



Comparison of electric vehicle types considering the emissions and energy-ecological efficiency

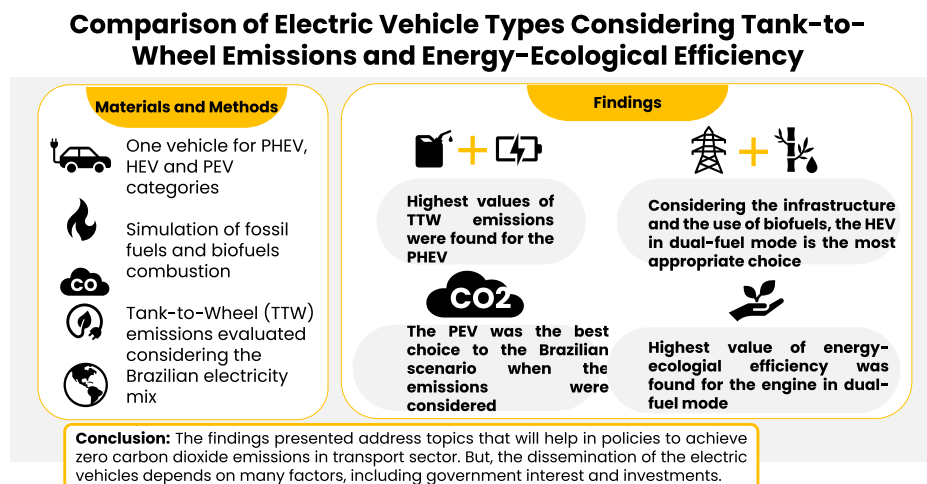
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Abstract

This study presents a comparison of three electric vehicle types to propose the best choice to implement the electric mobility in Brazil, considering the Tank-to-Wheel (TTW) emissions of the internal combustion engine in single-fuel mode (ICE-SF) fueled with biogas, bioethanol, gasoline A, or Brazilian gasoline (27% bioethanol + 73% gasoline A), and of the internal combustion engine in dual-fuel mode (ICE-DF) fueled with 50% biogas + 50% bioethanol. The emissions related to the Brazilian electricity mix were analyzed to calculate the impacts of the electric mode. Moreover, the energy-ecological efficiency of the internal combustion engine was measured to analyze the negative impacts on human and environmental health when fueled with different fuels, in single-fuel and dual-fuel modes. The findings show that bioethanol has the lowest energy-ecological efficiency (27%) due to its performance regarding the human toxicity and pollution factor indicators. On the other hand, biogas in the ICE-SF achieved the highest energy-ecological efficiency (64%), followed by 50% biogas and 50% bioethanol in the ICE-DF (49%). Considering the Brazilian scenario, the plug-in electric vehicle appears as the best choice due to its lower TTW emissions. However, considering the Brazilian infrastructure and its potential to produce biofuels, the hybrid electric vehicle was better than the other electric vehicle types analyzed when it is fueled with bioethanol in single-fuel mode or bioethanol and biogas in dual-fuel mode. The relevance of this paper remains in the fact that the findings might help in the achievement of zero carbon dioxide emissions in the transport sector.

Graphical abstract



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Keywords Electric vehicles · Emissions · Energy-ecological efficiency · Tank-to-Wheel

Extended author information available on the last page of the article

List of symbols

$%e$	Percentage of ethanol
$%g$	Percentage of gasoline A
$1.4\text{-DCB}_{\text{eq}}$	1.4-Dichlorobenzene, substance used to calculate the level of human toxicity
A_{electric}	Electric autonomy
$\text{BTE}_{\text{bioethanol}}$	Brake thermal efficiency of the internal combustion engine when fueled with bioethanol
$\text{BTE}_{\text{gasoline}}$	Brake thermal efficiency of the internal combustion engine when fueled with gasoline A
$\text{C}_2\text{H}_5\text{OH}$	Gasoline
C_b	Battery capacity
CH_4	Methane
CO_2	Carbon dioxide
CO_2_{eq}	Equivalent carbon dioxide
$E_{\text{Brazilian mix}}$	Emission related to the Brazilian electricity mix
E_{consump}	Energy consumption needed in the internal combustion engine
$E_{\text{electric mode}}$	Emission related to the electricity consumption
$\text{FC}_{\text{bioethanol}}$	Bioethanol consumption
$\text{FC}_{\text{biogas}}$	Biogas consumption
FC_{fuel}	Fuel consumption
$\text{FC}_{\text{gasoline A}}$	Gasoline A consumption
$f_{1,4\text{DCBeq}}$	Equivalent 1.4-dichlorobenzene emission factor
$f_{\text{CO}_2\text{eq bioethanol}}$	Equivalent carbon dioxide emission factor resulted from the bioethanol combustion
$f_{\text{CO}_2\text{eq biogas}}$	Equivalent carbon dioxide emission factor resulted from the biogas combustion
$f_{\text{CO}_2\text{eq fuel}}$	Equivalent carbon dioxide emission factor
$f_{\text{CO}_2\text{eq gasoline A}}$	Equivalent carbon dioxide emission factor resulted from the gasoline A combustion
f_{specie}	Specie emission factor
H_2O	Water steam
LHV_{fuel}	Low heating power of the fuel
$\text{LHV}_{\text{gasoline A}}$	Low heating value of the gasoline A
N_2	Nitrogen
NO_x	Nitric oxides
n_{fuel}	Number of mols of the fuel
n_{specie}	Number of mols of the specie
O_2	Oxygen
$\text{TTW}_{\text{BR gasoline}}$	Tank-to-Wheel for the Brazilian gasoline
$\text{TTW}_{\text{ICE-DF}}$	Tank-to-Wheel for the internal combustion engine in dual-fuel mode
$\text{TTW}_{\text{ICE-SF}}$	Tank-to-Wheel for the internal combustion engine in single-fuel mode
W_{fuel}	Molecular weight of the fuel
W_{specie}	Molecular weight of the specie

z	Proportion of biogas in the mixture
y	Proportion of bioethanol in the mixture

Greek letters

ε	Energy-ecological efficiency
η	Brake thermal efficiency of the internal combustion engine
Π	Pollution indicator
Π_{GW}	Pollution factor that considers the emissions that contribute to the global warming
Π_{HT}	Pollution factor that considers the emissions that contribute to human toxicity
$\rho_{\text{bioethanol}}$	Bioethanol density
ρ_{biogas}	Biogas density
ρ_{fuel}	Fuel density
$\rho_{\text{gasolineA}}$	Gasoline A density

