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Hybrid vigor: Why hybrids with sustainable biofuels are better than pure electric vehicles

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ABSTRACT

Life cycle assessment (LCA) was used to evaluate the greenhouse gas emissions (GHG) of traditional internal combustion engine vehicles (ICEV), hybrid vehicles (non-plug-in or plug-in), and battery electric vehicles (BEV), fueled with biofuels or recharged with electricity from Brazilian or European matrix, including recharging losses. The study shows that calculated GHG emissions for hybrid vehicles using biofuels are lower than observed for BEVs even in Brazil, where the carbon intensity of the electricity matrix is low compared to most countries. In addition, we show that the emissions of a non-hybrid traditional internal combustion vehicle using biomethane is lower than a BEV. It was also observed that combining Brazilian biofuels with hybrid vehicles results in a higher traveled distance for each kilogram of GHG emitted compared to a BEV.

The carbon footprint reduction for metallic batteries in future scenarios was considered in the sensitivity analysis, which shows that biofuels still remain a better option. We hope these results can be useful for guiding public policies for transport decarbonization, considering hybrid vehicles fueled with biofuels as an economical and more effective alternative than battery electric vehicles to reach the sustainable goal of carbon net zero emissions by 2050.

Introduction

Climate change requires decarbonization actions in many economic sectors in the world. The transition to renewable energies is the main way to achieve net zero carbon emissions (International Energy Agency, 2021; IRENA, 2021). In the transport sector, an increasing fossil fuels substitution is expected on the energy matrix, with variable technological routes applied. The utilization of electric vehicles has been appointed as a major plan to reduce carbon emissions in the next decades. The 2021 Outlook of International Renewable Energy Agency (IRENA) related that 67 % of emission reduction in the transport sector will come from electrification and hydrogen use and only 6 % from biofuels consumption (IRENA, 2021).

Notably, there is a strong move toward battery electric vehicles (BEVs), which have been frequently presented as “zero emission vehicles” and, therefore, the most effective route to decarbonize the fleet. This perception is incorrect because it does not consider the vehicle lifecycle emissions, but promotes public policies incentivizing battery electric vehicle production and adoption in order to replace internal combustion engine vehicles. (Andersson & Börjesson, 2021; IEA, 2021; Joubert, 2022). When life cycle emission is considered, the environmental performance of electric vehicles greatly varies due to several factors, such as the emissions of the electricity mix being used for the battery production and recharge, battery mass, lifespan, among others (Cox et al., 2020; Elgowainy et al., 2018; Ellingsen et al., 2017; Esd, 2014; Knobloch et al., 2020; Wu et al., 2019).

Abbreviations: BEV, Battery Electric Vehicle; BioCNG, Biogas-based Compressed Natural Gas; CBIO, Decarbonization credit; CNG, Compressed Natural Gas; EDS, Electric Drive Share; ICEV, Internal Combustion Engine Vehicles; GHG, Greenhouse Gases; HEV, Hybrid Electric Vehicles; LCA, Life Cycle Assessment; PHEV, Plug-in Hybrid Electric Vehicles; WLTP, Worldwide harmonized Light-duty vehicles Test Procedure.

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Although BEVs do not have direct exhaust emissions, many studies show that the production of their metallic batteries is intensive in GHG emissions (Ellingsen et al., 2014; Hao et al., 2017; Kallitsis et al., 2020; Kelly et al., 2020; Kim et al., 2016; Qiao et al., 2017), impacting the electric vehicles (EV's) life cycle. The electric power generation for battery recharging is another source of indirect GHG emissions, especially when electric losses on the grid, recharger, and battery system are considered (ANEEL, 2015; CEER, 2020) (Apostolaki-Iosifidou et al., 2017; Kostopoulos et al., 2020; Sears et al., 2014). Thus, although many countries have defined policies to ban the production of combustion engines as early as the next decade for the adoption of BEVs instead, this decision needs to be evaluated based on more in-depth analysis, considering local scenarios.

Brazil has a very successful case in reducing emissions in the transport sector and is well positioned contributing to ambitious climate goals following a different path than BEVs through biofuels. In 1975, the country created the National Alcohol Program (ProAlcool) by a federal government decree, in response to the first oil crisis (Brito et al., 2019). The program started with the production of anhydrous ethanol to be blended with gasoline in Otto cycle car engines (Bajay, 2004). At the same time, the program incentivized the development of 100 % ethanol fueled engines (E100), which were launched in 1979. In 2003, the "flex (ible)-fuel" technology started, where the user has the flexibility to mix different volumes of gasoline and ethanol, in any proportion. Ultimately, this flex-fuel technological configuration ended-up dominating the light vehicle's Brazilian market and, consequently, increasing the demand for ethanol as fuel (Gonçalves et al., 2022).

It has been demonstrated that sugarcane ethanol can reduce up to 80 % of the GHG emissions when compared to gasoline (Macedo et al., 2008; Seabra et al., 2011). The same performance can be achieved with biomethane (Bordelanne et al., 2011). Furthermore, the biofuel production chain generates jobs, with multiple social and economic benefits (Formann et al., 2020; Goldemberg et al., 2008; Machado et al., 2015; Moraes et al., 2015; Ribeiro, 2013; Souza et al., 2018; Souza et al., 2022). Additionally, as new sugarcane farms can be implemented in areas of degraded pasture, the development of new biorefineries might lead to the restructuring of native forests, increasing environmental sustainability (Bordonal et al., 2018).

Brazil, although considered one of the major global GHG emitters, largely due to forest fires (SEEG, 2022), contributes with only 2.3 % of global emissions (World Bank, 2022). Nevertheless, the country has proposed an ambitious transport decarbonization program, to contribute to reducing the sector's emissions. This effort is in line with the Paris Agreement, where Brazil has set ambitious goals: its Nationally Determined Contributions (NDC) aims at cutting 37 % of its GHG emissions by 2025 and 43 % by 2030 compared to 2005 levels (Gonçalves et al., 2020). To achieve these goals, the transport sector, responsible for 45 % of Brazilian anthropic emissions (EPE, 2022), should be one of the main contributors to the GHG abatements. To support this achievement, in 2017 Brazil launched the National Biofuel Policy (Renovabio), a robust methodology to allocate the negative externality from fossil fuel use and contribute to the goals bound by Paris Agreement (Brasil, 2017). This policy includes the Life Cycle Assessment (LCA) tool to measure biofuel's carbon emissions produced in Brazil, rewarding the energetic-environmental efficiency.

In the Renovabio Program, each CO_2 ton results in one carbon credit, called CBIO, to the biofuel producer, which can be traded on the Brazilian Stock Exchange (B3). In this program, the more efficient (less carbon intensive) biofuel production is, more CBIOs will be generated by the biofuel producer. In addition, the program rewards the producers achieving negative net emissions by adding a 20 % bonus in the efficiency note, fostering the adoption of additional carbon capture (and storage) related to the biofuel production (Brasil, 2017). Therefore, a virtuous cycle is created, incentivizing the continuous efficiency improvement of biofuels, the higher investment in bioenergy technologies, and the biofuel growth production (Grangeia et al., 2022; Grassi & Pereira, 2019).

The Net Zero scenarios indicate that there will be fossil fuel consumption in 2050, at some level (International Energy Agency (IEA), 2021; BP, 2023). Furthermore, when we compare the decarbonization plans shown by the Paris Agreement signatory countries with the carbon emission reductions needed (estimated by IPCC), there is a significant gap (Jarraud & Steiner, 2019). This way, the energy transition effort will require technologies that provide net negative emissions. The sustainable biofuels production associated with carbon capture through Biomass Energy Carbon Capture and Storage (BECCS) can offer negative carbon emissions (Moioli & Schildhauer, 2022), with low environmental impact (Cooper et al., 2022). Thus, in the future, biofuels can offer more than only carbon net zero, they can be an effective and economic way to reduce the carbon in the atmosphere.

In the energy transition, biofuels can be even better if combined with fleet electrification. To target the carbon net zero goals, efficiency growth is an imperative need. According to IRENA, a quarter of emission reduction will come from increasing efficiency (IRENA, 2021). Electric engines have more than 90 % efficiency (Campanari et al., 2009; Hayes et al., 2011; Smith, 2010), and internal combustion engines had an efficiency between 14 and 42 %, depending on the fuel and technology adopted (Athanasopoulou et al., 2018; Singh et al., 2015; Travesset-Baro et al., 2015). Hence, the association of low carbon footprint biofuels with electric engine efficiency generates a potential synergy, which can surpass the carbon emission reduction expected by BEVs, pointing to a strategically better path for the energy transition.

There are important studies available in the literature linking GHG emissions of biofuels and electric vehicles use (Boureima et al., 2012; Tessum et al., 2014; Meier et al., 2015; de Souza et al., 2018; Pero et al., 2018; Glensor et al., 2019; Cox et al., 2020; Andersson & Börjesson, 2021). However, there are few studies comparing the life cycle GHG emissions of vehicles with biofuels produced in Brazil and electric vehicles recharged in the Brazilian electricity matrix, such as the study by Vargas et al. (2022). In a complementary way and contributing to innovation, our study: has a greater number of vehicles in the comparison; considers the plug-in hybrid in the analysis; brings biomethane, in addition to sugarcane ethanol; considers emissions associated with the construction of electric vehicle charging infrastructure; makes a comparison of the electric vehicle in Brazil and in Europe; and highlights the losses occurred in the transmission, distribution, and charger sets (charger, control module, and battery).

In addition, a sensitivity analysis is performed considering variations on the electric drive share in plug-in hybrid vehicles, and we also discuss future scenarios and the roles of batteries and biofuels in the transport sector decarbonization. In short, this research intends to provide comprehensive data to guide the development of new, sustainable public policies for the transport sector.

