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COMPARISON OF THE LIFE-CYCLE GREENHOUSE GAS EMISSIONS OF COMBUSTION ENGINE AND ELECTRIC PASSENGER CARS IN BRAZIL

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EXECUTIVE SUMMARY

To meet the Brazilian government's targets of cutting greenhouse gas (GHG) emissions by half in 2030 compared to 2005 levels, and achieving climate neutrality by 2050, the transport sector needs to approach zero emissions. The passenger car market in Brazil is currently dominated by flex-fuel internal combustion engine vehicles (ICEVs), capable of running on both hydrous ethanol and gasoline C, a blend of gasoline and 27vol.% anhydrous ethanol. In total, ethanol makes up about half of the fuel consumption (by volume) of the passenger car fleet, either as hydrous ethanol or in the gasoline C blend, and is mostly produced from domestic sugarcane. Differing from other major vehicle markets, the sales shares of hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and battery electric vehicles (BEVs) in Brazil remain at low levels. In light of the climate change mitigation targets set by the Brazilian government, questions arise regarding which power train and fuel technologies will allow the passenger car fleet to approach zero GHG emissions in the long term.

This study presents a life-cycle assessment of the GHG emissions of passenger cars of different power train types and fuel pathways. Given the economy-wide nature of Brazil's net-zero emissions target, the analysis assesses tailpipe emissions, emissions from fuel and electricity production, and emissions from vehicle and battery manufacturing. The study compares the life-cycle emissions of ethanol- and gasoline-powered flex-fuel ICEVs, BEVs, HEVs, and PHEVs. It also assesses the emissions impact of hydrogen fuel cell electric vehicles (FCEVs) fueled by natural gas- and electricity-based hydrogen. Detailed sales data is used to build representative vehicles for the three largest segments in domestic sales: compact, medium, and compact SUVs. While ICEVs and BEVs are compared in all three segments, HEVs and PHEVs are included in the assessment for medium cars and FCEVs are evaluated for the SUV segment. In addition to assessing the life-cycle emissions of vehicles sold today, the study estimates the emissions of vehicles sold in 2030 considering the future development of the electricity and fuel mix, different hypotheses for future ethanol usage, and potential improvements in the vehicles' energy efficiency.

The main findings are summarized in Figure ES1. The figure presents the life-cycle GHG emissions per distance driven over a vehicle's lifetime (in g $CO_{2\ eq.}$/km) for average flex-fuel ICEVs and BEVs by vehicle segment, as well as for HEVs and PHEVs in the medium segment. Total emissions are distinguished by vehicle and battery production, maintenance, fuel combustion, fuel or electricity production, and indirect land use change (ILUC) for biofuels. For flex-fuel ICEVs and HEVs, emissions are calculated using the market average shares of gasoline C and hydrous ethanol consumption. The error bars indicate emissions when vehicles operate solely on gasoline C (upper values) and solely on hydrous ethanol (lower values). PHEVs are assumed to use gasoline C, as there are currently no flex-fuel PHEV models available.

As shown, the life-cycle GHG emissions of BEVs are well below those of any other power train and fuel mix considered, due to their high energy efficiency during operation and Brazil's low-carbon grid mix. For vehicles sold in 2023, **BEVs have emissions 65%–67% lower** than flex-fuel ICEVs driving on the average mix of gasoline C and ethanol. In contrast, HEVs and PHEVs show a limited GHG emission benefit compared to ICEVs. **HEVs have 14% lower emissions** than flex-fuel ICEVs when driving on the same gasoline C and ethanol mix. Current **PHEVs**, which exclusively use gasoline C, **only show 3% lower emissions** than flex-fuel ICEVs using the average mix of gasoline C and ethanol.

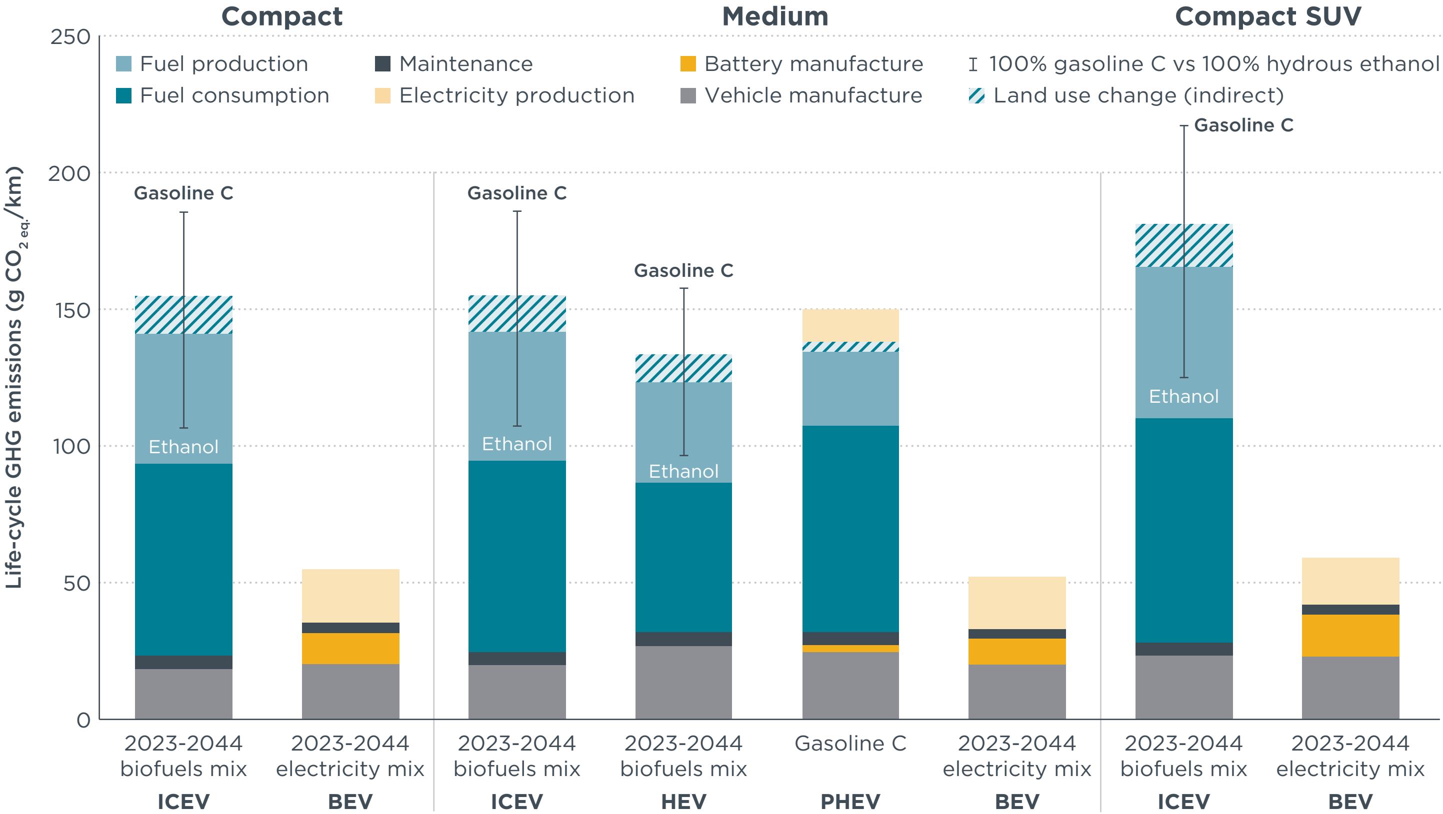

Figure ES1. Life-cycle GHG emissions of compact, medium, and compact SUV segment flex-fuel ICEVs and BEVs, as well as medium segment HEVs and PHEVs sold in Brazil in 2023. Error bars indicate the cases of operating solely on gasoline C (higher value) or solely on hydrous ethanol (lower value).

A potential improvement in the fuel economy of future flex-fuel ICEVs sold in 2030, alongside the projected increase of the ethanol share in the average fuel mix, would result in 12% lower life-cycle emissions than 2023 models. The small reductions in life-cycle emissions compared to the status quo of current flex-fuel ICEVs are insufficient to align the emissions of the Brazilian passenger car fleet with Brazil's climate targets. Aligning the transport sector with the goal of reaching net-zero emissions economy-wide by 2050 will instead require a shift to electric vehicles.

The life-cycle GHG emissions of flex-fuel vehicles driving solely on hydrous ethanol are about 31% lower than when driving on the average mix of gasoline C and hydrous ethanol. When using only gasoline C, emissions are 20% above those of ICEVs using the average mix of gasoline C and ethanol. The findings are similar for flex-fuel HEVs. This indicates that the use of Brazilian ethanol can reduce emissions significantly compared to fossil gasoline. However, even when assuming HEVs would solely operate on ethanol over the entire lifetime, the life-cycle emissions would be 85% higher than for BEVs using the average grid mix. Furthermore, even given that the share of hydrous ethanol in all fuel consumed is projected to increase from 35vol.% to 55vol.% by 2050, the case of flex-fuel ICEVs or HEVs solely running on ethanol are not representative of fleet average consumption.

The life-cycle GHG emissions of hydrogen FCEVs can approach those of BEVs, but only when solely powered by green hydrogen. However, when including energy losses during hydrogen production and compression, this is at a cost of using three times more electric energy than BEVs. Supporting the uptake of BEVs is thus the most efficient way to decarbonize the passenger car fleet in Brazil.

POLICY RECOMMENDATIONS

The findings of this study have implications for two policy developments in Brazil: the fuel economy standards of the upcoming Green Mobility and Innovation Program (PROMOVI), which is the continuation of the Rota 2030 program, and the RenovaBio biofuels policy. Further, the findings suggest actions to support the automotive industry and consumers in the transition to electric vehicles to meet the Government's climate targets.

Defining the upcoming PROMOVI goals in terms of CO_2 emissions instead of energy consumption needs to be based on the emission factors of the current market average shares of ethanol and gasoline C to maintain the effectiveness of the program. The program should define new corporate average goals that can be achieved fully through energy efficiency improvements, including a shift to BEVs and FCEVs. The goals of PROMOVI will be defined in terms of CO_2 emissions instead of energy consumption. This shift creates uncertainty regarding how emissions are determined, particularly for flex-fuel ICEVs. The climate impact of flex-fuel ICEVs depends on if they solely operate on hydrous ethanol, on gasoline C, or on a mix of these fuels. To better represent real-world fuel consumption and related emissions, the market average shares of ethanol and gasoline C should be considered for the CO_2 emission values of flex-fuel ICEVs. Eventual increases in ethanol market share should not substitute for improvements in vehicle energy efficiency.

To achieve climate targets in the transport sector, PROMOVI could determine corporate goals that prepare for a shift to BEVs or FCEVs. Increasing sales of BEVs and FCEVs in the near term will allow the Brazilian passenger car fleet to decarbonize faster. Due to the long lifetime of passenger vehicles in the national fleet, delays in the introduction of BEVs may result in the need for more ambitious policy actions in the near future. To realize the GHG emission reduction potential of FCEVs, it should be ensured that renewable electricity-based hydrogen is used in the transport sector.

Incentives for production of BEVs in Brazil would combine their environmental benefits with economic competitiveness. The current lack of domestic BEV production puts the Brazilian automotive industry at risk of losing competitiveness in international markets. The continued production of ICEVs exclusively could result in a reduction of vehicle exports and an increase in BEV imports. In parallel to public support for BEV production in Brazil, investments in research and development on energy efficiency improvements, which manufacturers can choose to spend to receive the current Rota2030 benefits, could be steered to BEVs and FCEVs. This would incentivize domestic production of these vehicles. Benefiting from the clean domestic grid, Brazil-made batteries would further strengthen the life-cycle emission benefit of BEVs.

Incentivize the use of ethanol over fossil gasoline for the existing flex-fuel vehicles fleet and include ILUC emissions in the RenovaBio program to improve the sustainability of ethanol. Substituting gasoline for sugarcane-based ethanol yields lower life-cycle GHG emissions from vehicles. Therefore, even though sales of new vehicles should shift towards BEVs, increasing the market share of ethanol compared to fossil gasoline remains a relevant tool to reduce emissions of flex-fuel vehicles in the short term. However, any increase in ethanol production should be met with policies that ensure production expansion will not increase its average carbon intensity. Introducing ILUC emissions in the RenovaBio program would provide a greater relative incentive for second-generation fuel production, as well as incentivize more efficient production at existing, first-generation ethanol facilities.

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INTRODUCTION

Reaching the climate change mitigation goals established in the Paris Agreement to limit global warming to well below 2°C above pre-industrial levels requires swift and deliberate global actions to reduce greenhouse gas (GHG) emissions. Brazil's Nationally Determined Contribution (NDC) determines emission reductions of 37% by 2025 and 50% by 2030, compared to 2005 levels, as well as reaching net-zero emissions by 2050 (Government of Brazil, 2022). Acting on climate change is a priority for the country's new administration, which creates new momentum for climate mitigation strategies, including the deployment of zero-emission vehicles, a sector in which the country has fallen behind its peers.

