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COMPARATIVE ANALYSIS OF GHG EMISSIONS IN THE LIFE CYCLES OF BATTERY ELECTRIC, HYBRID, AND CONVENTIONAL VEHICLES FUELED WITH ETHANOL/GASOLINE

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Abstract. *Much of the effort to control greenhouse gas (GHG) emissions in the transportation sector has focused on the use of biofuels and the promotion of technological innovations in propulsion systems. Therefore, studies aimed at comparing the environmental impacts associated with different vehicle technologies are necessary to identify pros and cons for the environment when using a particular system. Thus, this work developed a comparative study of GHG emissions associated with the life cycles of battery electric vehicles (BEV), hybrid electric vehicles (HEV) and conventional vehicles, the last two evaluated with ethanol and gasoline type E27. Life Cycle Analysis principles were applied to quantify the inputs and outputs linked to the climate change category. Initially, available data was gathered from the literature corresponding to the life cycle stages of the vehicles in question, as well as the fuels used. Then, we sought to meet the structure of the ISO 14000 series of standards. The inventory was analyzed using Microsoft™Excel™ software. The functional unit chosen was 1 km traveled. The results obtained show that HEV with ethanol presented itself as the best technology, climatically followed by BEV.*

Keywords: *battery electric vehicle, hybrid electric vehicle, ethanol, gasoline, Life Cycle Assessment*.

1. INTRODUCTION

Direct CO_2 emissions linked to the transportation sector increased by 29% between the years 2000 and 2016. In this period, this sector was responsible for about 23% of global CO_2 emissions associated with the generation and consumption of energy and, as of 2014, contributed 14% of global emissions of greenhouse gases (GHG). In this context, light utility vehicles accounted for 45% of total emissions and are therefore considered the largest emitters of GHGs in this sector (SLoCat, 2018).

Besides the growth of the light vehicle fleet around the world, the data presented above is a consequence of the fact that most of these cars are powered by fossil fuels, specifically gasoline. The use of fossil fuels entails a large amount of GHG emissions, thus contributing to the intensification of global warming (Maga et al., 2019). Furthermore, efforts to control GHG emissions and the search for sustainability in the transportation sector have focused on the use of alternative fuels from renewable sources, such as ethanol, as well as the promotion of technological innovations in power trains (Balat et al., 2008; Chrispim et al., 2019).

Ethanol is a biofuel produced from biomass that presents itself as an alternative to gasoline in the transportation sector. Brazil represented about 29% of the world production of this biofuel in 2021 (REN21, 2022). Between 2022 and 2023, the country produced about 27.37 billion liters of ethanol derived from sugarcane, especially anhydrous ethanol, which had an increase of 14% in relation to the amount produced between 2021 and 2022. Regarding ethanol from corn, the increase was 14.4%, having been about 3.97 billion tons (CONAB, 2023).

Battery electric vehicles (BEV) and hybrid electric vehicles (HEV), although they do not represent recent technological innovations, have been employed in this context of electrification of transport worldwide. In Brazil, the trend of replacing conventional gasoline vehicles by electric vehicles has been growing every year, so that there is a great expectation for the rise and consolidation of electric cars in the market in the coming decades (Sanches, 2021). Therefore, studies that contribute to the understanding about the environmental impacts and to what extent the electric vehicles are more advantageous compared to conventional ones in terms of GHG emissions are necessary in view of the current technological transition.

Life Cycle Analysis or Assessment (LCA) is a quantitative tool that allows the analysis of the impacts caused on the environment by the provision of products or services and assist in recommending solutions so that environmental problems related to a particular activity are mitigated or even eliminated. This analysis considers the entire life cycle of a product from its design and development to the final activities of its life, which may include collection, sorting, reuse, recycling, and waste treatment (Carrillo et al., 2018).

The quantification of emissions related to a particular process has brought a new perspective to the analysis of environmental, social, and economic impacts, all taken into consideration in this evaluation. Through this type of analysis, it is also possible to investigate and compare in a broader way the stages of the life of a product that most impact the environment and that even today raise questions about environmental problems, as is the case of fuel production chains (Šenitková & Bednárová, 2015).