Methodology

For this study, the Life Cycle Assessment (LCA) was used to compare the GHG emissions between electric vehicles (pure and hybrid) and internal combustion engines fueled by gasoline, sugarcane ethanol, and biomethane, in Brazil. The analysis considered the current state of the art available to produce the vehicle and lithium-ion batteries present in electric vehicles. The used LCA approach was attributional, and the functional unit considered in this comparison is the amount, in grams, of carbon dioxide equivalent emitted per kilometer (CO_2e/km). The inventory of GHG emissions associated with the fuel life cycle, from well-to-wheels, and the emissions associated with vehicle manufacturing, electricity generation, and recharging infrastructure, was obtained from data available in specific literature. Aiming at full transparency regarding the choices made, life cycle inventory data is described in detail. A summary of the study scope is presented in Fig. 1.

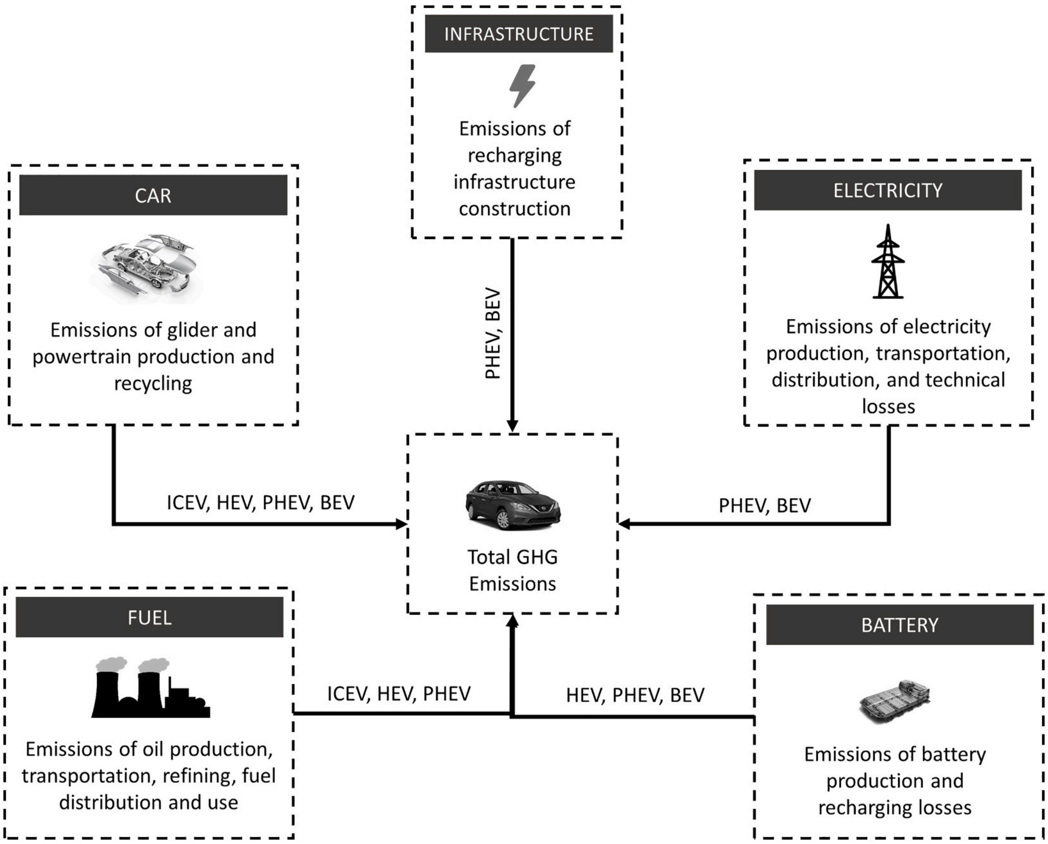

Fig. 1. Summary of the study scope for GHG emissions.

Vehicles and specifications

For this study, vehicles from similar categories were chosen for comparison. The vehicles specifications were collected on the manufacturer's website or in the literature. Kia Niro LX, Toyota Prius A Premium, and Hyundai Ioniq were the non-plug-in Hybrid Electric Vehicles (HEV) considered. For the Plug-in Hybrid Electric Vehicles (PHEV), Kia Niro LXS, Toyota Prius A Premium, and Hyundai Ioniq were chosen. For the Internal Combustion Engine Vehicle (ICEV), Toyota Corolla Flex Fuel was chosen, available in Brazil to use with gasoline and hydrated ethanol at any ratio. For the Battery Electric Vehicle (BEV), Kia Niro EX, Nissan Leaf S Plus, and Hyundai Ioniq were chosen. Table 1 brings the specifications of all listed vehicles. It is important to note that the WLTP (World Harmonized Light-Duty Vehicles) was adopted for plug-in hybrid vehicle consumption. This standard test considers vehicle roading 65 % of the time in electric mode and 35 % with the internal combustion engine. Also, only the Toyota Corolla (ICEV) has flex technology, which is already available in the Brazilian market. Therefore, for comparison purposes, regarding the calorific power of fuels, hybrid vehicles' fuel yield using hydrated ethanol was considered to be 30 % less compared to the available manufacturer's information for gasoline A and 15 % more with biomethane.

Carbon intensity of fuels

The carbon intensity associated with the well-to-wheel life cycle

Table 1
Technical specifications of the vehicle models.

Vehicle	Engine	Li-ion Battery energy (kWh)	Battery weight (kg)	Vehicle gross weight (kg)	Fuel yield (km/L of Gasoline)	Electric range (km/kWh)	Source
Corolla ICEV	2.0 L	–	–	1405	12.6	–	(TOYOTA, 2022)
Niro HEV	1.6 L	1.6	38.5	1406	21.3	–	(KIA, 2021)
Prius HEV	1.8 L	1.3	40	1375	30,4	–	(TOYOTA, 2021)
Ioniq HEV	1.6 L	1.56	38.5	1375	29.4	–	(HYUNDAI, 2021b)
Niro PHEV	1.6 L	8.9	117	1535	19.6	4.7	(KIA, 2021)
Prius PHEV	1.8 L	8.8	115	1530	30.0	4.5	(TOYOTA, 2021)
Ioniq PHEV	1.6 L	8.9	110	1495	22.1	5.3	(HYUNDAI, 2021c)
Leaf 1 BEV	110 kW	40	303	1594	–	6.2	(Nissan, 2020; NISSAN USA, 2021a, 2021b)
Leaf 2 BEV	110 kW	62	439.7	1749	–	6.2	(Nissan, 2020; NISSAN USA, 2021a, 2021b)
Niro BEV	150 kW	64	457	1748	–	6.0	(KIA, 2021)
Ioniq BEV	100 kW	38.3	340	1527	–	6.5	(HYUNDAI, 2020, 2021a, 2021b, 2021c)

(that includes emissions of production, transport, refining, distribution, and use) of gasoline A, hydrous ethanol (E1G route), and biomethane was prospected from national average values in the 2022 year, based on the Renovabio certifications. The annual average intensity emissions data associated with the electricity production in the Brazilian and European Electric Matrix are described in Brazilian National Energy Balance for the 2018 year. The values considered are described in Table 2.

Average mileage

The average life of a medium-sized Brazilian fleet is ten years (SINDIPEÇAS, 2021), while the average annual mileage is 12,900 km (km) (KBB, 2021). Therefore, in 10 years, the vehicle will travel approximately 130,000 km. There is evidence that electric vehicle owners travel 630 km more, per year, than those who own internal combustion engine vehicles (Cesar, 2021), reaching an average mileage of 13,530 km/year. Nissan offers an eight-year battery warranty or 160,000 km for the Nissan Leaf (NISSAN USA, 2021b). These are the same conditions that Tesla offers for Standard Model 3 in the US and Canada (Tesla Motors Inc., 2022). Considering this information, we adopted the number usually considered for electric vehicles in most of studies, a total of 160,000 km, to calculate the emissions for all vehicles listed in this study. It is assumed that the battery supports such mileage.

Vehicle production emissions

The GHG emissions data related to vehicle production were obtained from Bieker (2021), and are shown in Table 3. The data consider the production and recycling of the glider and powertrain of compact and medium-sized cars in European Union and the United Kingdom, in 2019. No peer-reviewed Brazilian data were found for GHG emissions from vehicle production (glider and powertrain). It was considered that the European data are robust and reliable, although they should be higher than what would be observed in Brazil, which has a less carbon-intensive energy matrix. Anyway, even if the values are different in Brazil, with a probable reduction in emissions for all vehicles considered in the study, the relative comparison would lead us to similar conclusions. It is also important to point out that the emissions factor considered for ethanol-fueled ICEV was the same as the one considered for the gasoline-fueled ICEV.

Batteries production emissions

Lithium-ion batteries are primarily used in the composition of electric and hybrid cars, with China being the world's largest producer and holding a broad domain of the entire production chain. China is responsible for refining more than 50 % of the lithium, graphite, and cobalt used in batteries, as well as for manufacturing more than 70 % of battery cell components by 2022 (IEA, 2021).

As indicated in the introduction, several studies report the GHG emissions associated with the production of lithium-ion batteries. The indicated values vary significantly, depending on the scope assumptions of the study. Table 4 presents NCM lithium-ion battery manufacturing emissions reported in the literature, in kilograms of carbon dioxide equivalent (kg CO_2e), for three major battery-supplying countries worldwide. China, Japan, and South Korea accounted for just over three-quarters of the world's electric vehicle battery manufacturing from 2014 to 2021 (Mann et al., 2018).

Considering that Brazil does not produce batteries locally and China is the largest producer, emissions of 114.5 kg CO_2e/kWh of battery capacity were considered, a value obtained through the average of the numbers presented in Table 3.

We did not consider the emissions associated with the transport to Brazil, recycling, or disposal of batteries at the end of their life. There is still not enough data on recycling, second life use or even the consequences of disposal. This is a very recent innovation, and most batteries are still in their first life (Reid, 2022). It is also not known what percentage of replacement would be associated with battery failures, which would generate a high impact on life cycle emissions. In August 2021, GM recalled the Bolt model on a large scale due to a battery problem (Kane, 2021). This is estimated to cause a significant increase in emissions associated with these vehicles, but the numbers are uncertain. It is not known which destination was given to the replaced batteries. Due to the mentioned reasons, end-of-life GHG emissions were disregarded.