The transportation sector in Brazil was responsible for 13% of national GHG emissions in 2020, and was the third largest source of emissions after agriculture (35%) and land use change (27%) (World Resources Institute , 2023). Road transportation alone accounts for 94% of the energy demand within the transport sector, of which about 46% comes from light-duty vehicles (Empresa de Pesquisa Energética [EPE], 2023). In 2022, the country had a vehicle stock of about 38 million passenger cars and 1.6 million new car sales (Associação Nacional dos Fabricantes de Veículos Automotores [ANFAVEA], 2023), it constitutes the world's seventh largest passenger car market (Organisation Internationale des Constructeurs d'Automobiles [OICA], 2023). The Brazilian market is characterized by ethanol-gasoline flex-fuel internal combustion engine vehicles (ICEVs), representing 92% of passenger cars sales in 2020 (ADK Automotive, 2021), and a high share of sugarcane-based ethanol in the average fuel consumption mix. The remainder of passenger car sales are ICEVs solely powered by gasoline (5%), diesel-powered ICEVs (3%), and hybrid electric vehicles (HEVs) (less than 1%) (ADK Automotive, 2021). The sales shares of plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs) combined increased from 0.1% in 2020 to 0.5% in 2022 (EV-volumes, 2023).

The BEV and PHEV sales shares in Brazil are low compared to other major vehicle markets, such as China (27% in 2022), Europe (21%), and the United States (7%), as well as below the global average sales share of 13% (Chu & Cui, 2023). With vehicle production volumes of 2.18 million light-duty vehicles in 2022, of which 1.82 million were passenger cars, Brazil is the eighth largest producer of light-duty vehicles and the fifth largest producer of passenger cars (OICA, 2023). Within the global transition to electric vehicles, the lack of domestic BEV production compromises the international competitiveness of the Brazilian automotive industry.

To align the transport sector in Brazil with the national climate targets for 2025 and 2030, and to reach net-zero emissions by 2050, it is important for policymakers to understand which power train types and fuel pathways are most capable of reducing GHG emissions. This study presents a life-cycle assessment (LCA) of the GHG emissions of passenger cars in Brazil to compare the full climate impact of these vehicles. In addition to emissions at the tailpipe, it covers emissions from fuel and electricity production, as well as from vehicle and battery manufacturing. The study compares the life-cycle GHG emissions of average flex-fuel ICEVs and BEVs across the compact, medium, and compact SUV passenger car segments, and further assesses the emissions of HEVs, PHEVs, and hydrogen-powered fuel cell electric vehicles (FCEVs). After a comparison of the emissions over the lifetime of vehicles sold in 2023, the study estimates how these emissions would change for vehicles sold in 2030.

The study is structured as follows: details of the goal and scope of the LCA, data analysis, and fuel, electricity, and vehicle characteristics are presented in the data and methodology section. The results section presents a comparison of the life-cycle GHG emissions of flex-fuel ICEVs and BEVs, and HEVs and PHEVs where applicable, for current and future vehicles. It further presents the life-cycle GHG emissions of FCEVs powered by different hydrogen pathways. The study closes with a summary and conclusions section, followed by policy recommendations.

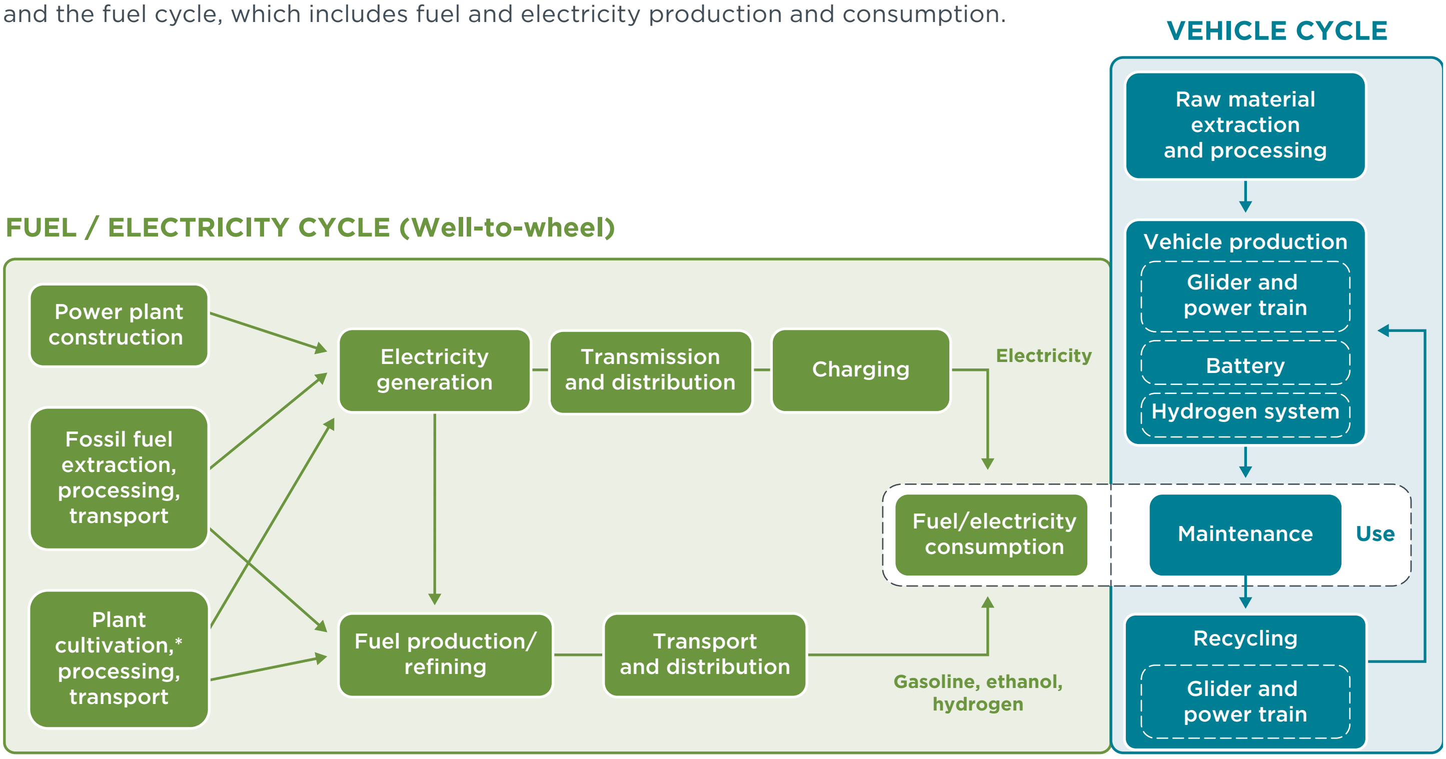
DATA AND METHODOLOGY

Goal and scope

The goal of this LCA is to identify which power train types and energy pathways allow the largest reduction of GHG emissions of passenger cars in Brazil within existing and alternative policy frameworks. The study compares the life-cycle GHG emissions of flex-fuel ICEVs and BEVs in the small, medium, and compact SUV segments, and where possible, HEVs, PHEVs, and hydrogen FCEVs. In addition to comparing the GHG emissions over the lifetime of vehicles sold in 2023, the study estimates the emissions of vehicles sold in 2030.

The functional unit of the comparison is grams of CO_2 equivalent per kilometer traveled during the lifetime of the vehicles (g $CO_{2\ eq.}$/km), for which methane (CH_4) and nitrous oxide (N_2O) emissions are considered, based on the 100-year global warming potential factors from the Intergovernmental Panel on Climate Change (2021). This LCA generally follows an attributional approach and considers the average GHG emissions that can be attributed to a vehicle. For the vehicles' use phase, it considers the changes in the average fuel or electricity mix during the vehicles' lifetimes. Some values, like the indirect land use change (ILUC) emissions from biofuel production, are captured by a consequential approach. Accordingly, those values reflect the changes the production causes in the broader economy.

The general scope and system boundary of this study are shown in Figure 1. They are based on the scope and methodology of an LCA of passenger cars in Europe, the United States, China, and India previously published by the International Council on Clean Transportation (Bieker, 2021). The scope covers the GHG emissions of the vehicle cycle, which incorporates the production, maintenance, and recycling of the vehicles, and the fuel cycle, which includes fuel and electricity production and consumption.



* Includes indirect land use change (ILUC) emissions for biomass and biofuel production

Figure 1. General scope and system boundary of the LCA.

In the vehicle cycle, the emissions corresponding to battery production for BEVs and PHEVs, including raw material extraction and processing, are presented separately from the emissions of the production of the rest of the vehicle, denoted as glider and power train. Similarly, emissions corresponding to the production of the hydrogen storage tank and fuel cell in FCEVs are presented separately. The vehicle cycle also covers the use of consumables and the in-service replacement of parts of the vehicle. Table 1 summarizes the GHG emissions considered in the vehicle cycle.

Table 1. Scope of GHG emissions in the vehicle cycle adopted in this study.

Data	Summary of scope
Glider and power train	Production of the vehicle, including raw material extraction and processing, component manufacture, vehicle assembly; recycling of vehicle components, time-sensitive hybrid of avoided burden and cut-off approach
Battery	Production of battery packs, including extracting and processing of raw materials, cell production, and pack assembly
Hydrogen system	Production of hydrogen tanks and fuel cells, including raw material extraction and processing, and component manufacture
Maintenance	In-service replacement of consumables, including tires, exhaust/aftertreatment, coolant, oil, etc.

Emissions associated with the fuel and electricity cycle, or well-to-wheel (WTW) emissions, include the GHG emissions corresponding to fossil fuel, biofuel, electricity, or hydrogen production (well-to-tank, WTT), and the emissions of fossil fuel combustion in the vehicle (tank-to-wheel, TTW). For fossil fuels, the scope of this analysis includes crude oil extraction (including flaring), processing and transport, and fuel refining and distribution, all associated methane leakage, and the combustion of the fuels in the vehicles. Methane and nitrous oxide emissions during the (incomplete) combustion of fossil fuels and biofuels are also accounted for.

For biofuels, the scope covers the emissions of feedstock cultivation, processing, and transport, as well as emissions from biofuel production and distribution. The CO_2 emissions of fuel combustion are not considered, as these are compensated by the biogenic CO_2 uptake during the growth of the respective plants. For the production of biofuels, this analysis includes ILUC emissions. These correspond to the regional and global expansion of area used for agriculture which indirectly results from biofuel demand in Brazil. They reflect the clearing of above-ground biomass and the change of soil carbon when converting natural vegetation to agriculture.

The life-cycle emissions of electricity production include the upstream and direct emissions of electricity generation, as well as building new power plant infrastructure for renewable energies. Energy losses in transmission and distribution are also accounted for. The carbon intensity of the fuel and electricity production considers the current biofuel blends and electricity mix, as well as their projected development during the vehicles' lifetime.

For hydrogen, the analysis distinguishes between natural gas- and electricity-based hydrogen. Other pathways, such as biogas- and ethanol-based hydrogen, have yet to be commercially explored, and were not included in this study. For natural gas-based hydrogen, the extraction, processing, and transport of the fossil fuel, as well as the emissions during the steam reforming process are accounted for, including methane emissions in all steps. Electricity-based hydrogen considers the life-cycle GHG emissions of electricity generation and the energy losses during electrolysis. All hydrogen pathways consider the energy consumption of hydrogen compression and short-distance transportation. Table 2 summarizes the scope of emissions in the fuel and electricity cycle.

Table 2. Scope of GHG emissions in the fuel and electricity cycle.

Data	Summary of scope
Fossil fuels	Crude oil/natural gas extraction (including flaring), processing and transport, and fuel refining and distribution; fuel combustion, including methane and nitrous oxide emissions from the vehicle
Biofuels	Feedstock cultivation/waste collection, processing, and transport, and production and distribution of fuel, ILUC GHG emissions of plant cultivation; methane and nitrous oxide emissions from the vehicles
Electricity	Life-cycle GHG emissions of electricity generation (including power plant infrastructure), transmission, distribution and charging losses
Hydrogen	Electricity-based hydrogen: GHG emissions of electricity, adjusted by energy losses during electrolysis and hydrogen compression; natural gas-based hydrogen: natural gas extraction, processing and transport, steam reforming and hydrogen compression, all steps including methane leakage; not included: long-distance hydrogen transport

This study does not cover GHG emissions corresponding to the construction and maintenance of the infrastructure for vehicle production, infrastructure for vehicle fueling and charging, or road infrastructure.

Representative vehicle models

The comparison of the life-cycle GHG emissions of vehicles with different power train types is based on sales-weighted average vehicle characteristics of passenger cars in the compact, medium, and compact SUV segments. The following sections describe how these characteristics are obtained.

In 2020, a total of 1.95 million light-duty vehicles were sold in Brazil (ANFAVEA, 2023). Of these, 1.62 million were passenger cars, of which the compact (30%) and medium car (26%), and compact SUV segments (25%) dominate the market (ADK Automotive, 2021).[1] The remainder of passenger car sales mainly corresponds to subcompact (5%), large and extra-large cars (7%), and extra-large SUVs (5%). Minivan and off-road vehicles correspond to 1% each.

Most passenger cars in Brazil are flex-fuel ICEVs (92% in 2020), with the remainder being gasoline-powered ICEVs (5%), diesel-powered ICEVs (3%), and HEVs (less than 1%). For PHEVs and BEVs, the sales share increased from 0.2% in 2020 and to 0.7% in 2022, while no FCEVs were sold in these years (EV-volumes, 2023).

