the Environment issued Ordinance MMA No. 71 of March 21, 2022, with the purpose of establishing the National Program for Methane Emission Reduction - Methane Zero. Among the program's strategic objectives is the sustainable use of biogas and biomethane as renewable sources of energy and fuel.

Thus, the advances identified at the federal level can support important innovations in the energy sector, regarding biogas and biomethane, enabling new markets. However, these regulations depend on dissemination and implementation to produce the expected effects. Moreover, being regulated sectors, the activity requires the proper attention of the National Agency of Petroleum, Natural Gas, and Biofuels to operate adequately.

4.2. Standards of the National Agency of Petroleum, Natural Gas, and Biofuels (ANP) applicable to the biogas and biomethane sectors

Biogas and biomethane became part of the Brazilian energy matrix with the issuance, by the National Agency of Petroleum, Natural Gas, and Biofuels (ANP), of Resolution No. 8 of January 30, 2015, and Resolution No. 685 of June 29, 2017, as a result of Law No. 12,490/2011 (Ferraz Junior et al., 2022). The ANP addressed biogas and biomethane for the first time with the issuance of Resolution No. 8/2015, specifying biomethane derived from agro-silvopastoral and commercial organic products and waste intended for vehicular use (CNG) and residential and commercial installations. In the recitals of said Resolution, the ANP stated that biomethane meets the definition of biofuels established in Law No. 12,490/2011, which strongly expresses the regulatory agency's interpretation of the classification.

The presence of siloxanes in landfill and sewage biogas interferes with the preservation of engines, boilers, and turbines, generating operational impacts and loss of thermal efficiency (Silva, 2015; Coelho et al., 2018), and since at that time there was no proper methodology for the analysis and control of siloxanes defined by the regulatory agency, Resolution No. 8/2015 dealt exclusively with agro-silvopastoral and commercial organic waste. Resolution No. 685/2017 only occurred years later, while awaiting the definition of this methodology. With the issuance of Resolution No. 685/2017, the ANP established rules for the approval of quality control and the specification of biomethane derived

from landfills and sewage treatment plants intended for vehicular use and residential, industrial, and commercial installations to be marketed throughout the national territory. On this occasion, the ANP established normative concepts for biogas, biomethane, and producer.

The activity was completely regulated by the ANP with the issuance of Resolution No. 734 of June 28, 2018, which regulated the authorization for the exercise of biofuel production activity and the authorization for the operation of the biofuel production facility. Once again, for the purposes of Resolution No. 734/2018, the ANP established normative concepts, now for biofuels. In 2022, the ANP replaced Resolution No. 685/2017 with Resolution No. 886/2022, which became the current rule to establish the specification and rules for the approval of quality control of biomethane derived from landfills and sewage treatment plants intended for vehicular use and residential, industrial, and commercial installations, to be marketed in the national territory. Among the obligations provided for in the regulation, biomethane producers must analyze the levels of siloxanes, chlorinated, and fluorinated compounds, as well as remove siloxanes, halogenated compounds, and contaminants that may cause harm to public health and the environment, keeping the biomethane in accordance with ANP specifications.

In accordance with Law No. 9,478/1997, article 68-A, those interested in carrying out economic activities in the biofuels industry require authorization from the ANP, which must consider the following:

(i) verification of the conditions provided for in specific legislation;

(ii) establishment of a company or consortium under Brazilian laws, with headquarters and management in the country;

(iii) the basic installation project, in compliance with technical norms and standards;

(iv) environmental licensing;

(v) the approved safety control project for the facilities by the competent authority; and

(vi) holding fully paid-up share capital or presenting other sufficient sources of financing for the venture.

In Chapter IV of Resolution No. 734/2018, which deals with the construction of biofuel production facilities, the ANP also established minimum criteria for the construction, operation, and alteration of units, which must comply, at a minimum, with the sector regulations and standards issued by the ANP, the Brazilian Association of Technical Standards (ABNT), the municipality of location, the Fire Department, and the environmental agency.

Due to the normative hierarchy, agricultural production, the manufacture of agricultural and food products, and the generation of electricity are not subject to regulation and authorization by the ANP when linked to the establishment in which the biofuel production unit will be built, modified, or expanded, in light of the explicit provision of article 68-A, paragraph 6, of Law No. 9,478/1997. However, also by force of Law No. 9,478/1997, article 68-A, paragraph 7, the biofuel production unit that produces or trades electricity must comply with the regulations established by the competent authorities.

Regarding the commercialization of biomethane, there is a specificity. Chapter VIII of Resolution No. 734/2018, which deals with the acquisition and commercialization of biofuels, separately addresses

the commercialization of ethanol, biodiesel, and biomethane. However, the only biofuel authorized to be marketed in the domestic market directly to the end consumer is biomethane. This reality provides unique opportunities in the biomethane market that can be leveraged for sector development.