Land use change

Emissions attributed to changes in land use were not considered. The premises adopted by Renovabio were that to be eligible for the program's carbon credits (CBIOs), the biofuel produced could not have come from a deforested area, as of 2018 (Brasil, 2018). In addition, biomass production must comply with Rural Environmental Registry (CAR), as provided in the Brazilian Forest Code (Moreira et al., 2018). Namely, the CAR is a national electronic public record, mandatory for all rural properties, to integrate environmental information from rural properties and possessions in order to create a database for control, monitoring, environmental and economic planning, and combat against deforestation (Brasil, 2022; MAPA, 2022). More than 90 % of the volume of ethanol sold in Brazil meets the requirements set out in Renovabio (Unica, 2022). Additionally, the congregation of biofuels with

Table 2
Carbon intensity of fuels and electricity production.

Fuel/Electricity (year)	g CO_2e/MJ	g CO_2e/L	g CO_2e/kWh	Source
Gasoline A (2022)	87.4	2817.8	–	(Brasil, 2018)
Hydrous ethanol (2022)	28.2	602.1	–	(Unicadata, 2022)
Biomethane (2022)	10.0	0.367	–	(Unicadata, 2022)
Brazil Electric grid (2018)	–	–	99.6	(EPE, 2022)
Europe Electric grid (2018)	–	–	322.8	(EPE, 2022)

Table 3
GHG emissions for glider and powertrains without battery.

Vehicle	$tCO_2e/t_{vehicle}$	Source
Ethanol/Gasoline ICEV	5.2	(Bieker, 2021)
CNG or BioCNG ICEV	5.5	
PHEV (without battery)	5.7	
BEV (without battery)	4.7	

Table 4
Emissions from Li-ion battery manufacturing at leading global suppliers.

Country battery production	Battery mass (kg)	Battery capacity (kWh)	Emissions (kgCO_2e/kWh)	Source
South Korea	253	26.6	172	(Ellingsen et al., 2014)
South Korea	303	24	140	(Kim et al., 2016)
China	170	28	104	(Hao et al., 2017)
China	188.7	27	117	(Qiao et al., 2017)
China	253	26.6	140	(Kallitsis et al., 2020)
China	188.7	27	100	(Kelly et al., 2020)
Japan	188.7	27	98	(Kelly et al., 2020)
Average	220.7	26.6	114.5	–

livestock production can maintain the output for food and increase the biofuels at the same time, with a reduction for necessary areas (Souza et al., 2022). Considering the assumptions set out here, it is expected that the expansion of the biofuel supply in Brazil will not cause negative effects on land use in the coming years. Rather, this can be a factor of production rationalization, which may be beneficial for the reduction of carbon intensity of the culture. New technologies have been adopted to increase production and yield, as it will be discussed in Section 3.4.

Emissions associated with charging infrastructure

The need to expand existing infrastructure to generate electricity and recharge electric vehicles was taken into account in this study. A meta-analysis based on 11 scientific articles on the subject, conducted by FVV and Frontier Economics, showed that emissions associated with the creation of charging stations, expansion of the electricity grid, and energy storage to deal with intermittent sources of generation, vary from 0.09 to 1.97 tons, during the lifetime of an electric car (Both & Steinfort, 2020). Based on this study, the medium value of 1.03 tons/life of additional CO_2e was adopted for the lifespan of electric vehicles that make up this article.

Energy losses

The recharging of an electric vehicle involves losses related to the charger, car recharging module, and battery, in addition to electric grid transmission and distribution losses. These losses increase the need to generate electricity, which negatively impacts the emission of GHG associated with PHEVs and BEVs. This study considered, in the Brazilian scenario, 4.0 % of energy transmission losses and 7.5 % of technical distribution losses, according to data from National Electric Energy Agency (ANEEL, 2015). For the European scenario, 2.5 % of transmission losses and 4.0 % of distribution losses were considered (CEER, 2020). Losses for the complete charging set (charger, control module, and battery) vary greatly depending on the type of charger, power, and charging time. Losses can be higher, up to 30 %, or lower, below 10 %, mainly depending on the recharge voltage used (low or high voltage). An average loss of 15 % was considered for the charging set, in line with data published for some studies (Sears et al., 2014, Apostolaki-Iosifidou et al., 2017, Kostopoulos et al., 2020).

Results and discussions

Comparative results

The results of greenhouse gas emissions calculated for selected vehicles, based on the proposed LCA, are shown in Fig. 2, and detailed in Table 5. The lowest GHG emissions were detected for HEVs with biomethane, an average of 59.5 gCO_2e/km, while the highest emissions value was found for the ICEV with gasoline A, 269.3 gCO_2e/km. The BEV in Brazil would have 61 % lower emissions than the ICEV fueled with gasoline A, but 42 % higher than ICEV fueled with biomethane. The ICEV roading with ethanol sugarcane presented estimated emissions 15 % higher than the average of the BEV. However, it is an excellent result considering the comparison between a traditional ICEV, which is not optimized for ethanol, and a BEV. The HEV with ethanol sugarcane showed 26 % lower emissions than BEV in Brazil, and 71 % lower than ICEV with gasoline A in comparison.

The results for GHG emissions in ICEV with gasoline A and ethanol sugarcane are similar to those found by de Souza et al. (2018). The emissions showed to BEV considering the European electric matrix are in line with Ricardo Energy and Environment (2020) and Andersson and Börjesson (2021). For BEV recharged in Brazil, we found values 15 % lower than Vargas et al. (2022), reflecting the normal differences in LCA inputs in relation to the vehicle model used, the carbon intensity of the electrical matrix and the size of the battery size.

When fueled with biofuels, results showed that ICEVs in Brazil have lower GHG emissions than expected for a BEV in Europe. An incredible result is observed with biomethane, for even when used in a traditional ICEV their estimated emissions are 49 % lower than BEV in Europe and 30 % lower than the BEV in Brazil. The simulation of biomethane used in HEV showed more significant results, with global carbon emissions reducing up to 78 % compared to an ICEV powered by gasoline A. The mentioned results of biomethane are in line with observed values by Ternel et al. (2021).

According to data from the Brazilian Biogas Association (Abiogás), Brazil has the potential to produce 82.5 billion cubic meters of biogas per year, considering the sugarcane-based energy, sanitation, animal

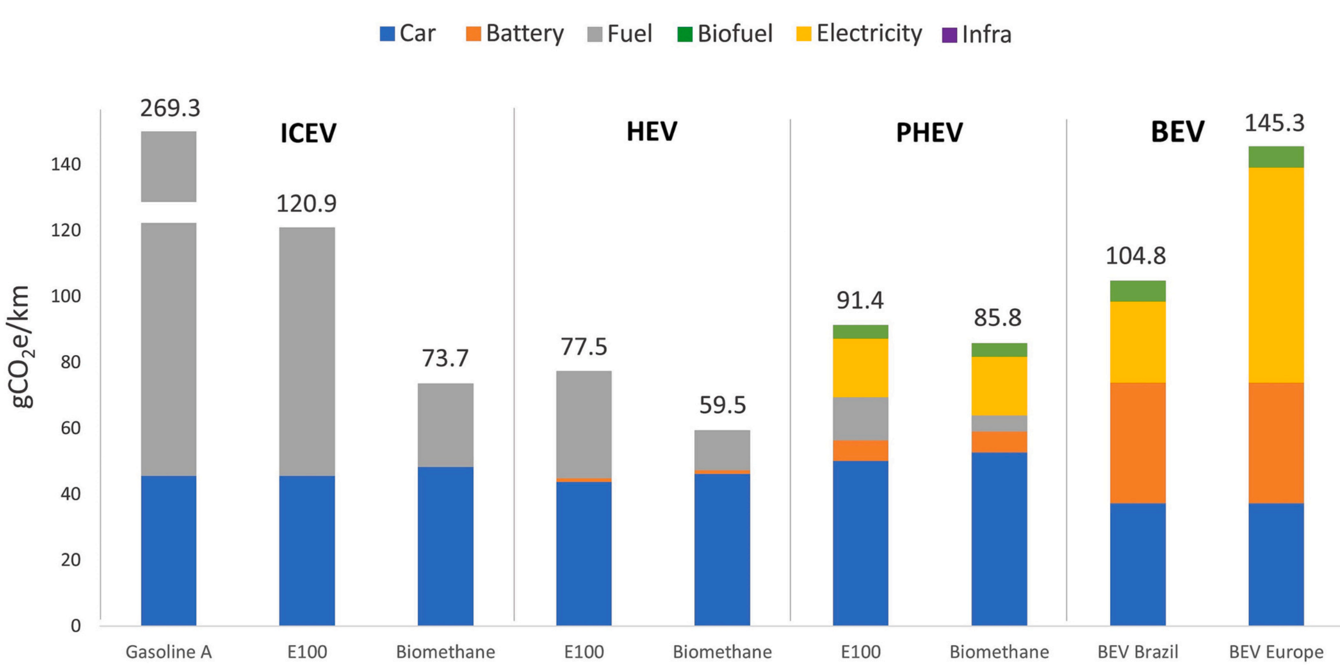

Fig. 2. Comparison of the average GHG emissions in the LCA for selected vehicles.

Table 5
average GHG emissions (gCO_2e/km) of selected vehicles by category, fuel, and components.

	ICEV			HEV		PHEV		BEV	
	Gasoline A	E100	Biomethane	E100	Biomethane	E100	Biomethane	Brazil	Europe
Car	45.7	45.7	48.3	43.8	46.3	50.1	52.7	37.3	37.3
Battery	–	–	–	1.06	1.06	6.35	6.35	36.5	36.5
Fossil fuel	223.6	0	0	0	0	0	0	–	–
Biofuel	0	75.2	25.4	32.6	12.1	13.0	4.83	–	–
Electricity	–	–	–	0	0	17.7	17.7	24.6	65.0
Infrastructure	–	–	–	0	0	4.18	4.18	6.44	6.44
TOTAL	269.3	120.9	73.7	77.5	59.5	91.4	85.8	104.8	145.3

protein, and agricultural production sectors in the country (CIBIOGÁS, 2021). On a conservative estimate, half of this biogas can be converted to biomethane (RCGI, 2017). Such production, together with ethanol, would be enough to supply the entire Brazilian fleet of light vehicles, even with low-efficiency ICEVs. Besides, it would also be enough to substitute two-thirds of Brazil's fossil diesel consumption, whose volume in 2021 was close to 55 billion liters (ANP, 2022). It is important to observe that great part of emissions associated with Brazilian sugarcane ethanol are related to the use of diesel in machines and tractors in the field. If biomethane is used to replace diesel in farms, the life cycle emissions of ethanol will also be reduced, in a positive cascade effect.

