RESEARCH ARTICLE

Energy-ecological efficiency of dual-fuel series plug-in hybrid electric vehicle considering WTW emissions

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Abstract

This paper discussed the possibility of replacing the internal combustion engine of the series plug-in hybrid electric vehicle (PHEV) powered by gasoline A and Brazilian gasoline in single-fuel mode by one fuelled with 50% bioethanol and 50% biogas in dual-fuel mode. The simulation of the combustion of the fuels selected, such as bioethanol, biogas and gasoline A, was carried out through GASEQ software to calculate the energy-ecological efficiency of the single-fuel and dual-fuel modes. The well-to-pump (WTP) emissions of the bioethanol and biogas production from sugarcane were evaluated through GREET software. The tank-to-wheel (TTW) emissions were determined to each series PHEV operating modes. Thus, the well-to-wheel (WTW) emissions were calculated through the sum of the WTP, TTW and electricity mix emissions. According to the results, the energy-ecological efficiency for the dual-fuel mode was 10.7% and 24.1% higher than that found for the single-fuel mode powered by gasoline and Brazilian gasoline, respectively. The analysis showed that the losses during the biogas production aggravate linearly the WTP emissions, and consequently, the WTW emissions of the series PHEV. Besides that, the dual-fuel mode presented 15.5% and 12.8 less TTW emissions than the single-fuel mode powered by gasoline A and Brazilian gasoline, respectively. Compared to the emission standards, the dual-fuel mode presented TTW emissions 30.5% higher than the European Union emission standard by 2021. Although the dual-fuel mode does not meet any of the emission standards, this engine mode can be an alternative to at least reduce the tailpipe emissions.

Keywords Bioethanol · Biogas · Dual-fuel · Energy-ecological efficiency · Series PHEV · Well-to-wheel emissions

Introduction

The biofuel can be a sustainable option to reduce the global warming caused by greenhouse gas (GHG) emissions as a replacement for fossil fuels. Looking for this replacement, in Brazil, the Proálcool Program encourages the production of bioethanol from sugarcane to feed light-duty vehicles with flex spark-ignition engines. Brazil presents a relevant potential to produce biofuels, taking advantage of the conversion of organic wastes generated in the agroindustry. Also, Brazil has a mainly renewable electrical matrix, which 64.9% of the electricity generated comes from hydroelectric plants (EPE 2020a), which gives the advantage to implement electric vehicles in its fleet. In 2019, renewable sources were responsible for 46.1% of the internal energy supply in Brazil, such as hydraulic power, wind power, solar power, sugarcane sources and biodiesel (EPE 2020a). The energy consumption of the transport sector increased by 3.3% in 2019, due to the use of biofuels, totalizing 25%. However, the most used fuels were gasoline (25.3%) and diesel oil (41.9%). Despite the low consumption of biofuels, Brazil is ahead of other member countries of the Organization for Economic Cooperation and Development (OECD), which presented 5% use of renewable fuels in the transport sector in 2017 (EPE 2020a).

The electric vehicles (EV) are also an alternative to decrease the negative environmental effects caused by fuel consumption. The plug-in hybrid electric vehicle (PHEV) is

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a type of EV that can be an alternative to reduce the GHG, once it can operate using an electric motor powered by a lithium-ion (Li-ion) battery or by an internal combustion engine (ICE). However, the components of the different types of EV, in this case the PHEV, have advantages and disadvantages. The Li-ion battery presents advantages such as higher power and energy densities, and longer battery life than the other battery types. This battery type is selected because of its low self-discharge rate, which means the amount of charge lost when the battery is not used, and the absence of the memory effect, phenomenon that occurs in older batteries compound by NiCd, basically, making them acquire a charge capacity less and less, when a proper care in recharging is not carried out. But the disadvantage is that the Li-ion battery cost is relatively higher than the other battery types. However, the manufacturing cost of these batteries tends to decrease due to several factors, i.e. mass production, and its cost reduction will reinforce the importance of the renewable energy as an alternative to fossil fuels that aggravates the negative impacts on the environment and human health (Asif and Singh 2017).

On the other hand, the ICE operates with fossil fuel or biofuel and can be classified as the Otto cycle (spark-ignition), in which the fuel-air mixture is injected into the chamber and the combustion is made by the spark valve, or Diesel cycle (compression-ignition), which the ignition is caused when the fuel is sprayed in the chamber after the air is compressed. Although focusing on the decrease of the GHG emissions caused by the PHEV, two points need to be considered: first, the electricity that powers the electric system has to be renewable, but it depends on the electricity source prevalent in each region; second, the ICE needs to be fuelled with biofuels, such as bioethanol and biogas, once they cause lower negative effects than the fossil fuels, or adapting the ICE to operations in dual-fuel mode.

The dual-fuel mode is a technology projected to burn two fuels at the same time. In this mode, an ICE (Otto or Diesel) is adapted to inject a gaseous fuel with air through the port injection, and a liquid fuel through a valve inside the chamber. This can reduce the environmental impact caused by the tailpipe emissions, once a percentage of more pollutant fuel can be replaced with a percentage of a less pollutant fuel.

In this study, the series PHEV Chevrolet Volt will be analysed. In general, the series PHEV presents differentiated operating modes, depending on the battery state of charge and driver's requests. The main modes are charge-sustaining (CS) mode, charge-depleting (CD) mode, EV mode and ICE mode (Singh et al. 2019). In the CS mode, the ICE is the main power source, and the battery state of charge is controlled to stay within a limit between 30 and 40%, depending on the battery type and the vehicle, to avoid any damage to the battery and decreasing of its number of recharge cycles. On the other hand, in CD mode, the battery is the main

power source, and its state of charge is controlled to decrease during the operation of the vehicle. In this mode, the battery needs the power supplied by the ICE to meet the driver's requests, and the battery loss is greater, which can reduce its lifetime. In EV mode, the series PHEV operates as a battery electric vehicle (BEV), being powered exclusively by the battery. Finally, in ICE mode, the series PHEV operates as an internal combustion engine vehicle (ICEV), consuming fuel to generate power (Singh et al. 2019).

To evaluate or compare the environmental impact caused by the PHEV and other EV types, and ICEV, the GHG emissions were analysed. De Souza et al. (2018) investigated the characteristics of PHEV, ICEV and BEV to analyse their environmental performance. According to the results, the PHEV and the ICEV presented similar environmental impacts since they use ethanol or gasoline as fuel. Otherwise, the PHEV and the BEV presented higher results for human toxicity potential, because of the impact of the Li-ion battery production, but PHEV shows better results than BEV because of the lower weight of the battery (de Souza et al. 2018). Also, the GHG emissions depend on the electricity grid mix and the vehicle usage (Plötz et al. 2018).

Some studies related to the life cycle assessment of the PHEV were published. De Souza et al. (2018) carried out a life cycle assessment to assess the well-to-wheel (WTW) for ICEV, PHEV and EV. The authors considered the ICEV with ICE powered by E25 gasoline, mixture of ethanol and gasoline (flex fuel vehicles), and ethanol, the PHEV with the ICE powered by gasoline and the pure EV powered by electricity. The results showed that the ICEV fuelled with gasoline and in flex-mode presented the highest global environment impacts and suggested to analyse the impact categories isolated. Chen et al. (2018) investigated the life cycle CO_2 emissions of the PHEV and the BEV; through their performance and energy consumption over a 4-month period and concluded that when the vehicles were in high speed or high acceleration conditions, the distance-normalized life cycle CO_2 emissions of PHEV and BEV were higher than ICEV fuelled with gasoline. In the studies found, none analysed the life cycle assessment of the biogas and bioetanol from sugarcane through a detailed simulation on GREET software, considering the losses during the production process and its well-to-pump emissions.

In the case of dual-fuel mode, studies were directed to analyse its characteristics applied in ICEV with Otto cycle or Diesel cycle. Niu et al. (2016) studied the use of gasoline enriched with hydrogen in the Otto cycle and concluded that flame developing duration and combustion duration were reduced with the addition of hydrogen in gasoline. Chen et al. (2019) evaluated the Otto cycle fuelled with methanol and natural gas in the dual-fuel mode. According to the results, the methanol induced to a faster burning rate, improved the brake thermal efficiency and reduced the

equivalent brake specific fuel consumption. In case of Diesel cycle, Shan et al. (2016) investigated the effects of exhaust gas recirculation on combustion and emission characteristics of the Diesel engine fuelled with direct-injected diesel and port-injected biogas. The results showed that, when the exhaust gas recirculation rate increases, the combustion phase retards and the ignition delay in the engine gets prolonged. Karagöz et al. (2016) conducted a study using port-injected hydrogen and direct-injected diesel in the Diesel cycle and concluded that the brake thermal efficiency was decreasing with the increase of hydrogen in the mixture.

Up to date, from the previous literature review, no scientific works were published analysing dual-fuel mode in the PHEV using biofuels. To address this gap, this study aims to evaluate the possibility of replacing the single-fuel spark-ignition engine (SFSIE) of the series PHEV Chevrolet Volt II Generation powered by gasoline with the ICE powered by biogas and bioethanol from sugarcane, operating in dual-fuel mode. For this analysis, the well-to-wheel (WTW) emissions will be analysed through the well-to-pump (wTP), tank-to-wheel (TTW) emissions and electricity mix emissions. The energy efficiency of the Chevrolet Volt operating modes will also be analysed, and the energy-ecological efficiency of the ICE fuelled with different fuels in single-fuel and dual-fuel modes will be determined. Also, the bioethanol and biogas mass flow will be calculated for operation in dual-fuel mode. It is expected that the contributions of this article will fortify the environmental criteria that can enable decision-making to promote more sustainable end environmentally friendly vehicle technologies. Besides that, it is expected that the results reinforce the importance of using biofuels to power the electric vehicles, aiming to reduce greenhouse gas emissions and promote human and environmental health in the coming years.