Abbreviations

BEV	Battery electric vehicle
EA	Electric autonomy
EM	Electric motor
EV	Electric vehicle
FC	Fuel consumption
GHGs	Greenhouse gases
HC	Hydrocarbons
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
ICE-DF	Internal combustion engine in dual-fuel mode
ICE-SF	Internal combustion engine in single-fuel mode
LPG	Liquefied petroleum gas
PHEV	Plug-in hybrid electric vehicle
PM	Particulate matter
TTW	Thank-to-Wheel

Introduction

Some types of electric vehicles (EVs) have an internal combustion engine (ICE), such as the hybrid electric vehicle (HEV) and the plug-in hybrid electric vehicle (PHEV), which must be considered in the tailpipe emission assessment.

One common drawback of the ICE when fueled with non-renewable fuels is the high level of negative impact on the environment, caused by the emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2) and pollutants gases as particulate matter (PM), nitric oxides (NO_x), hydrocarbons (HC), which increase global warming and human toxicity.

The ICE can operate in single-fuel mode, in which only one fuel is injected into the chamber, or in dual-fuel mode, with the necessary adaptations, in which two fuels are injected into the chamber. The internal combustion engine in dual-fuel mode (ICE-DF) is a technology projected to burn two fuels at the same time during the combustion process when gaseous fuel is burned predominantly with a percentage of liquid fuel, which is used to start the ignition (Liu et al. 2015). The use of the ICE fueled with biofuel contributes to reducing the dependence on fossil fuels and the GHGs emissions, consequently decreasing the negative impacts caused by burning non-renewable fuels (Ramachandran and Stimming 2015). Therefore, the use of biofuels in the ICE can be pointed out as a strategy to increase the eco-friendly options for urban mobility transport, which are necessary to achieve smart, efficient, and sustainable cities (Soares et al. 2021).

In the seek for alternatives to replace fossil fuels, Brazilian governmental agencies have created policies, such as *RenovaBio* and *Route 2030*. The *RenovaBio* is a national biofuels policy established in 2017 by ANP (National Agency for Oil—in Portuguese, *Agência Nacional do Petróleo, Gás Natural e Biocombustíveis*) aiming to: provide contributions to the fulfillment of the commitments determined by the country under the Paris Agreement; promote an expansion of biofuels in the energy matrix; and ensure predictability for the fuel market, inducing gains in energy efficiency and reduction of greenhouse gas emissions during the entire production process, availability and use of biofuels. *Route 2030* is the label given to Law n. 13.755 that encourages research and development of projects in the automotive area, extending to the production of its components and strategic vehicle production systems. Among the main guidelines of this program, it can be highlighted the promotion of the use of biofuels, the development of alternative forms of propulsion, and, consequently, the enhancement of the Brazilian energy matrix. Brazil has a relevant potential for producing biofuels from biomasses, such as bioethanol, biogas, and hydrogen (green or blue), due to its prominent position in the world ranking of producers of sugarcane and cassava, and the possibility of conversion of the many organic wastes generated by the agroindustry.

The vehicles powered by ICE compose the majority fleet of light-duty vehicles in Brazil, which corresponded to almost 43,800,000 vehicles in 2020 (Sindipeças e Abipeças 2021). Besides that the transport sector is the main source of GHG emissions, responsible for 47% equivalent carbon dioxide (CO_2_{eq}) emitted in 2019 (Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa—SEEG 2020). Thus, it is necessary to apply methods (as in Guimarães, Leal Junior et al. 2017; 2018) and develop public policies and governmental incentives to mitigate the emissions caused by this sector. Guimarães (2019) evaluate the carbon

regulations (carbon tax, carbon cap, carbon cap-and-trade, etc.) and propose some actions (such as the use of biofuels; the use of electric vehicles; actions to increase energy efficiency; and the elaboration of emissions inventory) to help mitigate the carbon emission in the transport sector.

The literature shows the use of fossil fuels to power the ICE-DF, such as gray hydrogen and gasoline (Wu et al. 2016; Sun et al. 2019). However, according to Da Silva César et al. (2019), the costs related to hydrogen production, logistics, and storage make its use unfeasible in many scenarios.

Other studies are dedicated to evaluating the emissions of different types of EVs, aiming at finding some strategies to reduce the negative impacts on the environment and human health. Andersson and Börjesson (2021), for example, assessed the greenhouse gas emissions of different types of EVs fueled with renewable fuels, such as first-generation and second-generation biofuels. According to their results, the PHEV could help the most to reach the ambitious climate goals when compared to the battery electric vehicle (BEV).

The literature already points out that the use of EVs fueled with biofuels could reduce significantly the emissions caused by conventional vehicles fueled with fossil fuels (Gupta et al. 2021; de Moraes et al. 2022a, b). Recently, de Moraes et al. (2022a) evaluated different fuels and biofuels applied to the direct internal reforming system of a fuel cell electric vehicle and calculated well-to-tank and tank-to-wheel emissions. Through the life cycle analysis, the authors showed that the fuel cell electric vehicle powered by gasoline A reduced the emissions by 83.85% in comparison to the conventional vehicle, and 63.09% compared to the HEV. Moreover, the biofuels analyzed (sugarcane bioethanol and biomethane) reduced the emissions in the study, then, their use could help meet the future tailpipe emission standards provided by European Union and the USA.

de Moraes et al. (2022b), in its turn, analyzed the emissions from the solid oxide fuel cell fueled with different types of fuels. The findings showed that, from the thermodynamic point of view, the solid oxide fuel cell powered by bioethanol or biomethane presented a performance similar to that obtained for gasoline, but these biofuels presented a lower negative environmental impact than gasoline and glycerine.