Additionally, the ANP issued Resolution No. 828 dated September 1, 2020, which establishes the information contained in quality documents and the submission of quality data for fuels produced in the national territory or imported, among other provisions. The regulation applies to fuels in general, including biomethane, and aims to ensure the quality and compliance of national fuels. The quality certificate for the marketed biomethane must be issued daily by the producer, including an indication of the raw material used for biogas generation.

Under the RenovaBio program, the ANP issued Resolution No. 758 dated November 23, 2018, which regulates the certification of efficient production or importation of biofuels and the accreditation of inspection firms. Ultimately, Resolution No. 758/2018 established criteria, procedures, and responsibilities regarding the granting, renewal, suspension, and cancellation of the Efficient Biofuel Production Certificate, as well as defined the accreditation requirements for inspection firms responsible for biofuel certification. Resolution No. 758/2018 certified the technological routes of biodiesel, biomethane, alternative fuels synthesized by hydroprocessed esters and fatty acids (HEFA), first and second-generation sugarcane ethanol, first-generation sugarcane and corn ethanol, and second-generation corn ethanol. However, the list is not exhaustive, and economic agents interested in obtaining the Efficient Biofuel Production Certificate for different biofuels or production routes may submit to the ANP the documentary evidence of compliance with the requirements.

In the current scenario of energy transition and intense research on new fuel technological routes, the role of the ANP in promoting and controlling the safety of such developments must also be highlighted. Considering the importance of encouraging research on fuels and biofuels, the ANP issued Resolution No. 21, dated May 11, 2016, to regulate experimental fuel, i.e., fuel or biofuel, pure or in mixture, that do not yet have ANP specifications. Ultimately, with Resolution No. 21/2016, the ANP seeks to facilitate the introduction of new fuels and biofuels into the market, preceded by controlled tests. Thus, in addition to established and accepted cases, the federal regulation allows for significant innovation in the fuel sector.

4.3. State programs and policies on biogas and biomethane

Brazil has a highly heterogeneous situation regarding the existence of legislation regulating biogas and biomethane. According to data compiled by the Brazilian Service of Support for Micro and Small Enterprises (SEBRAE, n.d.), eight states have a current state policy or program on biogas or biomethane, two states have the regulation in progress, five states regulate biogas and biomethane only for tax (ICMS) purposes, and twelve states do not have regulations on these matters. These data were gathered in Table 2.

TABLE 2 - States with policies for the biogas and biomethane sector, Brazil, 2022.

Region	State	Name of the regulation	Regulation number
Midwest	Goiás	State Policy on Biogas and Biomethane	Bill No. 349/2018, in progress
Midwest	Mato Grosso	ICMS for Biogas and Biomethane	ICMS Agreement 24, dated 08/04/2016
Midwest	Mato Grosso do Sul	-	-
Federal District	Brasília	-	-
Northeast	Alagoas	-	-
Northeast	Bahia	ICMS for Biogas and Biomethane	ICMS Agreement 24, dated 08/04/2016
Northeast	Ceará	ICMS for Biogas and Biomethane	Decree No. 32,600, dated 19/04/2018
Northeast	Maranhão	-	-
Northeast	Paraíba	ICMS for Biogas and Biomethane	Decree No. 39,110, dated 11/04/2019
Northeast	Pernambuco	-	-
Northeast	Piauí	Piaui Program for Incentive to Clean Energy Development	Law No. 6,901, dated 28/11/2016
Northeast	Rio Grande do Norte	-	-
Northeast	Sergipe	-	-
North	Acre	-	-
North	Amapá	-	-
North	Amazonas	-	-
North	Pará	ICMS for Biogas and Biomethane	ICMS Agreement 06/19, dated 13/03/2019
North	Rondônia	-	-

North	Roraima	State Policy for Incentive to Generation and Utilization of Solar, Wind, and Biomass Energy	Law No. 1,109, dated 04/10/2016
North	Tocantins	-	-
Southeast	Espírito Santo	State Policy for Incentive to Renewable Energies	Decree No. 3,453-R, dated 05/12/2013
Southeast	Minas Gerais	State Policy on Biogas and Biomethane	Bill No. 5,240/2018, in progress
Southeast	Rio de Janeiro	State Policy for Renewable Natural Gas (RNG)	Law No. 6,361, dated 18/12/2012
Southeast	São Paulo	São Paulo Biogas Program	Decree No. 58,659, dated 04/12/2012
South	Paraná	State Policy on Biogas and Biomethane	Law No. 19,500, dated 21/05/2018
South	Rio Grande do Sul	State Policy on Biomethane	Law No. 14,864, dated 11/05/2016
South	Santa Catarina	State Policy on Biogas	Law No. 17,542, dated 12/07/2018

SOURCE: (SEBRAE, n.d.).

