THE FUTURE OF LIGHT-DUTY VEHICLES IN BRAZIL: TENDENCIES AND CHALLENGES FOR A GREENER FLEET

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ABSTRACT

This work aims to analyze the possible Brazilian solutions for a cleaner light-duty vehicles fleet and discuss the challenges of adopting the main alternatives: (i) natural gas and biomethane, (ii) electrification and hybrids, and (iii) biofuels, consisting of qualitative analysis through bibliographic and exploratory research. A table shows the landmarks, future perspectives, and challenges for developing each alternative tackled in this work. The Petroleum Crisis in 1973 was a landmark for energetic Brazilian history. Due to the high petroleum prices in the mid-1970s, the Brazilian government and entrepreneurs took concrete actions toward alternative fuel solutions. Brazil has peculiar characteristics that can make electrification not the best or the only solution for a greener fleet. Brazil must find its path toward a low-carbon economy without throwing away its already know-how and traditional experienced trajectory.

Keywords: Light-duty vehicles; Regulation; Cleaner transportation; Alternative-fuel vehicles.

RESUMO

Este trabalho tem como objetivo analisar as possíveis soluções brasileiras para uma frota de veículos leves mais limpa e discutir os desafios da adoção das principais alternativas: (i) gás natural e biometano, (ii) eletrificação e híbridos, e (iii) biocombustíveis, consistindo de análise qualitativa por meio de pesquisa bibliográfica e exploratória. Uma tabela mostra os marcos, as perspectivas futuras e os desafios para o desenvolvimento de cada alternativa abordada neste trabalho. A Crise do Petróleo em 1973 foi um marco para a o setor energético brasileiro. Devido aos altos preços do petróleo em meados da década de 1970, o governo brasileiro e os empresários tomaram medidas concretas para viabilizar soluções com combustíveis alternativos. O Brasil tem características peculiares que podem fazer com que a eletrificação não seja a melhor ou a única solução para uma frota mais verde. O Brasil deve encontrar o caminho para uma economia de baixo carbono sem jogar fora o seu *know-how* e sua tradicional trajetória experiente.

Palavras-chave: Veículos leves; Regulação; Transporte mais limpo; Veículos com combustível alternativo.

1. INTRODUCTION

Over recent years, pollutants and greenhouse gas (GHG) emissions to the atmosphere have been increasing substantially. According to the National Oceanic and Atmospheric Administration (NOAA), the concentration of carbon dioxide in the atmosphere reached 412.5 ppm (parts per million) in 2020, the highest level in the last 800.000 years. Compared to pre-industrial periods, the carbon dioxide level has never achieved more than 300 ppm (LINDSEY, 2021). The energy sector is responsible for approximately 73% of the world's equivalent carbon dioxide emissions, including transportation, electricity generation, heat generation, industrial activities, and construction. In 2016, the transport sector alone sent to the atmosphere around 7.9 $GtCO_2e$ (GE and FRIEDRICH, 2020).

In light of the Paris Agreement, where signatory countries assumed the responsibility of taking action against climate change (UNITED NATIONS, 2021), governments and technical institutions have been elaborating restriction policies against fossil fuels and supporting policies for alternative transportation fuels to develop cleaner transportation. Many solutions are being developed worldwide, such as biofuel, electrification, hydrogen, and biomethane, which can potentially assume protagonism in the future as technology advances. In this sense, some countries instituted support policies for electric vehicles over the last decade, trying to reduce pollutants and GHG emissions. Subsidies and electrification targets were implemented in the United States, China, and most European countries (IEA, 2021). In Britain, the sale of new petrol and diesel light-duty vehicles will be banned from 2030. In Norway, this deadline is even earlier: 2025. The state of California (US) and the province of Quebec (Canada) assumed the commitment to ban the sale of new gasoline-powered passenger cars from 2035 (REUTERS, 2020).

Cleaner transportation is also a concern for the Brazilian government, even more because Brazil is one of the 2015 Paris Agreement signatories' countries, ratifying the agreement at the 26^{th}

UN Climate Change Conference of the Parties (COP26), held in Glasgow, UK, in 2021 (UNITED NATIONS, 2021). For the Brazilian energy transition towards a cleaner future, the government is assessing several viable alternatives for road transportation, including increasing energy efficiency, alternative sources of energy, and an internal combustion engine phase-out program. In the meantime, Brazil will keep following up on existing efficiency policies already implemented in the country, such as the Brazilian Motor Vehicle Air Pollution Control Program (PROCONVE) and the Brazilian Vehicle Labeling Program (PBVE). Alternative technologies for light-duty vehicles are flex-fuel vehicles, already widespread in Brazil for the usage of gasoline and ethanol, electrification of the fleet, plug-in hybrid vehicles, biomethane, hydrogen, and others (EPE, 2020).