Recently, García et al. (2021a, b) investigated the use of dual-fuel mode in the hybrid electric truck with a reactivity-controlled compression ignition diesel-gasoline engine, by analyzing its hybrid architecture impact and its fuel consumption. According to the authors, tank-to-wheel emissions could be reduced by 15%. It can be explained by the fact that in the dual-fuel mode, the most pollutant fuel can be replaced by a percentage of a less pollutant fuel, or two biofuels can be used, contributing even more to the environment (García et al. 2020, 2021a, b). It is relevant in the Brazilian scenario that has an electricity matrix mainly renewable and

a great possibility of producing biofuels from biomass, such as sugarcane.

In addition, there was not found any paper analyzing the energy-ecological and TTW emissions from the ICE of EV powered by biofuels from sugarcane, especially, in dual-fuel mode. Besides, none of the studies found considered a specific country to evaluate the best choice of EV for its fleet. To address this research gap, this paper presents a comparison of three EV types to propose the best choice to implement the electric mobility in Brazil, considering the Tank-to-Wheel (TTW) emissions of the internal combustion engine in single-fuel mode (ICE-SF) fueled with biogas, bioethanol, gasoline A, or Brazilian gasoline (27% bioethanol + 73% gasoline A), and of the internal combustion engine in dual-fuel mode (ICE-DF) fueled with 50% biogas + 50% bioethanol. Moreover, the analysis considered the potential of using biofuel, infrastructure, and electricity grid sources to propose the best choice of EV for the Brazilian fleet, aiming to present an alternative to reduce the environmental negative impacts.

Thus, this study presents a comparison of the emissions caused by three types of EVs to propose the best choice to implement electric mobility in the Brazilian transport sector, considering its infrastructure, electricity mix, and potential for biofuel production. The TTW emissions of the ICE-SF mode fueled with biogas, bioethanol, gasoline A, or Brazilian gasoline, and of the ICE-DF fueled with 50% biogas and 50% bioethanol were determined. The emissions related to the Brazilian electricity mix were calculated to analyze the impact of the EV operating in 100% electric mode. Besides that, the energy-ecological efficiency was considered to analyze the negative impacts on human health and the environment. For this purpose, the pollution factor (that considers human toxicity and global warming) and the pollution indicator were measured. The findings of this study could be used to support the implementation of public policies regarding EVs fleet composition and to prioritize the investments related to the development of new biofuels.

From this Introduction, this study was divided into four topics. First, the methodological procedures are presented in Sect. [Methodological procedures](#), detailing the three EV types analyzed, the simulation of combustion of different fuels, and the calculation of the TTW emissions and the energy-ecological efficiency. In Sect. [Results and discussion](#), the findings are discussed. In Sect. [Conclusions](#), the conclusions are presented.

Methodological procedures

In this section, the equations to calculate the Tank-to-Wheel (TTW) emissions of the EVs will be shown. Therefore, one EV was chosen for each category, such as plug-in hybrid

electric vehicle (PHEV), hybrid electric vehicle (HEV), and battery electric vehicle (BEV), considering their availability in the country. The TTW emissions are measured considering the Brazilian electricity matrix, and the internal combustion engine, in single-fuel (ICE-SF) and dual-fuel (ICE-DF) modes, fueled with fossil fuels and biofuels from sugarcane. For energy-ecological efficiency, the method proposed by Carneiro and Gomes (2019) is applied to estimate the negative impacts caused to human and environmental health. Thus, this section is divided into five items: 2.1 details the features of the three EVs chosen for this study; 2.2 demonstrates the simulation of gasoline A, bioethanol, and biogas on GASEQ; 2.3 shows the TTW emissions of the EVs chosen, considering the emissions related to the Brazilian electricity mix; 2.4 demonstrates the method used to calculate the energy-ecological efficiency of the HEV and PHEV in ICE-SF and ICE-DF; and, 2.5 presents the parameters used in this study.

Electric vehicles analyzed




The features of the three EVs chosen to perform the proposed study are presented in Table 1. The BEV is a type of EV that only operates with the energy provided by the grid through the plug and when the energy is over, it needs to be connected to a recharge station. Different from the BEV, the HEV does not operate with the electricity provided by the grid, but by the energy generated through the conversion of the fuel consumed in the ICE into electricity to power the electric motor. Finally, the PHEV is a combination of the two types explained before, operating in two modes basically: electric mode, using the electricity provided by the grid; and conventional mode, using the ICE to provide the energy needed to power the electric motor. When the battery charge of the PHEV is over, this vehicle operates in conventional mode, and the battery is recharged by the spare energy that comes through the electric motor.

It is important to emphasize that these vehicle models were chosen because they are available for sale in Brazil, such as the Renault Zoe E-Tech and the Toyota Corolla Altis Hybrid. Although Chevrolet Volt II Generation is no longer manufactured or imported to Brazil, there are still vehicles in the fleet. Other models in the same category were not considered, since their technical characteristics and specifications are not similar.

Simulation of the combustion process on GASEQ

The combustion of gasoline A, bioethanol, and biogas (60% CH₄) was simulated through the GASEQ software to quantify the emission factors and calculate the next items of this section: the tank-to-wheel emissions and the energy-ecological efficiency of the EVs presented in Table 1. The Brazilian

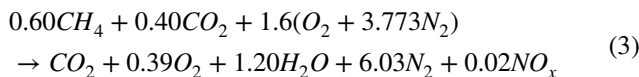
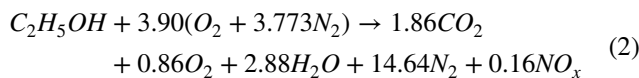
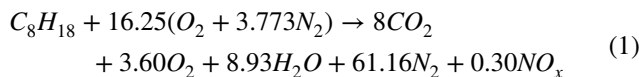
Table 1 Types of electric vehicles analyzed (Data based on their manufacturer manual)

BEV		HEV		PHEV	
			Brand	Brand	Brand
Renault	Toyota	Chevrolet	Zoe E-Tech	Corolla Altis Hybrid	Volt II Generation
Model	Model	Model	181 kW	96.6 kW	111 kW
EM power	EM power	EM power	385 km	135 kW	75 kW
EA	ICE power	ICE power	52 kWh	16.3 km/l	85 km
Battery capacity	FC	Battery capacity			18.4 kWh
		FC			15.87 km/l

EA electric autonomy; FC fuel consumption; EM electric motor; ICE internal combustion engine

gasoline was simulated based on the data of gasoline A (also known as pure gasoline), considering that the former has 73% of gasoline A and 27% of bioethanol. Moreover, Brazilian citizens who live on the border with Argentina, for example, can fill up their vehicles with pure gasoline, when the fuel price is more advantageous.