The considerations presented above justify, therefore, the importance of a better understanding about the environmental impacts and effects caused by the current scenario of technological transition related to the light vehicle fleet in Brazil, comparing the consequences of the use of the two main fuels used in this category of vehicles. Moreover, the context exposed motivates the realization of studies to evaluate possible solutions to the impasses inherent to the transport sector, using the LCA tool. Thus, this work has as its main objective to compare the greenhouse gas emissions (CO_2, CH_4 and N_2O) associated with the life cycles of battery electric (BEV), hybrid electric (HEV) and conventional electric (ICEV) vehicles, the latter two being analyzed in two different scenarios of use: the first, in which both are fueled with E27 gasoline, and the second, in which the vehicles are fueled with ethanol.

2. LIFE CYCLE ASSESSMENT

Sustainability refers to the principle of seeking a balance between the availability of natural resources and their exploitation by society (Sousa, n.d.). Sustainability is supported on three pillars that indicate a balance between the social, environmental, and economic spheres. These three factors need to be integrated so that in fact sustainability occurs, that is, without these three dimensions, sustainability cannot be sustained (Magalhães, n.d.).

Achieving sustainability requires going through sustainable development. Thus, it becomes necessary to use methods and tools that assist in quantifying and comparing the impacts that the supply of products and services generate to the environment. In this context, one of the tools that meet this need is the Life Cycle Analysis or Assessment (LCA), which is one of the most modern methodologies for strategic environmental management (EnCiclo, 2014). LCA is internationally standardized by the International Organization for Standardization (ISO), which designates the procedures of the study execution, as well as their respective phase (Finkbeiner et al., 2006) s. The quantification of emissions related to a particular process has brought a new perspective to the analysis of environmental, social, and economic impacts, all taken into consideration in this evaluation. Through this type of analysis, it is also possible to investigate and compare in a broader way the stages of the life of a product that most impact the environment and that even today raise questions about environmental problems, as is the case of fuel production chains (Hauschild, 2018).

Usually in LCA studies, the third step, which consists of the life cycle impact assessment (LCIA), can take into consideration different impact categories, such as resource depletion, land use, water use, toxic effects on humans, smog, and acidification, for example. The categories to be analyzed depend on the objective set for the investigation. However, there are also some alternative approaches to LCIA, which focus on one environmental impact category only. This is the case with the Water Footprint, Resource Footprint, Ecological Footprint etc. approaches. In this work, we sought to analyze the impacts of vehicle use scenarios in the context of Climate Change, and therefore, we performed an LCA of the Carbon Footprint type.

2.1 Brazilian context of gasoline and ethanol use in the transportation sector

Some LCA studies have shown that while systems using ethanol as fuel or part of the fuel have higher potential impacts for acidification, systems using gasoline have higher potential for intensification of the greenhouse effect due to its higher global warming potential (GWP) (Souza et al., 2018). In addition, from a full life cycle perspective, much of the impacts associated with ethanol occur at its production stage while the impacts of gasoline occur primarily at its use stage (Cavalett et al., 2013).

In the 1930s in Brazil, the Federal Government instituted the use of ethanol as a motor fuel, starting to be used as a 5\% mixture with gasoline. However, it was in 1975, with the creation of the National Alcohol Program (Proálcool), that ethanol produced from sugarcane replaced a substantial part of the demand for gasoline produced in Brazil (Leite et al., 2009).

In 2003, flex-fuel vehicles, which use ethanol and gasoline, were introduced in the Brazilian market and over time began to be used on a large scale. Thus, the use of gasoline-ethanol blends and hydrated ethanol as fuels in vehicles with flex engines became more flexible (Leite et al., 2009). Thus, life cycle analyses become more interesting from the perspective of the fuel used, since most vehicles are of the same type in the Brazilian context.

2.2 Previous studies

There are many studies in the literature dealing with LCA of different vehicle/fuel systems considering various impact categories. Table 1 shows the main results available from some published studies.