Motor vehicles in Brazil include a wide variety of on-road vehicle types used primarily for passenger transport and goods movement applications. This work aims to analyze the possible Brazilian solutions for a cleaner light-duty vehicles fleet, classified and regulated differently from heavy-duty vehicles (DALLMANN and FAÇANHA, 2017), and discuss the challenges of adopting the main alternatives. We undertook a qualitative analysis through bibliographic and exploratory research. Section 2 will tackle the main regulation to reduce greenhouse gas emissions from light-duty vehicles in Brazil, and section 3 will discuss the Brazilian vision for a greener fleet and its challenges to adopting the most viable solutions for the country's actuality: (i) natural gas and biomethane, (ii) electrification and hybrids, and (iii) biofuels. Finally, section 4 will discuss the final remarks and conclusion.

2. THE BRAZILIAN REGULATION TO REDUCE AIR POLLUTION

In 1986, the Brazilian Government launched the Brazilian Motor Vehicle Air Pollution Control Program (PROCONVE), the first coordinated effort to protect air quality from carbon monoxide, hydrocarbons, nitrogen oxides, soot, and aldehydes, especially in larger urban areas. The main objectives of this regulation are to promote national technological development, create inspection programs for vehicles already in use, promote population awareness about motor vehicles' air pollution, implement follow-up measures, and improve liquid fuels quality to reduce pollutant emissions (CONAMA, 1986).

PROCONVE's target for controlling pollution from Otto Cycle light-duty vehicles is based on the US Programs LEV and CARB, enforcing the adoption of increasingly restrictive emission limits (SZWARCFITER et al., 2005). Vehicle manufacturers must demonstrate compliance with these limits through laboratory testing of cars (DALLMANN and FAÇANHA, 2017). The program is divided into phases, in which each one of them fosters new limits on exhaust emissions from light--duty vehicles (represented by the letter "L") and heavy-duty vehicles (represented by the letter "P"). The first phase of PROCONVE L1 was implemented on 1st January 1989 by the Conselho Nacional do Meio Ambiente - CONAMA (CONAMA, 1986). Since then, PROCONVE has continued to set more stringent emission limits in its subsequent phases. The CONAMA Resolution No. 492, published on 20th December 2018, set new phases for the program, called PROCONVE L7 and L8, valid for all domestic and imported vehicles commercialized in Brazil. The L7 phase entered into effect on 1st January 2022, and the L8 phase will be applicable from 1st January 2025 (CONAMA, 2018).

In general terms, PROCONVE L7 has established the following emission limits for passenger new cars: particulate material - 6 mg/km, carbon monoxide - 1.000 mg/km, aldehydes - 15 mg/km, and non-methane organic gases (NMOG) plus nitrogen oxides (NOx) - 80 mg/km. Figure 1 shows the evolution of PROCONVE mass emission limits of carbon monoxide, nitrogen oxides, and aldehydes for Otto Cycle passenger vehicles from the beginning of the program, in 1986, until today (CONAMA, 2018; DALLMANN and FAÇANHA, 2017).

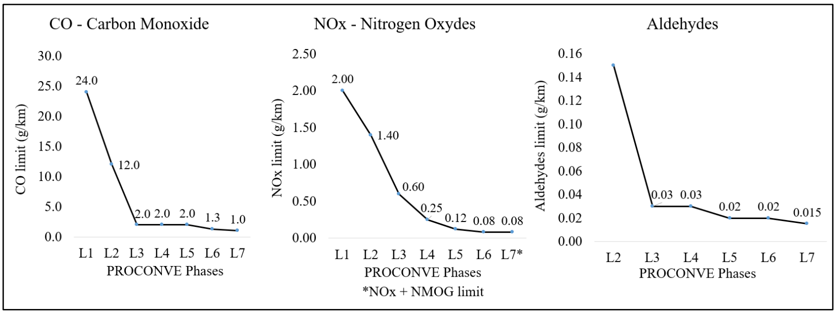

Figure 1 - Emission limits of carbon monoxide, nitrogen oxides, and aldehydes for Otto Cycle passenger vehicles per PROCONVE Phases

As emission restrictions grow, internal combustion engine manufacturers become more under pressure to develop cleaner motors while at the same time keeping the economic feasibility of projects. In this sense, new vehicles and fuels begin to show up as an alternative to the high costs of engineering a cleaner internal combustion engine run by gasoline or diesel. The next session will tackle some Brazilian visions for a greener light-duty vehicles fleet and the challenges of each alternative.

3. THE BRAZILIAN VISION FOR A GREENER FLEET

Common fuel types for light-duty vehicles in Brazil are (i) gasoline, produced to be blended with anhydrous ethanol, (ii) hydrous ethanol, mainly derived from the fermentation of Brazilian sugarcane, (iii) diesel, which sale is not allowed for passenger cars with payload capacity lower than 1.000 kg, and (iv) biodiesel, mainly derived from Brazilian soybean oil and blended with diesel at a volume percentage set by the government for sale (DALLMANN and FAÇANHA, 2017).