The "Hybrid vigor"

In the LCA approach, the data showed that non-plug-in hybrid vehicles (HEV) using biofuels have lower emissions than plug-in hybrids (PHEV) and purely electric vehicles (BEV). Similar behavior was observed by researchers in studies in France (Ternel et al., 2021) and Sweden (Andersson & Börjesson, 2021).

To illustrate more clearly the advantage of using biofuels in hybrid vehicles, Fig. 3 shows how many kilometers would be driven until one kilogram of GHG is emitted into the atmosphere for each vehicle. This data illustrates how much a vehicle can run to achieve the same comparative emission. An HEV with biomethane is the best case, as it would run 16.8 km to emit 1 kg of CO_2e, while a BEV in Brazil would run 9.5 km to produce the same emission, on average. The worst case is the internal combustion engine vehicle ICEV with gasoline A, which emits 1 $kgCO_2e$ after roading only 3.7 km.

The results make clear that hybrid vehicles with biofuels would run higher mileage than electric vehicles before emitting the first kilogram of GHG. The results suggest that biofuels, such as sugarcane ethanol and biomethane, combined with hybrid vehicles seem to be a more effective alternative for decarbonizing light fleet vehicles, in comparison to BEVs, even in a clean electrical matrix like Brazil. We elusively call this combination "hybrid vigor", a phenomenon observed in biology where the hybrid organism has higher quality for desired phenotypes when compared to its parents (Harrison, 1948; Tiwari, 2022), drawing an analogy with ICEVs and BEVs as parents.

There are many reasons for the observed reduction in carbon emissions when biofuels are used with hybrid vehicles. First, hybrids require smaller batteries, which can represent from 25 % to only 8 % of a BEV (Table 1), reducing the environmental stress caused by mining, such as reported by Liu et al. (2019), Luckeneder et al. (2021) and Canelas and Carvalho (2023). Second, smaller batteries reduce the carbon footprint of each vehicle's production. Third, hybrid vehicles are quite efficient if compared to traditional vehicles, as it can be seen in the fuel yield presented in Table 2. Finally, the sustainable biofuels have a low carbon intensity (Table 2) that naturally generates lower emissions.

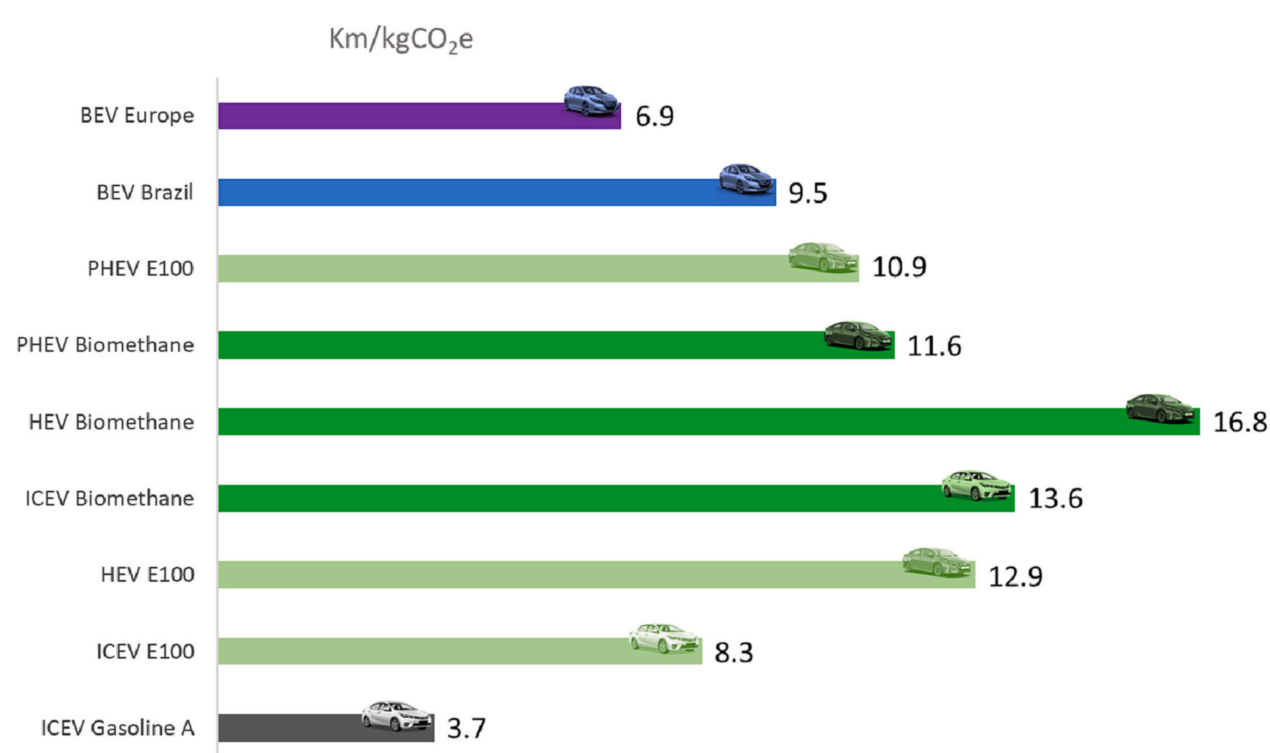

Fig. 3. Kilometers driven for each category of vehicles to emit 1 kg of CO_2e.

Electric share in Plug-in Electric Vehicle (PHEV)

Since a PHEV can be operated in either electric drive mode (charged using the electricity grid) or internal combustion engine mode (fuel-powered), it is interesting to assess how the electric drive share (EDS) affects the vehicle's GHG emissions. The EDS denotes the percentage of total distance accomplished in electric drive mode. The GHG emissions for PHEV shown in Fig. 2 are based on the standard test, which considers vehicles working 65 % in electric mode and 35 % in fuel mode. The EDS of a PHEV in real life would be different. Fig. 4 illustrates the GHG emission profile of PHEV at different percentages of electric mode.

The three sloping lines of Fig. 4 represent PHEV GHG emissions when fueling the ICE with gasoline A (orange line), sugarcane ethanol (light green line), and biomethane (dark green line). The purple and blue horizontal dashed lines reference BEV emissions in Europe and Brazil, respectively. In EDS 0 %, the PHEV consumes exclusively fuel (gasoline, ethanol, or biomethane). In EDS 100 %, the PHEV is only in electric mode. The emissions are associated with car and battery manufacturing, fuel or electricity use, and the associated infrastructure emissions with electric cars.

It can be observed in Fig. 4 that a higher electric mode use reduces emissions in PHEV, in comparison with gasoline or ethanol fuel mode. However, whatever the EDS, the PHEV with biofuels has lower emissions than the BEV. E100 PHEV emissions are below the BEV level in all driving modes. The ascending curve of PHEV with biomethane indicates that the more the vehicle runs on electricity, the associated emissions are greater. It reinforces the idea that biomethane is an alternative with lower associated carbon intensity than the European and Brazilian electricity matrix. Moreover, it represents an incentive for investing in biofuel-powered combustion engines in PHEVs.

Another interesting observation worth mentioning is the fact that PHEV shows lower emissions than BEV. Minor batteries present in PHEV justify this observation and reinforce that synergies occur between biofuels and small batteries use. As an additional advantage to PHEV, the use of electric mode allows to reduce the noise and possible local combustion emissions, which may be suitable for the center of large cities; on the other hand, biofuels can be refueled quickly and increase the range and the vehicle autonomy. The future biofuels and batteries decarbonization, in their life cycle, should boost this synergy, keeping the PHEV with lower emissions than the BEV.

End-of-life batteries: second life and recycling

The second life and recycling batteries are two important discussions in an electrification future. Continuous wear is part of the chemical battery nature. After a certain number of charge and discharge cycles, the battery no longer meets the needs of an electric vehicle, reducing its range to a critical level for many users. The estimated lifespan for electric vehicle batteries is 5 to 8 years (Haram et al., 2021) when its recharge does not reach more than 80 % of the nominal capacity. However, this battery is still used for other applications, such as the "second life" applications.

The most traditional usage for batteries' second life is to store energy from the grid, serving as large "no breaks", releasing energy when necessary. Secondary applications extend battery lifespan by 7 to 10 years on average (Haram et al., 2021). Therefore, average lifespan would reach around 15 years. After this period, it is necessary to give them a destination.

The main problem with usual batteries is the substantial number of metals needed for their production (lithium, copper, cobalt, aluminum, or rare earth). Mining these elements generates many environmental impacts, such as high carbon emissions. Recycling reduces the need to mine critical raw materials, reducing the overall environmental impact of batteries.

Carbon emissions can be 7 to 31 % lower with recycled batteries today (Cusenza et al., 2019; Koroma et al., 2022; Qiao et al., 2019). However, the recycling process is quite complex since the batteries are produced with a resistant casing, which is difficult to separate later (Blankemeyer et al., 2021). In addition, different types of batteries and even batteries of the same chemical composition will have different physical arrangements, depending on the structural model adopted by the manufacturer, imposing additional difficulties for recycling (Zhao et al., 2021).

There are many questions about the actual scale of battery recycling, although it is understood that it is necessary to make hybrid and pure electric vehicles viable as a sustainable solution in the energy transition. In all scenarios, recycling batteries is essential.