Methodology

The series PHEV Chevrolet 2016 II Generation was selected to evaluate the impacts on health and the environment through the analysis of the energy efficiency and the energy-ecological efficiency associated with an assessment of the WTW emissions considering the WTP, TTW and electricity mix emissions, aiming to replace the single-fuel spark-ignition engine (SFSIE) fuelled with Brazilian gasoline (27% ethanol) by the dual-fuel spark-ignition engine (DFSIE) fuelled with sugarcane biogas and bioethanol. The GREET software will be used to evaluate the WTP emissions of the Brazilian sugarcane bioethanol and biogas production pathways. Besides that, the mass flow for bioethanol and biogas for dual-fuel operation will be calculated. So, this item will be divided into six sections: the "Series PHEV operating modes" section describes the operating modes of the

Chevrolet Volt; the "Mass flow rate of bioethanol and biogas in dual-fuel mode" section presents the estimative of mass flow rate of sugarcane biogas and bioethanol for the DFSIE; the "Energy efficiency of series PHEV" section shows the calculation of energy efficiency of the series PHEV operating modes; the "Simulation of the combustion using GASEQ" section demonstrates the simulation of gasoline A, bioethanol and biogas combustion on GASEQ software; the "Energy-ecological efficiency" section demonstrates the estimation of the human toxicity and the global warming indicator and the calculation of the energy-ecological efficiency of the PHEV; the "Well-to-pump, tank-to-wheel, well-to-wheel emissions and electricity mix" section shows the WTP emissions of the Brazilian sugarcane bioethanol and biogas production pathways, the TTW emissions of the series PHEV with the SFSIE and with the DFSIE fuelled with sugarcane biogas and bioethanol and the electricity mix emissions, to calculate the WTW emissions; and the "Parameters and considerations adopted in the study" section shows the parameters adopted in this study.

Series PHEV operating modes

The Chevrolet 2016 II Generation has four operating modes: electric vehicle mode operating with one motor (EVM-1M), electric vehicle mode operating with 2 motors (EVM-2M), extended-range mode with 1 motor (ERM-1M) and extended-range mode with 2 motors (ERM-2M). In the EVM-1M operating mode, the series PHEV operates as a pure EV, where the battery provides all the power that the vehicle needs (Fig. 1). In this mode, the vehicle receives electric power through the charger, and it is stored in the battery. The battery provides direct current that is transformed into alternative current by the inverter, which supply the electric motor (EM). The EM transmits power to the transmission system through a gear set consisting of ring gear, planetary gear and solar gear. This mode presents better efficiency in lower speeds and distances.

In the EVM-2M operating mode, the generator turns into an auxiliary electric motor. It happens when the generator couples to the ring gear, which is inside of the EM (Fig. 2). In this mode, the electric power provided by the charger and stored in the battery powers both EM and generator. The generator coupled to the ring gear provides power to the EM and, depending on the battery state of charge and the driver's need, the remaining energy is directed from the EM to recharge the battery. Here, the EM speed request reduces with the actuation of the generator.

When the battery reaches the minimum state of charge level, the series PHEV no longer operates as an EV until it is plugged into the charger again. Then, the ICE starts, and the series PHEV operates in ERM-1M mode, which has only one EM operating, as shown in Fig. 3. In this study,

Fig. 1 EVM-1M operating mode of the series PHEV Chevrolet Volt
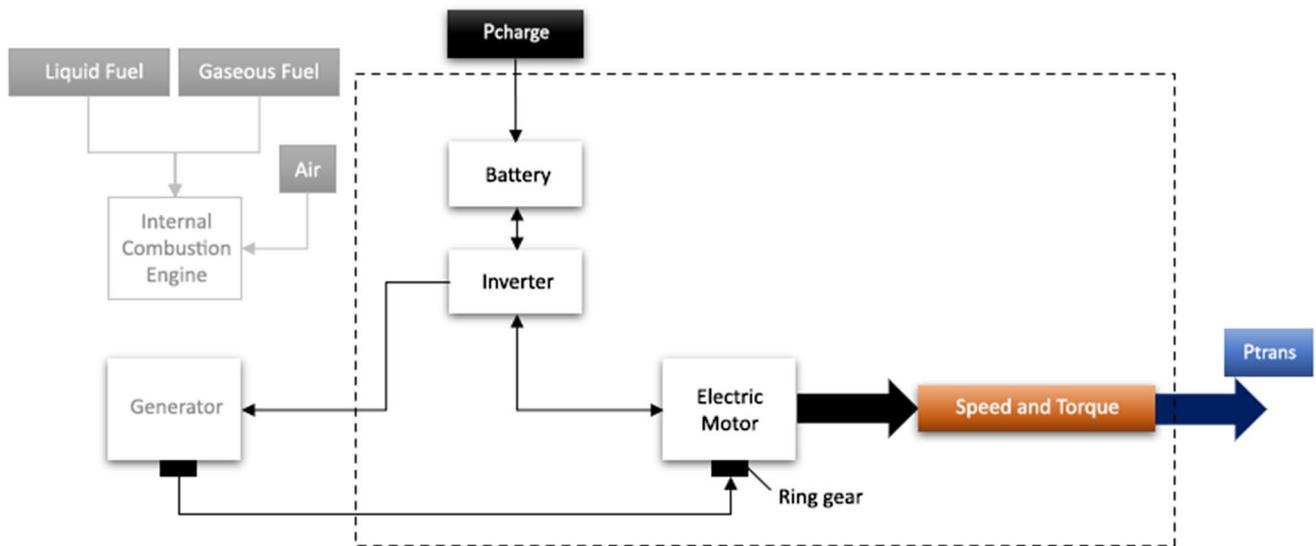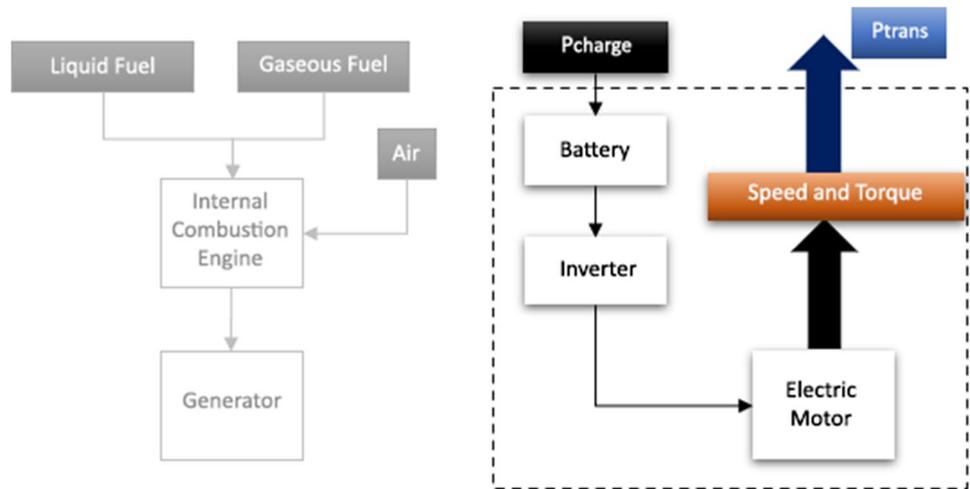
Fig. 2 EVM-2M operating mode of the series PHEV Chevrolet Volt

as already mentioned, the ICE operates in dual-fuel mode, being fuelled with a gaseous fuel (sugarcane biogas), a liquid fuel (sugarcane bioethanol) and air, releasing exhaust gases from combustion. In this mode, the ICE is coupled to the generator, which only has the function of transforming the mechanical energy provided by the ICE in electrical energy to power the EM. Here, the battery reached the minimum state of charge limit but still provides power to the EM when additional power is needed. The advantage of the ERM-1M is that the ICE only couples to the generator, allowing the vehicle to operate at low speed in city driving.

To increase the vehicle efficiency between 10 and 15% in the highways, the Chevrolet Volt combines power of the EM and the generator as an auxiliary motor, initiating the ERM-2M operating mode. In this mode, the ICE decouples from the generator and the generator couples to the ring gear of the EM (Fig. 4). The EM speed request reduces with the actuation of the generator, as in EV-2M operating mode. When the ICE and generator speeds are synchronized, they are coupled and the operation with two motors is achieved. An advantage of this mode is that ICE speed can be automatically adjusted to its optimal speed looking for more efficient operation, once the ICE speed is independent of the wheel speed. In case of more power needed, the ICE and the generator will supply the most part of the power, and an additional power will be
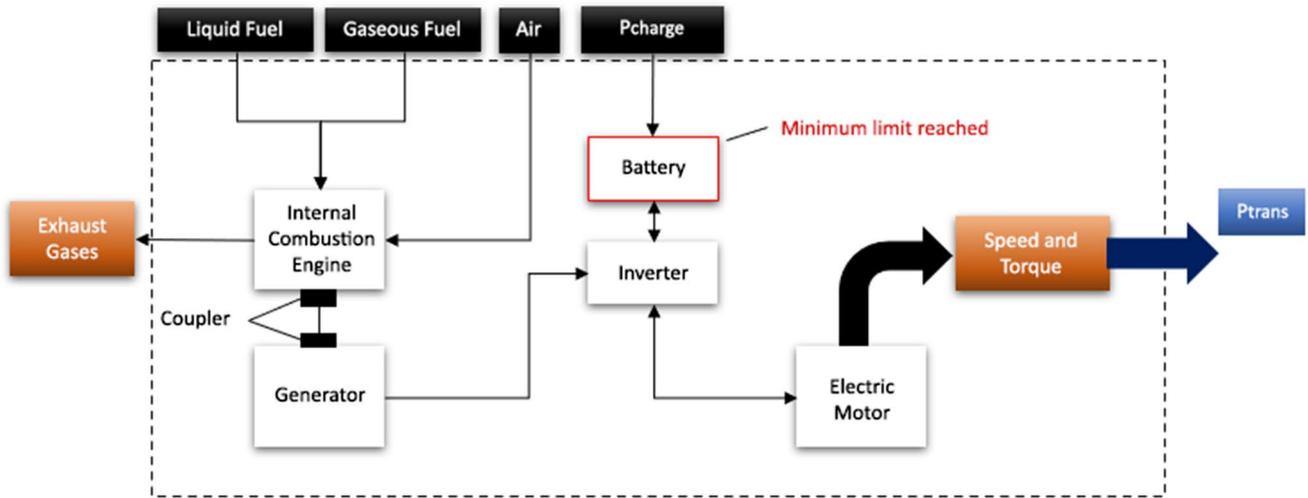
Fig. 3 ERM-1M operating mode of series PHEV Chevrolet Volt
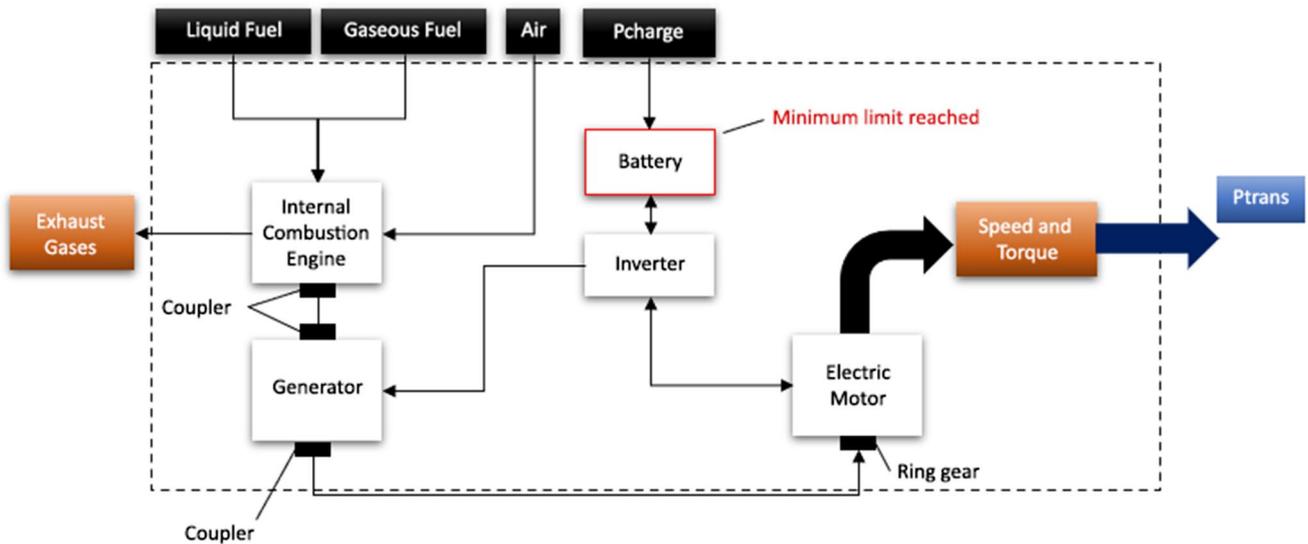
Fig. 4 ERM-2M operating mode of series PHEV Chevrolet Volt