Nowadays, flex-fuel is the dominant technology across all vehicle segments in Brazil, except for sports cars, off-road vehicles, and minivans. A flex-fuel vehicle is designed to run on gasoline and ethanol or any mix of both fuels (POSADA and FAÇANHA, 2015). After the petroleum crisis in 1973, the Brazilian government launched the National Alcohol Program - PROALCOOL in 1975 to gradually replace petroleum-based fuels with renewable fuels, mainly ethanol derived from sugarcane. Because of this policy, Brazil made its first energy transition in the mid-1980s, when about 70% of all new light-duty vehicles produced in the country were manufactured to run on ethanol. But this trend did not last very long due to the high competitiveness of combustion engines running on gasoline. In 2006, the Brazilian fleet of light-duty vehicles experienced another energy transition, but at this time to a flex-fuel motor fleet (gasoline or ethanol). Figure 2 shows the percentage of light-duty vehicles in Brazil by fuel type from the 1950s until 2020 (ANFAVEA, 2021).

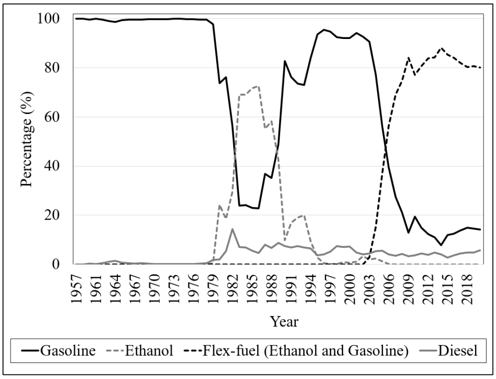

Figure 2 - Percentage of light-duty vehicles in Brazil by fuel type

According to the Brazilian Decennial Plan for Energy Expansion 2021/2030, passenger transportation activities will increase at a yearly rate of 3.2% until 2030 due to the increase in social demand for transportation, the rise in GDP per capita, and the reduction in the unemployment rate (EPE, 2021). With this scenario, the National Energy Plan - PNE-2050 published the Brazilian strategy for energy expansion until 2050, which addresses issues regarding the energy transition in the transport sector in Brazil. According to the strategy, biofuels will play a vital role in the Brazilian energy transition, especially in places facing more significant electrification challenges. Furthermore, Brazil has great potential to develop green hydrogen, lignocellulosic ethanol, natural gas, and biomethane (EPE, 2020). The sections below will discuss the leading alternatives for the energy transition for the Brazilian transport sector.

3.1 Natural gas and biomethane

First introduced in Italy in the mid-1930s, natural gas vehicles lacked popularity for decades until their fleet increased in the 1970s and 1980s after the energy Petroleum Crisis. Governments in both developed and developing countries have promoted the adoption of natural gas vehicles as a clean alternative to gasoline and diesel and reduced dependence on foreign oil (SANTOS, 2018; YEH, 2007). In 1987, Brazil launched the Gas Production Anticipation Plan (PLANGAS), the first program to incentivize the use of natural gas in buses and trucks instead of diesel. However, high natural gas prices, the precarious fueling infrastructure, and the conversion technology deficiency led PLANGAS to restrain its progress (ABREU, 2013).

The Ministry of Infrastructure's Administrative Rule No. 222 released natural gas by taxi drivers in 1991. In the following year, the Ministry of Mines and Energy's Administrative Rule No. 553 repealed Administrative Rule No. 222, authorizing the use of natural gas by urban buses, taxis, and freight vehicles. Notwithstanding, private light-duty vehicles were only allowed to run on natural gas in Brazil in 1996, with Decree No. 1.787/1996 (ABREU, 2013; BRAZIL, 1996; TEIXEIRA, 2003).

At the begging of the 2000s, the natural gas vehicles fleet experienced a rapid penetration in the Brazilian market until 2007. However, this penetration has roughly stagnated since 2008 (SANTOS, 2018). Brazil's vision for adopting natural gas for light-duty vehicles is gradual and slow. On the other hand, PNE-2050 evaluates GNV's technology maturity and its penetration in Brazil, subject to market conditions and infrastructure development (EPE, 2020).

The main challenges to the widespread adoption of natural gas vehicles in Brazil are: (i) the necessity of a large-scale establishment of production, importation, and supply infrastructure; (ii) the need for a distribution network expansion; (iii) the security of natural gas supply, and (iv) the development of a mature natural gas market (EPE, 2020). Furthermore, when it comes to fuel stations, they should have a unique infrastructure, including a compressor (to fuel cars with Compressed Natural Gas - CNG), special fueling pumps, and a tank. The installation of these types of equipment and the adaption of the fueling station facilities can be costly to fuel station owners. In addition, the majority of the natural gas vehicles in Brazil were initially sold as gasoline, ethanol, or flex-fuel vehicles, which were later converted to also run on CNG. Besides this technology being widespread by constant and long-distance drivers, such as taxi drivers and lightweight freight transporters, converting a vehicle to run on Compressed Natural Gas can demand a high initial investment (SANTOS, 2018).