Table 1. Previous LCA studies available in literature.

Reference	Short Objective	Main Conclusions
(Souza et al., 2018)	To evaluate and compare the environmental impacts associated with five different scenarios in the Brazilian context, namely: conventional vehicle with internal combustion engine using gasoline, conventional vehicle with internal combustion engine using hydrated ethanol, conventional vehicle with internal combustion engine using a mixture of gasoline and hydrated ethanol (flex vehicle), HEV plug-in, and BEV.	• Using ethanol as fuel leads to greater environmental impacts in the categories of acidification, eutrophication, photochemical oxidation. • The greatest impacts related to gasoline use are linked to the abiotic depletion potential of fossil fuels GWP. • EVs using lithium-ion batteries concentrate the greatest impacts for human toxicity. • BEVs have the lowest environmental impacts overall, followed by ethanol vehicles.
(Choma & Ugaya, 2017)	To identify the environmental impacts linked to the life cycle of BEVs in the Brazilian light fleet, focusing on the use phase, including energy consumption.	• BEV fared better for abiotic depletion, GWP, ozone depletion, and freshwater aquatic eco-toxicity. • Vehicle production was also responsible for much of the impacts in several categories, so early replacement of ICEVs with BEVs could also result in higher impacts.
(Lombardi et al., 2017)	Compare the impacts of a conventional gasoline vehicle, a pure EV, a gasoline plug-in HEV, and a battery fuel cell plug-in HEV, considering powertrain differences and inefficiencies while maintaining the chassis for all scenarios.	• In the case of the climate change, fuel depletion and cumulative energy demand indicators, the lowest value corresponds to the plug-in HEV with gasoline, followed by the plug-in HEV with fuel cell, pure electric and finally the gasoline-powered CV.
(Vargas et al., 2016)	To evaluate the potential environmental impacts of light passenger and cargo transport, with a scope referring to the Brazilian scenario in the year 2014, considering EVs and internal combustion (flex fuel, ethanol, and gasoline types).	• The worst results were observed for EV for four impact categories, abiotic depletion, human toxicity, terrestrial eco-toxicity, and eutrophication. • The flex vehicle fueled with anhydrous ethanol shows the worst results for acidification and photochemical oxidation categories. • The flex-fuel vehicle running on gasoline shows the worst results for the categories of abiotic depletion of fossil resources, GWP and ozone depletion.
(Faria et al., 2013)	Investigate the life cycle environmental and economic aspects of EV and conventional technologies focusing mainly on the primary energy source and GHG emissions during the vehicle operation phase.	• Compared to other technologies, EVs may be more sustainable from an environmental and economic perspective; however, three main factors are needed: improved battery technology, a green driving attitude, and an environmentally friendly electricity mix.

3. METHODOLOGY

As previously mentioned, the methodological structure of this work is based on the ISO 14040 and ISO 14041 standards. The scenarios were defined according to the car fleet and fuels most used by the Brazilian population today, which are shown in Table 2. Thus, the vehicle/fuel systems adopted for evaluation were: (1) light conventional vehicle with internal combustion engine/gasoline (ICEVg), (2) light conventional vehicle with internal combustion engine/ethanol (ICEVe), (3) hybrid electric vehicle/gasoline (HEVg), (4) hybrid electric vehicle/ethanol (HEVe) and, finally, (5) battery electric vehicle/electricity (BEV).

Table 2. Top-selling vehicles in Brazil in 2021 by technology.

Technology	Vehicle	Units Sold
ICEV	Jeep Renegade[1]	73,913
HEV	Toyota Corolla Cross[2]	11,027
BEV	Nissan Leaf Tekna[2]	439

Fonte: [1] Ribeiro (2022) e [2] Torres (2022)

We also considered the internal combustion engines of the ICEV and HEV as being of the flex type, and the gasoline that fuels them with a mixture of 27% ethanol, according to current Brazilian regulations. The focus of the analyses was on the three main GHGs listed by the Kyoto Protocol, namely carbon dioxide, methane, and nitrous oxide (CO_2, CH_4, and N_2O, respectively), because although other GHGs appear throughout the life cycle of vehicles, their overall contributions to the climate change impact category are usually small.