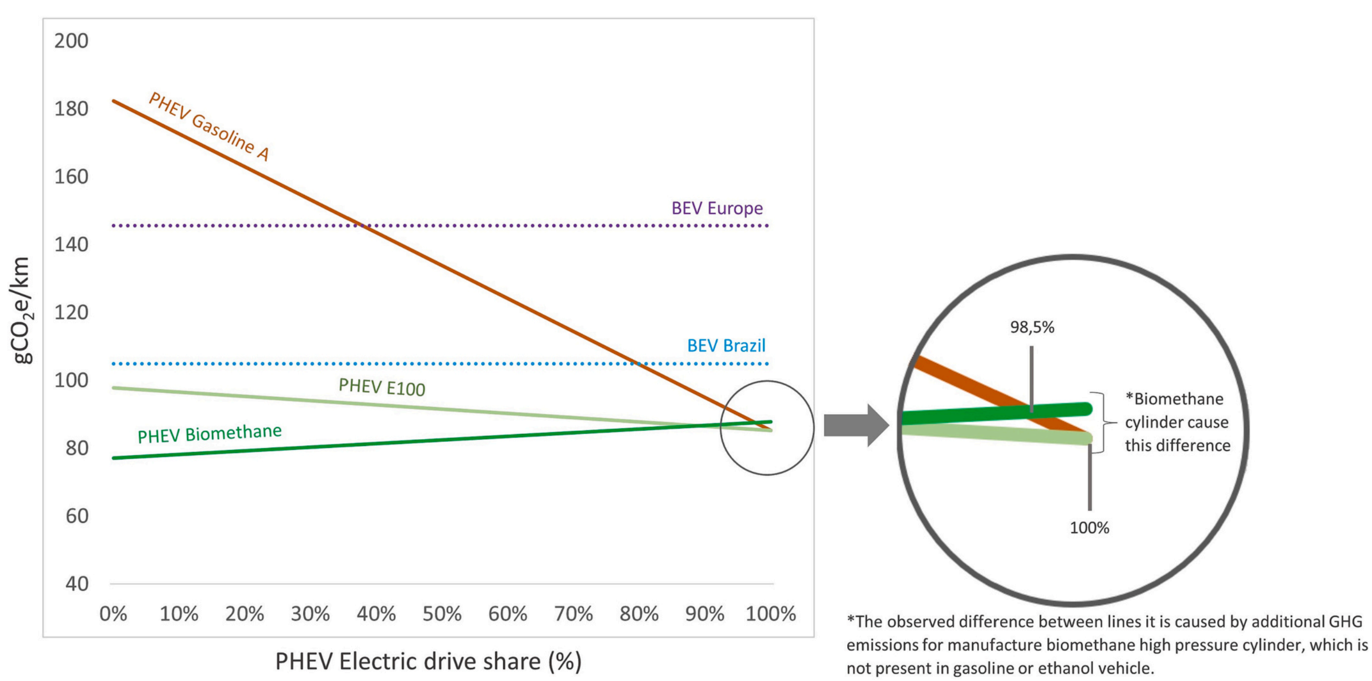

Fig. 4. EDS variation and its correlation with PHEV GHG emissions.

Evolution of carbon intensity for metallic batteries and biofuels

Nowadays, around three-quarters of the batteries are produced in Asia (Mann et al., 2018), with high emissions associated to this production. However, the Asian energy matrix is expected to experience reduced carbon intensity in the coming decades, which will substantially reduce the carbon footprint of batteries (IRENA, 2021). Today, the lowest value of battery manufacturing emissions is associated with the European supply chain, with values close to 60 kgCO_2e/kWh of battery capacity (Emilsson & Dahllöf, 2019), at least 52 % lower than when manufactured in Asia.

Furthermore, batteries with a higher production scale and energy density are expected to have carbon footprint reduction, in a (wide) range of 25 to 70 % by 2040 in comparison to 2017 GHG emissions levels (Cox et al., 2020). This means that, in the future, batteries could have a carbon footprint of less than a third of that observed in manufacturing them in Asia from 2015 to 2020, reducing almost proportionally the BEVs emissions associated.

Likewise, carbon emissions associated with biofuels are expected to decline over the next decade too, as producers seek to decarbonize their production process. The low carbon policies will be an incentive for biofuels producers. In Brazil, the carbon emission reduction in biofuel production generates more carbon credits (CBIOs), within the Renovabio certification (Grassi & Pereira, 2019). This question has led producers to implement continuous improvements to reduce the carbon intensity of their processes. The ongoing actions in this regard are as follows:

i) Biodigestion of filter cake, vinasse, and straw for the production of biomethane, which can be used to replace 100 % of the diesel used in the cultivation, harvesting, and transport of sugarcane (Zang et al., 2018). Also, the surplus produced can be sold, generating extra revenues for the producer; the biodigestion of these residues has the potential to increase energy output per hectare by 20 %, approximately (Parsaee et al., 2019);

ii) Replacement of fertilizers and chemical pesticides by the solids that remained of the biodigestion and biological alternatives, such as nutrient-fixing microorganisms, use of algae, biological pest control, and better use of available residues, with local applications (Formann et al., 2020);

iii) Development of new and more productivity biomass sources, as Energy Cane (Grassi & Pereira, 2019), and corn ethanol, with corn being produced as second crop in association with soybean, and biomass being utilized to run the mills (Brief, 2018);

iv) Investments in technology and precision agriculture, seeking a more efficient application of agricultural inputs and varietal management, leading to an increase in the longevity and yield of the crops (Almeida et al., 2021; Carrer et al., 2022; Santoro et al., 2017);

v) Adoption of new technologies such as bioenergy carbon capture and storage (BECCS), which in the sector has the potential to achieve a negative carbon footprint at an economically viable capture cost, less than USD 30/ton of buried CO_2 (Moreira et al., 2016).

It is worth mentioning that Brazil already has the production of second-generation ethanol (2G ethanol), which has a carbon footprint average estimated at 13.6 gCO_2e/MJ using current technology (Agroicone, 2021; KPMG, 2020). The value is 52 % minor than the average registered actually in Dynamic Renovabio Panel (ANP, 2021). There is a plant certified with 8.2 gCO_2e/MJ in operation (71 % minor than the number usage to calculate the GHG emissions in the present article), producing 2G ethanol from sugarcane bagasse in Brazil (RSB, 2022), a demonstration of the power of biofuels to reduce GHG emissions now.

In the next years, the sum of the described actions can bring biofuel production to carbon net zero emissions and even negative emissions with carbon capture (BECCS). In this way, hybrid vehicles with biofuels will emit much less than BEVs, even in optimistic scenarios for reduction of carbon intensity of the electrical matrix and batteries production.

Conclusions

The analysis presented in this study was focused on carbon emissions, understood to be an urgent topic that needs further analysis and society's response. Other impacts, including local particulate matter emissions produced by combustion vehicles, and water pollution associated with the production and use of the vehicles, batteries, fuels, and electricity generation, among others, were not assessed. Therefore, complementary studies are needed to what has been presented here.

The LCA demonstrated that hybrid vehicles (HEV and PHEV) with biofuels have lower GHG emissions than BEVs in Europe and Brazil, even though Brazil has a very clean electrical matrix. Brazilian biofuels are so competitive that a comparison of a traditional ICEV fueled with ethanol sugarcane or biomethane shows lower emissions than a BEV in Europe. This means that the usual combustion vehicles running today on these biofuels in Brazil have a smaller carbon footprint than pure electric vehicles running in Europe, considering the life cycle from well to wheels.

The emissions of battery manufacture, recharging, and associated infrastructure presented in Table 5 are significant and impact BEVs' carbon footprint in their life cycle. Energy-related emissions can be quite high depending on the associated electrical matrix and the losses incurred. With all these factors taken into account, the total emissions of a BEV can exceed those of a combustion vehicle, as seen in this study, and in agreement with other papers.

Uncertainties regarding the final disposal of batteries make difficult a complete assessment of the cradle-to-grave life cycle carbon emissions of electric vehicles. Most batteries are still in their first use, there are no clear numbers about the amount of these batteries that will be directed to “second life”, recycling or disposal. Recycling, which is the best-case scenario for BEVs, has major logistical and technological challenges and the associated carbon footprint is still unknown.

Results indicate that hybrids have many relative advantages over pure electric vehicles. The lowest GHG emissions were observed for non-plug-in hybrid vehicles (HEV) using biofuels. Next was the plug-in hybrid model (PHEV), which gives flexibility to consumers, being able to be fueled with electricity or biofuels, although they emit slightly more carbon than the non-plug-in option. The EDS sensitivity analysis showed that, both with ethanol and with biomethane, GHG emissions from PHEV are lower than emissions from BEV in Brazil or Europe. Highlight is given to biomethane, which emits less carbon when in combustion mode than in electric mode. Biomethane even emits less carbon in an ICEV than in a PHEV, reinforcing the importance of this biofuel to mitigate carbon emissions into the atmosphere by using a consolidated and widely available technology.

The synergy of sustainable biofuels with electrification in hybrid vehicles seems so fundamental in the decarbonization route that the use of hybrids may be not just a transitory alternative, an intermediate path, but the very end sought for the sustainable decarbonization of the vehicle fleet. This synergy is not exclusive to Brazilian biofuels, they are applicable to hybrid vehicles associated with sustainable bioenergy production in any country, especially in Asian countries like India. Banning the sale of internal combustion engine vehicles, as already advertised in Europe and California, could be a big mistake. The engine is not a problem.

Sustainable biofuels associated with combustion engines can reduce carbon emissions just as efficiently or more efficiently than expected for BEVs. Furthermore, in some regions outside the major capitals, it will be challenging to provide charging infrastructure for BEVs, making biofuels an even more interesting option, taking advantage of the existing structure for liquid fuels.

Due to the observed synergies between biofuels and electric vehicles, hybrid vehicles should not be considered as a temporary solution, a middle-ground for fleet decarbonization, but it should be analyzed as a major option, using current combustion engines (which can be improved), associated with electric engines, while vehicle fuel cells are in development. In the future, fuel cells can even increase the efficiency of this combination by replacing combustion engines. In this case, we would have a full electric vehicle powered by biofuel.