provided by the battery. In both ERM-1M and ERM-2M, the EM also recharge the battery when there is energy remaining, depending on the battery state of charge and the driver's need.

Mass flow rate of bioethanol and biogas in dual-fuel mode

When the engine is powered by two fuels, it is necessary to consider the proportion of each fuel injected and its LHV. The biogas mass flow rate of the DFSIE can be calculated as shown in Eq. (1).

$$\dot{m}_{biogas} = \frac{z \times P}{BTE_{dual\text{-}fuel}\left[(1 - z) \times LHV_{bioethanol} + z \times LHV_{biogas}\right]} \quad (1)$$

where $BTE_{dual\text{-}fuel}$ is the brake thermal efficiency of the DFSIE; P is the vehicle power, in kW; $\dot{m}_{biogas}$ is the biogas flow required, in kg/s; LHV_{biogas} is the low heating value of biogas, in kJ/kg; $LHV_{bioethanol}$ is the low heating value of bioethanol, in kJ/kg; z represents the proportion of bioethanol replaced by biogas, whose value varies between 0 and 100%, with $z = 0\%$ normal operation with ethanol and $z > 0\%$ dual-fuel mode operation with biogas. According to da Costa et al. (2020), the $BTE_{dual\text{-}fuel}$ is 36.1% for $z = 50\%$,

considering wide-open throttle (WOT) and 1800 rpm in the spark-ignition engine.

The bioethanol mass flow rate, in kg/s, of the DFSIE can be obtained from Eq. (2).

$$\dot{m}_{\text{bioethanol}} = \frac{\frac{P}{\text{BTE}_{\text{dual−fuel}}} − \left(\dot{m}_{\text{biogas}} \times \text{LHV}_{\text{biogas}}\right)}{\text{LHV}_{\text{bioethanol}}} \tag{2}$$

Energy efficiency of series PHEV

The energy efficiency is the amount of energy needed to complete a process. It means that the less energy is needed, the greater is the vehicle's efficiency. For each operating mode of the series PHEV, the energy efficiency is calculated in a different way depending on each transmission power, as shown in the following items.

Electric vehicle mode — 1 motor

In this operating mode, the electric motor (EM) depends on the power provided by the battery. So, the transmission power is calculated considering the battery power that passes through the EM, as shown in Eq. (3).

$$\eta_{trans} = \frac{P_{trans,EVM−1M}}{P_{bat} \times \eta_{EM}} \tag{3}$$

where η_{trans} is the transmission efficiency; $P_{\text{trans, EVM−1M}}$ is the EVM-1M transmission power, in W; P_{bat} is the battery power that supplies the EM, in W; η_{EM} is the EM efficiency. The battery power can be calculated through Eq. (4).

$$P_{bat} = \frac{C_{bat}}{R_{bat}} \times S_{av} \tag{4}$$

where C_{bat} is the battery capacity, in Wh; R_{bat} is the battery range, in km; and S_{av} is the average speed, adopted as 40 km/h in urban roads (CTB 2022).

In the EVM-1M, the only energy needed is provided by the charger that supplies the battery. Then, the EVM-1M energy efficiency can be calculated through Eq. (5).

$$\eta_{EVM−1M} \frac{P_{trans,\ EVM−1M}}{P_{charger}} \tag{5}$$

where P_{charger} is the charger power, in W, which can be calculated by dividing P_{bat} by the battery efficiency (η_{bat}), as shown in Eq. (6).

$$P_{charger} = \frac{P_{bat}}{\eta_{bat}} \tag{6}$$

Electric vehicle mode — 2 motor

In the EVM-2M, the EM depends on the power provided by the battery, but also the generator power, which operates as an auxiliary motor. Thus, the transmission power is calculated considering the battery and generator power, and the EM efficiency, as shown in Eq. (7).

$$\eta_{trans} = \frac{P_{trans,EVM−2M}}{\left(P_{bat} + P_{gen}\right) \times \eta_{EM}} \tag{7}$$

where $P_{\text{trans, EVM−2M}}$ is the EVM-2M transmission power, in W; P_{gen} is the generator power, in W.

In this operating mode, the EM is powered by the energy provided by the charger and the generator power. So, the EVM-2M energy efficiency can be calculated through Eq. (8):

$$\eta_{EVM−2M} = \frac{P_{trans,EVM−2M}}{P_{charger} + P_{gen}} \tag{8}$$

Extended-range mode — 1 motor

In this operating mode, the EM is mainly powered by the energy provided by the engine, and the battery supplies the EM when an auxiliary power is needed. So, the transmission power is calculated considering the power provided by the ICE that passes through the generator, which converts the mechanical energy into electrical energy and supplies the EM, as shown in Eq. (9).

$$\eta_{trans} = \frac{P_{trans,ERM−1M}}{\left(P_{ICE} + \eta_{gen}\right) \times \eta_{EM}} \tag{9}$$

where P_{ICE} is the ICE power, in W; $P_{\text{trans, ERM−1M}}$ is the ERM-1M transmission power, in W; η_{gen} is the generator efficiency.

For this operating mode, the EM is powered by the energy supplied by the fuel consumption and small power supplied by the charger, adopted as 30%. So, the ERM-1M energy efficiency can be calculated as shown in Eq. (10).

$$\eta_{ERM−1M} = \frac{P_{trans,ERM−1M}}{1000 \times \left(\dot{m}_{biogas} \times LHV_{biogas} + \dot{m}_{bioethanol} \times LHV_{bioethanol}\right) + 0.3 \times P_{charger}} \tag{10}$$

where $P_{\text{trans, ERM−1M}}$ is the ERM-1M transmission power, in W; P_{charger} is the charger power, in W; 0.3 is the lower power supplied by the charger, which is provided to the electric motor by the battery.

Extended-range mode — 2 motor

In the ERM-2M, the EM is powered by the ICE and by the generator, which turns to operate as an auxiliary motor

supplied by the battery. So, the transmission power in this mode ($P_{\text{trans, ERM}-2M}$), in W, can be calculated as shown in Eq. (11).

$$\eta_{trans} = \frac{P_{trans,ERM-2M}}{(P_{ICE} + P_{gen} + P_{bat}) \times \eta_{EM}} \qquad (11)$$

In this operating mode, the series PHEV is powered by the fuel consumption in the ICE, and by a small power provided by the charge that supplies the generator and the EM. Thus, the energy efficiency of the series PHEV operating on ERM-2M ($\eta_{\text{ERM}-2M}$) considers the energy supplied by the fuel consumption, the generator power and a small power provided by the charge, as shown in Eq. (12).

$$\eta_{ERM-2M} = \frac{P_{trans,ERM-2M}}{1000 \times (\dot{m}_{biogas} \times LHV_{biogas} + \dot{m}_{bioethanol} \times LHV_{bioethanol}) + P_{gen} + 0.3 \times P_{charger}} \qquad (12)$$

Simulation of the combustion using GASEQ

Through the simulation using GASEQ software, it was possible to evaluate the combustion reaction of gasoline A (Eq. 13), bioethanol (Eq. 14) and biogas with 60% CH_4 and 40% CO_2 (Leme and Seabra 2017) (Eq. 15), considering an air excess coefficient equal to 30%, for gasoline-air and bioethanol-air mixtures, and 40% for biogas-air mixture (Coronado et al. 2009). The fuel-air mixture for gasoline, bioethanol and biogas was analysed separately and after was applied the proportion of each fuel, considering SFSIE BTE for gasoline A and Brazilian gasoline (27% ethanol), and DFSIE BTE for bioethanol and biogas.

$$C_8H_{18} + 16.25(O_2 + 3.773\,N_2) \rightarrow 8.0CO_2 + 3.60O_2 \\ + 8.93H_2O + 61.16N_2 + 0.30NO_x \qquad (13)$$

$$C_2H_5OH + 3.90(O_2 + 3.773\,N_2) \rightarrow 1.86CO_2 \\ + 0.86O_2 + 2.88H_2O + 14.64N_2 + 0.16NO_x \qquad (14)$$

$$0.60CH_4 + 0.40CO_2 + 1.6(O_2 + 3.773\,N_2) \rightarrow CO_2 \\ + 0.39O_2 + 1.20H_2O + 6.03N_2 + 0.02NO_x \qquad (15)$$
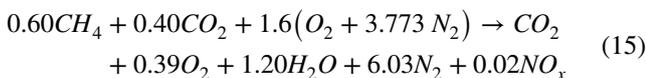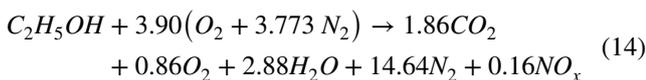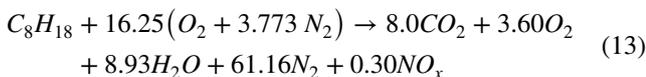
Energy-ecological efficiency