The **time horizon** of the study is associated with the moment of its realization, thus, whenever possible, data from the last two years was used. We also chose the attributional modeling approach. Thus, this work aims to verify which of the vehicle/fuel systems analyzed is more environmentally friendly in terms of climate change.

The **function** of the investigated systems was defined as a vehicle to transport a person over 1 km. Based on the function presented, the **functional unit** (FU) established for the study is 1 km traveled, i.e., the distance over which a person will be transported in a car. The choice of this FU was due to the ease of comparison between different LCA studies of vehicle/fuel systems, regardless of the useful life considered (Souza, 2015), since many works involving this subject employ "1 km" as the functional unit (Choma & Ugaya, 2017; Souza et al., 2018, 2016). The **reference flows** adopted in the different stages of analysis of this study considered the phase of use of the vehicles, taking as a reference the average useful life of a vehicle in Brazil which is 160,000 km (Souza et al., 2018).

3.1 Identification of study boundaries

Assessing the impacts associated with different vehicle/fuel systems requires an analysis that encompasses all phases of the vehicles' life cycle, as well as all phases of the energy sources' life cycle. That is, for vehicles, the phases of production, use, and end-of-life activities should be analyzed, and for energy sources, the phases of production and use of energy sources. Therefore, the present study considers the complete life cycles of vehicles, employing the cradle to grave approach, which comprises raw material extraction, energy flows, industrial production, distribution, use, and end-of-life. Similarly, the analysis of energy sources is followed, which is termed "well-to-wheel".

The different systems were categorized from the different energy sources and different powertrain technologies. These models were developed based on fuel characteristics (Schirmer & Ribeiro, 2017) and vehicles corresponding to the best-selling light vehicle fleet in Brazil in 2021 (Table 2). Thus, the boundaries of the systems that are the objects of this study are represented below:

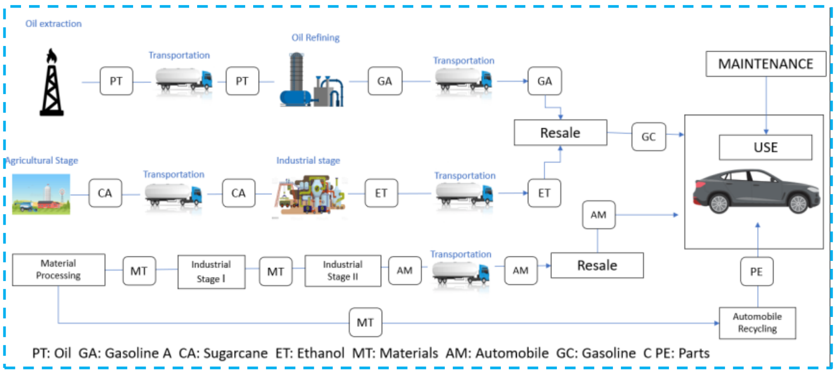

Figure 1. System boundary diagram for Scenario 1.

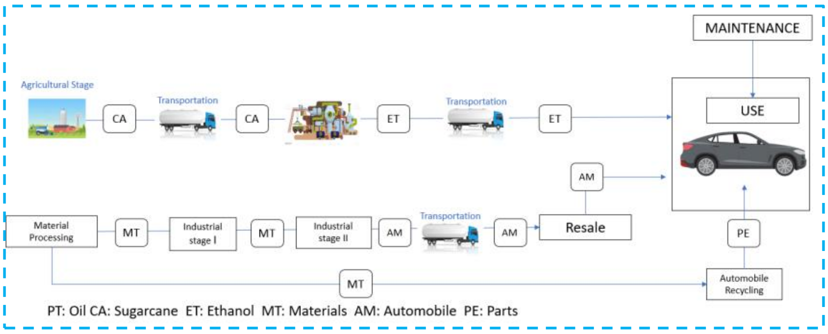

Figure 2. System boundary diagram for Scenario 2.