Natural gas can play an important role in the Brazilian energy transition due to its low greenhouse gas emissions when burnt compared to diesel and gasoline (EPE, 2020). In addition, natural gas can also be mixed with biomethane, a gaseous biofuel composed essentially of methane derived from the biogas purification, according to the National Agency of Petroleum, Natural Gas and Biofuels (ANP)'s Resolution No. 8/2015 (ANP, 2015). Biomethane can originate from organic animal waste, crop residues, and organic fractions from urban wastes (JENDE et al., 2015). In this sense, the environmental sanitation provided by biomethane generation allows natural gas vehicles to place this vehicle in a better position for environmental issues.

3.2 Electrification and hybrids

After the Petroleum Crises occurred in the 1970s, public interest in electric vehicles (EVs) began to grow as an alternative solution to high petroleum prices. In 1974, the Brazilian engineer João Conrado do Amaral Gurgel presented the first EV produced in Latin America: Gurgel Itaipu, a small vehicle with 60 to 80 km of autonomy. Later in 1981, a new model was presented: the Itaipu E-400, with a load capacity of 400 kg and up to 80 km of autonomy. The model was helpful to the national electricity company, the national telecommunication company, and some private companies in Brazil (BITU, 2021; PAIVA, 2021).

Besides the relatively high efficiency and low operating cost, the Itaipu E-400 had a weakness common to all EVs until today: the expensive and limited batteries and its relatively short lifespan. All Gurgel EV models had their manufacturing ended in 1983, with the replacement of the electric engine to petrol or ethanol engine produced by Volkswagen (BITU, 2021). The Brazilian EV had no success, and Gur-gel closed its activities in 1996 (PAIVA, 2021).

Nowadays, Brazil has a mature market for internal combustion engine vehicles (ICEV), making the Brazilian transition towards electrification a big challenge. Besides urban pollution mitigation being an opportunity for electric vehicle deployment, fleet electrification in Brazil does not appear to rush as in other countries. Possible reasons are that Brazil does not face a severe energy security threat and does not have extreme air pollution as other countries do (VELANDIA VARGAS et al., 2020).

PNE-2050 considers the electrification of the transportation sector as one of the solutions to a low-carbon economy, including smart grids and smart cities. The more optimistic scenario envisages 15% EV penetration until 2050 and a total replacement of ICEVs with EVs and hybrid-electric vehicles after 2045. But to achieve this more optimistic scenario, PNE-2050 points out some critical challenges that Brazil must overcome. First, light-duty electric vehicles are costly by Brazilian consumer standards. Second, Brazil has poor recharging infrastructure. And third, there is an absence of governance and public policies to guide EVs implementation in Brazil (EPE, 2020).

In 2015, as a MERCOSUL member, the Brazilian government published Resolution No. 97/2015, which reduced EV import tax from 35% to zero. This resolution is applied to electric vehicles and hydrogen fuel cell vehicles, assembled or disassembled, with a minimum range of about 80 km on a single charge (CAMEX, 2015). However, this resolution was valid until December 2021, and further orientation is needed by the Brazilian government (BIANCHIN, 2021). Currently, bill No. 5308/2020 addresses tax incentives for electric vehicles and hybrid electric vehicles negotiated in Brazil, reducing the tax on industrialized products (IPI) to zero (CÂMARA DOS DEPUTADOS, 2020).

When it comes to infrastructure, a legal framework for the commercial recharging of electric vehicles was issued only in 2018, by the National Agency of Electric Energy (ANEEL), by the resolution No. 819, aiming to reduce legal uncertainties for entrepreneurs and allow them to offer their electricity at a free, market-based price. Before this resolution, commercial recharging was not allowed in the country, which shows how slow the country's electrification movement is (ANEEL, 2018; VELANDIA VARGAS et al., 2020).

Besides the low number of public policies at the federal level, several local governments are very interested in EVs and hybrid vehicles at both state and municipality levels. Many major cities have already underway demonstration projects (ARAUJO and AMORIM, 2017). In July 2021, the town of São Paulo sanctioned municipal law No. 17.563/2021, which allows electric and hybrid vehicle owners to deduct the Automotive Ownership Tax (IPVA) credits to pay Urban Land and Building Tax (IPTU) over the first five years after the vehicle purchase (SÃO PAULO, 2021). At the state level, eight Brazilian states have al ready exempted electric, and hybrid cars owners from paying the Automotive Ownership Tax (IPVA) in their territory: the Rio Grande do Sul, Paraná, Rio de Janeiro, Rio Grande do Norte, Pernambuco, Piauí, Maranhão, and Ceará (PERONI, 2021). This scenario indicates the decentralized policy movement in Brazil towards fleet electrification, a similar situation that occurs in the United States.

