Electric or internal combustion vehicles? A Life Cycle Assessment in São Paulo

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Electric or Internal Combustion Vehicles? A Life Cycle Assessment in São Paulo

Abstract

To reduce Greenhouse Gases (GHG) emissions and contribute to Sustainable Development Goals (SDGs) 11 (Sustainable Cities) and 13 (Climate Action), replacing Internal Combustion Engine Vehicles (ICEVs) with Battery Electric Vehicles (BEVs) is a key policy action. This study evaluates and compares the GHG emissions of BEVs and ICEVs in a Global South megacity (São Paulo), with diverse fuel options (gasoline and ethanol) and a cleaner electricity mix, through a comprehensive Life Cycle Assessment (LCA), covering the Production Phase (Cradle-to-Gate), Use Phase (Well-to-Wheel), and End-of-Life Phase. Factors such as battery capacity fade, driving style, and driving cycle are also considered. Results indicate that gasoline-fuelled ICEVs are significantly worse in terms of GHG emissions. BEVs, particularly with Brazil's clean electricity grid mix, offer substantial emission reductions for light-duty vehicles. Using ethanol as a fuel can be a viable interim practice, as emissions from ethanol-fuelled ICEVs are comparable to BEVs. The recycling of vehicles and batteries and the potential for secondary battery use are crucial parameters affecting overall emissions across different scenarios. This research aims to aid policymakers in developing effective strategies and public policies for energy efficiency and GHG emission reduction in vehicles. It advances knowledge on vehicle emissions by utilizing comprehensive data from a city with diverse fuel options and a cleaner energy mix. Notably, this paper is a pioneer in applying a full LCA to BEV adoption in a Global South city.

Keywords: Life Cycle Assessment, Battery Electric Vehicles, Internal Combustion Engines Vehicles; GHG emissions

Word Count:

List of Abbreviations

LCA	Life Cycle Assessment
ICEV	Internal Combustion Engine Vehicle
EV	Electric Vehicle

BEV	Battery Electric Vehicle
GHG	Greenhouse Gases
NMC	Nickel Cobalt Manganese Oxide
WtW	Well-to-Wheels
WtT	Well-to-Tank
TtW	Tank-to-Wheels
EoL	End-of-Life
CTG	Cradle-to-Gate
GWP	Global Warming Potential
BIW	Body-in-White - car body's frame joined together before painting.
HVAC	Heating, Ventilating and Air Conditioning
SDG	Sustainable Development Goal

1. Introduction

Climate change is one of the most significant global challenges facing the world today. It is caused by a variety of factors, including human activities such as the burning of fossil fuels, deforestation, and industrial processes, which result in the release of Greenhouse Gases (GHGs) into the atmosphere. As such, reducing GHG emissions is critical to addressing climate change. This requires global cooperation and collective action to reduce emissions from all sectors of the economy, including transportation, agriculture, and energy production [1], [2].

In order to reduce GHG emissions, and thus, contributing to the achievement of Sustainable Development Goals (SDGs) 11 (Sustainable Cities and Communities) and 13 (Climate Action), one of the main policy actions is to replace Internal Combustion Engine Vehicles (ICEV) by Battery Electric Vehicles (BEV). The global electric car stock reached around 16 million vehicles in 2021, a steep increase from a total of around 10 million vehicles in 2020. The 6.6 million electric vehicles sold in 2021 represented nearly 10% of global car sales [3]. In the Brazilian context, the city of São Paulo signed the COP26 agreement, making the commitment of accelerating the substitution of light duty internal combustion engine vehicles by 2040. Moreover, the electric or hybrid car fleet has experienced a very expressive growth, reaching 38,149 units in 2020, from just 618 units in 2012 [4].

Electric vehicles, differently than the often used Zero-Emission Vehicles (ZEV) denomination suggests, do in fact incur GHG emissions, not only in its use, but across all lifetime phases, from material acquisition to end-of-life destination.

LCA is a method designed to assess the environmental impact caused by products, processes or activities. The objective is to quantify and evaluate material and energy flows that occur across all the lifetime phases of a product, which includes material acquisition, processing and manufacture, distribution, use, repair and end-of-life scenarios, as well as the associated wastes and emissions releases to the environment.