The “Hybrid Vigor” is an important indication to be considered by lawmakers and policymakers for reducing the fossil fuel utilization and GHG emissions on the fleet. Hybrids with biofuels are a viable and available technological route that can offer fewer GHG emissions and environmental stress in fleet decarbonization. Public policies need to consider this in energy transition planning before taking decisions in any direction.

Finally, it is expected that scale gains, technological improvements, decarbonization of production processes, and recycling, will cause significative reduction in batteries' carbon footprint in the coming decades, reducing the total emissions associated with the life cycle of BEVs. Likewise, it is expected that biotechnological advances in cultivation, harvesting, transport, and decarbonization of production process, including carbon capture (BECCS), will reduce the carbon intensity of biofuels to lower, or even negative values. If so, the combination of sustainable biofuels with electrification must be the final solution for fleet vehicles decarbonization.

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CRediT authorship contribution statement

Marcelo Antunes Gauto: Conceptualization, Methodology, Investigation, Writing – original draft, Formal analysis, Visualization. **Marcelo Falsarella Carazzolle:** Conceptualization, Methodology. **Marilene Elizabete Pavan Rodrigues:** Conceptualization, Writing – original draft, Writing – review & editing. **Ricardo Simões de Abreu:** Conceptualization, Writing – review & editing, Validation. **Tomaz Carraro Pereira:** Conceptualization, Writing – review & editing. **Gonçalo Amarante Guimarães Pereira:** Conceptualization, Methodology, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Datasets related to this article can be found at https://data.mendeley.com/datasets/khgntzsc9g Gauto, Marcelo (2022), “Hybrid Vigor Article”, doi: 10.17632/khgntzsc9g.2, an open-source online data repository hosted at Mendeley Data.

References

ANEEL - Agência Nacional de Energia Elétrica. (2015). Perdas de Energia - Informações Técnicas - ANEEL. Available at: https://www.aneel.gov.br/informacoes-tecnicas/-/asset_publisher/CegkWaVJWF5E/content/perdas/654800?inheritRedirect=false (Accessed: 9 September 2021).

Agroicone. (2021). *SUSTAINABILITY OF RAÍZEN'S ETHANOL: Ethanol production from sugarcane for a thriving and sustainable economy*. São Paulo.

Almeida, G. M. de, et al. (2021). Machine learning in the prediction of sugarcane production environments. *Computers and Electronics in Agriculture, 190*, Article 106452. https://doi.org/10.1016/J.COMPAG.2021.106452

Andersson, Ö., & Börjesson, P. (2021). The greenhouse gas emissions of an electrified vehicle combined with renewable fuels: Life cycle assessment and policy implications. *Applied Energy, 289*(February). https://doi.org/10.1016/j.apenergy.2021.116621

ANP - Agência Nacional do Petróleo, Gás e Biocombustíveis. (2021). Painel Dinâmico de Certificações de Biocombustíveis RenovaBio — Português (Brasil), 09/09/2021. Available at: https://www.gov.br/anp/pt-br/centrais-de-conteudo/paineis-dinamicos-da-anp/paineis-dinamicos-do-renovabio/painel-dinamico-de-certificacoes-de-biocombustiveis-renovabio (Accessed: 9 September 2021).

Apostolaki-Iosifidou, E., Codani, P., & Kempton, W. (2017). Measurement of power loss during electric vehicle charging and discharging. *Energy, 127*, 730–742. https://doi.org/10.1016/J.ENERGY.2017.03.015

Athanasopoulou, L., Bikas, H., & Stavropoulos, P. (2018). Comparative well-to-wheel emissions assessment of internal combustion engine and battery electric vehicles. *Procedia CIRP, 78*, 25–30. https://doi.org/10.1016/J.PROCIR.2018.08.169

Bajay, S. V. (2004). National Energy Policy: Brazil. *Encyclopedia of Energy*, 111–125. https://doi.org/10.1016/B0-12-176480-X/00482-4

Bieker, G. (2021). *A global comparison of the life-cycle greenhouse gas emissions of combustion engine and electric passenger cars*. The international Counil of Clean Transportation [Preprint], (July).

Blankemeyer, S., et al. (2021). Investigation of the potential for an automated disassembly process of BEV batteries. *Procedia CIRP, 98*, 559–564. https://doi.org/10.1016/j.procir.2021.01.151

Bordelanne, O., et al. (2011). Biomethane CNG hybrid: A reduction by more than 80% of the greenhouse gases emissions compared to gasoline. *Journal of Natural Gas Science and Engineering, 3*(5), 617–624. https://doi.org/10.1016/J.JNGSE.2011.07.007

Bordonal, R. de O., et al. (2018). Sustainability of sugarcane production in Brazil. A review. *Agronomy for Sustainable Development, 38*(2), 13. https://doi.org/10.1007/s13593-018-0490-x

Both, D., & Steinfort, T. (2020). *Cradle-to-Grave Life-Cycle Assessment in the Mobility Sector*. Frontier Economics Ltd. [Preprint]. Available at: https://www.fvv-net.de/fileadmin/user_upload/medien/materialien/FVV_LCA_Life-cycle_analysis_Frontier_Economics_R595_final_2020-06_EN.pdf.

Boureima, F., et al. (2012). Environmental assessment of different vehicle technologies and fuels. *WIT Transactions on the Built Environment, 128*, 15–26. https://doi.org/10.2495/UT120021

BP. (2023). BP Energy Outlook 2023 edition 2023 explores the key trends and uncertainties. In *BP Energy Outlook* (pp. 1–53). Available at https://www.bp.com/en/global/corporate/energy-economics/energy-outlook.html.

Brasil, G.F. do. (2017). Política Nacional de Biocombustíveis (Renovabio). Available at: http://www.planalto.gov.br/ccivil_03/_ato2015-2018/2017/lei/L13576.htm.

Brasil, G.F. do. (2018). Resolução ANP 758 de 2018, tabela 20. Available at: https://atosoficiais.com.br/anp/resolucao-n-758-2018-regulamenta-a-certificacao-da-producao-ou-importacao-eficiente-de-biocombustiveis-de-que-trata-o-art-18-da-lei-no-13-576-de-26-de-dezembro-de-2017-e-o-credenciamento-de-firmas-inspetoras?origin=institui.

Brasil, G.F. do. (2022). Agricultura e pecuária: inscrever imóvel rural no cadastro ambiental rural (CAR), Agricultura e pecuária: inscrever imóvel rural no cadastro ambiental rural (CAR). Available at: https://www.gov.br/pt-br/servicos/inscrever-imovel-rural-no-cadastro-ambiental-rural-car. (Accessed 28 May 2022).

Brief, P. (2018). *Análise socioeconômica e ambiental da produção de etanol de milho no centro oeste brasileiro*.

Brito, T. L. F., et al. (2019). Transitions between technological generations of alternative fuel vehicles in Brazil. *Energy Policy, 134*, Article 110915. https://doi.org/10.1016/J.ENPOL.2019.110915

Campanari, S., Manzolini, G., & Garcia de la Iglesia, F. (2009). Energy analysis of electric vehicles using batteries or fuel cells through well-to-wheel driving cycle simulations. *Journal of Power Sources, 186*(2), 464–477. https://doi.org/10.1016/J.JPOWSOUR.2008.09.115

Canelas, J., & Carvalho, A. (2023). The dark side of the energy transition: Extractivist violence, energy (in)justice and lithium mining in Portugal. *Energy Research & Social Science, 100*, Article 103096. https://doi.org/10.1016/J.ERSS.2023.103096

Carrer, M. J., Filho, H. M. S., Vinholis, M. M. B., & Mozambani, C. I. (2022). Precision agriculture adoption and technical efficiency: an analysis of sugarcane farms in Brazil. *Technological Forecasting and Social Change, 177*, Article 121510. https://doi.org/10.1016/J.TECHFORE.2022.121510

CEER. (2020). *2nd CEER Report on Power losses* (March) (pp. 1–165). Available at: https://www.ceer.eu/documents/104400/-/-/fd4178b4-ed00-6d06-5f4b-8b87d630b060. Available at:.

Cesar, J. (2021). Donos de carros elétricos rodam mais que os de carros a gasolina. Available at: https://insideevs.uol.com.br/news/513519/donos-carros-eletricos-comparacao-gasolina/ (Accessed: 9 December 2021).

CIBIOGÁS. (2021). Nota Técnica: N° 001/2021 – Panorama do Biogás no Brasil 2020. *1*(1), 1–15.

Cooper, J., Dubey, L., & Hawkes, A. (2022). The life cycle environmental impacts of negative emission technologies in North America. *Sustainable Production and Consumption, 32*, 880–894. https://doi.org/10.1016/J.SPC.2022.06.010

Cox, B., et al. (2020). Life cycle environmental and cost comparison of current and future passenger cars under different energy scenarios. *Applied Energy, 269*(February), Article 115021. https://doi.org/10.1016/j.apenergy.2020.115021

Cusenza, M. A., et al. (2019). Reuse of electric vehicle batteries in buildings: an integrated load match analysis and life cycle assessment approach. *Energy and Buildings, 186*, 339–354. https://doi.org/10.1016/j.enbuild.2019.01.032

de Souza, L. L. P., et al. (2018). Comparative environmental life cycle assessment of conventional vehicles with different fuel options, plug-in hybrid and electric vehicles for a sustainable transportation system in Brazil. *Journal of Cleaner Production, 203*, 444–468. https://doi.org/10.1016/J.JCLEPRO.2018.08.236

Pero, F., Delogu, M., & Pierini, M. (2018). Life cycle assessment in the automotive sector: a comparative case study of internal combustion engine (ICE) and electric car. *Procedia Structural Integrity, 12*, 521–537. https://doi.org/10.1016/j.prostr.2018.11.066