The plug-in fleet electrification opens several possibilities for turning cities smarter and greener. One of the possibilities is the Vehicle-to-Home, or Vehicle-to-Grid, alternative which refers to the reciprocal flow of power between an electric vehicle and the grid, shifting the demand curve and reducing costs attained by avoiding peak tariffs at times of high demand. In this sense, electric vehicles as energy storage elements could boost the adoption of localized renewables (UDDIN et al., 2018). Another sustainable possibility is the implementation of car-sharing systems in urban areas. Car-sharing companies could offer a rent a car service on a short-term basis to urban users, shifting the car ownership concept towards the “mobility as a service” (MaaS), or the “mobility on demand” concept (MOUNCE and NELSON, 2019).

Furthermore, the adoption of EVs in Brazil could contribute to the development of autonomous vehicles. Countries like Belgium, France, Italy, the United Kingdom, and the United States are already planning to operate a transport system for driverless cars (MOUNCE and NELSON, 2019). Despite these incentives, a key concern has been the impact of electric vehicle operations on the degradation of lithium-ion batteries (UDDIN et al., 2018).

Lithium-ion batteries for EVs consist of (i) various metals, such as lithium, nickel, iron, cobalt, aluminum, copper, manganese, steel, (ii) carbonaceous materials, such as graphite and carbon black, and other materials such as (iii) plastics, (iv) electrolytes, (v) binder, and (vi) lithium salts (XU et al., 2017). The average lithium-ion battery life span is between 5 to 10 years. However, overall age remains a hurdle because high ambient temperatures accelerate battery aging (DINGER et al., 2010). In this sense, EV adoption in Brazil could shorten the battery life span because of the tropical temperatures in most Brazilian territories.

Future perspectives of lithium-ion batteries, however, revolve around niobium. Brazil is the world’s largest producer of this gray metal that turns bluish when oxidized (OMONDI, 2017). The Brazilian company CBMM, the world’s dominant niobium producer, has already established partnerships with technology companies worldwide to develop niobium-bearing lithium-ion batteries. It is envisaged that these batteries could provide rapid charging to EVs (less than 10 minutes) without the risk of damage or explosion and a life span of 20 years, with morethan 10,000 recharging cycles (up to five times more than typical lithium-ion batteries) (KINCH, 2021).

3.3 Biofuels

Biofuels are derived from biomass and can replace petroleum--based fuels in internal combustion engines. The main biofuels used in Brazil are (i) ethanol, obtained from sugarcane, and (ii) biodiesel, produced from vegetable oil or animal fat (ANP, 2020). The country is recognized worldwide as a leader in biofuels production, distribution, and use and has implemented several policies to develop the biofuel market: (i) the National Alcohol Program - PROALCOOL, implemented in 1975 as an alternative to the Petroleum Crisis, (ii) the National Biodiesel Production and Use Program - PNPB, launched in 2004, and more recently (iii) the Biofuel National Policy - RenovaBio, introduced in 2016, and (iv) the Fuel of the Future Program, introduced in 2021 (EPE, 2021).

PROALCOOL proved to be highly effective in stimulating demand for ethanol. In the mid-1980s, more than 70% of all new light-duty vehicles produced in Brazil were manufactured to run on ethanol (see Figure 2). On the other hand, the development of national biodiesel has been strengthened and gained commercial scale with the policies: PNPB, RenovaBio, and the Fuel of the Future Program. Due to their renewable feature, the Brazilian government considers biofuels as an alternative to achieve sustainability and energy security (EPE, 2021). Nevertheless, biofuel production presents particular challenges to the environment that need to be assessed, such as (i) fossil energy applied to the biofuel production supply chain, (ii) production and application of synthetic fertilizers - and other chemicals - to the soil, (iii) deforestation, and (iv) impacts of large monoculture areas to biodiversity. In addition, some authors highlight the negative effect of the biofuels industry on food production, putting pressure on food prices up and increasing social inequalities (BERMANN, 2012; HESPANHOL, 2008; OLIVEIRA, 2011). The limited availability of arable lands on the planet makes biofuels unable to meet all the global demand for fuels without affecting the world's food security (ANGARITA et al., 2008).

Sections 3.3.1 and 3.3.2 will tackle the two biofuels which stand out in Brazil: ethanol and biodiesel.

3.3.1 Ethanol

From 1994 until 2020, Brazil produced 547 million tonnes of sugar cane yearly, being the world's leading producer, as shown in Figure 3 (FAO, 2021). The primary source of Brazilian ethanol is sugar cane.The history of this crop is intertwined with the country's energetic history itself, positioning Brazil as a world leader in bioenergy since the 1960s (STOLF and OLIVEIRA, 2020).