In this study, the emissions of flex-fuel ICEVs and BEVs are compared in the compact, medium, and compact SUV segments. For vehicles of these power train types, life-cycle GHG emissions are calculated based on segment average vehicle weight, battery capacity, and fuel or electricity consumption. The segment average characteristics of flex-fuel ICEVs are derived from combining 2020 vehicle model sales data from ADK Automotive (2021) with segment classification and fuel consumption data from the National Institute of Metrology, Quality, and Technology (INMETRO, 2023). Due to the more dynamic market development for BEVs, 2022 sales and vehicle characteristics data from EV-volumes (2023) were combined with the segment classification and electricity consumption data from INMETRO. In the medium segment, the emissions of HEVs and PHEVs are also assessed. For HEVs, the average weight and fuel consumption are determined as described for flex-fuel vehicles, while for PHEVs, the

1 The assignment of vehicle models to Brazilian segments is based on Ordinance No. 169 (INMETRO, 2023). In Brazil, passenger cars have a maximum mass in running order of 2,720 kg, a maximum total mass of 3,856 kg, and up to eight seats (excluding the driver's seat). Passenger car segments are further distinguished by the area defined by the maximum length and width of a model. For instance, a compact car has an area from 6.5 m^2 and less than 7.0 m^2, while a medium car has an area of less than 8.0 m^2. A compact SUV has an area of less than 8.0 m^2, while large and extra-large SUVs exceed this value. Also, SUVs are defined by the ground clearance, as well as ramp, approach, and departure angles.

Mini Countryman was the only PHEV model in the medium segment sold in Brazil from 2020 to 2022.

The emissions of FCEVs are assessed in the compact SUV segment. As no FCEVs were sold in Brazil between 2020 and 2022, the Hyundai Nexo, one of the few models on the global market, is used as representative model. Despite attracting interest from national ethanol and car manufacturers, no models equipped with direct-ethanol fuel cells are commercially available or are expected to be soon. Thus, these hypothetical vehicles are not considered in this analysis. Table 3 provides an overview of selected vehicle characteristics.

Table 3. Vehicle characteristics of the compact, medium, and compact SUV segments.

Segment	Power train type	Engine power (kW)	Curb weight (kg)	Footprint [a] (m^2)
Compact	Flex-fuel ICEV	66	1039	3.7
	BEV	100	1455	3.8
Medium	Flex-fuel ICEV	80	1100	3.8
	HEV	95	1415	4.3
	PHEV	169 + 65 [b]	1390	4.2
	BEV	116	1390	3.8
Compact SUV	Flex-fuel ICEV	87	1261	3.9
	BEV	110	1708	4.3
	FCEV	120	1814	4.5

[a] Vehicle footprint as defined by the vehicle wheelbase and axle width.
[b] Internal combustion engine power and electric motor power.

VEHICLE CYCLE

Glider and power train

The GHG emissions corresponding to the production and recycling of the glider and power train are derived from the power train-specific and vehicle mass-dependent factors from Hill et al. (2020). The glider and power train correspond to the vehicle without the battery of BEVs and PHEVs, and without the hydrogen system of FCEVs. This means that the mass of these components is subtracted from the total vehicle weight. The weight of the battery is estimated from the battery capacity (see Table 5) and assumes a specific energy of the battery pack of 148 Wh/kg (Hill et al., 2020). The resulting emissions of the glider and power train are shown in Table 4.

Table 4. GHG emissions of the production and recycling of the glider and power train, and of the maintenance of vehicles produced in 2023.

Segment	Power train type	Vehicle production and recycling (t $CO_{2\,eq.}$)	Maintenance (g $CO_{2\,eq.}$/km)
Compact	Flex-fuel ICEV	5.4	4.6
	BEV	5.8	3.6
Medium	Flex-fuel ICEV	5.8	4.7
	HEV	7.7	5.2
	PHEV	7.2	5.2
	BEV	5.8	3.6
Compact SUV	Flex-fuel ICEV	6.7	5.0
	BEV	6.7	3.7
	FCEV	8.8	3.5

For vehicles produced in 2030, the mass of the glider and power train is assumed to be the same as for 2023 models. Still, the emissions displayed in Table 4 are assumed to be 15% lower, which is based on the projected decarbonization of the industry and power sectors (Bieker, 2021; Hill et al., 2020).

Battery

Table 5 shows the GHG emissions from the battery production for current electric vehicles. They are derived from the battery capacities of the considered models and a GHG emissions factor of 67 kg $CO_{2\,eq.}$ per kWh of battery capacity. This factor corresponds to the carbon intensity of producing lithium nickel manganese cobalt oxide (NMC622) based batteries (Bieker, 2021), weighted with the 2022 global electric vehicle battery production corresponding to China (76%), the United States (7%), the European Union (7%), Japan (5%), and South Korea (5%) (IEA, 2022a), and the carbon intensities from the GREET model (Argonne National Laboratory, 2020). This variant of lithium-ion batteries is assumed for all vehicles in this study, as it is the most common type on the global market. For reference, the production emissions for lithium iron phosphate based batteries would be 20% lower, at 54 kg $CO_{2\,eq.}$/kWh. The GHG emission benefits from battery recycling, which reduces the GHG emissions impact of batteries (see Tankou et al., 2023), are not considered in this study.

Batteries are assumed to last longer than the vehicle lifetime. This assumption is based on studies showing that state-of-the-art lithium-ion batteries offer 90%–95% of their initial capacity even after 3,000 full cycles of fast charge and discharge (Harlow et al., 2019). With real-world ranges of 200 km to 400 km, 3,000 cycles correspond to a mileage of 600,000 km to 1,200,000 km, respectively. These numbers far exceed the lifetime mileage discussed below. It is thus generally expected that BEV batteries last longer than the vehicles. The GHG emission benefit of a potential second-life usage, for instance as stationary storage for the electric grid (Tankou et al., 2023), is not accounted for in this study.

Table 5. Battery capacity and GHG emissions from battery production of the BEVs and PHEVs sold in Brazil in 2023 and 2030.

Segment	Power train type	2023 vehicle model		2030 vehicle model	
		Gross capacity (kWh)	GHG emissions (t $CO_{2\,eq.}$)	Gross capacity (kWh)	GHG emissions (t $CO_{2\,eq.}$)
Compact	**BEV**	50	3.4	60	2.5
Medium	**PHEV**	10	0.7	12	0.5
	BEV	41	2.7	49	2.1
Compact SUV	**BEV**	66	4.4	79	3.3

For the hypothetical 2030 vehicle models, the emission factor to produce lithium-ion batteries is reduced to 53 kg $CO_{2\,eq.}$ per kWh. This is based on an assumed shift from NMC622- to NMC811-based batteries and a general reduction of the carbon intensity of battery production by 20% (Bieker, 2021). For BEVs and PHEVs, battery capacity and range have continuously increased over the past several years. We assume this trend (which can be explained by the falling costs of battery production) will continue, resulting in an average increase of 20% compared to current models.

Hydrogen system

The GHG emissions corresponding to the hydrogen fuel tank and fuel cell were also obtained from the GREET model (Argonne National Laboratory, 2020). For a FCEV passenger car in the SUV segment the model provides emissions of 4.2 t $CO_{2\,eq}$. As discussed by Bieker (2021), similar values are used in other LCA studies (Agora

Verkehrswende, 2019; Fraunhofer Institute for Systems and Innovation Research ISI, 2019; Hill et al., 2020).

Lifetime mileage

The latest official data on the survival curve of passenger cars in the Fourth National Inventory of Anthropogenic Greenhouse Gas Emissions (Ministry of Science, Technology and Innovations of Brazil, 2020) shows that 50% of vehicles age 22–23 years are still in use in Brazil. Based on this evidence, this study considers an average vehicle lifetime of 22 years.

The development of the annual mileage over vehicle age is obtained from the National Inventory of Atmospheric Emissions for Road Vehicles (Ministry of Environment, 2014). Combining 22 years of usage with the yearly mileage results in an accumulated lifetime mileage of 288,000 km.

Note that the annual mileage of passenger cars is higher in their early years of operation compared to later years. The National Inventory of Atmospheric Emissions for Road Vehicles considers that the annual mileage decreases linearly by 600 km/year (Ministry of Environment, 2014). This means that the carbon intensity of the fuel and electricity mix in the first years is accounted in higher proportion than in later years.

Maintenance

Over their lifetime, vehicles require the replacement of components, such as tires, exhaust aftertreatment systems, and other parts, as well as the use of consumables such as coolant and oil. As discussed by Bieker (2021), combustion engine vehicles generally require more maintenance than electric vehicles, and thus also correspond to slightly higher GHG emissions associated with maintenance. To account for corresponding GHG emissions, the power train type- and vehicle weight-specific emission factors are derived from Hill et al. (2020) and scaled with the weight of the considered vehicle models. Table 4 shows the derived distance-specific factors (in g $CO_{2\ eq.}$/km).

FUEL AND ELECTRICITY CYCLE

Real-world fuel and electricity consumption

The fuel and electricity consumption values considered in this study are generally based on those reported by Brazil's labeling program, Programa Brasileiro de Etiquetagem Veicular, coordinated and published by INMETRO (2023). For flex-fuel ICEVs and HEVs, the labelling program applies a correction to adjust the type-approval fuel consumption values to those found under real-world conditions.[2] In this study, the adjusted values reported for individual vehicle models in their respective segments are weighted with 2020 sales data from ADK Automotive (2021). Brazil's fuel economy standards of the Rota 2030 program require the corporate average energy consumption of passenger cars sold from 2022 to be reduced to an average of about 1.62 MJ/km (Presidency of the Republic, 2018), down from a target value of about 1.82 MJ/km for vehicles sold from 2017 to 2021 (Presidency of the Republic, 2012). Acknowledging this improvement, we assume that vehicles sold today are, on average, more energy efficient than those sold in 2020. Mirroring the relative reduction in corporate average energy consumption value, the type-approval energy consumption values of 2020 vehicles are thus reduced by 11% before being adjusted to real-world

2 The Brazilian norms ABNT NBR 7024 for highway and ABNT NBR 6601 for urban driving conditions use the same testing procedure as the U.S. Environmental Protection Agency Federal Test Procedure (FTP75). For the labelling program, the tested fuel consumption in the urban and highway drive cycles are increased by factors of 18% and 35%, respectively, as well as by a constant term. The corrected values are then weighted by a share of 55% urban and 45% highway driving (INMETRO, 2023).

conditions. Table 6 shows the real-world fuel or electricity consumption for the individual power trains and segments. The fuel consumption values in liters per 100 km correspond to gasoline C blend.

Table 6. Real-world fuel, electricity, and hydrogen consumption of current passenger cars in Brazil.

Segment	Power train type	Fuel or hydrogen consumption (L/100 km[a] or kg/100 km)	Electricity consumption (kWh/100 km)	Total energy consumption (MJ/km)
Compact	**Flex-fuel ICEV**	6.6	-	2.0
	BEV	-	23.4	0.8
Medium	**Flex-fuel ICEV**	6.6	-	2.0
	HEV	5.1	-	1.5
	PHEV	4.3	14.2	1.3 + 0.5
	BEV	-	22.9	0.8
Compact SUV	**Flex-fuel ICEV**	7.7	-	2.3
	BEV	-	20.6	0.7
	FCEV	1.1	-	1.3[b]

[a] Fuel consumption expressed in liters of gasoline C (E27) per 100 km, LHV = 29.6 MJ/L.
[b] LHV for hydrogen equal to 120 MJ/kg (Prussi et al., 2020).

An update of the methodology for BEV electricity consumption values in the labeling program, which applies from September 2023 onwards, divides the type-approval electricity consumption values (in kWh/100 km) by a factor of 0.7 to adjust them to real-world driving conditions (INMETRO, 2023). This procedure is similar to the methodology used for the label values of the U.S. Environmental Protection Agency (U.S. EPA, 2017). The corrected electricity consumption values for individual vehicle models are weighted with 2022 sales shares in the respective segments (EV-volumes, 2023).

For PHEVs, real-world fuel and electricity consumption is determined by how much they are driven in combustion engine-powered charge-sustaining mode and in the predominantly electric charge-depleting mode, as well as by the fuel and electricity consumption in these two modes. As the only medium sized PHEV currently available in Brazil has not been tested by INMETRO yet, the fuel and electricity consumption values in the charge-sustaining and charge-depleting modes are taken from U.S. EPA label tests (U.S. EPA & U.S. Department of Energy [U.S. DOE], 2022).[3] The fuel and electricity consumption in these two modes are weighted with an electric driving share of 50%, as observed for this model, on average, in real-world operation of private consumers in Germany (Plötz et al., 2022). Note that in the United States, the electric driving share of this model is found to be only around 30% (Isenstadt et al., 2022).

For FCEVs, the hydrogen consumption of the Hyundai Nexo is not provided in the Brazilian labeling program. Therefore, the values from the similar U.S. EPA labeling program are used (U.S. EPA & U.S. DOE, 2022). For hypothetical average flex-fuel ICEVs and HEVs sold in 2030, we optimistically assume an 11% energy efficiency improvement compared to current vehicles. This is based on the expectation that a higher corporate average energy efficiency standard will be implemented for vehicles sold after 2028, and that this new standard could mandate a similar improvement as Rota 2030 required for 2022 vehicles compared to those sold in 2017. For BEVs, in contrast, electricity consumption is assumed to remain the same.

3 The U.S. EPA fuel consumption values correspond to the reference fuel used in the type-approval process. Based on the respective energy density (in MJ/L), these values are adjusted to the energy density of the fuel blending in Brazil.

For PHEVs sold in 2030, we assume that the battery capacity, and thus electric range, is 20% higher than for current models (again assuming a continuation of currently observed trends). Based on the relation of electric range and real-world electric driving share for PHEV models in Europe (Plötz et al., 2022), we estimate this would increase real-world electric driving share from 50% to 55%. This increase would reduce average fuel consumption by 10%, while increasing electricity consumption by the same amount.

GHG emissions of the fossil fuel and biofuel blends

Flex-fuel ICEVs in Brazil can be driven on two main commercial fuels: hydrous ethanol (E100) and gasoline C, or a mix of the two. Gasoline C (E27) is a blend of fossil gasoline which contains 27vol.% of anhydrous ethanol. Some HEV models can operate on both fuels. There is currently no PHEV model that can be run on hydrous ethanol.