For these analyses, two ICEs were used, such as ICE-SF and ICE-DF. The ICE-SF was fueled with gasoline A, Brazilian gasoline (27% ethanol), bioethanol, or biogas; and the ICE-DF was fueled with 50% bioethanol and 50% biogas. For the simulation, an air excess coefficient equal to 30% was adopted for gasoline A and bioethanol, and 40% was adopted for biogas (Coronado et al. 2009). The reaction combustion of gasoline A, bioethanol, and biogas is, respectively, presented in Eqs. (1–3), which were calculated in this study through the universal equation: $Fuel + (O_2 + 3.773N_2) \rightarrow CO_2 + H_2O$. The other elements were taken from the simulation results, complete the equation.



Tank-to-Wheel emissions

The Tank-to-Wheel (TTW) emissions consider the emissions from fueling the vehicle at the gas station to disposing of exhaust gases from the fuel combustion. The TTW emissions for the ICE-SF and ICE-DF can be calculated through Eqs. (4 and 5), respectively, as provided by Soares et al. (2021). For Brazilian gasoline, the calculation of the TTW emissions considers 27% bioethanol and 73% gasoline A, being calculated as can be seen in Eq. (6)

$$TTW_{ICE-SF} = \left(\frac{f_{CO2 \text{ eq fuel}} \times \rho_{fuel}}{FC_{fuel}} \right) \quad (4)$$

$$TTW_{ICE-DF} = z \left(\frac{f_{CO2 \text{ eq biogas}} \times \rho_{biogas}}{FC_{biogas}} \right) + y \left(\frac{f_{CO2 \text{ eq bioethanol}} \times \rho_{bioethanol}}{FC_{bioethanol}} \right) \quad (5)$$

$$TTW_{BR\ gasoline} = \%e \left(\frac{f_{CO_2\ eq\ bioethanol} \times \rho_{bioethanol}}{FC_{bioethanol}} \right) + \%g \left(\frac{f_{CO_2\ eq\ gasoline\ A} \times \rho_{gasoline\ A}}{FC_{gasoline\ A}} \right) \tag{6}$$

where $f_{CO_2\ eq\ fuel}$ is the $CO_2\ eq$ emission factor resulted from the fuel combustion, in $kg\ CO_2\ eq/kg\ fuel$; ρ_{fuel} is the fuel density, in kg/m^3 ; FC_{fuel} is the fuel consumption, in km/l ; $f_{CO_2\ eq\ biogas}$ is the $CO_2\ eq$ emission factor from the biogas combustion, in $kg\ CO_2\ eq/kg\ biogas$; ρ_{biogas} is the biogas density, in kg/m^3 ; FC_{biogas} is the biogas consumption, in km/l ; $f_{CO_2\ eq\ bioethanol}$ is the $CO_2\ eq$ emission factor from the bioethanol combustion, in $kg\ CO_2\ eq/kg\ bioethanol$; $\rho_{bioethanol}$ is the bioethanol density, in kg/m^3 ; $FC_{bioethanol}$ is the bioethanol consumption, in km/l ; z is the proportion of biogas in the mixture, where $z = 0$ indicates operation with bioethanol only and $z > 1$ indicates operation in dual mode with biogas; y is the proportion of bioethanol ($1 - z$); $\%e$ is the percentage of ethanol; $\%g$ is the percentage of gasoline A; $f_{CO_2\ eq\ gasoline\ A}$ is the $CO_2\ eq$ emission factor resulted from the gasoline A combustion, in $kg\ CO_2\ eq/kg\ gasoline\ A$; $\rho_{gasoline\ A}$ is the gasoline A density, in kg/m^3 ; $FC_{gasoline\ A}$ is the gasoline A consumption, in km/l .

In the Chevrolet and Toyota manuals, the fuel consumption provided for the PHEV and BEV models refers to the gasoline A consumption. For the others fuels, it was necessary to estimate the consumption. The energy consumption will be calculated, through Eq. (7), to mensurate the energy consumption needed in the ICE. Thus, the fuel consumption can be calculated through Eq. (8), considering the energy consumption found (Soares et al. 2021).

$$E_{consump} = \frac{LHV_{gasoline\ A} \times \rho_{gasoline\ A}}{1000 \times FC_{gasoline\ A}} \tag{7}$$

$$FC_{fuel} = \frac{LHV_{fuel} \times \rho_{fuel}}{E_{consump} \times 1000} \tag{8}$$

where $E_{consump}$ is the energy consumption needed in the ICE, in MJ/km ; $LHV_{gasoline\ A}$ is the low heating value of the gasoline A, in $MJ/kg\ gasoline\ A$; FC_{fuel} is the fuel consumption, in km/l ; LHV_{fuel} is the low heating power of the fuel, in $MJ/kg\ fuel$.

The emissions related to the electricity consumption will be calculated for the BEV and PHEV, as shown in Eq. (9), once the HEV is a type of EV that only consumes energy provided by the ICE.

$$E_{electric\ mode} = \frac{C_b \times E_{Brazilian\ mix}}{A_{electric}} \tag{9}$$

where $E_{electric\ mode}$ is the emission related to the electricity consumption, when operating in electric mode, in $gCO_2\ eq/km$; C_b is the battery capacity, in kWh ; $E_{Brazilian\ mix}$ is the emission related to the Brazilian electricity mix; $A_{electric}$ is the electric autonomy of the vehicle, when operating in electric mode, in km .