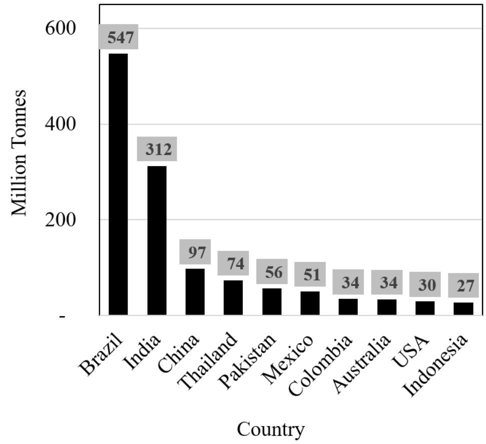

Figure 3 - Average Production of Sugar Cane: Top 10 producers (1994 - 2020)

Brazil launched the National Alcohol Program - PROALCOOL in 1975, the first alcohol fueling program developed. This program aimed to balance the current account, improve energy security, and generate employment and income, being a response from the government to urgently search for an alternative fuel to petroleum-based fuels after the Petroleum Crisis occurred in 1973.

PROALCOOL can be divided into two phases. The first one consists of the progressive blending of ethanol into gasoline between 1975 and 1979. The second one consists of the total substitution of fossil fuels for renewable ones, which occurred between 1979 and 1985. Light-duty vehicles fueled by ethanol quickly took the lead in Brazilian production, surpassing 70% of the new cars produced in the early 1980s (see Figure 2). However, the so-called "oil shock" with the sharp decline in oil prices soon after 1985 added to the rise in sugar prices on international markets, and the withdrawal of subsidies by the government discouraged domestic ethanol and boosted the resumption of gasoline-fueled vehicles production (EPE, 2021; STOLF and OLIVEIRA, 2020).

In the 2000s, Brazil adopted a new strategy for ethanol: (i) its compulsory addition to gasoline and (ii) the production of flex-fuel vehicles, which were manufactured to run on ethanol, gasoline, or a mixof both fuels (POSADA and FAÇANHA, 2015). So, users of flex-fuel vehicles could respond to oil and ethanol price oscillations at the pump, gaining operational flexibility. In this sense, flex-fuel light-duty vehicles have taken the lead in the domestic automotive industry since 2006, with a production rate of around 80% of all new light-duty vehicles in Brazil (see Figure 2). However, according to Stolf and Oliveira (2020), the flex-fuel technology alone was not the only one responsible for the ethanol success, but all the technological development of the previous decades, government incentives, and the agricultural industry progress in Brazil.

Precious resources, such as research and market development (including the incentives from PROALCOOL), were fundamental for the evolution of the sugar industry in Brazil. The sugar mills have evolved into sugar-alcohol plants, which, with the cogeneration of electricity from the sugar cane bagasse, have evolved into sugar-energy plants (STOLF and OLIVEIRA, 2020). Nowadays, this evolution is moving towards greater energy efficiency through the energetic use of second-generation ethanol and residual biogas (EPE, 2020). Utilizing the lignocellulosic biomass for second-generation ethanol would be preferable over first-generation ethanol for less competition with food production, fewer changes in land use, and less deforestation (DIAS et al., 2011).

3.3.2 Biodiesel

Biodiesel is a renewable fuel from vegetable oils and animal fats, mainly produced by esterification and transesterification or enzymatic processes. In addition, it is also possible to get biodiesel from livestock-related waste and used cooking oil (CAMPOS and CARMÉLIO, 2009; FERREIRA et al., 2020).

Brazil has been developing biodiesel technology since the 1970s, with a partnership between the National Technology Institute - INT and the Technological Research Institute - IPT. First, researchers were concomitant with the country's ethanol production development (ANGARITA et al., 2008). However, biodiesel exploitation only gained commercial scale after creating PNPB in 2004. Besides encouraging the production of renewable diesel, PNPB also intends to (i) foster the inclusion of family farming in the productive biodiesel chain, (ii) ensure minimal prices, quality, and supply reliability, and (iii) stimulate biodiesel production from different feedstocks. During the same year, and to achieve PNPB goals, the Brazilian government launched the Social Fuel Seal, granting federal tax subsidies and greater access to credit to biodiesel producers certified as promoters of the productive inclusion of family farmers (CAMPOS and CARMÉLIO, 2009; FERREIRA et al., 2020; MAPA, 2019)

In 2005, the Brazilian government established Law No. 11.097/2005, introducing biodiesel into the national energy matrix, allowing a volume rate of 2% of biodiesel in the petroleum diesel commercialized in the country. The law defined biodiesel as a fuel derived from renewable biomass intended for compressed-ignition internal combustion engines use or for other energy generation types, capable of replacing, partially or totally, fossil fuels (BRAZIL, 2005). According to (FERREIRA et al., 2020), this law established an open technological path for biodiesel production in Brazil, allowing several different processes and a wide range of raw materials. The admixture rate of 2% of biodiesel (B2) was initially proposed in 2004 as an option and, in 2008, as mandatory.