The energy-ecological efficiency (ε) is the name of the method proposed by Cârdu and Baica (2001) (Eq. 16) to consider the potential of air pollution and the efficacy in converting fuel into energy (Carneiro and Gomes 2019). Through this method, it is possible to estimate the human toxicity and the global warming indicators, as shown in Eqs. (17) and (18).

$$\varepsilon = \left[c\,\frac{\eta}{\eta + \Pi} \ln(K \pm \Pi) \right]^n \qquad (16)$$

$$\Pi_{GW} = \frac{f_{CO2\,eq}}{LHV_{fuel}} \qquad (17)$$

$$\Pi_{HT} = \frac{f_{1,4DCBeq}}{LHV_{fuel}} \qquad (18)$$

where Π_{GW} considers the emissions that contribute to global warming, expressed in kg $_{\text{eq pollutant}}$/MJ$_{\text{fuel}}$; and Π_{HT} considers the emissions that contribute to human toxicity, expressed in kg 1.4DCB$_{\text{eq}}$/kg$_{\text{fuel}}$, where 1.4-dichlorobenzene is a substance used to calculate the level of human toxicity (Carneiro and Gomes 2019). The equivalent carbon dioxide emission factor ($f_{CO2\,eq}$) and the equivalent 1.4-dichlorobenzene emission factor ($f_{1,4DCBeq}$) can be calculated through Eqs. (19) and (20), as follows:

$$f_{CO2\,eq} = f_{CO2} + 28f_{CH4} + 265f_{N2O} \qquad (19)$$

$$f_{1,4DCBeq} = 4.54f_{SO2} + 56.71f_{NOx} + 38.75f_{PM} \qquad (20)$$

The specie emission factor (f_{specie}) is the emission factor of each species resulting from the combustion of the air-fuel mixture, in kg$_{\text{specie}}$/kg$_{\text{fuel}}$, calculated by Eq. (21):

$$f_{\text{specie}} = \frac{(n_{\text{specie}} \times W_{\text{specie}})}{(n_{\text{fuel}} \times W_{\text{fuel}})} \qquad (21)$$

The pollution indicator, Π, is compounded by Π_{HT} and by Π_{GW} and is calculated through Eq. (22), expressed in kg$_{\text{eq pollutant}}$/MJ$_{\text{fuel}}$:

$$\Pi = 0.742\,\Pi_{HT} + 0.258\,\Pi_{GW} \qquad (22)$$

Finally, the energy-ecological efficiency can be obtained through Eq. (23), applying c, K and n constant values considered by Carneiro and Gomes (2019):

$$\varepsilon = \left[2.01\,\frac{\eta}{\eta + \Pi} \ln(1.645 \pm \Pi) \right]^{1.7} \qquad (23)$$

Well-to-pump, tank-to-wheel, well-to-wheel emissions and electricity mix

The WTW emissions consider the emission since the sugarcane plantation until the consumption by the vehicle and its exhaust gases. To calculate the WTW emissions, the WTP and the TTW were evaluated and then summed. As the vehicle analysed in this study is a series

Table 1 Inputs and outputs inserted to create the "Brazilian Sugarcane to 1G2G Ethanol with Vinasse Allocation" process

Inputs	Value	Unit	Source type
Sugarcane straw	$2.21e^{-3}$	Ton	Primary resource
Sugarcane bagasse	$7.21e^{-3}$	Ton	Primary resource
Sugarcane	$4.67e^{-2}$	Ton	Output of a previous process
Lime (CaO)	$4.11e^{-5}$	Ton	Pathway: lime production from limestone
Residual oil	$3.00e^{-3}$	mmBTU	Pathway: residual oil (petroleum) from crude oil
Outputs	Value	Unit	
Ethanol (main output)	1.00	Gal	Losses: 0%
Vinasse	$4.73e^{-2}$	m^3	Energy-based allocation factor: 0.0%

Table 2 "Ethanol transportation to refuelling station – produced and used in Brazil" process

Transportation	Distance value	Unit	Origin–destination	Fuel
Heavy-duty truck	380	mi	Ethanol plant–bulk terminal–refuelling station	Conventional diesel from the USA to Brazil

PHEV, the electricity mix generation emissions will also be summed in the WTW results. First, the Brazilian sugarcane bioethanol and biogas production pathway were analysed through GREET software to simulate the emissions of the sugarcane plantation and the bioethanol and biogas production until their availability at the supply pump. Then, the TTW were analysed considering the point where the vehicle is filled with fuel until the exhaust gases are discarded. Three electricity mixes were considered to calculate the electric vehicle mode emissions.

Well-to-pump emissions

The GREET software was used to analyse the WTP emissions from Brazilian sugarcane bioethanol and biogas production pathways. The measure units are in the international measurement system only for simulation proposes. First, the Brazilian sugarcane bioethanol production was simulated through the existing process on GREET named as "Brazilian Sugarcane to Ethanol with Electricity Export". This process was changed to "Brazilian Sugarcane to 1G2G Ethanol with Vinasse Allocation" and the inputs and outputs applied to create it are shown in Table 1, considering 1 gal of ethanol. The lime was added for pH adjustment proposes of the sugarcane juice. Thus, the pathway for ethanol production from sugarcane with vinasse co-production was created. After that, a process was created to simulate the transportation of the ethanol produced in Brazil to the refuelling station and then was named as "Ethanol transportation to refuelling station – produced and used in Brazil" (Table 2). For this process, the conventional diesel that powers the heavy-duty

Table 3 Resources added to create the sugarcane biogas production pathway

Resource	LHV (MJ/kg)	Density (kg/m^3)	Carbon ratio (%)	Sulphur ratio (%)
Vinasse	-	1.031	1.960	0.0142
Vinasse biogas	27.4	0.784	0.558	0.0189

trucks was considered to be imported from the USA to Brazil because of its amount imported into Brazil in 2019, which was 10,778,100 m^3 while the national production was 40,914,849 m^3 (Brazilian Agency of Petrol Natural Gas and Biofuels - ANP 2019). Thus, the US Diesel was used to prioritize the diesel produced in Brazil for its own consumption by Brazilian fleets from other segments, so that there is no shortage of this fuel. The emissions caused by the transportation process was calculated automatically by the GREET software, considering the values included in its database, and added in the WTP emissions.

To create the sugarcane biogas production pathway, the resources were added to the GREET database, as shown in Table 3. The proportion of 12.5 m^3 vinasse/m^3 ethanol and the vinasse allocation factor of 0.94 were considered. The "biogas production from Vinasse via anaerobic digestion" process was created considering the proportion of 23.72 m^3 biogas/m^3 vinasse, as shown in Table 4. The biogas transportation is conducted from the sugarcane bioethanol plant to the refuelling station via pipeline, which natural gas pipeline parameters were reused for biogas, considering 50 miles, approximately, with 14% urban share. Thus, the "Vinasse Biogas Production to Brazilian Refuelling Station" pathway was created.

Table 4 "Biogas production from vinasse via anaerobic digestion" process

Inputs	Value	Unit	Source type
Electricity	0.46	kWh	Single pathway: distributed — Brazil mix
Vinasse	$1.04e^{-6}$	km^3	Output of a previous process
Outputs	Value	Unit	
Biogas	$2.74e^{-5}$	km^3	Losses: 2% (evaporation: 60% CH_4; 40% CO_2)

Finally, the WTP emissions for sugarcane bioethanol and biogas were calculated through Eqs. (24) and (25), respectively. For bioethanol, the emissions since the production until the transport were considered. For biogas, the percentage of losses of 0–2% (Afrane and Ntiamoah 2011) during the production stage was considered.

$$WTP_{bioethanol} = \frac{fCO_{2 \text{ eq bioethanol}} \times E_{consump}}{LHV_{bioethanol} \times \rho_{bioethanol}} \quad (24)$$

$$WTP_{biogas} = \left(\frac{fCO_{2 \text{ eq trans biogas}} \times E_{consump}}{LHV_{biogas} \times \rho_{biogas}} \right) + \%Losses \times \left(\frac{fCO_{2 \text{ eq prod biogas}} \times E_{consump}}{LHV_{biogas} \times \rho_{biogas}} \right) \quad (25)$$

where $WTP_{bioethanol}$ is the WTP emissions related to the sugarcane bioethanol production, in $gCO_{2 \text{ eq}}/km$; $fCO_{2 \text{ eq bioethanol}}$ is the equivalent $CO_{2 \text{ eq}}$ emission factor of the bioethanol production, in $kgCO_{2 \text{ eq}}/m^3$ bioethanol; $\rho_{bioethanol}$ is the bioethanol density, in kg/m^3; WTP_{biogas} is the WTP emissions related to the vinasse biogas, in $gCO_{2 \text{ eq}}/km$; $fCO_{2 \text{ eq trans biogas}}$ is the equivalent $CO_{2 \text{ eq}}$ emission factor of the biogas transportation, in $kgCO_{2 \text{ eq}}/m^3$ biogas; ρ_{biogas} is the vinasse biogas density, in kg/m^3; %Losses is the percentage of losses during the biogas production process; $fCO_{2 \text{ eq prod}}$ is the $CO_{2 \text{ eq}}$ emission factor of the biogas production, in $kgCO_{2 \text{ eq}}/m^3$ biogas. The $E_{consump}$ is the energy consumed by the ICE of the Chevrolet Volt, considering gasoline A as fuel, according to the manufacturer's specifications, and can be expressed through Eq. (26).

$$E_{consump} = \frac{LHV_{gasoline A} \times \rho_{gasoline A} \times FC_{gasoline A}}{1000} \quad (26)$$

where $E_{consump}$ is the energy consumption needed by the ICE, in MJ/km; $LHV_{gasoline A}$ is the low heating value of the

gasoline A, in MJ/kg; $\rho_{gasoline A}$ is the gasoline A density, in kg/m^3; $FC_{gasoline A}$ is the gasoline A consumption provided by the manufacturer, in l/km.