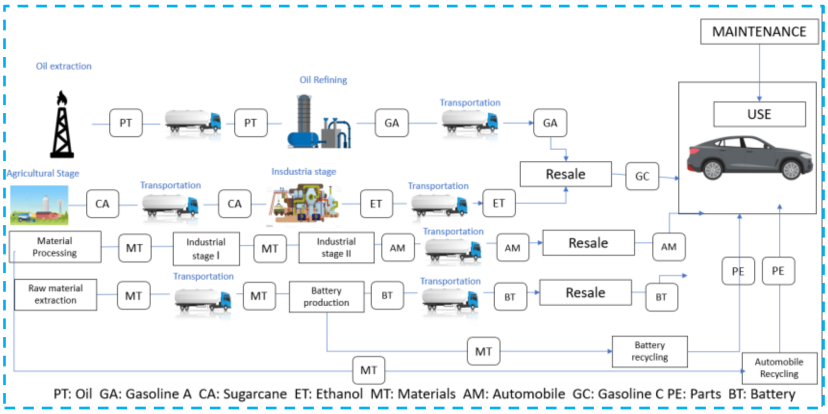

Figure 3. System boundary diagram for Scenario 3.

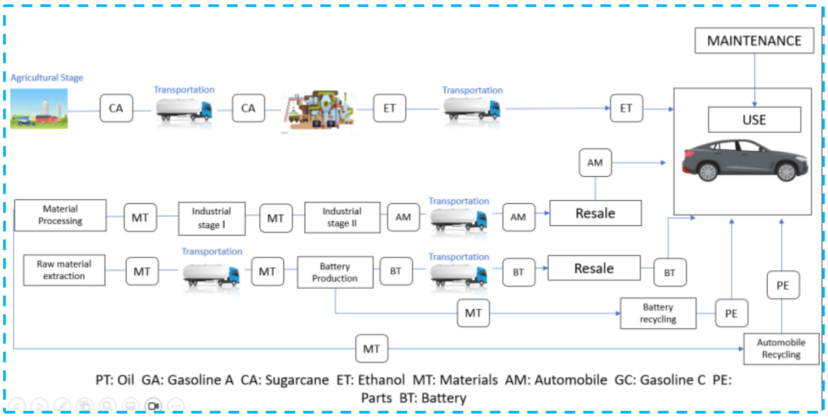

Figure 4. System boundary diagram for Scenario 4.

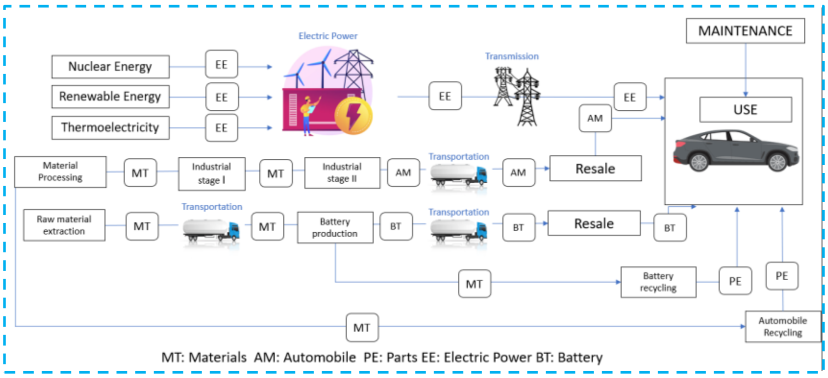

Figure 5. System boundary diagram for Scenario 5.

3.2 Life cycle inventory analysis

The life cycle inventory analysis step, according to ISO 14040, involves the collection of data and the procedures used to quantify the material and energy inputs and outputs, in the form of emissions to air, water, and soil, throughout the life cycle of the product of interest. The boundaries initially proposed for the study were defined based on similar works present in the literature (Boureima et al., 2009; Faria et al., 2013; Souza et al., 2018).