In September 2009, the National Energy Policy Council - CNPE increased the percentage of biodiesel to 5% by Resolution No. 6/2009, and the B5 became mandatory in Brazil on 1st January 2010 (CNPE, 2009). In 2016, Law No. 13.263/2016 established a progressive increase in the biodiesel percentage in the mixture with petroleum diesel, providing the schedule for B8 (8%), B9 (9%), and B10 (10%) (Brazil, 2016). However, in 2018, CNPE issued Resolution No. 16/2018, establishing the mandatory progressive increase of biodiesel percentage towards 15% (B15) until March 2023 (CNPE, 2018). Nonetheless, the biodiesel blending has been reduced on an ad hoc basis since 2020 due to fuel price shocks over the last two years of the Covid-19 pandemic (AGÊNCIA BRASIL, 2020a, 2020b; GAUDARDE, 2022, 2021). Figure 4 summarises the timeline of the Brazilian case.

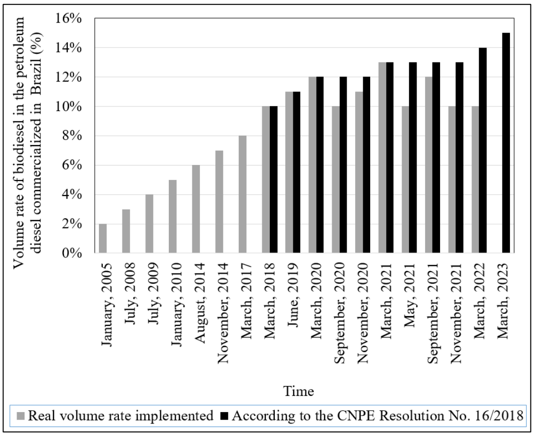

Figure 4 - The volume rate of biodiesel in the petroleum diesel commercialized in Brazil: real volume rate implemented vs CNPE Resolution No. 16/2018

Each region in Brazil has its peculiarities regarding feedstock and motivations for biodiesel production. The opportunity in the North region is to use African palm (dendê) and babassu oils to produce biodiesel, enabling power generation in remote areas and supplying local waterway transport. In the Northeast region, the encouragement for biodiesel production would come from the social inclusion and job generation appeals for drought-resistant castor bean cultivation. There is the possibility of local soy processing in the Center-West region, reducing diesel oil transport freight costs. Biodiesel production could substitute diesel oil in large urban areas in the South and Southeast regions, contributing to air pollution reduction and sustainability growth (ANGARITA et al., 2008).

Generally, biodiesel has a higher cost of production than petroleum diesel. In this sense, governmental impositions, such as the mandatory blending of biodiesel with petroleum diesel, have helped develop the actual biofuel market in Brazil, as long as biodiesel's economic viability is considered a barrier to its development.

3.4 Landmarks, perspectives and challenges

Finally, a summary of the points raised in this section is presented in Table 1, which shows the landmarks, future perspectives, and challenges for the development of each alternative tackled in this work.

Table 1 - Landmarks, future perspectives, and challenges for the development of (i) natural gas and biomethane, (ii) electrification and hybrids, and (iii) biofuels for light-duty vehicle use in Brazil

Fuel	Brazilian Landmarks	Future perspectives	Challenges
Natural Gas and Biomethane	1973 - Petroleum crisis. 1987 - Brazil launched PLANGAS. 1991 - Released the use of natural gas by taxi drivers. 1992 - Authorized the use of natural gas by urban buses, taxis, and freight vehicles. 1996 - Private light-duty vehicles are allowed to run on natural gas.	- Natural gas is viewed as an essential element in the energy transition. - Natural gas can be mixed with biomethane, a gaseous biofuel related to environmental sanitation.	- Infrastructure development. - Distribution network expansion. - Supply security of natural gas. - Natural gas market development. - Costs related to fuel station adaptation. - Costs related to gasoline or diesel vehicle conversion to run on natural gas.
Electrification and Hybrids	1973 - Petroleum crisis. 1974 - First electric vehicle produced in Latin America. 2015 - Reduction of EV import tax from 35% to zero. 2020 - Bill addressing a reduction to zero of the tax on industrialized products. 2021 - Biggest Brazilian city (São Paulo) sanctioned EV tax incentives.	- Vehicle-to-Grid technologies, using EVs as energy storage elements. - Development of car-sharing systems in urban areas. - Adoption of autonomous vehicles. - Lithium-ion batteries with niobium.	- Recharge infrastructure. - Absence of a robust federal-level policy. - Batteries capacity. - Battery’s environmental impacts. - High costs of EVs to the low-income population.

Table 1 - Landmarks, future perspectives, and challenges for the development of (i) natural gas and biomethane, (ii) electrification and hybrids, and (iii) biofuels for light-duty vehicle use in Brazil (cont.)