5. Barriers to biogas and biomethane in Brazil

The business environment is impacted by the regulatory framework of the sector and the political agenda. While the lack of a political agenda allows for unpredictability and divergence in the business environment, the deficient regulatory framework makes the activity complex, increases transaction costs, hinders business models, and reduces sector competitiveness. The designs of the biogas and biomethane market are influenced by rules from the energy sector, which is highly regulated, and rules from other sectors such as sanitation, agriculture, environment, and climate change. The world as a whole has significant potential for biogas and biomethane production, but biogas and biomethane have not received the necessary attention in the political agenda, as hydrogen has, for example.

The BEP (i17, 2021a) identified several regulatory barriers in the biogas and biomethane sector, deserving attention:

(i) lack of specific regulation for the injection of biomethane into gas distribution networks in most states;

(ii) lack of regulation for the construction of diffuse biogas networks; and

(iii) lack of clarity in the licensing rules for biogas projects.

In this context, national regulatory and licensing standards in these areas tend to contribute to sector development. These regulatory

barriers have been partially addressed by Law No. 14,134/2021, Decree No. 11,003/2022, and Resolutions No. 734/2018 and No. 828/2020. However, the regulatory environment remains complex and clearer norms are needed to enable operation.

Although most biogas production plants in operation in Brazil are small-scale, representing almost 80% of the units, biogas has also been challenged by the installation and maintenance costs of small-scale projects. Small-scale biogas and biofuel production projects tend to develop innovative business models, redefine agent relationships, and involve elements of the production, supply, and transportation chain. Therefore, small-scale biogas and biomethane production projects require sectoral policies that promote market development, including adequate dissemination of sector viability and competitiveness.

It is known that biomethane is a fuel equivalent to natural gas, which allows injecting it into the distribution grid for natural gas itself, always taking due precautions (Ferraz Junior *et al.*, 2022). In this sense, biomethane has to make use of the natural gas distribution infrastructure, with no need for adaptations (IEA, 2021; IGU, 2021). However, the challenge inherent to expanding the existing grid for the transport of biomethane should be considered as a relevant infrastructure barrier in Brazil (MME & EPE, 2020; Costa, 2021).

Thus, the biogas and biomethane sectors in Brazil face regulatory, political, market, and infrastructure challenges. Although significant progress has been made in recent months, federal legislation is insufficient, and state-level legislation is not uniform across all states. The country must intensify the inclusion of biogas and biomethane in the political agenda of the energy sector, provide economic incentives, promote research, improve the dissemination of technological routes, and use biogas and biomethane as a decarbonization strategy for energy transition, aiming to become a global leader in these sectors.

6. Opportunities for biogas and biomethane in Brazil

Incentive programs and mandatory blends (mandates) are seen as important for the development of biomethane (Costa, 2021; IEA, 2021), for reducing carbon dioxide emissions, and for increasing environmental benefits (Machado et al., 2021). In Brazil, the development of biogas can occur through existing policies and programs such as RenovaBio, ABC+ Plan, and Fuel of the Future, with a greater presence in the agendas for modernizing the electricity sector. It is also important to define mechanisms for accountability, incentives, and control in the urban solid waste sector, with preferred technological routes for energy utilization (i17 2021a). The success of biomethane also depends on overcoming costs, availability, and quality, which, in other words, can be understood as achieving the level of a reliable energy source (IEA, 2021).

RenovaBio has been a successful strategy to incentivize biofuels in Brazil and favor renewable energies (Costa, 2021). The data from the Energy Efficiency Score, gathered by ANP (2022) in the RenovaBio Dynamic Panel, show that biomethane has the best average Energy Efficiency Score of all biofuels. The average calculation considered data from the period 2018 to 2020 from all units of all companies classified in all Brazilian states. Biome-

thane achieved an average score of 77.38, among average scores of biofuels ranging from 57.23 to 77.38 (ANP, 2022). This indicates that biomethane proportionally emits more decarbonization credits than any other fuel under the program.

Similarly, the data on the average percentage of eligible volume per biofuel gathered by ANP in the RenovaBio Dynamic Panel demonstrate that biomethane is the only one that can have entirely eligible production. The average calculation also considered data from the period 2018 to 2020 from all units of all companies classified in all Brazilian states. Biomethane reached an average of 100% eligibility, among eligibility averages of biofuels ranging from 41.65% to 100% (ANP, n.d.).