In this work, the most up-to-date data available in the literature was used, thus following the procedure adopted by other authors in works published in the last 5 years on the subject in question. However, it should be remembered that uncertainty arises in various ways throughout the LCA process, where specific issues of methodology and scarcity of data, for example, lead the LCA professional to choose between different study approaches (Barahmand & Eikeland, 2022) and to consider the use, with reservations, of older bases to compose life cycle inventories. Briefly, the data collection performed in this study occurred according to each proposed system and subsystem. The main data sources for each system are listed below:

- Automobiles (production and recycling): GREET® 2021 software database.
- Gasoline A (production and use): Inventory presented by Borges (2004).
- Ethanol (production and use): Data presented by Cavalett et al. (2013).
- Electricity: Result of GHG emissions associated with the Brazilian electricity matrix in 2021 disclosed in EPE (2022)
- Batteries (recycling): Data obtained from the work of (Fisher et al., 2006).
- The emission factors for the non-inventory data were obtained from GREET® 2021.

In this work, the characterization factors measured against the 2013 IPCC AR5 GWP were used. All emission factors employed are based on the same methodology for the climate change category, as is the case of the GREET® 2021 software, whose emission factors are used in several subsystems of the study in question. As for the emission factor for ethanol production, we used the result of Cavalett et al. (2013) obtained from the ReCiPe Midpoint (H) method, which is also based on IPCC AR5 to assess the impacts associated with the category of climate change. Table 3 presents the characterization factors according to IPCC AR5 considering the time horizon of 100 years.

Table 3. GHG characterization factors provided by IPCC AR5.

GHG	CF
CO_2	1
CH_4	28
N_2O	265

Fonte: Dinato et al. (2018).

The GREET® 2021 software was used in the study because of its accessibility, being a free LCA program. However, it was sought to use, whenever possible, data closer to the Brazilian reality, since GREET® has much of its data referring to the U.S. context.

4. RESULTS AND DISCUSSION

Regarding the ICEVg, it was observed that the car's production for scenario 1 is responsible for about 13.86% of the total $CO_{2\text{-eq}}$ emissions. This phase considered the output of the vehicle components and the assembly. The relatively low value can be justified by using electric energy with low associated $CO_{2\text{-eq}}$ emissions; in addition, one should consider optimizing production processes and reducing GHG emissions. Fuel production, in this case, ethanol and gasoline A, adds up to about 20.13% of $CO_{2\text{-eq}}$ emissions. The addition of ethanol to gasoline tends to reduce the contribution of emissions in the production of fuel because, during the cultivation of sugar cane, there is capture of CO_2 from the atmosphere. Exhaust emissions are responsible for approximately 65.13% of the total GHG emissions, and the recycling of cars accounts for 0.89% of these emissions. In Figure 6, the results for scenario 1 are presented.

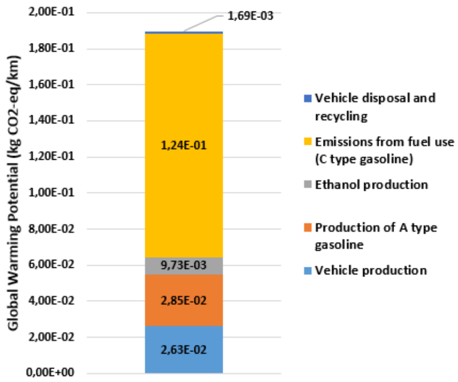

Figure 6. Contribution of each stage in the total GHG emissions relative to the ICEVg.

As for the ICEVe, it was found that the vehicle production stage is responsible for about 29.61% of total $CO_{2\text{-eq}}$ emissions. The production of the fuel, which in this case is ethanol, accounts for approximately 66.00% of GHG emissions. Emissions associated with ethanol burning during vehicle use contribute about 2.50% of the GHG release into the atmosphere. Emissions related to vehicle recycling contribute about 1.90% of the total emissions. The results are shown below.