Tank-to-wheel emissions

The TTW emissions of the SFSIE and the DFSIE can be calculated considering the fuel consumption, the $f_{CO2 \text{ eq}}$ related to fuel combustion and the fuel density, as shown in Eqs. (27) and (28), respectively.

$$TTW_S = f_{CO2 \text{ eq fuel}} \times \rho_{fuel} \times FC_{fuel} \quad (27)$$

$$TTW_D = z \left(f_{CO2 \text{ eq biogas}} \times \rho_{biogas} \times FC_{biogas} \right) + y \left(f_{CO2 \text{ eq bioethanol}} \times \rho_{bioethanol} \times FC_{bioethanol} \right) \quad (28)$$

where TTW_S is the tank-to-wheel emissions of the SFSIE, in gCO_{2eq}/km; $f_{CO2 \text{ eq fuel}}$ is the equivalent $CO_{2 \text{ eq}}$ emission factor which resulted from the fuel combustion, in $kgCO_{2 \text{ eq}}/kg$ fuel; ρ_{fuel} is the fuel density, in kg/m^3; FC_{fuel} is the fuel consumption, in l/km; TTW_D is the DFSIE tank-to-wheel emissions, in gCO_{2eq}/km; FC_{biogas} is the vehicle biogas consumption, in l/km, $FC_{bioethanol}$ is the vehicle bioethanol consumption, in l/km; z is the biogas proportion replacing bioethanol; y is the proportion of bioethanol in the dual-fuel mode ($y = 1 - z$). For TTW emissions of SFSIE, the proportion of bioethanol replaced is zero, so z is equal to 0. For TTW emissions of DFSIE, the z value applied is 50% as considered by da Costa et al. (2020).

As previously said, the fuel consumption provided by Chevrolet is related to the gasoline A consumption. So, it is necessary to calculate the bioethanol consumption in the ICE through the energy consumption calculated previously in Eq. (26). Then, the bioethanol and biogas consumptions were measured individually through the energy needed in the ICE, as shown in Eq. (29).

$$FC_{fuel} = \frac{1000 \times E_{consump}}{LHV_{fuel} \times \rho_{fuel}} \quad (29)$$

For comparative purposes, the fuel consumption and the TTW emissions will be calculated for Brazilian gasoline (27% ethanol) through Eqs. (30) and (31), respectively.

$$FC_{BR \text{ gasol}} = \frac{1000 \times E_{consump}}{0.73 \left(LHV_{gasoline A} \times \rho_{gasoline A} \right) + 0.27 \left(LHV_{bioethanol} \times \rho_{bioethanol} \right)} \quad (30)$$

$$TTW_{BR\ gasol} = \left[0.73\left(f_{CO2\ eq\ gasoline\ A} \times \rho_{gasoline\ A}\right) + 0.27\left(f_{CO2\ eq\ bioethanol} \times \rho_{bioethanol}\right)\right] \times FC_{BR\ gasol} \qquad (31)$$

where $FC_{BR\ gasol}$ is the vehicle Brazilian gasoline consumption, in l/km; $TTW_{BR\ gasol}$ is the TTW emissions of the Brazilian gasoline, in $gCO_{2\ eq}$/km.

Electricity mix

In this item, the electricity mix emissions were analysed for the series PHEV Chevrolet Volt, considering its electrical energy consumption of 0.202 kWh/km and three electricity mixes: Brazil electricity mix, Spain electricity mix and EU electricity mix. According to EPE (2020b), the Brazilian mix generated about 83,361 GWh of electricity from coal, natural gas, oil-fuel and diesel oil, emitting 416.3 gCO_{2eq}/kWh, in 2019, referred to as the national interconnected system. In the same year, the Spanish mix emitted 190 gCO_{2eq}/kWh, considering the electricity generation (REE 2020). IRENA (2018) provided the EU electricity mix emission of 75 gCO_{2eq}/km. Through these data, the electricity mix emissions can be calculated by Eq. (32). The data for Brazil, Spain and EU was provided by differents agents, considering the most recent ones. As the year of each data is different, the calculation will show approximate results, seeking to highlight the importance of clean energy in the country and the reduction of emissions in the electricity sector.

$$E_{electricity\ mix} = fCO_{2\ eq\ electric\ mix} \times EE_{consump} \qquad (32)$$

where $E_{electricity\ mix}$ is the electricity mix emissions, in $gCO_{2\ eq}$/km; $fCO_{2\ eq\ electric\ mix}$ is the $CO_{2\ eq}$ emission factor of the electricity mix, in gCO2eq/kWh; $EE_{consump}$ is the electrical energy consumption of the series PHEV Chevrolet Volt, in kWh/km.

Parameters and considerations adopted in the study

The considerations and parameters adopted in this study to determine the energy efficiency of the series PHEV and evaluate the replacement of the SFSIE fuelled with gasoline by the DFSIE fuelled with sugarcane biogas and bioethanol are presented in Table 5.

Results and discussion

In this study, the mass flow rate of bioethanol and biogas was calculated, and the energy efficiency of each series PHEV operating mode was determined. The emission factors were determined to calculate the energy-ecological efficiency and the TTW emissions of the series PHEV with the DFSIE fuelled with sugarcane bioethanol and biogas. Besides that, the

WTP emissions were analysed by using the GREET software to simulate the Brazilian sugarcane bioethanol and biogas production pathways. The electrical energy emissions were calculated considering the Brazil, Spain and European Union electricity mixes, and then the WTW emissions were evaluated.

Bioethanol and biogas mass flows in dual-fuel mode

The bioethanol and biogas mass flows in the DFSIE were calculated, considering the z value equal to 50%. The simulation can be done with any other z value, but the 50% ratio was applied in this study because of the $BTE_{dual-fuel}$ calculated by da Costa et al. (2020), which considered 50% bioethanol and 50% biogas. Equation (1) was applied to calculate the biogas mass flow of the DFSIE, adopting 36.1% $BTE_{dual-fuel}$ (da Costa et al. 2020). Then, the bioethanol mass flow was measured through Eq. (2). The values found for bioethanol and biogas mass flows were 0.00375 kg/s or 13.49 kg/h, each.

Energy efficiency of series PHEV

As explained in the previous items, the operating modes of the series PHEV depend on the sources that power each mode. Thus, the transmission power and the energy efficiency were calculated for each operating mode through Eqs. (3), (4), (5), (6) (7), (8), (9), (10), (11) and (12), and the results are shown in Table 6. In EVM-1M, the high efficiency can be explained by the direct conversion of the electrical power into mechanical power, approaching the efficiency of a purely electric vehicle. The EVM-2M presented greater efficiency than the EVM-1M because of the assistance of the generator power, which turns the ring gear and provides mechanical energy to the EM. In the case of the ERM-1M, the efficiency falls sharply due to the conversion of mechanical-electrical-mechanical power provides by the engine-generator-motor-transmission gear set. Finally, in the ERM-2M, the energy efficiency increased by 14.7% due to the combination of the ICE and the generator, resulting from the synchronization of both speeds.

Simulation on GASEQ and pollution indicators

The bioethanol-air, biogas-air and gasoline A-air mixtures were analysed separately through simulation of Eqs. (13), (14) and (15) on the GASEQ software to evaluate the pollution indicators of each mixture. Tables 7, 8 and 9 show the reactants and product species of each simulation and the emission factors of the products related to the global

Table 5 Parameters and considerations adopted

Parameter	Value	Unit	Reference
Density — anhydrous ethanol	791	kg/m^3	ANP (2019)
Density — sugarcane vinasse	1031	kg/m^3	Prasad and Shih (2016)
Density — vinasse biogas	0.784	kg/m^3	Neto et al. (2017)
Density — gasoline A	742	kg/m^3	ANP (2019)
Density — Brazilian gasoline	754	kg/m^3	ANP (2019)
Sulphur ratio —– sugarcane vinasse	0.0142	%	Rahman et al. (2018)
Sulphur ratio — vinasse biogas	1.89	%	Rahman et al. (2018)
Carbon ratio — sugarcane vinasse	1.955	%	Siles et al. (2011)
Carbon ratio — vinasse biogas	55.84	%	Leme and Seabra (2017)
LHV — anhydrous ethanol	28,261	kJ/kg	ANP (2019)
LHV — vinasse biogas	27,400	kJ/kg	Calculated by the authors
LHV — gasoline A	43,543	kJ/kg	ANP (2019)
LHV — Brazilian gasoline	39,356	kj/kg	ANP (2019)
Proportion of vinasse from ethanol	12.5	m^3/m^3 ethanol	Christofoletti et al. (2013)
Proportion of biogas from vinasse	23.72	m^3 biogas/m^3 vinasse	Parsaee et al. (2019)
Allocation factor	0.94	-	Calculated by the authors
Power — electric motor	111.109	W	Chevrolet
Power — engine	75,316	W	Chevrolet
Power — generator	53,690	W	Chevrolet
Transmission efficiency	80	%	Xue et al. (2014)
Battery efficiency	90	%	Fathabadi (2018)
Electric motor efficiency	85	%	Xue et al. (2014)
Generator efficiency	85	%	Xue et al. (2014)
Battery capacity	18,400	Wh	Chevrolet
All-electric range	85	km	Chevrolet
Electric energy consumption	0.202	kWh/km	Chevrolet
Average speed	40	km/h	CTB (2022)
Fuel consumption — gasoline	0.0630	l/km	Chevrolet
Molecular weight — gasoline	114	g	-
Molecular weight — ethanol	46	g	-
Molecular weight — biogas	60	g	-
Constant — c	2.01	-	Carneiro and Gomes (2019)
Constant — K	1.645	-	Carneiro and Gomes (2019)
Constant — n	1.7	-	Carneiro and Gomes (2019)
Air excess coefficient — biogas	40	%	Coronado et al. (2009)
Air excess coefficient — bioethanol	30	%	Coronado et al. (2009)
Air excess coefficient — gasoline A	30	%	Coronado et al. (2009)
ϕ — gasoline-air	0.77	-	Calculated by the authors
ϕ — bioethanol-air	0.77	-	Calculated by the authors
ϕ — biogas-air	0.75	-	Calculated by the authors
Z value	50	%	da Costa et al. (2020)
$BTE_{dual\text{-}fuel}$ (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 (2020b)
Spain electricity mix	190	gCO$_{2eq}$/kWh	REE (2020)
EU electricity mix	75	gCO$_{2eq}$/kWh	IRENA (2018)
% Losses during biogas production	0–2	%	Afrane and Ntiamoah (2011)