Elgowainy, A., et al. (2018). Current and future United States light-duty vehicle pathways: Cradle-to-grave lifecycle greenhouse gas emissions and economic

assessment. *Environmental Science & Technology, 52*(4), 2392–2399. https://doi.org/10.1021/acs.est.7b06006
Ellingsen, L. A. W., Hung, C. R., & Strømman, A. H. (2017). Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions. *Transportation Research Part D: Transport and Environment, 55*, 82–90. https://doi.org/10.1016/J.TRD.2017.06.028
Ellingsen, L. A.-W., et al. (2014). Life cycle assessment of a lithium-ion battery vehicle pack. *Journal of Industrial Ecology, 18*(1), 113–124. https://doi.org/10.1111/JIEC.12072
Emilsson, E., & Dahllöf, L. (2019). *Lithium-Ion Vehicle Battery Production*. https://doi.org/10.13140/RG.2.2.29735.70562
EPE. (2022). Balanço energético nacional 2021, BEN Relatório Síntese 2021 Ano base 2020. Available at: https://www.epe.gov.br/pt/publicacoes-dados-abertos/publicacoes/balanco-energetico-nacional-2021 (Accessed: 12 May 2022).
Esd, A. (2014). Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles Energy Systems Division. Available at: www.anl.gov.
Formann, S., et al. (2020). Beyond sugar and ethanol production: Value generation opportunities through sugarcane residues. *Frontiers in Energy Research, 8*(November), 1–21. https://doi.org/10.3389/fenrg.2020.579577
Glensor, K., Muñoz, María Rosa, & B.. (2019). Life-cycle assessment of Brazilian transport biofuel and electrification pathways. *Sustainability (Switzerland), 11*(22). https://doi.org/10.3390/su11226332
Goldemberg, J., Coelho, S. T., & Guardabassi, P. (2008). The sustainability of ethanol production from sugarcane. *Energy Policy, 36*(6), 2086–2097. https://doi.org/10.1016/j.enpol.2008.02.028
Gonçalves, D. N. S., Goes, G. V., & D'Agosto, M. A. (2020). *Energy transition to Brazil: Paris Agreement Compatible Scenario for the Transport sector up to 2050* (March) (p. 16). Available at: www.climate-transparency.org. Available at:.
Gonçalves, F. de O., et al. (2022). Thorough evaluation of the available light-duty engine technologies to reduce greenhouse gases emissions in Brazil. *Journal of Cleaner Production, 358*, Article 132051. https://doi.org/10.1016/J.JCLEPRO.2022.132051
Grangeia, C., Santos, L., & Lazaro, L. L. B. (2022). The Brazilian biofuel policy (RenovaBio) and its uncertainties: an assessment of technical, socioeconomic and institutional aspects. *Energy Conversion and Management: X, 13*, Article 100156. https://doi.org/10.1016/j.ecmx.2021.100156
Grassi, M. C. B., & Pereira, G. A. G. (2019). Energy-cane and RenovaBio: Brazilian vectors to boost the development of Biofuels. *Industrial Crops and Products, 129*, 201–205. https://doi.org/10.1016/J.INDCROP.2018.12.006
Hao, H., et al. (2017). GHG emissions from the production of lithium-ion batteries for electric vehicles in China'. *Sustainability, 9*, 504. https://doi.org/10.3390/SU9040504
Haram, M. H. S. M., et al. (2021). Feasibility of utilising second life EV batteries: applications, lifespan, economics, environmental impact, assessment, and challenges. *Alexandria Engineering Journal, 60*(5), 4517–4536. https://doi.org/10.1016/j.aej.2021.03.021
Harrison, G. (1948). "HETEROSIS"?L'. *Genetics, 33*, 439–446. Available at: https://academic.oup.com/genetics/article/33/5/439/6032125. (Accessed 11 August 2022).
Hayes, J. G., et al. (2011). Simplified electric vehicle power train models and range estimation'. In *2011 IEEE Vehicle Power and Propulsion Conference* (pp. 1–5). IEEE. https://doi.org/10.1109/VPPC.2011.6043163.
HYUNDAI. (2020). 2020 Hyundai IONIQ Electric 38.3 kWh - specifications. Available at: https://www.evspecifications.com/en/model/ced6a3. (Accessed 23 September 2021).
HYUNDAI. (2021a). 2021 Hyundai Ioniq Electric | EV Hatchback | Hyundai USA. Available at: https://www.hyundaiusa.com/us/en/vehicles/ioniq-electric (Accessed: 23 September 2021a).
HYUNDAI. (2021b). 2021 Hyundai Ioniq Hybrid | Hyundai USA. Available at: https://www.hyundaiusa.com/us/en/vehicles/ioniq-hybrid (Accessed: 23 September 2021b).
HYUNDAI. (2021c). 2021 Hyundai IONIQ plug-in hybrid features & specs | Hyundai USA. Available at: https://www.hyundaiusa.com/us/en/vehicles/ioniq-plug-in-hybrid/compare-specs (Accessed: 23 September 2021c).
IEA. (2021). Global EV Outlook 2021 - Accelerating ambitions despite the pandemic. *Global EV Outlook, 2021*, 101. https://iea.blob.core.windows.net/assets/ed5f4484-f556-4110-8c5c-4ede8bcba637/GlobalEVOutlook2021.pdf.
International Energy Agency. (2021). Net Zero by 2050: A roadmap for the global energy sector. *International Energy Agency*, 224. Available at: https://www.iea.org/reports/net-zero-by-2050.
International Energy Agency (IEA). (2021). Net Zero by 2050 a roadmap for the global energy sector. *Net Zero by, 2050*, 224. Available at https://www.iea.org/reports/net-zero-by-2050. Available at.
IRENA. (2021). World energy transitions outlook: 1.5 degrees pathway, International Renewable Energy Agency. Available at: https://irena.org/publications/2021/March/World-Energy-Transitions-Outlook.
Jarraud, M., & Steiner, A. (2019). Summary for policymakers. In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation: Special Report of the Intergovernmental Panel on Climate Change* https://doi.org/10.1017/CBO9781139177245.003
Joubert, M. (2022). EU'S vote could be the beginning of the end for combustion engine cars. Available at: https://news.northeastern.edu/2022/06/10/ban-on-combustion-engine-cars/.
Kallitsis, E., et al. (2020). Environmental life cycle assessment of the production in China of lithium-ion batteries with nickel-cobalt-manganese cathodes utilising novel electrode chemistries. *Journal of Cleaner Production, 254*, Article 120067. https://doi.org/10.1016/j.jclepro.2020.120067
Kane, M. (2021). GM expands massive battery recall to all chevrolet bolt EV/EUV. Insideevs. Available at: https://insideevs.com/news/528025/expands-battery-recall-bolt-ev/ (Accessed: 20 December 2022).
KBB. (2021). Você sabe quanto a quilometragem impacta o preço do carro usado? | KBB.com.br. Available at: https://www.kbb.com.br/detalhes-noticia/quilometragem-precos-carro-usado/?id=1802. (Accessed 9 December 2021).
Kelly, J. C., et al. (2020). *Globally regional life cycle analysis of automotive lithium-ion nickel manganese cobalt batteries mitigation and adaptation strategies for global change* (2020). *25* pp. 371–396). https://doi.org/10.1007/s11027-019-09869-2.
Agência Nacional do Petróleo, Gás e Biocombustíveis (2022). Dados estatísticos Available at:. https://www.gov.br/anp/pt-br/centrais-de-conteudo/dados-estatisticos. (Accessed 28 May 2022).
Mann, M., Mayyas, A., & Steward, D. (2018). Supply-chain analysis of li-ion battery material and impact of recycling. *National Renewable Energy Laboratory, Annual Merit Review and Peer Evaluation Meeting, June 19, 2018* (p. 28308). Available at: www.trademap.org.
MAPA - Ministério da Agricultura, Pecuária e Abastecimento (2022). O que é o cadastro ambiental rural (CAR) Available at: https://www.florestal.gov.br/cadastro-ambiental-rural. (Accessed 28 May 2022).
RCGI - Research Centre for Greenhouse Gas Innovation. (2017). Potencial de produção de biometano em São Paulo representa 46% da demanda do Estado por gás natural. Available at: https://www.rcgi.poli.usp.br/pt-br/potencial-de-producao-de-biometano-em-sao-paulo-representa-46-da-demanda-do-estado-por-gas-natural/ (Accessed 20 December 2022).
UNICAdata - Observatório da Cana e Bioenergia. (2022). Painel de certificação, metas e mercado de CBIOs. Observatório da Cana e Bioenergia. Available at https://observatoriodacana.com.br/listagem.php?idMn=142. (Accessed 20 December 2022).
KIA (2021) 2021 Kia Niro specifications. Available at: https://www.kiamedia.com/us/en/models/niro/2021/specifications (Accessed: 24 August 2021).
Kim, H. C., et al. (2016). Cradle-to-gate emissions from a commercial electric vehicle li-ion battery: A comparative analysis. *Environmental Science & Technology, 50*(14), 7715–7722. https://doi.org/10.1021/acs.est.6b00830
Knobloch, F., et al. (2020). Net emission reductions from electric cars and heat pumps in 59 world regions over time. *Nature Sustainability, 3*(6), 437–447. https://doi.org/10.1038/s41893-020-0488-7
Koroma, M. S., et al. (2022). Life cycle assessment of battery electric vehicles: Implications of future electricity mix and different battery end-of-life management. *Science of the Total Environment, 831*, Article 154859. https://doi.org/10.1016/j.scitotenv.2022.154859
Kostopoulos, E. D., Spyropoulos, G. C., & Kaldellis, J. K. (2020). Real-world study for the optimal charging of electric vehicles. *Energy Reports, 6*, 418–426. https://doi.org/10.1016/j.egyr.2019.12.008
KPMG. (2020). *Avaliação do ciclo de vida de produtos sucroenergéticos safra 19/20*. São Paulo.
Liu, W., Agusdinata, D. B., & Myint, S. W. (2019). Spatiotemporal patterns of lithium mining and environmental degradation in the Atacama Salt flat, Chile'. *International Journal of Applied Earth Observation and Geoinformation, 80*, 145–156. https://doi.org/10.1016/J.JAG.2019.04.016
Luckeneder, S., et al. (2021). Surge in global metal mining threatens vulnerable ecosystems. *Global Environmental Change, 69*, Article 102303. https://doi.org/10.1016/J.GLOENVCHA.2021.102303
Macedo, I. C., Seabra, J. E. A., & Silva, J. E. A. R. (2008). Green house gases emissions in the production and use of ethanol from sugarcane in Brazil: the 2005/2006 averages and a prediction for 2020. *Biomass and Bioenergy, 32*(7), 582–595. https://doi.org/10.1016/J.BIOMBIOE.2007.12.006
Machado, P. G., et al. (2015). The use of socioeconomic indicators to assess the impacts of sugarcane production in Brazil. *Renewable and Sustainable Energy Reviews, 52*, 1519–1526. https://doi.org/10.1016/j.rser.2015.07.127
Meier, P. J., et al. (2015). Potential for electrified vehicles to contribute to U.S. petroleum and climate goals and implications for advanced biofuels. *Environmental Science and Technology, 49*(14), 8277–8286. https://doi.org/10.1021/acs.est.5b01691
Moioli, E., & Schildhauer, T. (2022). Negative CO2 emissions from flexible biofuel synthesis: Concepts, potentials, technologies. *Renewable and Sustainable Energy Reviews, 158*, Article 112120. https://doi.org/10.1016/J.RSER.2022.112120
Moraes, M. A. F. D., Oliveira, F. C. R., & Diaz-Chavez, R. A. (2015). Socio-economic impacts of Brazilian sugarcane industry. *Environmental Development, 16*, 31–43. https://doi.org/10.1016/j.envdev.2015.06.010
Moreira, J. R., et al. (2016). BECCS potential in Brazil: Achieving negative emissions in ethanol and electricity production based on sugar cane bagasse and other residues. *Applied Energy, 179*, 55–63. https://doi.org/10.1016/j.apenergy.2016.06.044
Moreira, M. M. R., et al. (2018). Proposta de contabilização da mudança de uso da terra na política nacional de biocombustíveis (RenovaBio). In *Embrapa Meio Ambiente-Artigo em anais de congresso (ALICE)* (pp. 155–161).
Nissan. (2020). *Manual da bateria do Nissan Leaf 2020* (p. 49).
NISSAN USA. (2021a). 2022 Nissan LEAF range, charging & battery | Nissan USA. Available at: https://www.nissanusa.com/vehicles/electric-cars/leaf/features/range-charging-battery.html (Accessed: 27 August 2021).
NISSAN USA. (2021b). 2022 Nissan LEAF Specs & Prices | Nissan USA. Available at https://www.nissanusa.com/vehicles/electric-cars/leaf/specs/compare-specs.html#modelName=S%7C40kWh (Accessed: 27 August 2021).
Parsaee, M., Kiani, Kiani Deh, & M. and Karimi, K.. (2019). A review of biogas production from sugarcane vinasse. *Biomass and Bioenergy, 122*(January), 117–125. https://doi.org/10.1016/j.biombioe.2019.01.034