Energy-ecological efficiency

The energy-ecological efficiency is a method that compares the pollutant emissions caused by this process and the air quality standards (Cârdu and Baica 2001), to evaluate the potential of pollution of the fuels used and their efficacy (Carneiro and Gomes 2019). Thus, applying this method to the ICE fueled with biogas, bioethanol, gasoline A, and Brazilian gasoline will facilitate the comparison of their environmental impacts with other vehicle technologies, as well as single-fuel or dual-fuel modes. From this method, it is possible to estimate the negative impacts on human and environmental health. According to (Carneiro and Gomes 2019), the energy-ecological efficiency is calculated as shown in Eq. (10).

$$\epsilon = \left[2.01 \frac{\eta}{\eta + \Pi} \ln(1.645 \pm \Pi) \right]^{1.7} \tag{10}$$

where ϵ is the energy-ecological efficiency; η is the brake thermal efficiency of the ICE; and Π is the pollution indicator, in $kg\ eq\ pollutant/MJ\ fuel$. The pollution indicator Π consists of two pollution factors and can be expressed through Eq. (11) (Carneiro and Gomes 2019).

$$\Pi = 0.742\Pi_{HT} + 0.258\Pi_{GW} \tag{11}$$

where Π_{GW} (in $kg\ eq\ pollutant/MJ_{fuel}$) and Π_{HT} (in $kg\ 1.4DCB_{eq}/kg_{fuel}$) are pollution factors that consider the emissions that contribute to global warming and human toxicity, respectively. These pollution factors and their respective equivalent emission factors can be calculated through Eqs. (12–15) (Carneiro and Gomes 2019).

$$\Pi_{GW} = \frac{f_{CO_2\ eq}}{LHV_{fuel}} \tag{12}$$

$$\Pi_{HT} = \frac{f_{1,4DCBeq}}{LHV_{fuel}} \tag{13}$$

$$f_{CO_2\ eq} = f_{CO_2} + 28f_{CH_4} + 265f_{N_2O} \tag{14}$$

$$f_{1,4DCBeq} = 4.54f_{SO_2} + 56.71f_{NO_x} + 38.75f_{PM} \tag{15}$$

where f_{CO2eq} is the equivalent carbon dioxide emission factor, in $kg\ CO_{2eq}/kg\ fuel$; $f_{1.4DCBeq}$ is the equivalent 1,4-dichlorobenzene emission factor, in $kg\ 1,4-DCB_{eq}/kg\ fuel$; LHV_{fuel} is the low heating value of the fuel, in MJ/kg_{fuel} . The f_{specie} is the specie emission factor and can be calculated as can be seen in Eq. (16) (Carneiro and Gomes 2019).

$$f_{specie} = \frac{(n_{specie} \times W_{specie})}{(n_{fuel} \times W_{fuel})} \tag{16}$$

where n_{specie} is the number of mols of the specie; W_{specie} is the molecular weight of the specie; n_{fuel} is the number of mols of the fuel; W_{fuel} the molecular weight of the fuel.

Parameters and considerations adopted in this study

The parameters and considerations adopted for the TTW emissions and the energy-ecological efficiency of different fuels are presented in Table 2.

Results and discussion

In this study, the TTW emissions from ICE-SF and ICE-DF fueled with fossil fuels and biofuels from sugarcane were mensurated, well as their energy-ecological efficiency. Then,

Table 2 Parameters and considerations adopted

Parameter	Value	Unit	Source
Electric motor power–BEV	181	kW	Renault’s manual
Electric autonomy–BEV	385	km	Renault’s manual
Battery capacity–BEV	52	kWh	Renault’s manual
Electric motor power–HEV	96.6	kW	Toyota’s manual
ICE power–HEV	135	kW	Toyota’s manual
Fuel consumption–HEV	16.3	km/l	Toyota’s manual
Electric motor power–PHEV	111	kW	Chevrolet’s manual
ICE power–PHEV	75	kW	Chevrolet’s manual
EA–PHEV	85	Km	Chevrolet’s manual
Battery capacity–PHEV	18.4	kWh	Chevrolet’s manual
Fuel consumption–PHEV	15.87	km/l	Chevrolet’s manual
Gasoline molecular weight	114	g	Calculated by the authors
Ethanol molecular weight	46	g	Calculated by the authors
Biogas molecular weight	60	g	Calculated by the authors
Air excess coefficient–Biogas	40	%	Coronado et al. (2009)
Air excess coefficient–Bioethanol	30	%	Coronado et al. (2009)
Air excess coefficient–Gasoline	30	%	Coronado et al. (2009)
Density–Anhydrous ethanol	791	kg/m ³	ANP (2019)
Density–Sugarcane vinasse	1031	kg/m ³	Parsaee et al. (2019)
Density–Vinasse biogas	0.784	kg/m ³	ANA (2017)
Density–Gasoline A	742	kg/m ³	ANP (2019)
Density–Brazilian gasoline	754	kg/m ³	ANP (2019)
Density–Anhydrous ethanol	791	kg/m ³	ANP (2019)
LHV–Anhydrous ethanol	28,242	kJ/kg	ANP (2019)
LHV–Vinasse biogas	23,200	kJ/kg	Lima. and Passamani. (2012)
LHV–Gasoline A	43,543	kJ/kg	ANP (2019)
LHV–Brazilian gasoline	39,356	kJ/kg	ANP (2019)
Z	50	%	da Costa et al. (2020)
BTE _{dual-fuel} (for z = 50%)	36.1	%	da Costa et al. (2020)
BTE _{bioethanol}	25	%	Balki et al. (2014)
BTE _{gasoline}	23	%	Balki et al. (2014)
Brazil electricity mix	416.3	gCO _{2eq} /kWh	EPE (2020)

Table 3 Consumption of different fuels

Fuel	Consumption	Reference
<i>HEV–Toyota–Corolla Altis Hybrid</i>		
Gasoline A	23.57 km/l	Calculated by the authors (Eq. 8)
Bioethanol	16.30 km/l	Toyota
Biogas	0.013 km/l	Calculated by the authors (Eq. 8)
<i>PHEV–Chevrolet–Volt II Generation</i>		
Gasoline A	15.87 km/l	Chevrolet
Bioethanol	10.97 km/l	Calculated by the authors (Eq. 8)
Biogas	0.0089 km/l	Calculated by the authors (Eq. 8)

the pollutant emitted through the combustion process were simulated using the GASEQ software, whose results were used to calculate the energy-ecological efficiency. The comparison of three types of EVs (BEV, HEV, and PHEV) was made to investigate the most appropriate EV in the Brazilian context, considering the electricity mix, biofuel production, and infrastructure in the country.