Table 6 Transmission power and energy efficiency of the series PHEV operating modes

Operating mode	Parameter	Value	Unit
EVM-1M	$P_{\text{trans, EVM}-1\text{M}}$	5888	W
	$\eta_{\text{EVM}-1\text{M}}$	61.3	%
EVM-2M	$P_{\text{trans, EVM}-2\text{M}}$	42,397	W
	$\eta_{\text{EVM}-2\text{M}}$	67.0	%
ERM-1M	$P_{\text{trans, ERM}-1\text{M}}$	43,533	W
	$\eta_{\text{ERM}-1\text{M}}$	20.6	%
ERM-2M	$P_{\text{trans, ERM}-2\text{M}}$	93,612	W
	$\eta_{\text{ERM}-2\text{M}}$	35.3	%

Table 7 Reactants and products, and specie emission factors of the bioethanol-air mixture combustion

Reactants	No. moles	Mol. weight	
C_2H_5	1.00	29	
OH	1.00	17	
O_2	3.90	32	
N_2	14.71	28	
Products	No. moles	Mol. weight	f_{specie}
CO_2	1.86	44	1.78062
CH_4	0.00	16	$1.33461e^{-17}$
N_2O	0.00	44	$7.17009e^{-05}$
SO_2	0.00	64	0
NO_x	0.16	30	0.10326
PM	0.00	12	0

Table 8 Reactants and products, and specie emission factors of the biogas-air mixture combustion

Reactants	No. moles	Mol. weight	
CH_4	0.60	16	
CO_2	0.40	44	
O_2	1.60	32	
N_2	6.04	28	
Combustion products	No. moles	Mol. weight	f_{specie}
CO_2	1.00	44	1.61571
CH_4	0.00	16	$6.96471e^{-23}$
N_2O	0.00	44	$1.40849e^{-06}$
SO_2	0.00	64	0
NO_x	0.02	30	0.019929
PM	0.00	12	0

Table 9 Reactants and products, and specie emission factors of the gasoline A-air mixture combustion

Reactants	No. moles	Mol. weight	
C_8H_{18}	1.00	114	
O_2	16.25	32	
N_2	61.31	28	
Combustion products	No. moles	Mol. weight	f_{specie}
CO_2	7.95	44	3.06841
CH_4	0.00	16	$1.00281e^{-20}$
N_2O	0.00	44	$5.63895e^{-06}$
SO_2	0.00	64	0
NO_x	0.30	30	0.07831
PM	0.00	12	0

Table 10 Carbon dioxide and 1.4-dichlorobenzene equivalent factors of the fuels analysed

Fuel	$f\,CO_{2\,\text{eq}}$ (kg $CO_{2\,\text{eq}}$/kg fuel)	$f\,1.4\text{-DCB}_{\text{eq}}$ (kg 1–4 DCB_{eq}/kg fuel)
Gasoline A	3.0699	4.4411
Brazilian gasoline	2.7223	4.8232
Bioethanol	1.7825	5.8561
Biogas	1.6161	1.1302
50% bioethanol + 50% biogas	1.6993	3.4931

warming and human toxicity indicators that were determined through Eq. (21).

Equations (19) and (20) were applied to calculate the $f_{\text{CO2 eq}}$ and the $f_{1,\,4\text{DCBeq}}$. Table 10 shows the values found for bioethanol, biogas, 50% bioethanol + 50% biogas, gasoline A and Brazilian gasoline. As can be seen, the

highest $f_{\text{CO2 eq}}$ value was found for gasoline A due to the number of moles of CO_2 resulting in its combustion, with negligible value of CH_4 and N_2O. On the other hand, the bioethanol presented the highest $f_{1,\,4\text{DCBeq}}$ value. It is because of the f_{N2O} produced by combustion of bioethanol that had the highest value among the N_2O factors found for the other fuels.

Through these values, the Π_{GW} and the Π_{HT} were calculated through Eqs. (17) and (18), and then the pollution indicator was measured through Eq. (22). The results are shown in Fig. 5. As expected, gasoline A and Brazilian gasoline resulted in the highest Π_{GW} values due to their highest $f_{\text{CO2 eq}}$ value, being 15.5% and 12.2% higher than the value found for 50% bioethanol + 50% biogas. The bioethanol presented the highest Π_{HT} value, which is twice higher than gasoline A and 58.9% higher than Brazilian gasoline. Also, the Π_{HT} value found for bioethanol was 66.8% higher than that found for 50% bioethanol + 50% biogas, which application is the propose of this study. In the case of biogas, the lowest Π_{HT} and Π_{GW} were found, which were 66.8% and 3.3% lower than those values found for 50% bioethanol + 50% biogas, respectively.

The highest Π value was found for bioethanol, 57.5% higher than that found for 50% bioethanol + 50% biogas due

Fig. 5 Human toxicity, global warming and pollution indicators found for different fuels analysed
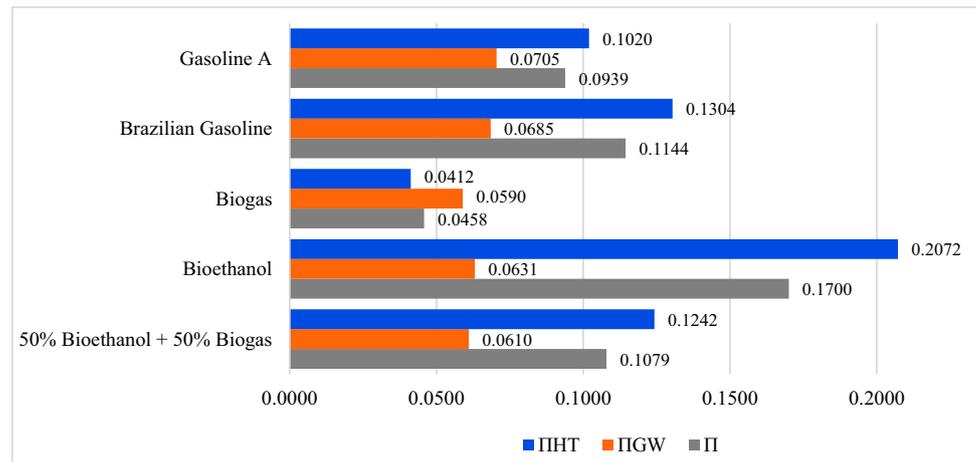
to its Π_{HT} value, which compounds 74.2% of the Π. On the other hand, as expected, the biogas presented the lowest Π value, which is 73%, 60% and 51.2% lower than those found for bioethanol, Brazilian gasoline and gasoline A, respectively. The 50% bioethanol + 50% biogas resulted in a Π value 15% higher than that found for gasoline A, but it was 5.7% lower when compared to the Brazilian gasoline. Thus, the DFSIE fuelled with 50% bioethanol and 50% biogas can contribute to reducing the GHG that aggravates the effects caused to human toxicity and global warming.

Energy-ecological efficiency in the series PHEV

The energy-ecological efficiency (ε) was calculated for series PHEV through Eq. (23) proposed by Carneiro and Gomes (2019), considering the SFSIE fuelled with gasoline A and Brazilian gasoline, and the DFSIE fuelled with 50% bioethanol and 50% biogas. In Brazil, the ICEV is also fuelled with ethanol, so the bioethanol was also analysed fuelling the SFSIE to comparison

proposes. It is important to highlight that the biogas only was simulated to determine the ε of the DFSIE, which has not been used as a main fuel.

First, the simulation was performed individually for each fuel-air mixture and after the percentage were applied, in case of the dual-fuel mode and the Brazilian gasoline. Figure 6 shows the ε of the SFSIE fuelled with gasoline A, Brazilian gasoline and bioethanol, and the DFSIE fuelled with 50% bioethanol and 50% biogas. In the latter, the proportion of 50% was multiplied to the bioethanol Π and then summed to the 50% biogas Π to determine the total Π and the ε of the DFSIE. For the Brazilian gasoline, 27% bioethanol was mixed in the gasoline, considering a SFSIE, then the Π and the ε were determined .

As can be seen, the highest ε value was found for the DFSIE due to the lowest level of species resulting from biogas combustion, even with the high species emission factors resulting from the bioethanol combustion, that threaten human health and the environment. The DFSIE

Fig. 6 Energy-ecological efficiency for different fuels in SFSIE and DFSIE
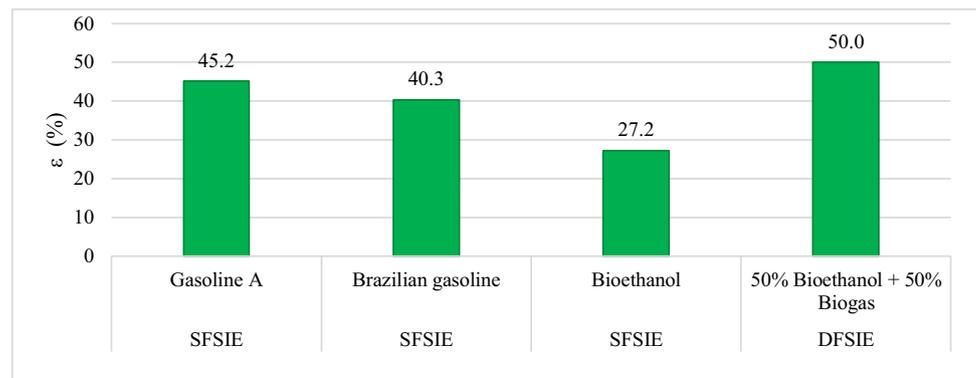
presented results that were 10.7% higher than gasoline A and 24.1% higher than the Brazilian gasoline, indicating that the proposal of this study is an alternative to reduce the negative impacts on the environmental and human health. However, bioethanol and biogas produced from sugarcane have a percentage of atmospheric CO_2 fixed during the growth of the plant, which is returned to the atmosphere after consumption, resulting in less negative impacts on the environment.

WTW emissions of series PHEV

From the analysis carried out through the GREET software, the WTP emissions from Brazilian sugarcane bioethanol and biogas production pathways were evaluated. Table 11 shows the CO_2, CH_4 and N_2O emission factors of the production and transportation of sugarcane bioethanol and biogas.