This study assesses the life-cycle GHG emissions of flex-fuel ICEVs and HEVs when driven on the market-average shares of gasoline C and hydrous ethanol consumption. The emissions from driving on this average mix are compared with the emissions of two extreme cases of operating either only on gasoline C or only on hydrous ethanol. For PHEVs, the assessment for vehicles sold in 2023 only considers gasoline C and electricity consumption, while the assessment of 2030 vehicles considers a mix of gasoline C and hydrous ethanol as for ICEVs and HEVs.

The majority of ethanol used in Brazil is first-generation ethanol from sugarcane (93% for anhydrous and 91% for hydrous ethanol in 2020), with the remainder produced from corn (7% for anhydrous and 9% for hydrous ethanol) (EPE, 2022b). Table 7 and Figure 2 present the carbon intensity of fossil gasoline, as well as sugarcane- and corn-based ethanol pathways, for anhydrous and hydrous ethanol separately. The emissions for fuel production (WTT) of individual ethanol pathways are derived from the Observatory of the Cane and Bioenergy of the Brazilian Sugarcane Industry Association (União da Indústria de Cana-de-Açúcar, 2023), which provides the average carbon intensity for biofuel producers certified in the RenovaBio program. For reference, the carbon intensity of the 2020 average blend of sugarcane- and corn-based ethanol is also displayed, which closely replicates the WTT values considered by the EPE's (2022b) report on the carbon intensity of ethanol and other fuels used in transportation.

Table 7. Fuel cycle (WTT, ILUC, TTW, and WTW) emissions of pathways for gasoline C and hydrous ethanol, as well as their lower heating value (LHV) and the 2020 volumetric share.

Fuel	Pathway	Share in blend (vol.%)	LHV (MJ/L)	WTT (excl. ILUC) (g $CO_{2\ eq.}$/MJ)	ILUC (g $CO_{2\ eq.}$/MJ)	TTW (g $CO_{2\ eq.}$/MJ)	WTW (g $CO_{2\ eq.}$/MJ)
Gasoline C	**Fossil gasoline**	73%	32.1	19.9	0	73.4	93.3
	Anhydrous ethanol from sugarcane	25%	22.4	27.2	8.7	-	35.9
	Anhydrous ethanol from corn	2%	22.4	23.3	34.5	-	57.8
	2020 gasoline C blend	100%	29.5	21.3	2.1	58.4	81.8
Hydrous ethanol	**Hydrous ethanol from sugarcane**	91%	21.3	27.9	8.7	-	36.6
	Hydrous ethanol from corn	9%	21.3	33.2	34.5	-	67.7
	2020 hydrous ethanol blend	100%	21.3	28.4	11.0	-	39.4

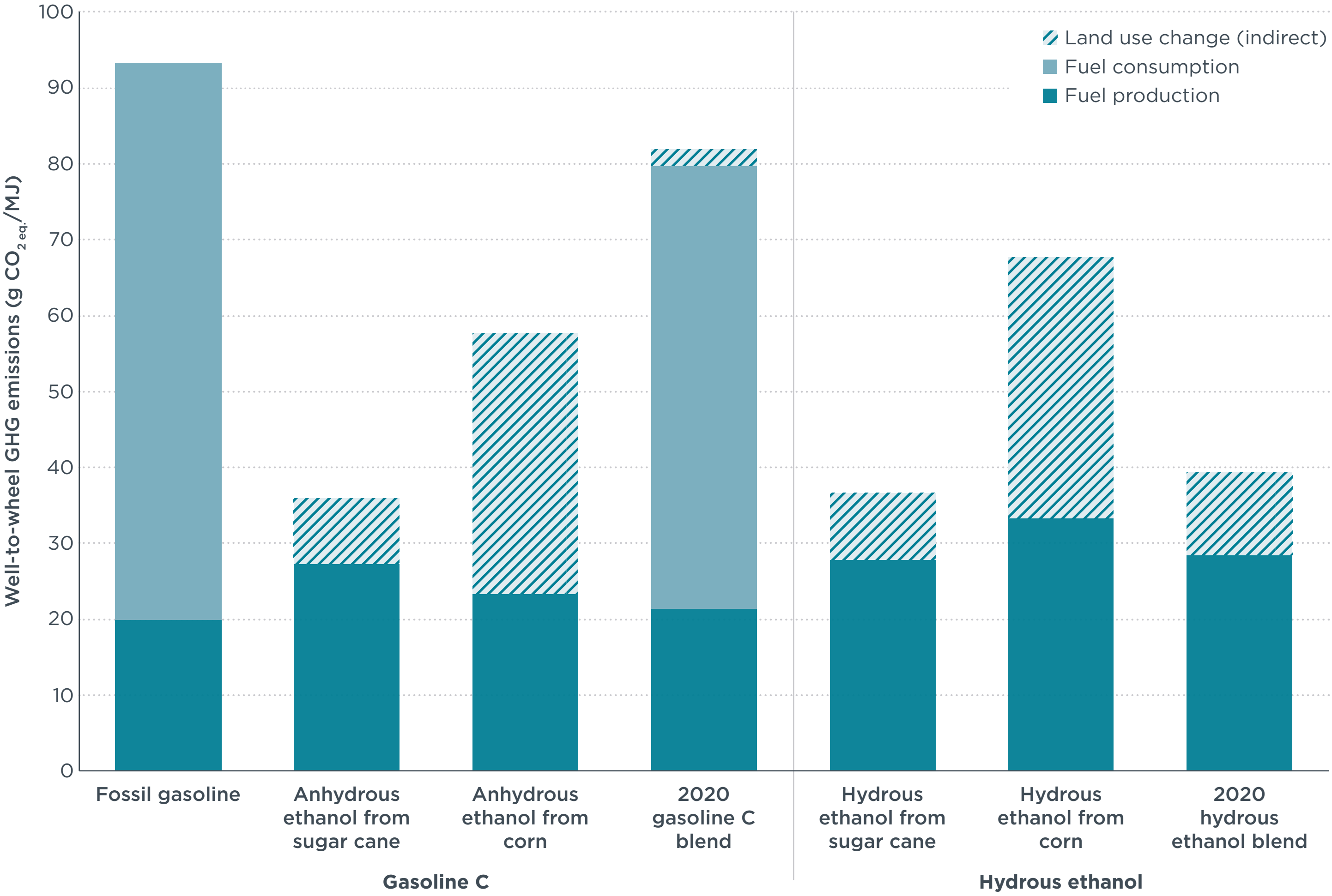


Figure 2. Comparison of WTW GHG emissions of gasoline C and hydrous ethanol, including the corresponding ethanol pathways in Brazil.

This study also considers ILUC emissions from the production of sugarcane and corn ethanol. These correspond to the regional and global expansion of area used for agriculture which indirectly results from biofuel demand in Brazil. A detailed methodological explanation of ILUC emissions calculations is provided by Marlins et al. (2014). As Brazil's biofuel program, RenovaBio, does not account for ILUC emissions, we use 25-year ILUC emission values from the International Civil Aviation Organization, which regularly publishes the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) (International Civil Aviation Organization, 2022). The ILUC emissions of sugarcane-based ethanol produced in Brazil are reported to be 8.7 g $CO_{2\ eq.}$/MJ, which is lower than the 13.6 g $CO_{2\ eq.}$/MJ determined with the GLOBIOM model (Valin et al., 2015), or the 14.2 g $CO_{2\ eq.}$/MJ considered by the California Air Resources Board (2015).[4] For corn-based ethanol produced in Brazil, there is no published assessment of ILUC emissions. Therefore, the value is approximated with CORSIA's value for U.S. corn of 25.1 g $CO_{2\ eq.}$/MJ. This value is similar to the 23.8 g $CO_{2\ eq.}$/MJ for U.S. corn considered by the California Air Resources Board, but lower than CORSIA value of 34.9 g $CO_{2\ eq.}$/MJ for global corn. These values indicate that corn-based ethanol is generally observed to have higher land-use change impacts than sugarcane-based ethanol.

For fossil gasoline, emissions from fuel production (WTT) are derived from the full fuel-cycle (WTW) emissions considered by the European Union's Fuel Quality Directive (Council of the European Union, 2015) and the U.S. Renewable Fuel Standard

4 All values are adjusted to an allocation of the land use change emissions over the biofuel output of a 25-year period.

Program (U.S. EPA, 2010), with the fuel combustion (TTW) emissions from a report by a consortium of the European Commission's Joint Research Centre, EUCAR, and Concawe (Prussi et al., 2020).

This study accounts for projected changes in the carbon intensity of the average gasoline C and hydrous ethanol fuel blends over the lifetime of the vehicles. For the gasoline C blend, the share of anhydrous ethanol of 27vol.% is maintained until 2050. However, the share of corn-based ethanol within that total anhydrous ethanol share is assumed to linearly increase from 7% in 2020 to 19% in 2027 and remain at this level until 2050 (EPE, 2022b), while the share of sugarcane-based anhydrous ethanol is expected to decrease from 93% in 2020 to 81% in 2027. For the average hydrous ethanol blend, based on projections in EPE (2022b), this study considers a linear increase of the share of corn-based ethanol from 9% in 2020 to 18% in 2027, with the share of sugarcane-based ethanol decreasing from 91% to 82% over the same period. The 2027 shares of sugarcane- and corn-based ethanol are assumed to be sustained until 2050. Second-generation ethanol currently accounts for a negligible share of total ethanol demand (0.0% in 2019 and 2020) and is expected to increase slightly to 1.3% by 2050 (EPE, 2022b). Therefore, this study only considers the carbon intensities of first-generation sugarcane and corn ethanol.

For emissions from driving on the average fuel mix, which is the market average share of gasoline C and hydrous ethanol consumption, this study assumes that the overall consumption shares of hydrous ethanol compared to gasoline C will increase. While the shares of gasoline C and hydrous ethanol consumption was at 65vol.% and 35vol.%, respectively, in 2020 (EPE, 2022b), it is assumed to linearly change to a ratio of 54vol.% to 46vol.% in 2032 (EPE, 2022b) and to 45vol.% to 55vol.% in 2050 (Plano Nacional de Energia, 2050; Ministry of Mines and Energy & EPE, 2020). Table 8 presents the lifetime average emission factors of fuels for flex-fuel passenger cars used from 2023 to 2044 and from 2030 to 2051. Note that these numbers already weigh decreasing annual mileage.

Table 8. Lifetime average WTT, TTW, ILUC, and overall fuel cycle (WTW) emissions of the fuel used in 2023 and 2030 passenger cars.

Fuel scenario	2023 vehicles				2030 vehicles			
	WTT (excl. ILUC) (g $CO_{2\ eq.}$/MJ)	ILUC (g $CO_{2\ eq.}$/MJ)	TTW (g $CO_{2\ eq.}$/MJ)	WTW (g $CO_{2\ eq.}$/MJ)	WTT (excl. ILUC) (g $CO_{2\ eq.}$/MJ)	ILUC (g $CO_{2\ eq.}$/MJ)	TTW (g $CO_{2\ eq.}$/MJ)	WTW (g $CO_{2\ eq.}$/MJ)
Gasoline C	21.3	2.7	58.4	82.3	21.2	2.8	58.4	82.4
Hydrous ethanol	28.8	13.2	0	42.1	28.9	13.5	0	42.4
Average mix of gasoline C and hydrous ethanol	24.2	6.8	35.5	66.6	24.5	7.3	33.5	65.3

Incomplete combustion in internal combustion engines, as well as the impact of aftertreatments on exhaust gases, lead to the production of methane and nitrous oxide emissions by the vehicle. These emissions are further explained in Bieker (2021a). On average, methane and nitrous oxide emissions from gasoline cars result in TTW GHG emissions of approximately 1 g $CO_{2\ eq.}$/km (Bieker, 2021). These are not included in the emission values displayed in Table 8 and are added separately in the calculations.

GHG emissions of electricity

The future development of the average electricity mix in Brazil is estimated from the shares of electricity generation technologies in the International Energy Agency's Stated Policy Scenario (IEA, 2022c), as presented in Figure 3. The scenario considers that electricity production in Brazil doubles until 2050, with the additional capacities being met by solar and wind power. Thus, the 87% share of renewables energies in 2020 increases to 95% in 2030 and 97% in 2050. For comparison, Figure A1 in the appendix shows an EPE projection for the development of the electricity mix until 2032, in which a similar increase in total electricity production is mainly met with additional hydropower and wind power, achieving a 90% share of renewables by 2027 (EPE, 2022b).