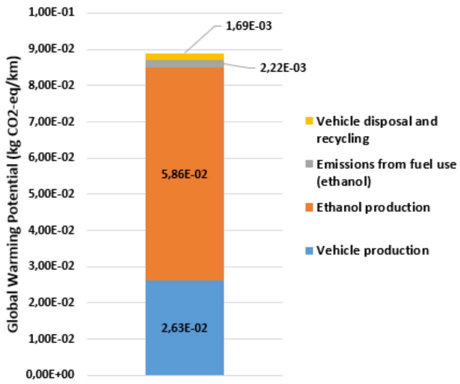

Figure 7. Contribution of each stage in the total GHG emissions relative to the ICEVe.

The results of the total contribution of each stage to the total $CO_{2\text{-eq}}$ emissions relative to HEVg are presented in Figure 8. The vehicle production stage corresponds to 18.95% of the total $CO_{2\text{-eq}}$ emissions. The sum of the contributions of ethanol and gasoline A production to the total emissions is 18.94%. The exhaust emissions from burning C gasoline during the use of the vehicle are responsible for most of the emissions in this scenario, about 60.86%. The lowest emissions are associated with vehicle and battery recycling, 1.24% and 0.01%, respectively.

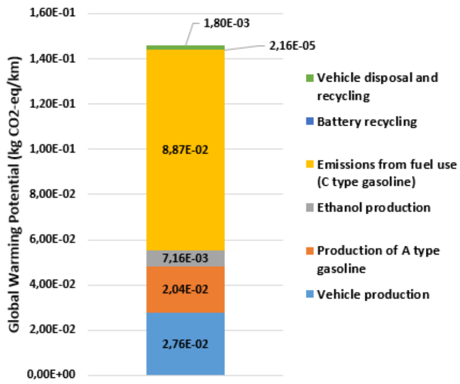

Figure 8. Contribution of each stage in the total GHG emissions relative to the HEVg.

Figure 9 shows the results of the contributions of each phase to the $CO_{2\text{-eq}}$ emissions relative to the fourth scenario. In the analyzed context, the production of the vehicle is responsible for 37.70% of the emissions. Ethanol production accounts for 57.63% of the total emissions. The burning of ethanol during vehicle use is responsible for 2.18% of the $CO_{2\text{-eq}}$ released into the atmosphere. 2.46% and 0.03% are attributed to the recycling of the car and battery, respectively.

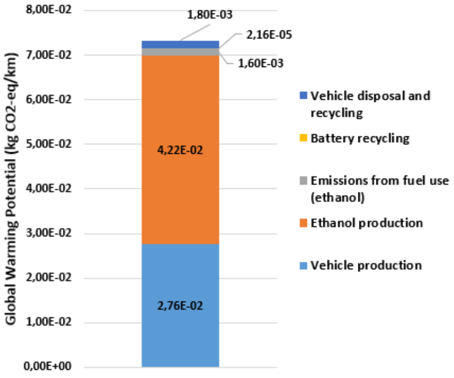

Figure 9. Contribution of each stage in the total GHG emissions relative to the HEVe.

The BEV production stage accounts for 74.44% of the total $CO_{2\text{-eq}}$ emissions, being the largest contribution among the production stages of the analyzed vehicles. The use of the vehicle is associated with about 23.20% of the total emissions. The two stages with the lowest emission values are the vehicle recycling stage, with 2.08% and the battery recycling stage, with 0.28% of the total $CO_{2\text{-eq}}$ emissions.

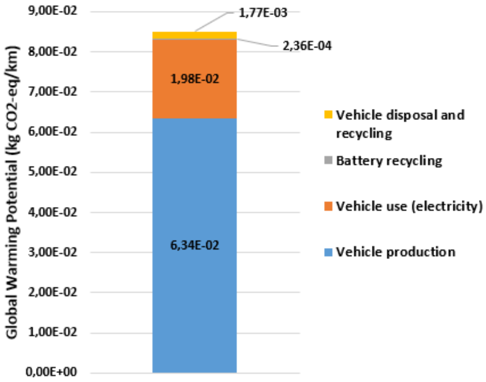

Figure 10. Contribution of each stage in the total GHG emissions relative to the BEV.