As previously said, the percentual of losses during the biogas production adopted is from 0 to 2%. To evaluate the

Fig. 7 Well-to-pump emissions of the biogas and bioethanol production, and of the consumption of 50% bioethanol and 50% biogas
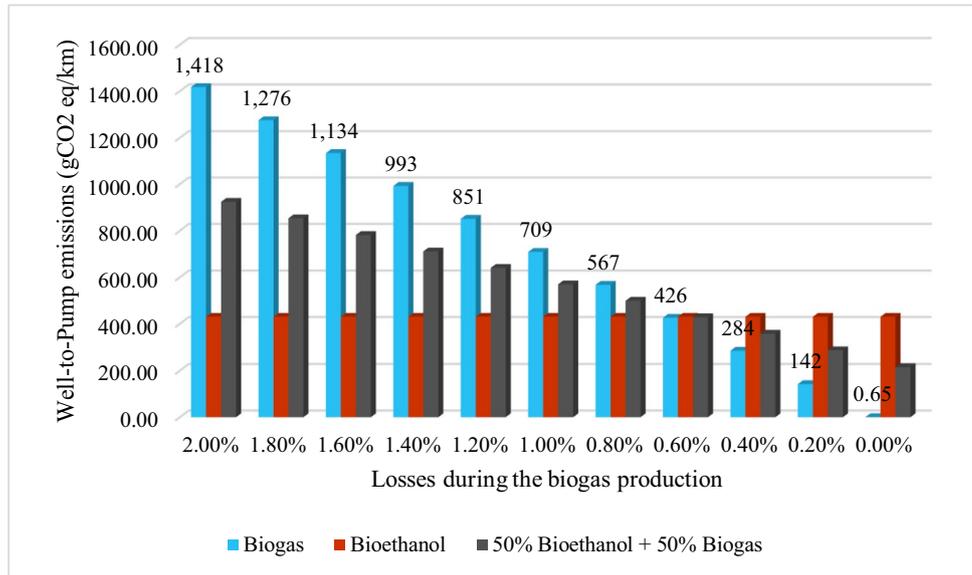
Fig. 8 TTW emissions for different fuels in series PHEV
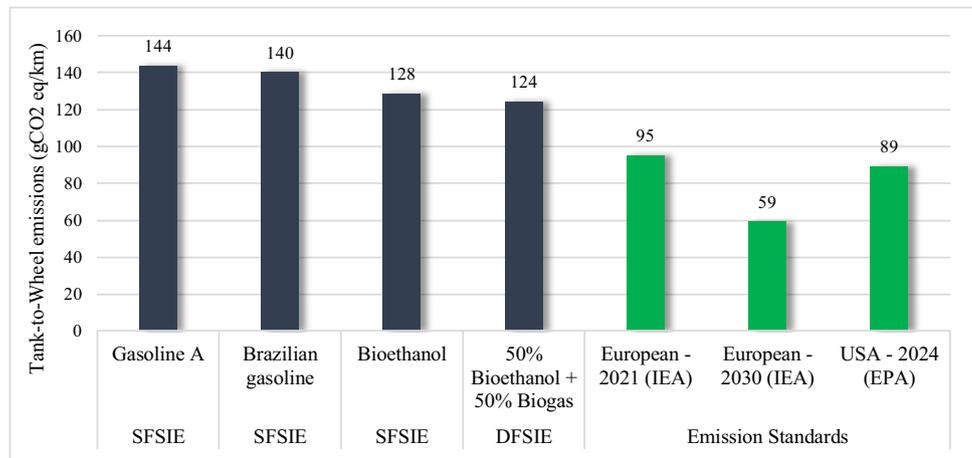
Table 11 Emission factors of the production and transportation of sugarcane bioethanol and biogas

Stage	$f\,CO_2$ (kgCO_2/m^3)	$f\,CH_4$ (kgCH_4/m^3)	$f\,N_2O$ (kg N_2O/m^3)
Bioethanol production	4.46e^{+3}	2.03e^0	5.84e^{-1}
Bioethanol transportation	5.00e^{+1}	6.00e^{-2}	0
Biogas production	1.74e^{+1}	2.61e^{+1}	6.00e^{-9}
Biogas transportation	4.80e^{-3}	7.07e^{-5}	1.34e^{-7}

WTP emissions of the biogas production (Eq. 25), and the bioethanol WTP emissions (Eq. 24), the energy consumption in the ICE fuelled with gasoline A was calculated in Eq. (26), which resulted in 2.04 MJ/km. In Fig. 7, it is possible to analyse the biogas and bioethanol WTP emissions and the WTP emissions when 50% bioethanol and 50% biogas are consumed. As can be seen, the percentage of losses during the biogas production process influences linearly the WTP emissions. Thus, the greater is the loss, the greater are the biogas WTP emissions, and consequently, the greater are the WTP emissions of the consumption of 50% bioethanol and 50% biogas in dual-fuel mode. It was assumed that no losses occurred during the bioethanol production process, so the bioethanol WTP emissions remain the constant value of 430 $gCO_{2\,eq}$/km. When 2% of biogas was lost during the production process, the biogas WTP emissions were 230% higher than the bioethanol WTP emissions. On the other hand, when the biogas production process presented 100% efficiency avoiding the losses during the process, the biogas WTP emissions would be eliminated, and the bioethanol WTP emissions resulted twice greater when compared to the dual-fuel mode. To match biogas WTP emissions with bioethanol WTP emissions, losses must be less than 0.6%, and consequently, less emissions will be achieved. Thus, the decreasing of the percentage of losses is the main way to reduce the WTP emissions during the vinasse biogas production.

Through Eqs. (27), (28) and (31), the TTW emissions of the SFSIE fuelled with gasoline A, the DFSIE fuelled with 50% bioethanol and 50% biogas and the SFSIE fuelled with Brazilian gasoline were determined. After that, Eq. (29) was applied to determine the biogas and bioethanol consumptions, and Eq. (30) was applied to determine the Brazilian gasoline consumption, since the gasoline A consumption was provided by the manufacturer. Table 12 shows the consumption found for each fuel and the TTW emissions are shown in Fig. 8. The biogas was analysed to illustrate the influence of its losses in the dual-fuel mode emissions, so it will not appear in the TTW and WTW emissions as the main fuel. It is observed that the DFSIE fuelled with bioethanol and biogas presented 15.5% and 12.8% less TTW emissions than the SFSIE fuelled with gasoline

A and Brazilian gasoline, respectively, indicating that the use of 50% biogas is an alternative to reduce the emissions caused by the DFSIE. Also, the SFSIE fuelled with bioethanol, nowadays, available in Brazilian refuelling stations, presented 3.4% more TTW emissions than the DFSIE. It happens because of the proportion of 50% biogas in DFSIE, which presents lower $CO_{2\,eq}$ emission factor, influencing the TTW emission results. Compared to the emission standards, the DFSIE presented TTW emissions 30.5% higher than the EU emission standard by 2021, while the SFSIE fuelled with gasoline A, Brazilian gasoline and bioethanol presented values 51.6%, 47.4% and 34.7% higher, respectively. Although the DFSIE does not meet any of the emission standards, this engine mode can be an alternative to at least reduce the tailpipe emissions. However, it is important to highlight that the DFSIE was fuelled with biofuels. Thus, this kind of fuel presents a percentage of carbon fixed through the photosynthetic reaction, which returns to the atmosphere after the plant consumption that may be deducted from the TTW emissions caused by the burn of bioethanol and biogas from sugarcane, resulting in less aggressiveness to the environment and human health. But it will be a purpose of a further work.

Three electricity generation mixes using coal, natural gas, oil-fuel and diesel oil as sources were analysed to determine the electricity mix emissions of the series PHEV Chevrolet Volt through Eq. (32), considering its electrical energy consumption. Table 13 shows the electricity mix emissions calculated for Brazil and Spain electricity mix, and for EU provided by IRENA (2018). The Spain electricity mix presented the lowest emission value, resulting in 48.8% less emissions than the EU electricity mix. According to REE (2020), 2.2% of the electricity in Spain was generated by fossil fuels and 4.9% by coal, in 2019, while in EU, these sources were responsible for the generation of 43% of the electricity needed for the set of countries belonging to the union in 2016, according to the last version of the European Environment Agency (EEA) report. The Brazil electricity mix resulted in 12% more emissions than the EU electricity mix. However, Brazil has a mainly renewable electrical matrix, which 64.9% of the electricity generated comes from hydroelectric plants (EPE 2020a), while the thermoelectric generation from coal and fossil fuels is responsible for only 6.4% of the national

Table 12 Fuel consumption of different fuels powering the ICE of the series PHEV

Fuel	Fuel consumption (l/km)
Gasoline A	0.0630
Brazilian gasoline	0.0686
Bioethanol	0.0911
Biogas	94.75

Table 13 Electricity mix emission values for different electricity mixes

Electricity mix	$E_{\text{electricity mix}}$ ($gCO_{2\,eq}$/km)
Brazil	84.1
Spain	38.4
European Union	75.0

Fig. 9 Well-to-wheel emissions of the sugarcane bioethanol and of the sugarcane bioethanol and vinasse biogas in dual-fuel mode
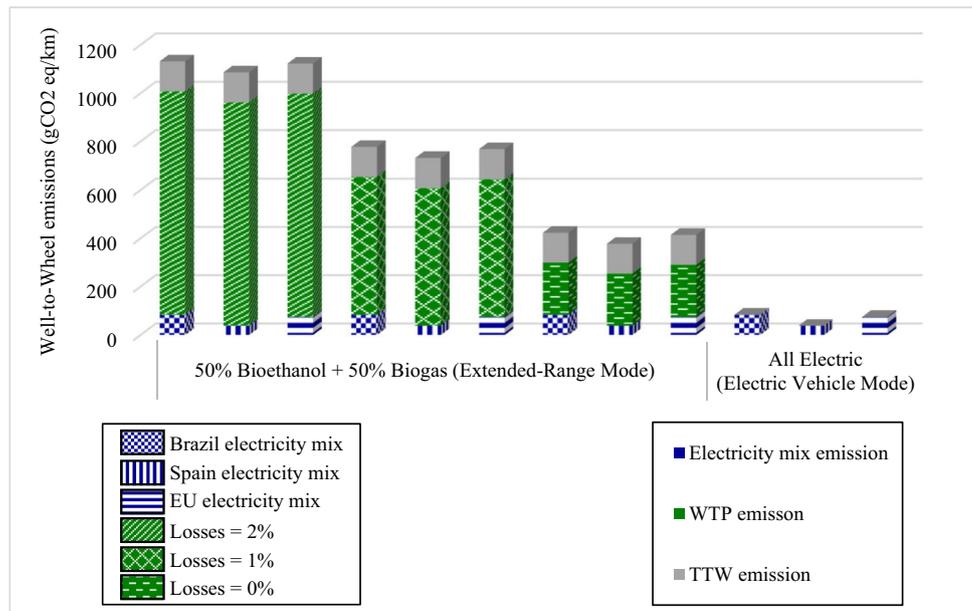
electricity generated (EPE 2020b). Besides that, Brazil presents 83% participation of renewable sources in the electrical matrix, while the world and the OECD presented 22% and 26%, respectively, in 2017 (EPE 2020a). So, if Brazil directs the electricity produced by the renewable electric matrix, it will be the least polluting among the three selected matrices.