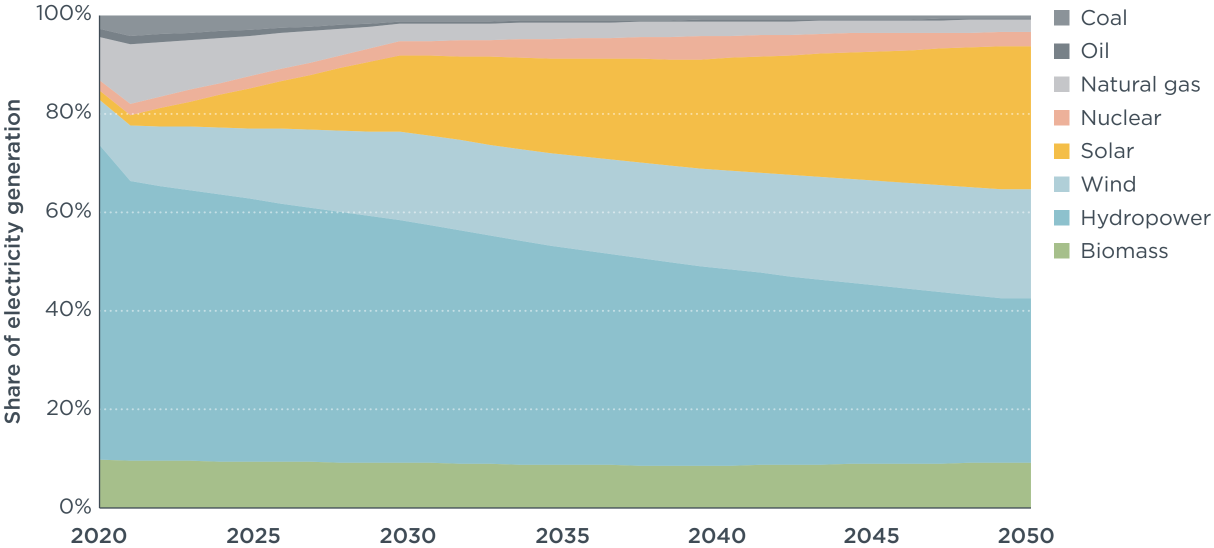


Figure 3. Projected shares of technologies in electricity generation in Brazil, according to the IEA's Stated Policy Scenario.

Based on the IEA scenario, Figure 4 presents the development of the life-cycle GHG emissions of the average electricity mix in Brazil from 2020 to 2050. For comparison, the figure also displays the development of the emissions when based on the EPE electricity mix scenario. This scenario projects the development of the mix until 2032. The shares of the electricity-generation technologies in the IEA and the EPE scenarios are applied as weights to the life-cycle carbon intensity factors presented by the EPE (2022b) (see Table A1). To account for energy losses in the electric grid, it further includes transmission and distribution losses of 16% (EPE, 2022a).

The EPE's carbon intensity factors are mainly based on the IPCC's global median life-cycle carbon intensity factors (Moomaw et al., 2011). The factors cover upstream emissions and emissions from new power plant construction throughout their lifetimes as a function of the electricity generated. Using a conservative approach, no reduction in these factors for future years is included, although the ongoing decarbonization of the industry will reduce the emissions of renewable power plant construction (Pehl et al., 2017).

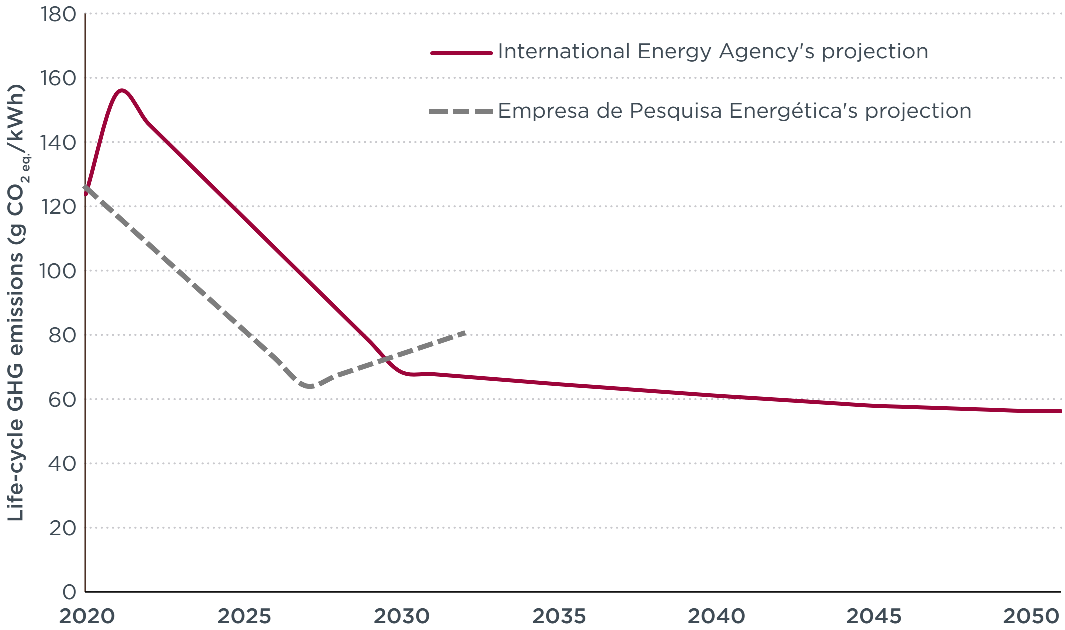


Figure 4. Development of the life-cycle GHG emissions of electricity consumption in Brazil, based on the electricity mix projections by IEA and EPE.

The lifetime average carbon intensity of the electricity consumption of passenger cars sold in 2023 is estimated to be 83 g $CO_{2\ eq.}$/kWh, which corresponds to the IEA's projection of the electricity mix from 2023 to 2044. For passenger cars sold in 2030, the carbon intensity is reduced to 63 g $CO_{2\ eq.}$/kWh, corresponding to the projected electricity mix from 2030 to 2051. These numbers consider the annual development of the life-cycle carbon intensity of electricity consumption and the decreasing annual mileage of the vehicles. As vehicles tend to have a higher annual mileage in their first years of use than in later years, this analysis accounts for the carbon intensity of the electricity mix in the first years with a higher proportion.

A purely renewable electricity mix of 33% solar and 67% wind energy is also considered, with life-cycle GHG emissions of 21 g $CO_{2\ eq.}$/kWh. We consider only solar and wind energy, as they are most scalable and often additional to existing plants. The share of the two follow their projected ratio in electricity production in the IEA's Stated Policy Scenario (compare Figure 3).

The energy losses during charging of vehicles are accounted for in the real-world electricity consumption values.

GHG emissions of hydrogen

This study compares the life-cycle GHG emissions of FCEVs using hydrogen produced from steam reforming of natural gas (grey hydrogen) with those of electrolysis-based hydrogen, either from the average grid mix or solely from the production of additional renewable electricity (green hydrogen). Hydrogen produced from natural gas corresponded to 62% of global production in 2021, coal-based hydrogen made up 19% of production, while the share of electricity-based hydrogen was 0.04% (IEA, 2022b). Still, renewable electricity-based hydrogen is anticipated to become the dominant pathway in the future. Table 9 shows the GHG emissions of natural gas- and electrolysis-based hydrogen (in kg $CO_{2\ eq.}$ per kg of hydrogen) for 2023 vehicles.

Life-cycle GHG emissions of natural gas-based hydrogen are based on the values for natural gas production in the United States provided by the GREET model (Argonne National Laboratory, 2020). They consider the extraction of natural gas, transport, and the hydrogen production process; all steps include methane leakage emissions.

For electricity-based hydrogen, the life-cycle GHG emissions are based on those of electricity production and an energy demand of 1.69 MJ electricity per MJ of hydrogen. This energy demand considers the production of hydrogen by electrolysis with an energy efficiency of 70% (Prussi et al., 2020), which corresponds to an energy loss of 0.43 MJ per MJ of hydrogen. It further includes energy losses of 0.25 MJ per MJ of hydrogen which occurs during hydrogen compression (Prussi et al., 2020). All pathways include the energy losses and emissions corresponding to the compression and short-distance transport of hydrogen. The energy losses of long-distance transport are not addressed in this study.

Table 9. Life-cycle GHG emissions of different hydrogen pathways in combination with electricity mix scenarios during the lifetime of vehicles sold in 2023.

Source or technology	Electricity mix	GHG production emissions (kg $CO_{2\ eq.}$/kg H_2)
Natural gas		10.1
Electrolysis	**2023-2044 mix**	4.7
	Renewables	1.2

RESULTS

2023 PASSENGER CARS

Figures 5, 6, and 7 present the life-cycle GHG emissions (in g $CO_{2\,eq.}$/km) for compact, medium, and compact SUV segment passenger cars over the lifetime of vehicles sold in 2023. All vehicles are assumed to use the market-average shares of gasoline C and hydrous ethanol consumption or average electricity mix, depending on power train type. The average fuel and electricity mix both account for the projected changes in the mix during the 22-year vehicle lifetime, which corresponds to the latest official national survival curve for passenger cars (Ministry of Science, Technology and Innovations of Brazil, 2020). For ICEVs, the emissions of driving either solely on gasoline C (upper values) or solely on hydrous ethanol (lower values) are indicated by error bars. The numbers within the figures compare the emissions of the respective power train and fuels to those of an average flex-fuel ICEV using the average fuel mix.

For the medium segment, Figure 6 also presents the life-cycle GHG emissions of HEVs and PHEVs. The figure shows the case of HEVs being driven by the same average fuel mix; the error bar indicates the cases of driving either solely on gasoline C or solely on hydrous ethanol. For PHEVs, only the option of driving on gasoline C is presented, as there currently are no PHEV models that operate on hydrous ethanol.

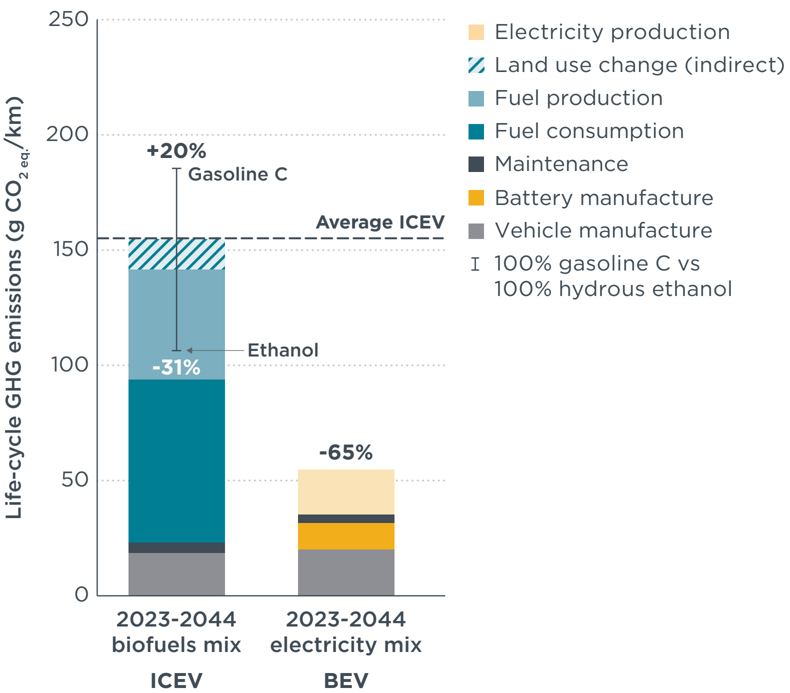


Figure 5. Life-cycle GHG emissions of compact segment flex-fuel ICEVs and BEVs sold in Brazil in 2023.

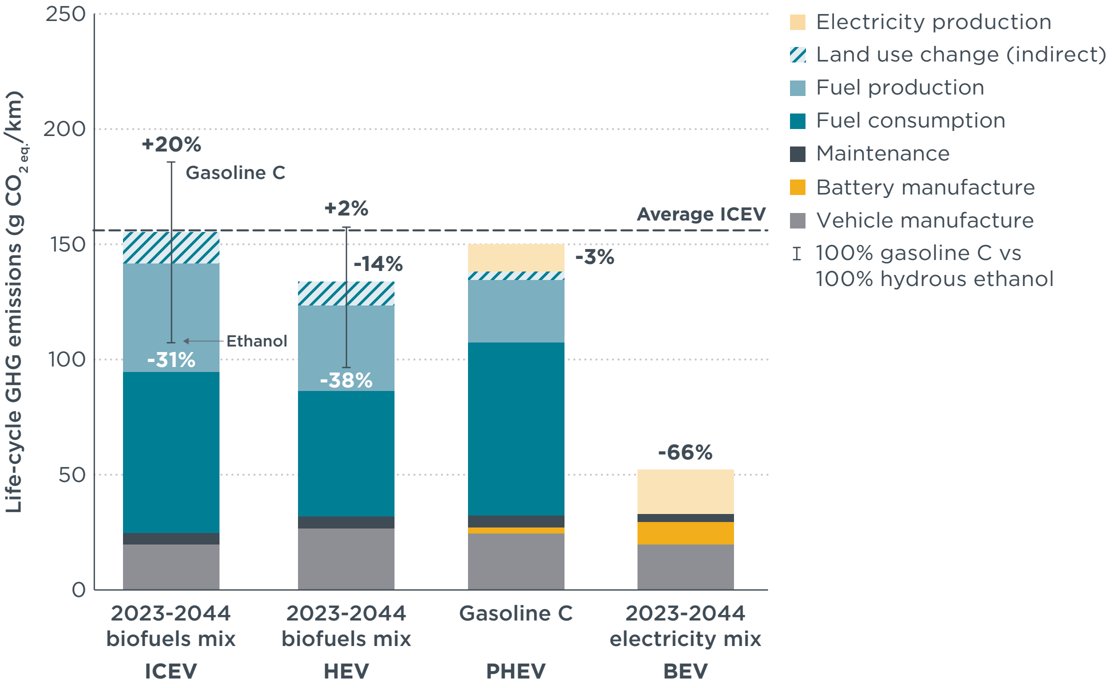


Figure 6. Life-cycle GHG emissions of medium segment flex-fuel ICEVs, HEVs, PHEVs, and BEVs sold in Brazil in 2023.