Tank-to-Wheel emissions

The TTW emissions of the ICE-SF powered by gasoline A, Brazilian gasoline, bioethanol or biogas, and the ICE-DF powered by bioethanol and biogas were determined. For the calculation, a 15 m³ cylinder was considered for biogas storage, stipulating a vehicle consumption of 12 km/m³ (Soares et al. 2021). The fuel consumption of the vehicles (in km/l) was calculated, and the results are shown in Table 3. The Brazilian gasoline consumption was not calculated because the TTW emissions were determined by applying the percentage of 73% gasoline and 27% bioethanol.

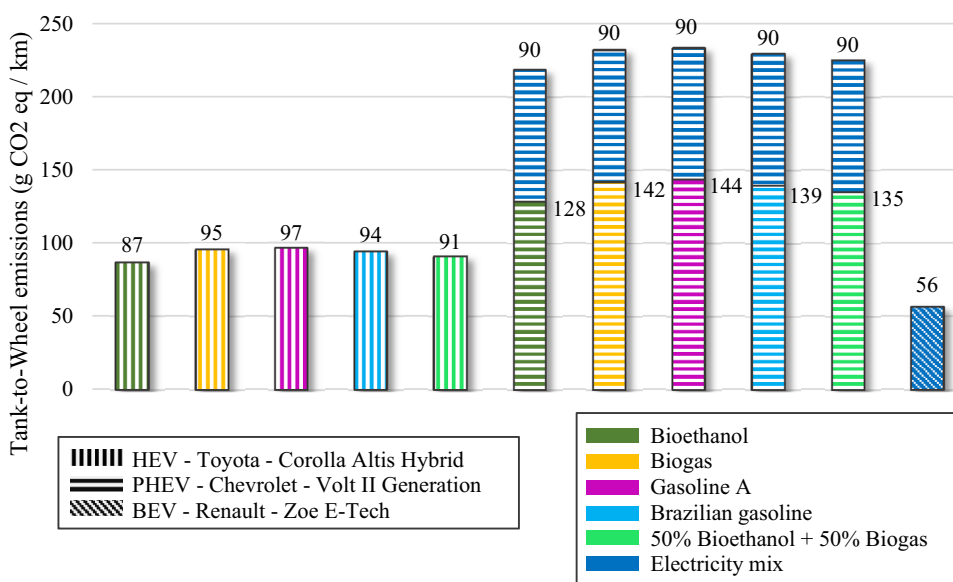
Through Eqs. (4–6) was possible to calculate the TTW emissions for the ICE-SF and the ICE-DF, and the TTW emissions related to Brazilian gasoline. In addition, the emissions related to the electricity mix were analyzed. It is necessary because the grid provides electricity to be stored in the BEV and PHEV batteries. Only the emissions from non-renewable energy sources were considered to compare the emissions from the Brazilian, Spanish and Union European matrices. The results are shown in Fig. 1.

The highest TTW emissions were related to the PHEV because this type of vehicle operates using the ICE and the energy provided by the grid. Firstly, the PHEV chosen for this analysis presented lower autonomy than the HEV. And, secondly, the PHEV presented electric autonomy and battery capacity 78% and 65% lower than the BEV analyzed in this study, respectively. It means that the BEV can store more energy and, consequently, travel more mileage in electric mode, presenting lower electric consumption, and then, emitting less g CO₂ eq per kilometer than the PHEV.

The electricity mix in Brazil is mostly composed of renewable sources: according to the Energy Research Company (in Portuguese, Empresa de Pesquisa Energética–EPE) (EPE 2020) only 6.4% of the electricity is generated provided by coal and fossil fuels. Therefore, the emissions related to electricity consumption can be drastically reduced or tend to zero since the renewable sources do not emit CO₂-eq, when compared to the TTW emissions caused by burning fuels. Thus, the electrification of the fleet could present gains, in terms of emissions, for the Brazilian transportation sector.

Regarding the infrastructure, the BEV and the PHEV have disadvantages, since the recharge stations are not available on large scale in Brazil. In 2018, the National Electric Energy Agency (in Portuguese, Agência Nacional de Energia

Fig. 1 Tank-to-Wheel emissions of the three types of electric vehicles analyzed



Elétrica–ANEEL) approved its first regulation about the offering of charging stations for EVs by interested parties. According to it, those interested in providing this service (in location as gas stations and shopping malls), should fill up a registration to carry out EV charging activities, including for commercial exploitation. Thus, energy distributors and local gas stations can install charging stations in their areas of operation for public or private charging. For this purpose, the agency requests some data from the interested party, such as the installation location, number of recharging points per station, and supply voltage. Nevertheless, more government incentives are needed to implement large-scale recharging stations.

Finally, it is important to mention that Brazil has a large potential for producing biofuels (bioethanol and biogas) from sugarcane biomasses since it is the major sugarcane producer in the world. Bioethanol from sugarcane is already available in refueling stations across the country. The advantage of using biofuels is that the CO₂ fixed during the

photosynthetic reaction returns to the atmosphere after the consumption of the plant. Thus, TTW emissions caused by biofuels would be deducted, reducing the negative impacts on human and environmental health. The findings showed that considering strictly the TWW level of emissions, BEV would be the best choice among the vehicles analyzed. However, considering the lack of infrastructure, the large availability of bioethanol, and the possible deduction of the carbon fixed from biofuels, the HEV fueled with bioethanol or bioethanol and biogas in dual-fuel mode would become the most appropriate for the Brazilian scenario.