Although Brazil has more than 520 biogas plants for energy purposes, with less than 10% of them producing biomethane (CIBIOGÁS, 2020; IGU, 2021), the RenovaBio Dynamic Panel points to the existence of only three plants with valid certificates in Brazil for the biomethane route in 2020 under RenovaBio, one in Ceará and two in Rio de Janeiro (ANP, 2023). In total, in 2020, only four plants were authorized by ANP to carry out biomethane production activities under RenovaBio, and the three mentioned held efficient production certificates, eligible to request the issuance of decarbonization credits (ANP, 2023).

Furthermore, biogas and biomethane are important decarbonization alternatives for the National Solid Waste Policy in WTE (waste-to-energy) plants, even though the main focus of the National Solid Waste Policy, established by Law No. 12,305 of August 2, 2010, is to mitigate environmental impacts (Costa, 2021). In the same decarbonization line, biogas and biomethane can be associated with CCS (carbon capture and storage), becoming known as bioCCS, such as capturing carbon dioxide in biogas purification plants to obtain biomethane (MME & EPE, 2020). A combined reading of Decree No. 11,003/2022 with Decree No. 11,075/2022 establishes procedures for the elaboration of Sectoral Plans for Mitigation of Climate Change and instituted the National System for Reduction of Greenhouse Gas Emissions, allowing the sector to organize around specific programs to redefine strategies for biogas and biomethane, as outlined in the strategies defined by MMA Ordinance No. 71/2022.

There is a significant growth space for the biogas and biomethane sectors in Brazil, with relevant opportunities. Biogas and biomethane are promising for the Brazilian energy matrix and for energy transition, facing a reality that demands decarbonization. It is important to disseminate sector opportunities, especially those linked to RenovaBio, as a measure to foster and accelerate the growth of biogas and biomethane production in the country.

7. Data analysis

Gaseous fuels include natural gas, biogas, hydrogen, and synthesis gas. They are playing an increasingly important role in accelerating the energy transition (IEA, 2021), with renewable gases being considered biogas, biomethane, blue hydrogen, green hydrogen, and low-carbon hydrogen (IGU, 2021). The international community understands that natural gas will promote integration between fossil fuels and renewable energies in the decarbonization pathway (MME & EPE, 2020; IGU, 2021), as natural gas accounts for about 25% of the world's energy supply and is the fossil fuel with the lowest greenhouse gas emissions (IGU,

2021). Thus, natural gas is addressed by political and legal agendas in the context of energy security (Machado *et al*., 2021).

The increase in the use of natural gas in the energy transition will lead to a greater demand for biogas and biomethane. There is a forecast for the progressive replacement of natural gas by biogas and biomethane. Biomethane is considered a technology associated with the transportation sector, with varied penetration in the fleet of light and heavy vehicles and in fuel cells for hydrogen production (MME & EPE, 2020). However, global production of biogas and biomethane still accounts for only 1% of global natural gas production. Estimates indicate that there is long-term growth potential in global production by up to twenty times, requiring the development of more production projects (IGU, 2021). In Brazil, only 1% of operational biogas plants produce biomethane, and this biomethane accounts for only 3% of the volume of biogas produced in the country. In 2019, there were only nine biogas plants in Brazil in operation producing biomethane (CIBIOGÁS, 2020).

The National Energy Balance 2021, base year 2020, shows the growth of installed capacity for electricity generation from biogas. If in 2011 the installed capacity of the source was 71 MW, this installed capacity jumped to 206 MW in 2020. The variation represents an increase of 135 MW in ten years and a growth of 190% in the period, proportions much higher than other sources (EPE, 2021). Although the share in global energy supply is small, production and demand for biomethane in the world are growing significantly (IEA, 2021).

In Brazil, the accumulated production of biogas in 2011 was 208 million Nm³, a volume that grows each year. In 2020, the accumulated production reached 1,829 million Nm³. The variation over these ten years represents an increase in production of 1,621 Nm³ and 779% growth in the period. The growth was also significant in the number of production plants, which increased from 57 in 2011 to 638 in 2020 (CIBIOGÁS, 2021). Biogas plants for energy purposes in Brazil, when classified by substrate origin, are distributed, for the year 2019, in the proportion of 80% in the agricultural sector, 12% in the industrial sector, and 8% in the urban sanitation sector. However, considering that plants in the agricultural sector are generally small-scale, the reality of the distribution of production volume is quite different for each sector. The contribution of each sector to the volume of biogas production for the year 2019 was in the proportion of 12% in the agricultural sector, 12% in the industrial sector, and 76% in the urban sanitation sector (CIBIOGÁS, 2020).