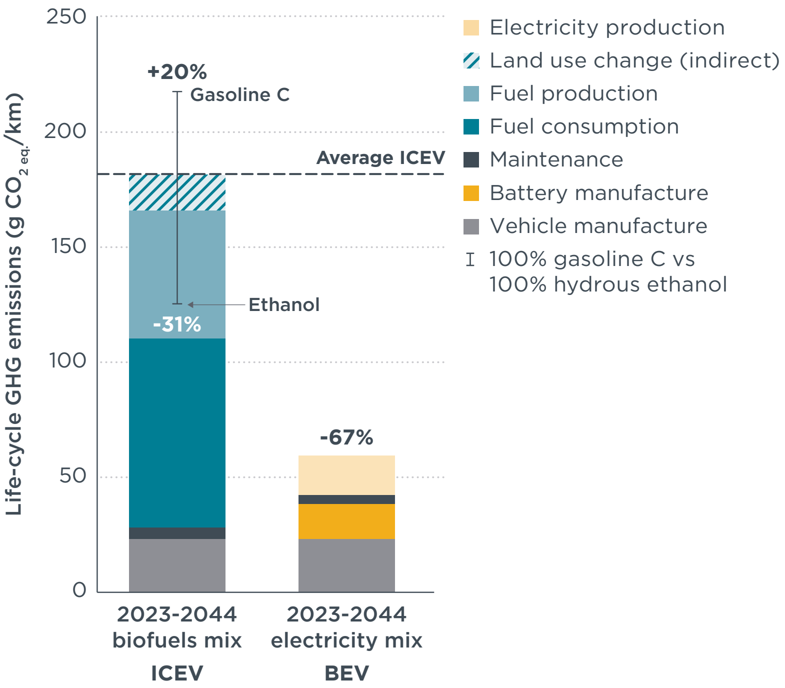


Figure 7. Life-cycle GHG emissions of compact SUV segment flex-fuel ICEVs and BEVs sold in Brazil in 2023.

BEVs have 65%–67% lower life-cycle GHG emissions than flex-fuel ICEVs.

The life-cycle GHG emissions of flex-fuel ICEVs operating on average shares of gasoline C and hydrous ethanol are 155 g $CO_{2\ eq.}$/km for average compact and medium segment cars, and 181 g $CO_{2\ eq.}$/km for average compact SUV segment cars. For BEVs, the life-cycle GHG emissions are 65%–67% lower, at 55 g $CO_{2\ eq.}$/km for compact, 52 g $CO_{2\ eq.}$/km for medium, and 59 g $CO_{2\ eq.}$/km for compact SUV segment cars. The lower GHG emissions of BEVs are due to two factors. First, the energy consumption of BEVs (0.7–0.8 MJ/km) is about three times lower than for comparable ICEVs (2.0–2.3 MJ/km). Second, the emissions of the lifetime average electricity mix are almost three times lower than those of the lifetime average mix of gasoline C and hydrous ethanol. While the 2023–2044 electricity mix has life-cycle GHG emissions of 23.1 g $CO_{2\ eq.}$/MJ (83.1 g $CO_{2\ eq.}$/kWh), the carbon intensity of the 2023–2044 average fuel mix is 66.6 g $CO_{2\ eq.}$/MJ.

The GHG emissions corresponding to battery production (9.5–15.3 g $CO_{2\ eq.}$/km) are small when compared to the large GHG emission benefit of BEVs during use. With one battery replacement over the vehicle lifetime, the life-cycle GHG emissions of BEVs would increase to 67 g $CO_{2\ eq.}$/km for compact, 62 g $CO_{2\ eq.}$/km for medium, and 75 g $CO_{2\ eq.}$/km for compact SUV segment cars. These values are still 57%–60% lower than those of flex-fuel ICEVs.

Operating ICEVs solely on hydrous ethanol results in 31% lower emissions than using the market average mix of the two fuels, while operating solely on gasoline C results in 20% higher emissions.

When solely driving on hydrous ethanol, the life-cycle GHG emissions of flex-fuel ICEVs are 107 g $CO_{2\ eq.}$/km for compact and medium segment cars, and at 125 g $CO_{2\ eq.}$/km for compact SUV segment cars, 31% lower than for the average fuel mix. In contrast, when driving only on gasoline C, the life-cycle emissions are 186 g $CO_{2\ eq.}$/km for compact and medium segment cars, and 217 g $CO_{2\ eq.}$/km for compact SUV segment cars, which is 20% higher than for the average fuel mix. Thus, the life-cycle GHG emissions of flex-fuel ICEVs solely operating on hydrous ethanol are twice those of BEVs. For ICEV's operating solely on gasoline C, the emissions are four times higher.

HEVs have 14% lower life-cycle GHG emissions than ICEVs when using the same average fuel mix.

The lower fuel consumption of HEVs compared to conventional flex-fuel ICEVs directly translates to lower life-cycle GHG emissions when vehicles of both power train types use the same fuel mix. In the medium segment, the energy consumption of average HEVs is 1.5 MJ/km, which is 22% lower than the 2.0 MJ/km for their ICEV counterparts. When using the average mix of gasoline C and hydrous ethanol, the life-cycle emissions of medium segment HEVs are 134 g $CO_{2\ eq.}$/km, which is 14% lower than for conventional flex-fuel ICEVs with the same mix. However, it is important to note that there are currently only a few flex-fuel HEV models available on the market, and none of these are in the medium segment. HEVs that drive on gasoline C only have life-cycle GHG emissions of 158 g $CO_{2\ eq.}$/km, which is 2% higher than for ICEVs that use the average mix of gasoline C and hydrous ethanol. In the case of solely running on hydrous ethanol, the life-cycle emissions of HEVs are at 97 g $CO_{2\ eq.}$/km, which is only 10% below ICEVs running solely on hydrous ethanol and 85% higher than for BEVs operating with the average grid mix.

In real-world operation, plug-in hybrids only have 3% lower emissions than flex-fuel ICEVs.

For PHEVs, the life-cycle GHG emissions are largely determined by how much they are driven on fuel or electricity. This study considers an electric driving share of 50%, which is an optimistic assumption compared to the average real-world usage in Europe (Plötz et al., 2022) and the United States (Isenstadt et al., 2022), considering both regions have a more extensive charging infrastructure network than in Brazil. For medium segment PHEVs, the life-cycle GHG emissions are 150 g $CO_{2\ eq.}$/km, or only 3% lower than for flex-fuel ICEVs driving on the market average mix of gasoline C and hydrous ethanol. Note that this value corresponds to using gasoline C, as there are currently no PHEV models available that can also drive on hydrous ethanol.

2030 PASSENGER CARS

This section presents an estimate of the life-cycle GHG emissions over the lifetime of passenger cars that are expected to be sold in 2030. Figures 8, 9 and 10 depict the life-cycle GHG emissions of compact, medium, and compact SUV segment passenger cars, respectively. These estimates are based on projections of the market-average shares of driving on gasoline C and hydrous ethanol, changes in these two fuels, and the development of the average electricity mix over 22-year vehicle lifetimes from 2030 to 2051. Further, future flex-fuel ICEVs and HEVs are assumed to have lower fuel consumption than vehicles sold in 2023, while future BEVs and PHEVs are assumed to have larger batteries than today. Hypothetical future PHEVs are assumed to be also capable of driving on hydrous ethanol and have a higher electric driving share due to increased battery capacity. For all power train types, the carbon intensity of vehicle and battery production are assumed to decrease.

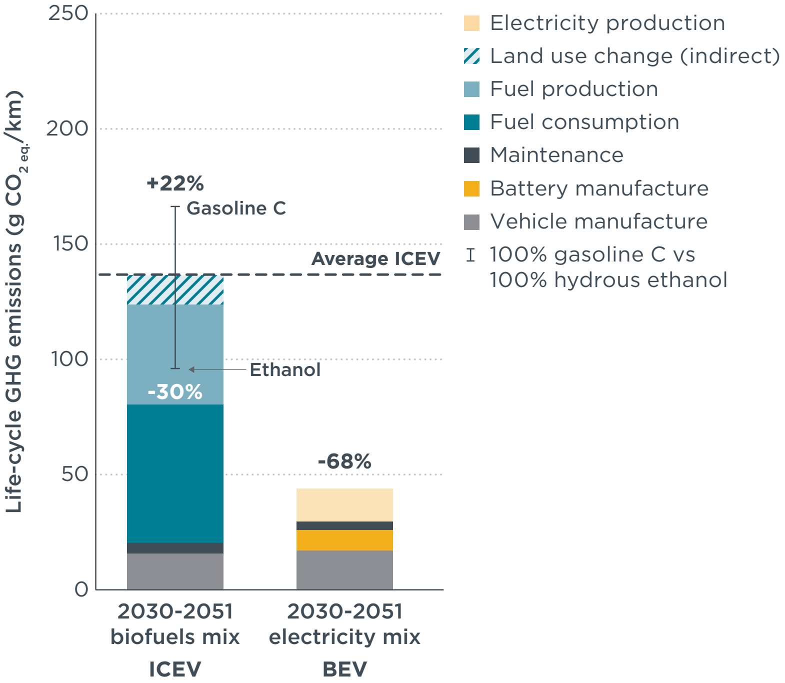


Figure 8. Life-cycle GHG emissions of compact segment flex-fuel ICEVs and BEVs sold in Brazil in 2030.

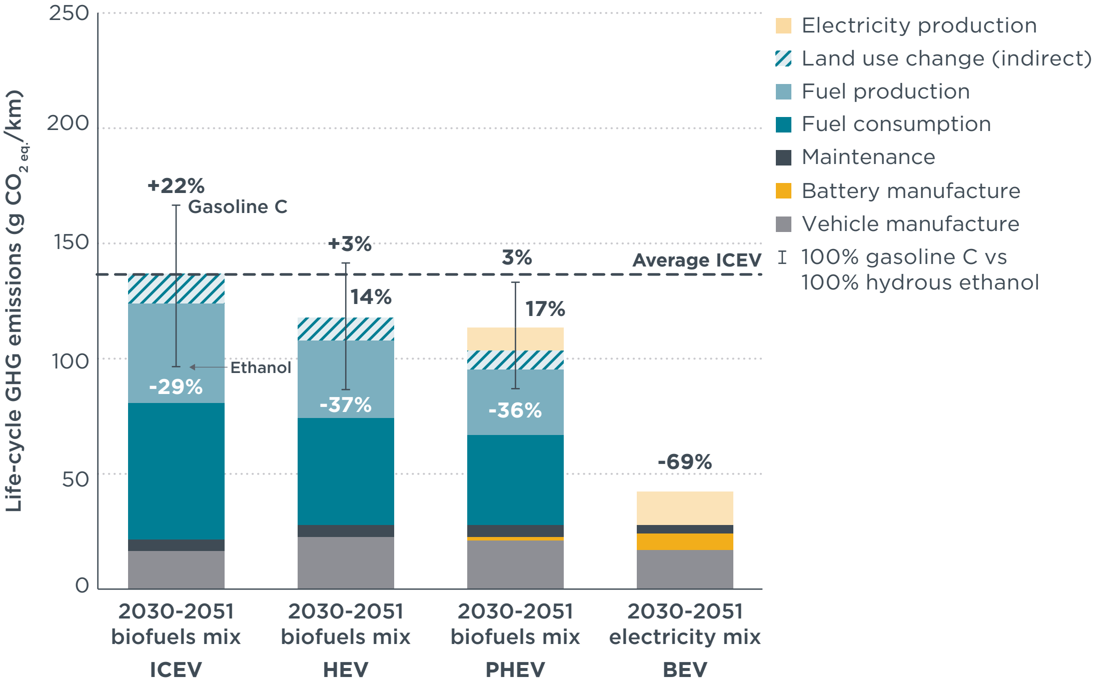


Figure 9. Life-cycle GHG emissions of medium segment flex-fuel ICEVs, HEVs, PHEVs, and BEVs sold in Brazil in 2030.

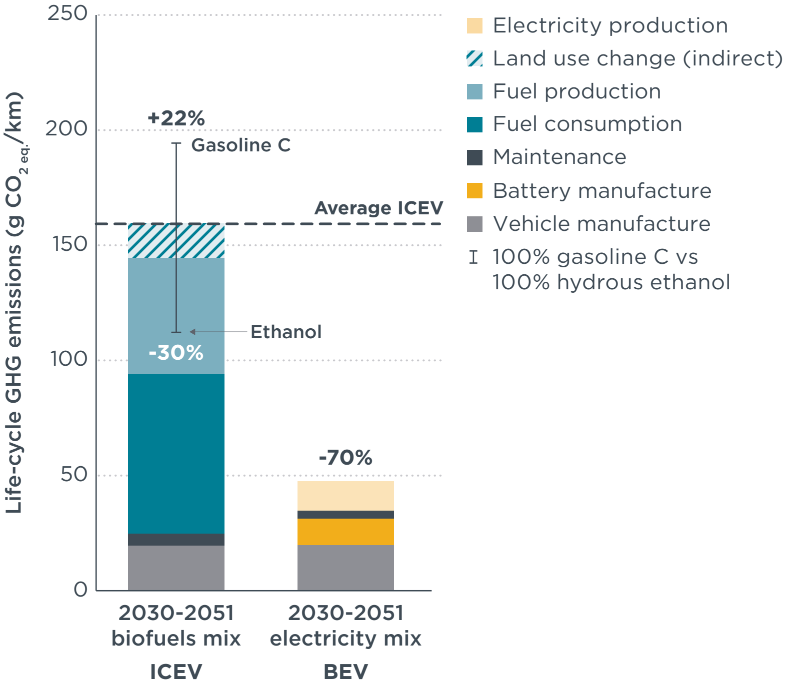


Figure 10. Life-cycle GHG emissions of compact SUV segment flex-fuel ICEVs and BEVs sold in Brazil in 2030.