Qiao, Q., et al. (2017). Cradle-to-gate greenhouse gas emissions of battery electric and internal combustion engine vehicles in China. *Applied Energy, 204*, 1399–1411. https://doi.org/10.1016/J.APENERGY.2017.05.041

Qiao, Q., et al. (2019). Electric vehicle recycling in China: Economic and environmental benefits. *Resources, Conservation and Recycling, 140*, 45–53. https://doi.org/10.1016/j.resconrec.2018.09.003. July 2018.

Reid, C. (2022). *Electric car batteries lasting longer than predicted delays recycling programs*. Forbes. Available at https://www.forbes.com/sites/carltonreid/2022/08/01/electric-car-batteries-lasting-longer-than-predicted-delays-recycling-programs/?sh=5ac402f75332. Available at.

Ribeiro, B. E. (2013). Beyond commonplace biofuels: Social aspects of ethanol. *Energy Policy, 57*, 355–362. https://doi.org/10.1016/j.enpol.2013.02.004

Ricardo energy & Environment. (2020). *Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA* (p. 456). DG Climate Action: European Commission. Available at: https://op.europa.eu/sv/publication-detail/-/publication/1f494180-bc0e-11ea-811c-01aa75ed71a1.

RSB. (2022). Granbio achieves Rsb certificate for its cellulosic ethanol in Europe. Available at: https://rsb.org/2021/04/26/granbio-achieves-rsb-certificate-for-its-cellulosic-ethanol-in-europe/ (Accessed 15 December 2022).

Santoro, E., Soler, E. M., & Cherri, A. C. (2017). Route optimization in mechanized sugarcane harvesting. *Computers and Electronics in Agriculture, 141*, 140–146. https://doi.org/10.1016/J.COMPAG.2017.07.013

Seabra, J. E. A., et al. (2011). Life cycle assessment of Brazilian sugarcane products: GHG emissions and energy use. *Biofuels, Bioproducts and Biorefining, 5*(5), 519–532. https://doi.org/10.1002/bbb.289

Sears, J., Roberts, D., & Glitman, K. (2014). Level 2 charging efficiency. In *2014 IEEE Conference on Technologies for Sustainability (SusTech)* (pp. 255–258).

SEEG - Sistema de Estimativas de Emissões e Remoções de Gases de Efeito Estufa. (2022). Emissões Totais Brasil. Available at: https://plataforma.seeg.eco.br/total_emission (Accessed 12 October 2022).

SINDIPEÇAS - Sindicato Nacional da Indústria de Componentes para Veículos Automotores. (2021). Relatório da frota circulante nacional. Available at: https://www.sindipecas.org.br/sindinews/Economia/2021/RelatorioFrotaCirculante_Marco_2021.pdf (Accessed: 9 December 2021).

Singh, B., Ellingsen, L. A. W., & Strømman, A. H. (2015). Pathways for GHG emission reduction in Norwegian road transport sector: Perspective on consumption of passenger car transport and electricity mix. *Transportation Research Part D: Transport and Environment, 41*, 160–164. https://doi.org/10.1016/J.TRD.2015.09.028

Smith, W. J. (2010). Can EV (electric vehicles) address Ireland's CO2 emissions from transport? *Energy, 35*(12), 4514–4521. https://doi.org/10.1016/J.ENERGY.2010.07.029

Souza, A., et al. (2018). Social life cycle assessment of first and second-generation ethanol production technologies in Brazil. *International Journal of Life Cycle Assessment, 23*(3), 617–628. https://doi.org/10.1007/s11367-016-1112-y

Souza, N. R. D. de, Cavalett, O., & Junqueira, T. L. (2022). Techno-economic and environmental assessment of bioenergy and livestock integrated systems in Brazil. *Sustainable Production and Consumption, 32*, 580–592. https://doi.org/10.1016/J.SPC.2022.05.013

Ternel, C., Bouter, A., & Melgar, J. (2021). Life cycle assessment of mid-range passenger cars powered by liquid and gaseous biofuels: Comparison with greenhouse gas emissions of electric vehicles and forecast to 2030. *Transportation Research Part D: Transport and Environment, 97*(May), Article 102897. https://doi.org/10.1016/j.trd.2021.102897

Tesla Motors Inc. (2022). New vehicle limited warranty. Available at: https://www.tesla.com/support/vehicle-warranty (Accessed 12 October 2022).

Tessum, C. W., Hill, J. D., & Marshall, J. D. (2014). Life cycle air quality impacts of conventional and alternative light-duty transportation in the United States. *Proceedings of the National Academy of Sciences of the United States of America, 111*(52), 18490–18495. https://doi.org/10.1073/pnas.1406853111

Tiwari, A. (2022). What is hybrid vigor?. Available at: https://www.scienceabc.com/nature/what-is-hybrid-vigor-definition-examples-and-a-brief-explanation.html (Accessed 12 October 2022).

TOYOTA. (2021). 2022 Prius prime full specs. Available at: https://www.toyota.com/priusprime/features/mpg_other_price/1235/1237/1239 (Accessed: 23 September 2021).

TOYOTA. (2022). Comparar versões: Corolla. Available at: https://www.toyota.com.br/modelos/corolla/comparativo/ (Accessed 23 September 2021).

Travesset-Baro, O., Rosas-Casals, M., & Jover, E. (2015). Transport energy consumption in mountainous roads. A comparative case study for internal combustion engines and electric vehicles in Andorra. *Transportation Research Part D: Transport and Environment, 34*, 16–26. https://doi.org/10.1016/J.TRD.2014.09.006

UNICA - União da Indústria de Cana de Açúcar e Bioenergia. (2022). Observatório da Cana, Estimativa do volume comercializado por unidades certificadas. Available at: https://observatoriodacana.com.br/listagem.php?idMn=142 (Accessed: 26 May 2022).

Vargas, J. E. V., Capaz, R. S., Souza, S. P., Cavalett, O., & Seabra, J. E. A. (2022). Evaluating decarbonisation pathways in road transportation via life cycle assessment. In C. R. Soccol, G. A. G. Pereira, C. G. Dussap, & L. P. S. Vandenberghe (Eds.), *Liquid Biofuels: Bioethanol. Biofuel and Biorefinery Technologies* (pp. 333–362). Springer. https://doi.org/10.1007/978-3-031-01241-9_15.

World Bank. (2022). Total greenhouse gas emissions. Available at: https://data.worldbank.org/indicator/EN.ATM.GHGT.KT.CE.

Wu, Z., et al. (2019). Assessing electric vehicle policy with region-specific carbon footprints. *Applied Energy, 256*, Article 113923. https://doi.org/10.1016/J.APENERGY.2019.113923

Zang, J. W., Martins, K. F., & Da Fonseca-Zang, W. A. (2018). Life cycle inventory for biomethane as a diesel substitute for the Brazilian ethanol industry - Case study. *Energy Procedia, 153*, 444–449. https://doi.org/10.1016/j.egypro.2018.10.048

Zhao, Y., et al. (2021). A review on battery market trends, second-life reuse, and recycling. *Sustainable Chemistry, 2*(1), 167–205. https://doi.org/10.3390/suschem2010011