Recent news indicates that the utilization of biogas potential in Brazil has grown by 0.5%, totaling the exploitation of 2% of the national potential (ABIOGÁS, 2020; [n.d.]). On the one hand, this indicates significant growth in the sector but, on the other hand, modest reach of the potential, which remains underutilized. There is certainly immense room for growth. The recent changes in biogas and biomethane regulations are viewed optimistically, as the biogas and biomethane sectors are constantly expanding.

8. Final considerations

The expansion of the biogas and biomethane market is expected by consumers and the productive sector, which recognize the high potential of this

energy source to bring together two extremely important ends for reducing GHG emissions. Biogas is a renewable energy source that reduces greenhouse gas emissions and results from the treatment processes of various waste. There is a high possibility that the production of biogas and biomethane will materialize as a business model based on the sustainability tripod, encompassing economic, environmental, and social elements due to the involvement and development of different actors.

Brazil has an extremely favorable scenario for biogas and biomethane, which should consolidate as renewable fuels with excellent environmental relations. The country that has a refined regulatory framework, good production potential, and a healthy business environment will have the best chances in the sector, which is still in its early stages worldwide. Brazil has the best production potential and can make the necessary adjustments to the regulatory framework to improve the business environment. Thus, it will be able to attract private investments and become a leader in the global biogas and biomethane market.

The main limitations of the present research are related to the improvement of technological routes for the utilization of various organic substrates for biogas production. The results of ongoing research may influence the estimates of biogas and biomethane, either by expanding the usable waste and effluents, or by the scientific confirmation of the various compositions of biogas and biomethane obtained in these processes from new organic substrates.

In addition, the data on the difference between the volume of production authorized by the ANP and the actual production can be further improved in the future, indicating the need for more detailed research through primary data collection to verify more specific issues such as plant idleness, productivity according to the residue used, the type of installation, among others.

Future analyses should consider subdivisions of the agricultural sectors, with a definition of which agricultural residues were studied and which agricultural residues, although omitted, could potentially be utilized by the sector, revealing more market characteristics. Furthermore, from a regulatory standpoint, future analyses should conduct a comparative study with other countries to define lessons learned and challenges in the sector, in order to enhance the recommendation of more assertive standards and public policies.

Acknowledgments

We acknowledge the financial support from the Human Resources Program of the National Agency of Petroleum, Natural Gas, and Biofuels (PRH--ANP), supported by resources from investments made by oil companies in the R, D & I Clause of ANP Resolution No. 50/2015 (PRH 33.1 - Referring to NOTICE No. 1/2018/PRH-ANP; FINEP/FUSP/USP Agreement Ref. 0443/19). We appreciate the support from the Research Centre for Greenhouse Gas Innovation (RCGI), located at the University of São Paulo (USP) and funded by the São Paulo Research Foundation (FAPESP) (2014/50279-4 and 2020/15230-5) and Shell Brazil, as well as the strategic importance of the support provided by National Agency of Petroleum, Natural Gas, and Biofuels (ANP) through regulatory incentives associated with investments from the Research, Development, and Innovation Clauses.

References

ABIOGÁS – Associação Brasileira do Biogás. *Nota Técnica: O potencial brasileiro de biogás*. São Paulo: ABiogás, 2020. Disponível em: <https://abiogas.org.br/wp-content/uploads/2020/11/NOTA-TECNICA_POTENCIAL_ABIOGAS.pdf>. Acesso em: jul. 2022.

_____. *ABiogás divulga novo potencial do biogás para o mercado brasileiro durante fórum em São Paulo*. Disponível em: < https://abiogas.org.br/abiogas-divulga-novo-potencial-do-biogas-para-o-mercado-brasileiro-durante-forum-em-sao-paulo/>. Acesso em: jul. 2022.

ABRELPE – Associação Brasileira de Empresas de Limpeza Pública e Resíduos Especiais. *Panorama dos resíduos sólidos no Brasil - 2020*. São Paulo: ABRELPE, 2020.

Almeida, J. N. S.; Rizzatto, M. L. Biogás de Vinhaça: uma revisão. *Scientific Electronic Archives*, 15(6), 77-80, jun. 2022.

AMBEV – Companhia de Bebidas das Américas. *Atitudes sustentáveis e economia*. 2020. Disponível em: https://www.ambev.com.br/sustentabilidade/residuo-zero-e-clima/. Acesso em: 30 out. 2022.

ANP – Agência Nacional do Petróleo Gás Natural e Biocombustíveis. *Painel Dinâmico RenovaBio, Certificação de Combustíveis*, atual. 2023. Disponível em:<https://app.powerbi.com/view?r=eyJrIjoiMzIzYzE5OWIt-ZWMyOC00ZDMzLWI5MzctM2U1NGNjNzYxNTAwIiwidCI6IjQ0OTlmNGZmLTI0YTYtNGI0Mi1iN2VmL-TEyNGFmY2FkYzkxMyJ9>. Acesso em: out. 2023.