Future BEVs have 68%–70% lower life-cycle GHG emissions than flex-fuel ICEVs. The life-cycle GHG emissions of future flex-fuel ICEVs driving on the projected 2030–2051 market average mix of gasoline C and hydrous ethanol are 136–137 g $CO_{2\,eq.}$/km for compact and medium segment cars, and 160 g $CO_{2\,eq.}$/km for compact SUV segment cars. In contrast, the life-cycle GHG emissions for BEVs sold in 2030 correspond to 44 g $CO_{2\,eq.}$/km for compact, 42 g $CO_{2\,eq.}$/km for medium, and 48 g $CO_{2\,eq.}$/km for compact SUV segment cars. BEVs sold in 2030 are thus estimated to have 68%–70% lower life-cycle GHG emissions than comparable flex-fuel ICEVs.

The rate of reduction of GHG emissions for future vehicles is faster for BEVs than for flex-fuel ICEVs.

While BEVs sold in 2030 are estimated to have 19% lower life-cycle emissions than BEVs sold in 2023, the emissions of 2030 flex-fuel ICEVs are 12% lower than today's ICEVs. Note that for BEVs, this reduction is despite assuming larger batteries. The reduction mainly results from the decrease in the average carbon intensity of the average electricity mix. The carbon intensity of the average electricity mix decreases from 37.8 g $CO_{2\,eq.}$/MJ in 2023, to 19.1 g $CO_{2\,eq.}$/kWh in 2030 (-49%), and to 15.7 g $CO_{2\,eq.}$/MJ in 2050 (-59%). In contrast, the carbon intensity of the average mix of gasoline C and hydrous ethanol is projected to decrease from 68.6 g $CO_{2\,eq.}$/MJ in 2023, to 67.1 g $CO_{2\,eq.}$/MJ in 2030 (-2%), and to 63.5 g $CO_{2\,eq.}$/MJ in 2050 (-7%). This reduction is a result of assuming a higher market share of hydrous ethanol compared to gasoline C. For flex-fuel ICEVs, the reduction in life-cycle GHG emissions is mainly due to the assumption that future models will have 11% lower fuel consumption.

The GHG emission benefit of future HEVs over ICEVs remains the same as for current vehicles.

Assuming that HEVs sold in 2030 have a 11% lower fuel consumption than HEVs sold in 2023, average medium segment models driven on the average mix of gasoline C and hydrous ethanol would have life-cycle GHG emissions of 118 g $CO_{2\,eq.}$/km. Just as for current models, this corresponds to a GHG emission benefit of 14% compared to conventional flex-fuel ICEVs. For future HEV models that solely operate on gasoline C, life-cycle GHG emissions would be at 141 g $CO_{2\,eq.}$/km, which is 3% higher than for flex-fuel ICEVs driving on the average mix of gasoline C and hydrous ethanol. Even when assuming that individual HEVs would drive solely on ethanol, the life-cycle GHG emissions of 87 g $CO_{2\,eq.}$/km would still be twice as high as for BEVs.

Future PHEVs could have 17% lower emissions than ICEVs, if using the same average fuel mix.

The electric range of future PHEVs are assumed to increase by 20%, which is estimated to reduce their fuel consumption by 10% compared to models sold in 2023. For future PHEV models operating on gasoline C and electricity, this would reduce life-cycle GHG emissions of the medium segment to 133 g $CO_{2\,eq.}$/km. This value is only 3% lower than for future flex-fuel ICEVs running on the average mix of gasoline C and hydrous ethanol, as these are assumed to have a lower fuel consumption than today's models. If potential future flex-fuel PHEV models run on the average mix of gasoline C and hydrous ethanol, their life-cycle GHG emissions would be 114 g $CO_{2\,eq.}$/km. The emissions of future PHEVs would thereby be 17% lower than for future conventional flex-fuel ICEVs, if using the same average fuel mix. Compared to future BEVs, however, such hypothetical flex-fuel PHEVs would still have 2.6 times higher life-cycle emissions.

HYDROGEN FUEL CELL ELECTRIC VEHICLES

Figure 11 shows the life-cycle GHG emissions of compact SUV segment FCEVs driving on hydrogen produced from natural gas (grey hydrogen), from the 2023–2044 average electricity mix, and from only renewable electricity (green hydrogen). The life-cycle GHG emissions of segment average flex-fuel ICEVs and BEVs are also presented. For BEVs, the figure presents emissions when operating on the average electricity mix or when driving solely on renewable electricity. Like the emissions from battery manufacturing in BEVs, the emissions from the hydrogen tank are displayed separately from those from vehicle manufacturing.

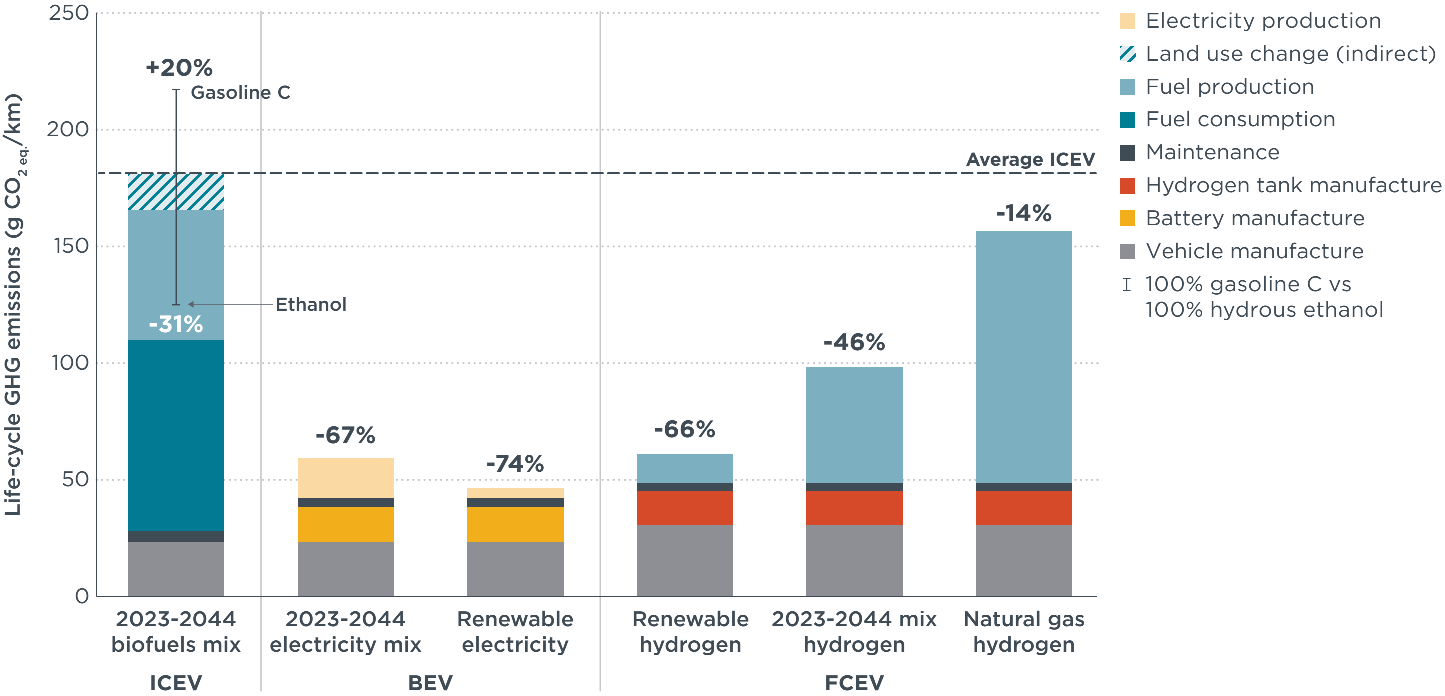


Figure 11. Life-cycle GHG emissions of compact SUV segment flex-fuel ICEVs and BEVs sold in Brazil in 2023 in comparison to FCEVs using hydrogen from different production pathways.

FCEVs operating on natural gas-based hydrogen have 14% lower emissions than ICEVs.

Compact SUV segment FCEVs powered by natural gas-based hydrogen correspond to life-cycle GHG emissions of 157 g $CO_{2\ eq.}$/km. This is 14% lower than for segment-average flex-fuel ICEVs using the market average shares of gasoline C and hydrous ethanol, and almost three times higher than BEVs driven on the average electricity mix.

Electricity-based hydrogen-powered FCEVs have 46%–66% lower emissions than ICEVs.

When driving on electricity-based hydrogen, the life-cycle emissions of FCEVs in the compact SUV segment are 99 g $CO_{2\ eq.}$/km when using the average electricity mix, and 61 g $CO_{2\ eq.}$/km when using only renewables. The average electricity mix based values are 46% lower than for flex-fuel ICEVs, while those for renewable electricity-based hydrogen are 66% lower. However, BEVs in the same segment have life-cycle emissions of 59 g $CO_{2\ eq.}$/km with the average grid mix and 46 g $CO_{2\ eq.}$/km for renewables.

Driving on electricity-based hydrogen needs up to three times more energy than directly using the electricity in BEVs.

The higher GHG emissions of FCEVs driving on electrolysis-based hydrogen compared to BEVs powered by the same electricity mix directly results from the high energy losses in the hydrogen pathway. In the first step of this pathway, the production of hydrogen by electrolysis is considered with an energy efficiency of 70% (Prussi et al., 2020). This corresponds to an energy loss of 0.43 MJ per MJ of hydrogen. With another 0.25 MJ per MJ of hydrogen for the compression of hydrogen (Prussi et al., 2020), the energy losses are 0.69 MJ per MJ of hydrogen. The FCEV model in the compact SUV segment, for instance, has an energy consumption of 128 MJ (1.07 kg) of hydrogen per 100 km. Adding the energy losses during hydrogen production and compression, the energy demand increases to 216 MJ per 100 km. This is three times higher than the 70 MJ of electricity per 100 km consumed by an average compact SUV segment BEV. When using the same electricity mix as the energy source, the GHG emissions from hydrogen production for the compact SUV segment FCEV is thus about three times higher than using the electricity directly in BEVs. For the 2023–2044 average electricity mix, the emissions corresponding to hydrogen production are 50 g $CO_{2\ eq.}$/km, while they are 17 g $CO_{2\ eq.}$/km for the direct use in BEVs. Using only additional renewable electricity corresponds to 14 g $CO_{2\ eq.}$/km for FCEVs and 5 g $CO_{2\ eq.}$/km for BEVs.

SUMMARY AND CONCLUSIONS

This study assesses which power train type and fuel choices allow the Brazilian passenger car fleet to align with the Government's targets of a 50% reduction of GHG emissions compared to 2005 by 2030 and reaching net-zero emissions by 2050. The results of the analysis show that for vehicles sold in 2023, BEVs have the lowest life-cycle emissions of all power train types. For average vehicles in the compact, medium, and compact SUV segments, current BEVs show 65%–67% lower life-cycle emissions than flex-fuel ICEVs using the market average shares of gasoline C and hydrous ethanol. The mitigation potential of HEVs and PHEVs, in contrast, is limited. HEVs show 14% lower life-cycle GHG emissions than flex-fuel ICEVs, but only when they operate on the same average mix of gasoline C and hydrous ethanol. PHEVs, of which all models currently available in Brazil rely on gasoline C, have about 3% lower emissions than comparable flex-fuel ICEVs. Hydrogen FCEVs show a wide range of emissions reduction potential, depending on how the hydrogen is produced. Only when driving on renewable electricity-based (green) hydrogen do they show similar GHG emissions as average electricity-powered BEVs.

The comparison of the life-cycle GHG emissions of the different power train options in Brazil shows the same trends as observed in China, Europe, India, Indonesia, and the United States (Bieker, 2021; Mera & Bieker, 2023). Vehicle characteristics, vehicle usage, as well as the fuel and electricity mix can differ greatly between these regions. In particular, the flex-fuel ICEVs powered by a high share of ethanol in Brazil show lower emissions than comparable gasoline ICEVs in other regions. Still, in all regions, BEVs show the lowest life-cycle GHG emissions of all available power train types. This benefit will increase with the continuous decarbonization projected for the Brazilian electricity mix.

BEVs

The large GHG emissions mitigation potential of BEVs is favored by the high share of renewables in the Brazilian grid as well as the higher energy efficiency of this power train technology. In fact, the energy consumption of average BEVs in the compact, medium, and compact SUV segments is three times lower than for respective average flex-fuel ICEVs. When compared to an ICEV fueled with the market average share of gasoline C and hydrous ethanol, BEVs sold in 2023 cut emissions by 65%–67%. If one battery replacement would be required during the lifetime of a BEV, which is generally not expected for current battery technologies, their life-cycle GHG emissions would still be 57%–60% lower than those of flex-fuel ICEVs. For vehicles sold in 2030, emissions are 68%–70% lower, even when optimistically assuming that future ICEVs will have 11% lower fuel consumption than 2023 models. When compared to ICEVs solely using hydrous ethanol, the life-cycle emissions of BEVs are 49%–53% lower for 2023 vehicles, and 54%–57% lower for 2030 vehicles. Compared with ICEVs solely running on gasoline C, the life-cycle emissions of BEVs are 70%–73% lower for 2023 vehicles, and 73%–75% lower for 2030 vehicles. Thus, electrifying the passenger car fleet has a much larger GHG emission reduction potential than expanding the use of ethanol. When pursuing a full decarbonization of the power sector in parallel, BEVs allow Brazil to reach net-zero emissions by 2050.