Calculation of the emission factors and pollutant indicators

In this section, the emission factors and pollutant indicators were simulated to calculate the energy-ecological efficiency of different fuels powering the ICE of the PHEV and the HEV. The combustion of gasoline A, bioethanol, and biogas

Table 4 Reactants and products of the bioethanol combustion, and the emission factor of the combustion product species

Reactants	No. Moles	Mol. Weight	
C ₂ H ₅	1,00,000	29	
OH	1,00,000	17	
O ₂	3,90,000	32	
N ₂	14,71,470	28	
Products	No. Moles	Mol. Weight	f _{specie}
CO ₂	1,86,156	44	1,7,806,226
CH ₄	0,00,000	16	1,335E-17
N ₂ O	0,00,001	44	7,17E-06
SO ₂	0,00,000	64	0
NO _x	0,15,834	30	0,1,032,641
PM	0,00,000	12	0

Table 5 Reactants and products of the biogas combustion, and the emission factor of the combustion product species

Reactants	No. Moles	Mol. Weight	
CH ₄	0,60,000	16	
CO ₂	0,40,000	44	
O ₂	1,60,000	32	
N ₂	6,03,680	28	
Products	No. Moles	Mol. Weight	f _{specie}
CO ₂	0,99,880	44	1,615,705,882
CH ₄	0,00,000	16	6,96471E-23
N ₂ O	0,00,000	44	1,40849E-06
SO ₂	0,00,000	64	0
NO _x	0,01,807	30	0,019,928,923
PM	0,00,000	12	0

was simulated through the GASEQ software, considering the values of the following species: CO₂, CH₄, N₂O, SO₂, NO_x, and particulate material (PM). These are the incognitos visualized in Eqs. (14–15) to mensurate the carbon dioxide and the 1,4-Dichlorobenzene emission factors and the pollutant indicators that contribute to global warming and human toxicity, respectively. Tables 4, 5 and 6 show the reactants and products of the bioethanol, gasoline A and biogas combustion, and the number of moles, molecular weight, and equivalent emission factor of each combustion product. The results shown in Tables 4, 5 and 6 were similar to those found in Soares et al. (2021).

To calculate the equivalent emission factors of the Brazilian gasoline, 27% ethanol needed to be added to gasoline A. Thus, 27% of the equivalent emission factors found for bioethanol were added to 73% of the equivalent emission factors found for gasoline A. A similar procedure was done to the ICE-DF powered by 50% bioethanol and 50% biogas, adding 50% of the equivalent emission factors found for bioethanol to 50% of the equivalent emission factors found for biogas. The equivalent emission factors of the ICE-SF fueled with bioethanol, biogas, gasoline A, or Brazilian gasoline, and the ICE-DF fueled with biogas and bioethanol are presented in Table 7. The CO₂, CH₄, and N₂O emission

Table 6 Reactants and products of the gasoline A combustion, and the emission factor of the combustion product species

Reactants	No. Moles	Mol. Weight	
C ₈ H ₁₈	1,00,000	114	
O ₂	16,25,000	32	
N ₂	61,31,100	28	
Products	No. Moles	Mol. Weight	<i>f</i> _{specie}
CO ₂	7,94,998	44	3,068,413,333
CH ₄	0,00,000	16	1,00281E-20
N ₂ O	0,00,001	44	5,63895E-06
SO ₂	0,00,000	64	0
NO _x	0,29,759	30	0,078,313,158
PM	0,00,000	12	0

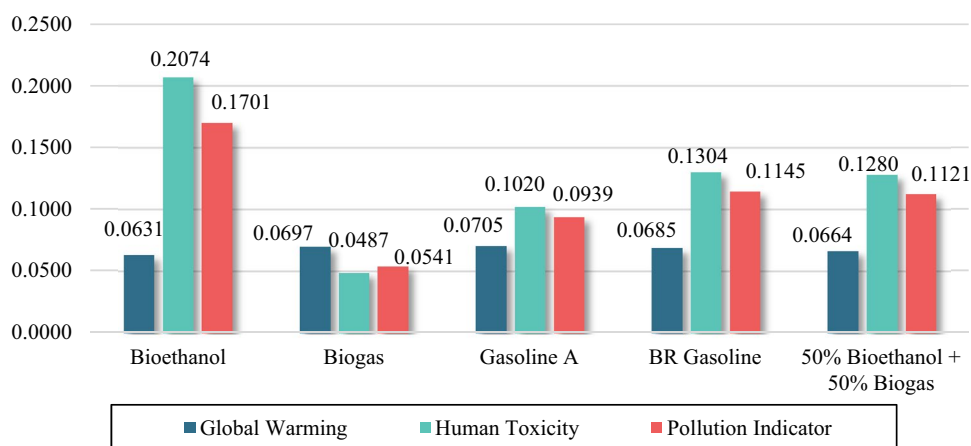
Table 7 Equivalent emission factors found for different fuels

Equivalent Emission Factors	Fuels				
	Bioethanol	Biogas	Gasoline A	BR Gasoline ^a	Dual-Fuel ^b
<i>f</i> _{CO₂ eq} (kgCO ₂ _{2eq} /kg _{fuel})	1,7825	1,6160	3,0699	2,7223	1,6993
<i>f</i> _{1,4-DCB eq} (kg 1.4DCB _{eq} /kg _{fuel})	5,8561	1,1301	4,4411	4,8231	3,4931

^aBrazilian Gasoline–27% bioethanol + 73% gasoline A

^bICE fueled with 50% bioethanol and 50% biogas

Fig. 2 Global warming and human toxicity and pollution indicators found for different fuels



factors were considered to calculate the $f_{\text{CO}_2 \text{ eq}}$, and the SO_2 , NO_x , and PM were considered to measure the $f_{1,4\text{-DCB eq}}$.

Gasoline A presented the highest $f_{\text{CO}_2 \text{ eq}}$ value among the fuels analyzed due to its highest value of CO_2 produced during its combustion. It is approximately 12.8% higher than the $f_{\text{CO}_2 \text{ eq}}$ found for Brazilian gasoline. On the other hand, the Brazilian gasoline resulted in 8.6% more $f_{1,4\text{-DCB eq}}$ than gasoline A. This can be explained by the percentage of 27% of bioethanol, which was the fuel that presented the highest $f_{1,4\text{-DCB eq}}$ value. The ICE-DF has 44.6% and 37.6% less $f_{\text{CO}_2 \text{ eq}}$ than gasoline A and Brazilian gasoline, respectively.

The pollution factors, which consider the global warming (Π_{GW}) and the human toxicity (Π_{HT}), and the pollution indicators (Π), were calculated. It is important to highlight that the Π is mainly composed by Π_{HT} , which represents 74.2% of its total. The results are shown in Fig. 2. As can be seen, the gasoline A presented the highest Π_{GW} among the fuels analyzed, due to its highest $f_{\text{CO}_2 \text{ eq}}$ value. Similarly, the bioethanol resulted in the highest Π_{HT} , due to its highest $f_{1,4\text{-DCB eq}}$ value. It increases the.