_____. *Resolução n.º 8, de 2 de fevereiro de 2015*. Brasília: DOU 2/2/2015. Disponível em: <https://atosoficiais.com.br/anp/resolucao-n-8-2015?origin=instituicao&q=8>. Acesso em: jul. 2022.

_____. *Resolução n.º 21, de 11 de maio de 2016*. Brasília: DOU 12/5/2016. Disponível em: <https://atosoficiais.com.br/anp/resolucao-n-21-2016?origin=instituicao&q=21>. Acesso em: jul. 2022.

_____. *Resolução n.º 685, de 29 de junho de 2017*. Brasília: DOU [s.d.]. Disponível em: <https://atosoficiais.com.br/anp/resolucao-n-685-2017-estabelece-as-regras-para-aprovacao-do-controle-da-qualidade-e-a-especificacao-do-biometano-oriundo-de-aterros-sanitarios-e-de-estacoes-de-tratamento-de-esgoto-destinado-ao-uso-veicular-e-as-instalacoes-residenciais-industriais-e-comerciais-a-ser-comercializado-em-todo-o-territorio-nacional?origin=instituicao&q=685>. Acesso em: jul. 2022.

_____. *Resolução n.º 734, de 28 de junho de 2018*. Brasília: DOU [s.d.]. Disponível em: <https://atosoficiais.com.br/anp/resolucao-n-734-2018-regulamenta-a-autorizacao-para-o-exercicio-da-atividade-de-producao-de-biocombustiveis-e-a-autorizacao-de-operacao-da-instalacao-produtora-de-biocombustiveis?origin=instituicao&q=734>. Acesso em: jul. 2022.

_____. *Resolução n.º 758, de 23 de novembro de 2018*. Brasília: DOU 27/11/2018. Disponível em: <https://atosoficiais.com.br/anp/resolucao-n-758-2018-regulamenta-a-certificacao-da-producao-ou-importacao-eficiente-de-biocombustiveis-de-que-trata-o-art-18-da-lei-no-13-576-de-26-de-dezembro-de-2017-e-o-credenciamento-de-firmas-inspetoras?origin=instituicao&q=758>. Acesso em: jul. 2022.

_____. *Resolução n.º 828, de 1º de setembro de 2020*. Brasília: DOU 2/9/2020. Disponível em: <https://atosoficiais.com.br/anp/resolucao-n-828-2020-dispoe-sobre-as-informacoes-constantes-dos-documentos-da-qualidade-e-o-envio-dos-dados-da-qualidade-dos-combustiveis-produzidos-no-territorio-nacional-ou-importados-e-da-outras-providencias?origin=instituicao&q=828>. Acesso em: jul. 2022.

_____. Resolução n.º 886, de 29 de setembro de 2022. Brasília: DOU 29/9/2022. Disponível em: <https://atosoficiais.com.br/anp/resolucao-n-886-2022-estabelece-a-especificacao-e-as-regras-para-aprovacao-do-controle-da-qualidade-do-biometano-oriundo-de-aterros-sanitarios-e-de-estacoes-de-tratamento-de-esgoto-destinado-ao-uso-veicular-e-as-instalacoes-residenciais-industriais-e-comerciais-a-ser-comercializado-no-territorio-nacional>. Acesso em: out. 2023.

Brasil. *Constituição da República Federativa do Brasil de 1988*. Brasília: DOU [s.d.]. Disponível em: <http://www.planalto.gov.br/ccivil_03/constituicao/constituicao.htm.> Acesso em: jul. 2022.

_____. *Decreto n.º 11.003, de 21 de março de 2022*.

Institui a estratégia federal de incentivo ao uso sustentável de biogás e biometano. Brasília: DOU 22.3.2022. Disponível em: <http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2022/decreto/D11003.htm>. Acesso em: jul. 2022.

_____. *Decreto n.º 11.075, de 19 de maio de 2022*. Estabelece os procedimentos para a elaboração dos planos setoriais de mitigação das mudanças climáticas, institui o Sistema Nacional de Redução de Emissões de Gases de Efeito Estufa e altera o Decreto nº 11.003, de 21 de março de 2022. Brasília: DOU 22.3.2022. Disponível em: <http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2022/decreto/D11075.htm>. Acesso em: jul. 2022.

_____. *Federative Republic of Brazil, Paris Agreement, Nationally Determined Contribution (NDC)*. Brasília: 2022. Disponível em: < https://unfccc.int/sites/default/files/NDC/2022-06/Updated%20-%20First%20NDC%20-%20%20FINAL%20-%20PDF.pdf> Acesso em: jul. 2022.