Fuel	Brazilian Landmarks	Future perspectives	Challenges
Biofuels	1970 - First researchers for ethanol and biodiesel development. 1973 - Petroleum crisis. 1975 - Brazil launches PROALCOOL. 1980 - Second phase of PROALCOOL. 1985 - The "oil shock" with the sharp decline in oil prices on international markets. 2000 - Compulsory addition of ethanol to gasoline and the production of flex-fuel vehicles. 2005 - Brazil launched the PNPB, introducing biodiesel into the national energy matrix. 2016 - Law No. 13.263/2016. 2018 - CNPE Resolution No. 16/2018.	Ethanol - Greater energy efficiency through the energetic use of second-generation ethanol and residual biogas. Biodiesel - Mandatory progressive increase of biodiesel percentage in the petroleum diesel towards 15% (B15) until March 2023. - Perspectives of social inclusion and job creation through productive biodiesel sector.	- Fossil energy is applied to the biofuel production supply chain. - Production and application of synthetic fertilizers. - Deforestation. - Impacts of large monoculture areas on biodiversity. - Negative effect on world´s food security. - Pressure on food prices. - Limited availability of arable lands on the planet.

4. CONCLUSIONS AND POLICY IMPLICATIONS

The Petroleum Crisis in 1973 was a landmark for energetic Brazilian history. Due to the high petroleum prices in the following years, the Brazilian government and entrepreneurs took concrete actions toward alternative fuel solutions. Besides the fact that research considering the energetic use of sugar cane was already underway since the 1960s, the first national policy for ethanol was launched only in 1975 with PROALCOOL. In addition, Brazilian engineer João Conrado do Amaral Gurgel only presented his first EV in 1974 due to the high petroleum-based fuel prices.

The Brazilian government's great incentive program to promote ethanol use in light-duty vehicles, along with the high petroleum prices in the mid-1970s, triggered an energetic transition in the Brazilian transport sector in the mid-1980s when about 70% of all new vehicles were manufactured to run on ethanol. However, market forces reverted this transition in the 1990s, when gasoline assumed the top position until the mid-2000s. Finally, in 2006, flex-fuel vehicles (running on gasoline and ethanol) took the lead in most manufactured cars in Brazil, with a market share of around 80% (see Figure 2).

About the milestones, future perspectives and challenges for the development of each alternative addressed in this work, presented in Table 1, it is concluded that the development of biofuel technology is an essential chapter in the history of the Brazilian automotive industry, especially ethanol derived from sugar cane. If, on the one hand, there have been solid governmental policies incentivizing the use of biofuels since the 1970s, on the other hand, the Brazilian natural conditions were crucial for these policies' success. Availability of arable areas, water resources, abundant solar radiation, and an extensive coastal strip are some of the favourable environmental characteristics of Brazil, which supports all the governmental ambitions toward biofuels.

When it comes to biofuels, Brazil has a relatively diversified portfolio. Potential technologies that might stand out in the following years are second-generation ethanol, biogas and biomethane, and ethanol fuel cells. These solutions toward a low carbon economy could be boosted with adequate and more decisive public policies, such as more legal certainties and more transparent investor rules for the biofuel market.

Environmental issues and energy justice of all the technological paths tackled in this work must be assessed closely. The mineral exploitation of raw materials to produce lithium-ion batteries and their relatively short life span could give out more environmental liabilities than a scenario without EVs. Besides that, the impact on electricity prices due to a higher EV charging demand could hamper energy access for the most vulnerable sections of the population.

Biofuel production can also be damaging to the environment. Fossil energy applied to the productive biofuel chain and synthetic fertilizers to the soil is some of the issues that need to be addressed for the future sustainability of the sector. Furthermore, it is essential not to overlook the possibility of negative social impacts of pressure on food prices and food security. Notwithstanding, the force of Brazilian agribusiness and its massive investments in technology could be decisive for improving productivity, increasing production, and protecting the environment.

Natural gas and biomethane can be essential in the Brazilian energy transition. Still, issues related to distribution infrastructure, market maturity, and legal uncertainty must be addressed for their development as alternatives for a greener fleet.

Other countries, however, have been intensely moving towards electrification of the light-duty vehicles fleet. The global electric car stock increased by 43% over 2019, exceeding the mark of 10 million electric vehicles on the world's roads. China, Europe, and the United States lead the market with 5.4 million, 3.3 million, and 1.8 million electric vehicles, respectively. The north-western European region has achieved the highest market share percentage of electric vehicles in their available vehicles fleet. In 2020, the sales share of new electric vehicles reached 75% in Norway, 50% in Iceland, and 30% in Sweden (IEA, 2021). This movement towards electrification from rich countries, mainly through significant public policies, can influence other countries to go in the same direction. However, Brazil has peculiar characteristics that can make electrification not the best or the only solution for a greener fleet. Brazil needs to find its path towards a low-carbon economy without throwing away its already know-how and traditional experienced trajectory.

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