Finally, the WTW emissions of the series PHEV were analysed through the sum of the WTP, TTW and the electricity mix emissions. For comparative proposes, the biogas WTP emissions considering 0%, 1% and 2% losses were selected to analyse the WTW emissions of the DFSIE. When the series PHEV operates in EVM, the only emissions are related to the electricity mix, as shown in Fig. 9. As can be seen, the DFSIE considering 2% losses in the biogas production process is responsible for the greatest WTW emission values, 62.2% and 329% higher than those values found for 1% and 0% losses. It is due to the higher biogas WTP emission, reinforcing the need to reduce losses during the biogas production. Considering the electricity mix, the series PHEV in ERM and EVM powered by the Spain electricity mix presented the lowest WTW emissions. On the other hand, Brazil generates only 1.3% of the national electricity from fossil fuels and, when considering the sugarcane production, Brazil takes the advantages due to its rank between the biggest sugarcane producer in the world.

Conclusion and further work

The results showed that the DFSIE fuelled with 50% bioethanol and 50% biogas can contribute to reducing the negative impacts to the environment. The energy-ecological efficiency of the DFSIE was 10.7% and 24.1% higher than that found for SFSIE fuelled with

gasoline and Brazilian gasoline, respectively. It is due to the pollution indicator of the biogas, 73%, 60% and 51.2% lower than those found for bioethanol, Brazilian gasoline and gasoline A, respectively. The percentage of losses during the vinasse biogas production aggravates linearly the WTP emissions, and consequently the WTW emissions, and is the main way to reduce these emissions. When 2% losses were considered, the biogas WTP emissions were 230% higher than the bioethanol WTP emissions. Otherwise, to match biogas WTP emissions with bioethanol WTP emissions, losses must be less than 0.6%, and consequently, less emissions will be achieved. Besides that, the dual-fuel mode powered by 50% bioethanol and 50% biogas presented 15.5% and 12.8% less TTW emissions than those found for the single-fuel mode powered by gasoline A and Brazilian gasoline, respectively. On the other hand, the dual-fuel mode presented TTW emissions 30.5% higher than the European Union emission standard provided by 2021. According to the results, the ICE in dual-fuel mode does not meet any of the emission standards, but this engine mode can be an alternative to at least reduce the tailpipe emissions. However, it is important to highlight that the DFSIE was fuelled with biofuels, which present a percentage of carbon fixed through the photosynthetic reaction, which returns to the atmosphere after the plant consumption, and may be deducted from the emissions caused by the burn of the biofuel. Among the tree electricity generation mixes analysed, the Spain electricity mix presented the lowest emissions value. The Brazil electricity mix resulted in 12% more emissions than the EU electricity mix. However, Brazil has a mainly renewable electrical matrix, while the thermoelectric generation from coal and fossil fuels was responsible for 6.4% of the national electricity generation. The comparison made in this study proved that the DFSIE fuelled with 50% bioethanol and 50% biogas is an alternative to replace the SFSIE fuelled with gasoline A or Brazilian gasoline, which presented higher energy-ecological efficiency, reducing the

negative impacts that aggravate the human toxicity and the global warming. For further work, the carbon fixation on the sugarcane plantation will be calculated and deducted to the emissions caused by the biofuels from sugarcane.

Nomenclature

%Losses: percentage of losses during the biogas production process; 1.4-DCB: 1.4-dichlorobenzene substance to calculate the human toxicity; $BTE_{dual-fuel}$: brake thermal efficiency of dual-fuel mode; c, K, n: constants (Eq. 16); C_2H_5: ethyl radical; C_8H_{18}: gasoline; C_{bat}: battery capacity, in Wh; CH_4: methane; CO_2: carbon dioxide; $CO_{2\,eq}$: equivalent carbon dioxide; $\mathcal{E}_{dual-fuel}$: energy-ecological efficiency of the dual-fuel mode; $E_{consump}$: energy consumption needed by the ICE of the Chevrolet Volt, in MJ/km; $EE_{consump}$: electrical energy consumption of the series PHEV Chevrolet Volt, in kWh/km; $E_{electricity\,mix}$: electricity mix emissions, in $gCO_{2\,eq}$/km; $f_{1.4-DCB\,eq}$: 1.4-dichlorobenzene emission factor, in kg 1.4-DCB_{eq}/kg_{fuel}; $FC_{bioethanol}$: vehicle bioethanol consumption, in l/km; FC_{biogas}: vehicle biogas consumption, in l/km; $FC_{BR\,gasol}$: vehicle Brazilian gasoline consumption, in l/km; FC_{fuel}: vehicle fuel consumption, in l/km; $FC_{gasoline\,A}$: vehicle gasoline A consumption, in l/km; $f_{CO2\,eq}$: equivalent carbon dioxide emission factor, in $kgCO_{2\,eq}$/kg_{fuel}; $f_{CO2\,eq\,bioethanol}$: equivalent carbon dioxide emission factor of the bioethanol production, in $kgCO_{2\,eq}$/m^3 bioethanol; $f_{CO2\,eq\,fuel}$: equivalent carbon dioxide emission factor resulted from the fuel combustion, in $kgCO_{2\,eq}$/kg_{fuel}; $f_{CO2\,eq\,trans\,biogas}$: equivalent carbon dioxide emission factor of the biogas transportation, in $kgCO_{2\,eq}$/m^3 biogas; $f_{CO2\,eq\,prod\,biogas}$: equivalent carbon dioxide emission factor of the biogas production, in $kgCO_{2\,eq}$/m^3 biogas; f_{specie}: emission factor of each species resulting from the combustion of the mixture, in kg_{specie}/kg_{fuel}; $LHV_{bioethanol}$: low heating value of bioethanol, in kJ/kg; LHV_{biogas}: low heating value of biogas, in kJ/kg; $LHV_{gasoline\,A}$: low heating value of gasoline A, in kJ/kg; $\dot{m}_{bioethanol}$: bioethanol mass flow, in kg/s; $\dot{m}_{biogas}$: biogas mass flow, in kg/s; N_2: nitrogen; N_2O: dinitrogen monoxide; NO_x: nitrogen oxide; O_2: oxygen; OH: hydroxyl; P: vehicle power, in kW; $P_{charger}$: charger power, in W; P_{ICE}: internal combustion engine power, in W; $P_{trans,ERM-1M}$: ERM-1M transmission power, in W; $P_{trans,ERM-2M}$: ERM-2M transmission power, in W; $P_{trans,EVM-1M}$: EVM-1M transmission power, in W; $P_{trans,EVM-2M}$: EVM-2M transmission power, in W; P_{bat}: battery power, in W; P_{gen}: generator power, in W; PM: particulate material; R_{bat}: battery range, in km; S_{av}: average speed, in km/h; SO_x: sulphur oxide; $TTW_{BR\,gasol}$: tank-to-wheel emissions of the Brazilian gasoline, in $gCO_{2\,eq}$/km; TTW

$_D$: tank-to-wheel emissions of the dual-fuel spark-ignition engine, in $gCO_{2\,eq}$/km; TTW_S: tank-to-wheel emissions of the single-fuel spark-ignition engine, in $gCO_{2\,eq}$/km; $WTP_{bioethanol}$: well-to-pump emissions related to the sugarcane bioethanol production, in $gCO_{2\,eq}$/km; WTP_{biogas}: well-to-pump emissions related to the vinasse biogas production, in $gCO_{2\,eq}$/km; y: proportion of bioethanol in the dual-fuel mode.; z: proportion of biogas in the mixture of the dual-fuel mode

Greek character

$\mathcal{E}$: energy-ecological efficiency; η_{bat}: battery efficiency; η_{gen}: generator efficiency; η_{EM}: electric motor efficiency; η_{ERM-1M}: ERM-1M energy efficiency; η_{ERM-2M}: ERM-2M energy efficiency; η_{EVM-1M}: EVM-1M energy efficiency; η_{EVM-2M}: EVM-2M energy efficiency; η_{trans}: transmission efficiency; Π: pollution indicator, in $kg_{eq\,pollutant}$/MJ_{fuel}; Π_{GW}: pollution indicator that contributes to global warming, in $kg_{eq\,pollutant}$/MJ_{fuel}; Π_{HT}: pollution indicator that contributes to human toxicity, in $kg_{1.4-DCB\,eq}$/kg_{fuel}; $\rho_{bioethanol}$: bioethanol density, in kg/m^3; ρ_{biogas}: biogas density, in kg/m^3; $\rho_{gasoline\,A}$: gasoline A density, in kg/m^3; ϕ: equivalent stoichiometry

Abbreviations

BEV: battery electric vehicle; CD: charge-depleting; CS: charge-sustaining; DFSIE: dual-fuel spark-ignition engine; EM: electric motor; ERM-1M: extended-range mode operating with 1 motor; ERM-2M: extended-range mode operating with 2 motors; EU: European Union; EV: electric vehicle; EVM-1M: electric vehicle mode operating with 1 motor; EVM-2M: electric vehicle mode operating with 2 motors; G2V: grid-to-vehicle; GHG: greenhouse gas; ICE: internal combustion engine; ICEV: internal combustion engine vehicle; Li-ion: lithium-ion; PHEV: plug-in hybrid electric vehicle; SFSIE: single-fuel spark-ignition engine; TTW: tank-to-wheel; USA: United States of America; V2G: vehicle-to-grid; WTP: well-to-pump; WTW: well-to-wheel; WOT: wide-open throttle

Author contribution LOS: conceptualization, methodology, investigation, formal analysis, writing — original draft and visualization

DRdM: conceptualization, methodology, investigation, formal analysis, writing — original draft and visualization

RAMB and LH-C: conceptualization, methodology, investigation, formal analysis, supervision and project administration

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