_____. *Lei n.º 9.478, de 6 de agosto de 1997*. Dispõe sobre a política energética nacional, as atividades relativas ao monopólio do petróleo, institui o Conselho Nacional de Política Energética e a Agência Nacional do Petróleo e dá outras providências. Brasília: DOU 7.8.1997. Disponível em: <http://www.planalto.gov.br/ccivil_03/leis/l9478.htm>. Acesso em: jul. 2022.

_____. *Lei n.º 11.909, de 4 de março de 2009*. Dispõe sobre as atividades relativas ao transporte de gás natural, de que trata o art. 177 da Constituição Federal, bem como sobre as atividades de tratamento, processamento, estocagem, liquefação, regaseificação e comercialização de gás natural; altera a Lei no 9.478, de 6 de agosto de 1997; e dá outras providências. Brasília: DOU 5.3.2009. Disponível em: <http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2009/lei/l11909.htm>. Acesso em: jul. 2022.

_____. *Lei n.º 12.305, de 2 de agosto de 2010*. Institui a Política Nacional de Resíduos Sólidos; altera a Lei no 9.605, de 12 de fevereiro de 1998; e dá outras providências. Brasília: DOU 3.8.2010. Disponível em: <http://www.planalto.gov.br/ccivil_03/_ato2007-2010/2010/lei/l12305.htm>. Acesso em: jul. 2022.

_____. *Lei n.º 13.576, de 26 de dezembro de 2017*. Dispõe sobre a Política Nacional de Biocombustíveis (RenovaBio) e dá outras providências. Brasília: DOU 27.12.2017. Disponível em: <http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/l13576.htm>. Acesso em: jul. 2022.

_____. *Lei n.º 14.134, de 8 de abril de 2021*. Dispõe sobre as atividades relativas ao transporte de gás natural, de que trata o art. 177 da Constituição Federal, e sobre as atividades de escoamento, tratamento, processamento, estocagem subterrânea, acondicionamento, liquefação, regaseificação e comercialização de gás natural; altera as Leis nºs 9.478, de 6 de agosto de 1997, e 9.847, de 26 de outubro de 1999; e revoga a Lei nº 11.909, de 4 de março de 2009, e dispositivo da Lei nº 10.438, de 26 de abril de 2002. Brasília: DOU 9.4.2021. Disponível em: <http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2021/lei/L14134.htm>. Acesso em: jul. 2022.

Cardoso, M; Mouette, D. Gás Natural Veicular de origem fóssil e renovável no transporte pesado do Brasil. 2022. *In: Anais XIII CBPE*. Itajubá, 2022.

Carletto, R. *Transporte sustentável: l'oréal lança primeira carreta a biometano que reduz em 90% emissão de co2 no transporte*, 2020. Disponível em: https://www.loreal.com.br/imprensa/not%C3%ADcias/2020/ago/transporte-sustentavel-loreal-carreta-a-biometano-reduz-emissao-de-co2. Acesso em: 12 nov. 2022.

CIBIOGÁS. *Nota Técnica nº 002/2020:* panorama do biogás no Brasil em 2019. Foz do Iguaçu: CIBIOGÁS, 2020.

_____. *BiogásData:* evolução do setor, 2021. Disponível em: <https://app.powerbi.com/view?r=eyJrIjoiNjQxYjg4N-jgtMTI0NC00NTk2LTk5OTQtMjFkNWMxZjM1ZTk5Ii-widCI6ImMzOTg3ZmI3LTQ5ODMtNDA2Ny1iMTQ2LT-c3MGU5MWE4NGViNSJ9>. Acesso em: jul. 2022.

_____. *Panorama do Biogás no Brasil 2021*. CIBiogás (Brasil) Relatório Técnico nº 001/2022. Foz do Iguaçu: CIBiogás, 2022

Coelho, S.; Garcilasso, V. P.; Ferraz Junior, A. D. N.; Santos, M. M. dos; Joppert, C. L. *Tecnologia de produção e uso de biogás e biometano*. São Paulo: IEE - USP, 2018.

Coelho, S. T. *et al.* Geração de eletricidade a partir de biomassa no Brasil: situação atual, perspectivas e barreiras. *In:* MOREIRA, José Roberto Simões (Org.). *Energias renováveis, geração distribuída e eficiência energética*. 2. ed. Rio de Janeiro: LTC, 2021.

Costa, H. K. de M. *Gestão de resíduos: experiência brasileira e casos internacionais*. São Paulo, 2021. Entrevista.