Ethanol-powered ICEVs

Flex-fuel vehicles represent the bulk of sales and of the passenger fleet in Brazil. For these vehicles, life-cycle GHG emissions vary largely between operating solely on gasoline C, solely on hydrous ethanol, or on a mix of the two fuels. For both 2023 and 2030 ICEVs, exclusively operating on ethanol corresponds to 29%–31% lower life-cycle emissions than operating on the market average shares of gasoline C and hydrous ethanol. Fueling the same vehicles solely with gasoline C, in contrast, corresponds to 20%–22% higher emissions than with the average mix.

While these results reflect that ethanol produced from Brazilian sugarcane has greater GHG emission benefits compared to using fossil gasoline, other factors cast doubt on the reliance on flex-fuel engines as Brazil's main GHG emissions mitigation pathway for passenger cars. Despite the countrywide availability of hydrous ethanol, Brazilian consumers still choose predominantly gasoline to fuel their cars. The consumption of gasoline C was almost twice as high as that of hydrous ethanol in 2020; it is projected that the share of hydrous ethanol consumption compared to gasoline C will increase from 35vol.% in 2020 to 55vol.% in 2050 (EPE, 2022b). Thus, focusing on flex-fuel ICEVs alone might not increase the use of hydrous ethanol to levels that are much higher than today. Policy actions to increase ethanol consumption, such as increases in the mandated blend of anhydrous ethanol in gasoline C, might bring environmental and other risks connected to the necessary increase in production. In particular, expanding the production of corn-based ethanol risks adverse environmental impacts like deforestation. In any case, even when assuming that a large share of the vehicle fleet could operate solely on hydrous ethanol, the associated GHG emissions would be more than twice as high as for BEVs driving on the average electricity mix.

Potential future improvements of the fuel economy of flex-fuel ICEVs could result in a meaningful reduction of life-cycle GHG emissions in the short term. If the fuel consumption of 2030 flex-fuel ICEVs is 11% lower than for models sold in 2023, life-cycle GHG emissions when operating on the average mix of ethanol and gasoline C would be 12% lower than for today's vehicles. However, this level of reduction is not enough to align the passenger car fleet with the Government's GHG emission reduction targets.

Hybrids and plug-in hybrids

Hybrids and plug-in hybrids have limited mitigation potential compared to current flex-fuel ICEVs. Current HEVs in the medium segment show 14% lower life-cycle GHG emissions than comparable flex-fuel ICEVs in Brazil, but only when operating on the same market average shares of gasoline C and hydrous ethanol. When solely using ethanol, the emission benefit of HEVs compared to ICEVs decreases from 14% to 10%. If HEVs only operate on gasoline C, which is the case for many of today's models, the life-cycle emissions are actually 2% higher than for flex-fuel ICEVs using the average market shares of gasoline C and hydrous ethanol.

The life-cycle GHG emissions of current PHEVs in the medium segment are about 3% lower than for comparable flex-fuel ICEVs. Although a real-world electric driving share of 50% can significantly reduce fuel consumption, current PHEV models can only run on gasoline C, which has a higher carbon intensity than the average mix of gasoline C and hydrous ethanol considered for flex-fuel ICEVs. Hypothetical future PHEV models operated on the average gasoline C and hydrous ethanol fuel mix that would further have an increased electric driving share of 55% would have 17% lower life-cycle emissions than future flex-fuel ICEVs.

Improving the fuel economy of future HEVs and PHEVs results in comparatively small reductions in the life-cycle GHG emissions. This is insufficient to allow the transport sector to align with Brazil's economy-wide GHG emission reduction targets.

Hydrogen FCEVs

Depending on how the hydrogen is produced, hydrogen FCEVs show a wide range of emissions. The life-cycle emissions of a compact SUV segment FCEV operating on natural gas-based (grey) hydrogen are only 14% lower than for comparable flex-fuel ICEVs. When operating on renewable electricity-based (green) hydrogen, they show 66% lower emissions than ICEVs. Using hydrogen produced from the average electricity mix results in 46% lower life-cycle GHG emissions than ICEVs. Including the energy losses during hydrogen production (through electrolysis) and hydrogen compression, the energy consumption of an FCEV is about three times higher than for a BEV. For this reason, the GHG emissions for FCEVs operating on electricity-based hydrogen are always higher than for BEVs using the same electricity mix. Note that the emissions from hydrogen tank production for FCEVs are similar to the emissions from battery production for BEVs.

FCEVs solely fueled by green hydrogen can potentially lead to greater life-cycle GHG emission reductions compared to current flex-fuel vehicles. In theory, they are thus also a pathway to align the Brazilian passenger car fleet with the Government's overall climate targets. With energy consumption three times higher compared to BEVs, however, the costs of hydrogen are a barrier to the mass adoption of FCEVs.

Larger vehicle segments have higher life-cycle emissions

When comparing vehicles of the same power train type across segments, the analysis shows that larger vehicles in the compact SUV segment have life-cycle emissions between 7%–15% above those of compact and medium segment cars. However, electric compact SUVs still have total emissions 44% below compact and medium segment flex-fuel ICEVs fueled solely with ethanol.

This study finds that BEVs show a large GHG emission benefit over gasoline C and ethanol-powered flex-fuel vehicles when accounting for the emissions of vehicle and battery production, as well as fuel and electricity production. Flex-fuel ICEVs only provide a limited GHG emissions reduction potential, even when assuming fuel economy improvements for future vehicles and an increase in the ethanol share. Similarly, HEVs and PHEVs only show a limited GHG emissions reduction potential. FCEVs can approach the low GHG emissions of BEVs, but only when solely powered by green hydrogen and at the cost of using three times more electric energy than BEVs. Supporting the uptake of BEVs is thus the most efficient way to reduce the climate impact of the passenger car fleet in Brazil. Aligning the transport sector with the long-term target of achieving carbon neutrality by 2050 requires a shift to electric vehicles.

POLICY RECOMMENDATIONS

Actions to decarbonize the passenger car fleet in Brazil are crucial to achieve the country's environmental goals. The results presented in this study indicate that a shift to BEVs allows the Brazilian passenger car fleet to approach zero emissions by 2050, while flex-fuel ICEVs, HEV, and PHEVs do not. FCEVs can offer similar reductions in GHG emissions as BEVs, but only when solely using renewable electricity-based hydrogen and at the cost of using three times more electric energy than BEVs.

Based on these findings, policymakers in Brazil could consider the following policy recommendations:

Defining the upcoming Green Mobility and Innovation Program (PROMOVI) goals in terms of CO_2 emissions instead of energy consumption needs to be based on the emission factors of the current market average shares of ethanol and gasoline C to maintain the effectiveness of the program. The program should define new corporate average goals that can be achieved fully through energy efficiency improvements, including a shift to BEVs and FCEVs. The goals of PROMOVI will be defined in terms of CO_2 emissions instead of energy consumption. This shift creates uncertainty regarding how emissions are determined, particularly for flex-fuel ICEVs. As presented in this study, the climate impact of flex-fuel ICEVs depends on whether they solely operate on hydrous ethanol, on gasoline C, or on a mix of these fuels. To better represent real-world fuel consumption and related emissions, the market average shares of ethanol and gasoline C should be considered for the CO_2 emission values of flex-fuel ICEVs. Eventual increases in ethanol market share should not substitute improvements in vehicle energy efficiency.

To achieve climate targets in the transport sector, PROMOVI could determine corporate goals that prepare for a shift to BEVs or FCEVs. Increasing sales of BEVs or FCEVs in the near term will allow the Brazilian passenger car fleet to decarbonize faster. Due to the long lifetime of passenger vehicles, delays in the introduction of BEVs may result in the need for more ambitious policy actions in the near future. To realize the GHG emission reduction potential of FCEVs, it should be ensured that only renewable electricity-based hydrogen is used in the transport sector.

Incentives for production of BEVs in Brazil would combine their environmental benefits with economic competitiveness. The current lack of domestic BEV production puts the Brazilian automotive industry at risk of losing competitiveness in international markets. The continued production of ICEVs exclusively could result in a reduction of vehicle exports and an increase in BEV imports. In parallel to public support for BEV production in Brazil, investments in research and development on energy efficiency improvements, which manufacturers can choose to spend to receive the current Rota2030 benefits, could be steered to BEVs and FCEVs. This would incentivize domestic production of these vehicles. Benefiting from the clean domestic grid, Brazil-made batteries would further increase the life-cycle emission benefit of BEVs.

Support Brazilian consumers in their adoption of electric vehicles. Consumers currently pay more for the purchase of BEVs than for comparable ICEVs, although the costs of future BEVs are expected to decrease. To jumpstart BEV uptake in the short-term, this cost gap could be bridged by directing existing vehicle purchase incentives to BEVs. Under its current purchase price thresholds, no BEV model is eligible in the current vehicle purchase incentive program.[5] The environmental impact of the purchase incentive program could be improved by increasing the purchase price threshold for BEVs given the large GHG emission benefit of these vehicles. At the same time, incentives for HEVs and PHEVs in the Rota2030 program could be reduced, as those vehicles have limited GHG emission reduction potentials. To balance potential public expenditures on BEV incentives, the Government could introduce a revenue neutral feebate program, in which such incentives are compensated by a higher taxation of sales of highly polluting vehicles. This type of feebate programs has successfully been introduced in France and other countries (Wappelhorst, 2022). Regional and city governments could also introduce non-financial benefits for BEVs, such as zero- or low-emission zones in cities, road access privileges, and dedicated parking spaces. In addition to developing a national charging infrastructure strategy, preferential electricity rates and tax incentives could encourage investment in charging infrastructure.

Incentivize the use of ethanol over fossil gasoline for the existing flex-fuel vehicles fleet and include ILUC emissions in the RenovaBio program to improve the sustainability of ethanol. As shown in the results, substituting gasoline for sugarcane-based ethanol yields lower life-cycle GHG emissions from vehicles. Therefore, even though sales of new vehicles should shift towards BEVs, increasing the market share of ethanol compared to fossil gasoline remains a relevant tool to reduce emissions of flex-fuel vehicles in the short term. However, any increase in ethanol production should be met with policies that ensure production expansion will not increase its average carbon intensity. Introducing ILUC emissions in the RenovaBio program would provide a greater relative incentive for second-generation fuel production, as well as incentivize more efficient production at existing, first-generation ethanol facilities.

5 The vehicle purchase incentive program was launched in June 2023 by Provisional Measure No. 1,175 (Presidency of the Republic, 2023) and provided financial incentives for acquiring passenger cars. The discounts ranged from 2,000 to 8,000 reais and could be applied for new vehicles with market prices of up to 120,000 reais. These discounts are defined based on four criteria: i) price (lower prices have higher discounts); ii) energy efficiency (higher discounts for higher energy efficiencies); iii) national content (higher discounts for vehicles with higher national content); and iv) fuel (discounts for flex-fuel vehicles are higher than gasoline exclusive vehicles). The prices of all BEV models available in Brazil are higher than the incentive threshold and these vehicles could not benefit from the program.

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APPENDIX

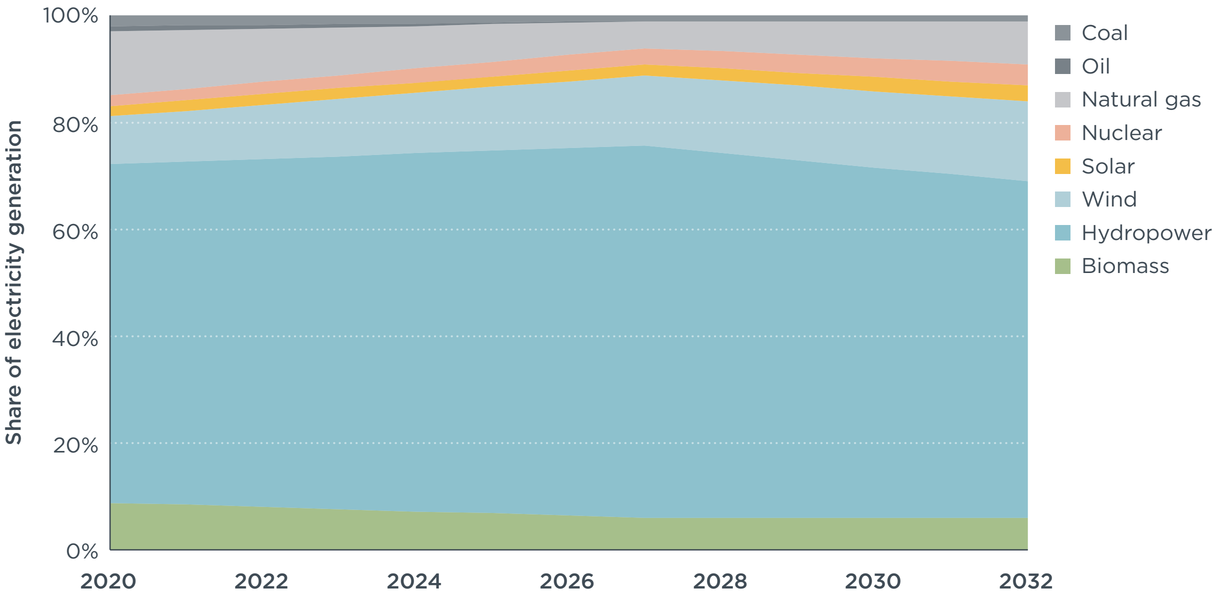

Figure A1. Projected shares of technologies in electricity generation in Brazil, according to EPE (2022b).

Table A1. Life-cycle GHG emissions of electricity-generation technologies.

Type	Electricity-generation technology	Life-cycle GHG emissions ($g\ CO_{2\ eq.}/kWh$)
Non-renewable	**Coal**	820
	Oil	1061
	Natural gas	490
	Nuclear power	12
Renewable	**Biomass**	58
	Solar	41
	Wind	11
	Hydropower	24

Source: EPE (2022b)

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