As seen in Figure 11, ICEVg has the highest impact in terms of GWP, emitting a total of 1.90E-01 kg $CO_{2\text{-eq}}$/km. This is due to the large amount of GHGs released into the atmosphere from gasoline combustion. However, this index tends to be lower than the world average due mainly to adding anhydrous ethanol to gasoline A. The HEVg corresponds to the second highest value of $CO_{2\text{-eq}}$ emissions, with a total of 1.46E-01 kg $CO_{2\text{-eq}}$ /km.

The ICEVe has the third highest impact, emitting about 8.89E-02 kg $CO_{2\text{-eq}}$/km. It is worth noting that the fourth highest $CO_{2\text{-eq}}$ emitter was the BEV, with a result of 8.51E-02 kg $CO_{2\text{-eq}}$/km. This vehicle has as one of its main characteristics that it has no exhaust emissions. Although it is not the one that least impacts the environment, it should be considered that the value could be higher if another electric matrix than the one from Brazil were admitted since it has a renewable base, emitting less $CO_{2\text{-eq}}$/kWh produced in other countries.

The vehicle with the lowest global warming potential is the HEVe, with 7.33E-02 kg $CO_{2\text{-eq}}$/km. Although the most significant contribution to total emissions is related to ethanol production in scenario 3, it is known that factors associated with the first phase of ethanol's life cycle, such as the increase in sugarcane productivity in recent years, among other reasons, contribute to the reduction of GHG emissions in the scenario in question.

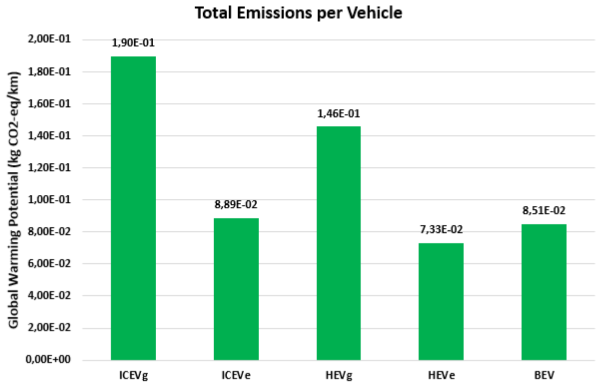

Figure 11. Global warming potential associated with each scenario analyzed.

5. CONCLUSIONS

The analysis and discussion related to the results obtained concerning the carbon footprint of the five scenarios considered in this study allow us to conclude that:

- ICEVg presents the highest global warming potential due to the higher GHG emissions due to gasoline burning.
- HEVe presented itself as the best technology for the climate change impact category. This result can be attributed to the optimization in the production step of both the vehicle and the ethanol. In addition, the fact that the HEV battery is smaller than the BEV battery also influences this result. This conclusion corroborates the current trend of large automakers betting on hybrid vehicles that use ethanol, another interesting alternative to solve the decarbonization issue (W. de Faria, n.d.).
- The BEV, despite having no exhaust emissions, ends up being the second-best alternative according to this study's results due to the battery's size, which has a higher energy density than the HEV battery. Furthermore, in the case of the Brazilian electric matrix, the indirect emissions associated with producing electricity for the use of the BEV are environmentally favorable.
- The ICEV presents a significant difference when comparing its use with gasoline and ethanol due to biofuel's renewable and clean nature.
- The two vehicles with the highest associated $CO_{2\text{-eq}}$ emissions use gasoline as fuel. However, the difference between the ICEVg and HEVg emissions is considerable. This fact can be justified by the specific consumption considered for the hybrid vehicle.
- Considering a single impact category, verifying the best technology among those analyzed is possible, which presents more advantages than the others in environmental terms. However, we propose a comparison between different impact categories to verify each system's advantages and disadvantages over the others.

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