Elia Neto, A. Captação e uso de água no processamento da cana-de-açúcar. *In*: Macedo, I. C. *et al.* (Orgs.). *A energia da cana-de-açúcar*: doze estudos sobre a agroindústria da cana-de-açúcar no Brasil e a sua sustentabilidade. [s.l.] UNICA – União da Indústria de Cana-de-açúcar, 2005.

_____. Estado da arte da vinhaça. *In: 2° Workshop Bioeconomia - Resíduos Urbanos e Agrícolas do IAC*. São Paulo, 1 de set., 2016.

EPE – Empresa de Pesquisa Energética. *Balanço energético nacional 2021*: ano base 2020. Rio de Janeiro: EPE, 2021.

_____. *Balanço energético nacional 2022*: ano base 2021. Rio de Janeiro: EPE, 2022.

FENABRAVE – Federação Nacional da Distribuição de Veículos Automotores. *Emplacamentos*. Disponível em: https://www.fenabrave.org.br/Portal/conteudo / emplacamentos. Acesso em: nov. 2022

Ferraz Junior, A. D. N.; Etchebehere, C.; Perecin, D.; Teixeira, S.; Woods, J. Advancing anaerobic digestion of sugarcane vinasse: current development, struggles and future trends on production and end-uses of biogas in Brazil. *Renewable and Sustainable Energy Reviews*, 157, 2022.

I17 – Instituto 17. *Biogás no Brasil: barreiras e recomendações para o desenvolvimento do setor.* Programa de energia para o Brasil – BEP (Brasil). Relatório Técnico 01-2021. São Paulo: Instituto 17, 2021a.

_____. *Biogás no Brasil*: potencial oferta a curto prazo. programa de energia para o Brasil – BEP (Brasil). Relatório Técnico 02-2021. São Paulo: Instituto 17, 2021b.

IEA – International Energy Agency. *World Energy Outlook 2021*. Paris: IEA Publications, 2021.

IGU – International Gás Union. *Global Renewable and Low-Carbon Gas Report*: 2021 Edition. Surrey: IGU, 2021.

IPCC – Intergovernmental Panel on Climate Change. *Sixth Assessment Report. Climate Change 2021*: the physical science basis. Cambridge: Cambridge University Press, 2021.

Machado, P. G.; Ichige, E. N. A.; Ramos, K. N.; Mouette, D. Natural Gas Vehicles in Heavy-Duty Transportation - A Political-Economic Analysis for Brazil. *Case Studies on Transport Policy,* 9(1): 22-39, 2021.

MMA – Ministério do Meio Ambiente. *Portaria MMA nº 71, de 21 de março de 2022*. Institui o Programa Nacional de Redução de Emissões de Metano - Metano Zero. Brasília: DOU 22.3.2022. Disponível em: < https://in.gov.br/en/web/dou/-/portaria-mma-n-71-de-21-de-marco-de-2022-387378473>. Acesso em: jul. 2022.

MME – Ministério de Minas e Energia; EPE – Empresa de Pesquisa Energética. *Plano Nacional de Energia - PNE 2050*. Brasília: MME – Ministério de Minas e Energia; EPE – Empresa de Pesquisa Energética, 2020.

Nachiluk, K. Alta na produção e exportações de açúcar marcam a safra 2020/21 de cana. *Análises e indicadores do agronegócio*, 16(6), 1-5, jun. 2021. Disponível em: http://www.iea.sp.gov.br/out/TerTexto.php?codTexto=15925#:~:text=O%20Brasil%20%C3%A9%20o%20maior,de%20litros%20de%20etanol1. Acesso em: 17/11/2022.

Rockström, J.; Steffen, W.; Noone, K. *et al.* A Safe Operating Space for Humanity. *Nature*, 46(1), set. 2009.

SEBRAE – Serviço Brasileiro de Apoio às Micro e Pequenas Empresas. *DataSebrae biogás*: biblioteca de legislação sobre o biogás. Disponível em: <https://datasebrae.com.br/biblioteca-legislacao-biogas/>. Acesso em: jan. 2022.

Silva, T. C. F. *Utilização de biogás de estações de tratamento de esgoto para fins energéticos*. São Paulo, Dissertação (Mestrado em Energia) – USP, 2015.

Steffen, W; Richardson, K.; Rockström, J. *et al.* Planetary boundaries: guiding human development on a changing

planet. *Sciencexpress*, jan. 2015.

UNFCCC – United Nations Framework Convention on Climate Change. *Nationally Determined Contributions Registry*. 2022. Disponível em: < https://unfccc.int/sites/default/files/NDC/2022-06/Updated%20-%20First%20NDC%20-%20%20FINAL%20-%20PDF.pdf> Acesso em: jul. 2022.