Energy-ecological efficiency

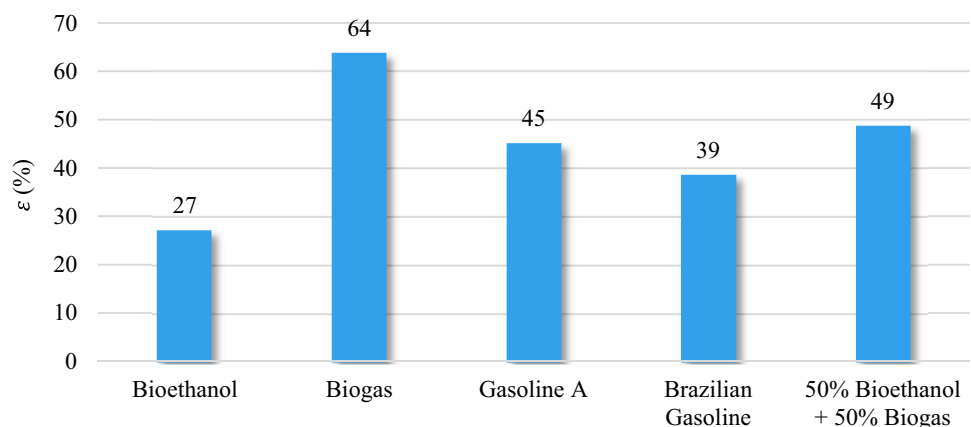
The energy-ecological efficiency (ϵ) was calculated for the ICE-SF fueled with biogas, bioethanol, gasoline A or Brazilian gasoline, and for the ICE-DF powered by 50% bioethanol and 50% biogas. As can be seen in Fig. 3, the ICE-SF fueled with biogas presented the highest ϵ because of the lowest pollution indicator and pollution factors found for this biofuel. The percentage of biogas in the ICE-DF increased its ϵ value, resulting in ϵ 25.6% higher than that found for Brazilian gasoline. The lowest ϵ was found for bioethanol because of its human toxicity pollution factor and pollution indicator, which presented the highest value among the fuels analyzed. Thus, the best choices to power the HEV and PHEV are the ICE-SF filled with biogas or fueling the ICE-DF with bioethanol and biogas.

Although bioethanol is largely available in Brazil, vehicle owners do not usually choose this fuel because its price is similar to the Brazilian gasoline price, and it has less energy per unit volume than Brazilian gasoline. Therefore, subsidies must be created to encourage the use of bioethanol, based on relatively low emissions compared to the use of fossil fuels.

The ICE-DF fueled with bioethanol and biogas presented a ϵ value higher than gasoline A, bioethanol, and Brazilian gasoline. Even though the ϵ value found for the dual-fuel mode is a little smaller than that the ϵ found for gasoline A, three points must be considered: first, the gasoline A is a fossil fuel, which means that its use should be reduced along the years (as well as Brazilian gasoline), and this fuel is not available in Brazil; second, the biofuel from sugarcane or any other biomass presents fixed CO_2 rate that must be deducted from the biofuel emissions; three, the ϵ value increases as the percentage of biogas is higher. Thus, the ϵ value of the ICE-DF fueled with bioethanol and biogas could be increased, as much as the ϵ value for bioethanol and biogas in the ICE-SF, once these biofuels present a percentage of carbon fixed on their biomass. Therefore, the dual-fuel option filled with biofuels seems to be more suitable for the Brazilian context.

These advantages have been shown to help owners, governments and/or manufacturers to consider choosing ICE-DF over ICE-SF fueled with Brazilian gasoline or bioethanol, in flex mode, as most of them may not prefer to pay more for a small difference between the resulting emissions, in exchange for less range. However, human, and environmental health must be at the heart of all decisions. The results found for biogas and bioethanol in dual-fuel mode, and for Brazilian gasoline were similar to Soares et al. (2021), supporting the method used to calculate the energy-ecological efficiency in this study.

Fig. 3 Energy-ecological efficiency for different fuels



Conclusions

This study presents a comparison of the emissions caused by three EV types to propose the best fleet composition to initially implement electric mobility in the transport sector, considering the Brazilian scenario (its infrastructure, electricity mix, and potential for biofuel production). The TTW emissions of the ICE-SF mode fueled with biogas, bioethanol, gasoline A, or Brazilian gasoline, and of the ICE-DF fueled with 50% biogas and 50% bioethanol were determined. Through the results, the BEV presented a lower level of TTW emissions among the vehicles analyzed. However, considering the infrastructure and availability of biofuels, the HEV fueled with bioethanol, in single-fuel mode, or 50% bioethanol, and 50% biogas, in dual-fuel mode, would be most appropriate for the Brazilian scenario. It is important to emphasize the specificities of the scenario: the lack of infrastructure (it does not have large-scale charging points), its electricity mix (which is mainly renewable), and its potential to produce biofuels, considering that the bioethanol from sugarcane is already available in the refueling stations across the country.

Besides that the results showed that the ICE-SF fueled with bioethanol presented the lowest energy-ecological efficiency (\mathcal{E}) found, and the ICE-DF powered by 50% bioethanol and 50% biogas presented the highest \mathcal{E} value found among the fuels analyzed. However, three points had already been presented in the last section point that the dual-fuel can be a better option. It is important to consider that governments are seeking for alternatives to reduce their carbon footprint, aiming at achieving carbon neutrality (most of them until 2050).

It is important to mention that the dissemination of EVs depends on many factors, including government interest and investments. The EVs analyzed in this study were chosen considering those that are already available in Brazil. The choice for bioethanol and biogas from sugarcane is justified by the availability of bioethanol in the refueling stations, and by the potential of increasing its production (as well as the biogas) since Brazil is one of the major sugarcane producers. For future research, public transport vehicles fueled with different biofuels and alternative fuels, such as hydrogen, will be analyzed. Also, an extended EV life cycle assessment should be carried out to calculate the Well-to-Wheel emissions, and the EV life cycle cost should be calculated to analyze its economic viability. Moreover, the carbon fixed by the sugarcane plantations could be considered. In addition, a scenario comparing other countries and their public policies to incentive the adoption of EVs could be evaluated.

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Declarations

Conflict of interest All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version. This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue. The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

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