The goal of this study is to evaluate and compare the life cycle Greenhouse Gas Emissions of two different powertrain vehicles, a Battery Electric Vehicle and an Internal Combustion Engine Vehicle, the dominant paradigm, in the context of the city of São Paulo. To reach this goal, a comprehensive Life Cycle Assessment (LCA) approach was adopted. Moreover, the incorporation of local factors into the analysis brings a deeper local understanding, which is of great importance in the particular case of global south countries, as the majority of published studies concentrate on the environments of either Europe, USA or China [5], meaning that overall literature on the subject remains with gaps to be filled. Furthermore, by choosing São Paulo as research context, this study brings data from a country that already uses diverse fuel options (as ethanol) and has a cleaner electricity mix, which means that the scenarios evaluated by this research bring more data and diverse conditions from those already presented in literature, enriching the scenarios and thus, presenting newer possibilities for support the discussion on public policies aiming at reducing GHG emissions in transport sector.

The contribution of this research is twofold. On the theoretical side, it aims to fill the gap in the literature on the contribution of BEVs to the reduction of GHG emissions reduction in the context of Global South, which has not been studied as extensively as the European and North American contexts, despite its relevance on a global scale, exemplified by the size of the

Brazilian fleet, and to provide a comprehensive LCA methodology. In addition, the study also provides results in an European context, which complements previous studies in highlighting the different implications of the two surrounding conditions. At the practical level, the results aim to support policy makers by providing a methodology to assess initial results on the environmental impact of BEVs adoption in the scenario of a city as São Paulo, considering the whole life cycle of the product, from material acquisition to different end-of-life scenarios.

The study is structured as follows. Section 2 proposes a theoretical background and identifies the literature gap that has been explored. The methodology is then presented in Section 3, followed by Section 4 presenting the results of the analysis. Conclusions and final remarks follow in Section 5, together with the proposed implications for theory and public policy.

2. Theoretical background

The environmental impact of electric vehicles in relation to ICEVs has been a topic of considerable interest in the literature, especially in the last 15 years. Since its introduction, the discussion on the topic received contributions from several authors, resulting in points of consensus and points of uncertainty, in which a dispute of different views still takes place.

For instance, the vast majority of studies are supportive of the view that BEVs have lower total life cycle emissions than ICEVs. Research conducted by Hawkins et al. [6], Nanaki et al. [7], Girardi et al. [8], Ellingsen et al. [9], Qiao et al. [10], Yang et al. [11] and Buberger et al. [12] all reached such conclusion, despite differences to be noticed in final results, due to methodological choices. Moreover, the overall distribution of the emissions in each of the phases of the life cycle for different powertrain technologies is also a consensual view. For ICEVs, the use phase is by far the most dominant regarding emissions, while for BEVs, the general picture is of a more equivalent distribution between the production and use phase.

Another point of general consensus in literature is the key role of clean electricity. Woo et al. [13] highlight the significant influence of different electricity mixes in the use phase emissions of BEVs. It is clear that clean electricity sources, such as hydro, wind and solar, represent an optimal scenario in the effort of reducing use phase emissions. On the other hand, electricity generation heavily dominated by coal is shown to be really prejudicial to the point of causing BEVs to have greater life cycle emissions than gasoline ICEVs [14], [6], [15]. Kucukvar et al. [16] provides a deeper analysis of this parameter, comparing different electricity mix scenarios in a European context.

Despite the points of general agreement above mentioned, there are still several factors that require further investigation, towards reaching a consensual position in literature. First, the environmental impact of the battery production is yet to be well defined, as different studies present considerably different outcomes. The differences are especially significant when comparing studies that adopt a bottom-up approach to those that adopt a top-down approach [17]. Specifically, Zackrisson et al. [18], Ellingsen et al. [19] and Majeau-Bettez et al. [20] all present higher battery production impact than the observed average from literature, whilst Dai et al. [21], Kelly et al. [22] and Emilsson et al. [23] are all positioned in a lower spectrum. Moreover, the battery recycling opportunities and feasibility in large scale operations are still a big question, with the imminent need of new studies to be incorporated in literature, as a very small amount addresses the subject with sufficient detail [5].

The effects of the driving behaviour, driving cycle, battery capacity fade and the study of other environmental impacts still needs investigation. Even though some studies in literature have already incorporated one or more of these factors in their methodology. Marques et al. [24] studied the effect of the driving style, or behaviour, in the battery's capacity fade, concluding that a more aggressive driving would lead to an earlier replacement of the battery. Karabasoglu et al. [25] evaluated the consumption (mi/KWh) in different driving cycle scenarios. Results were compared to EPA ratings, and it was concluded that the consumption in NYC, a city with heavy traffic and characterized by a high number of stops, similar to São Paulo, was the highest among studied driving cycles. Gong et al. [26], aimed to study how well traditional driving cycles ratings for BEVs represent real-world data, with the case study of Beijing. Their results demonstrate the importance of this variable in a study, as consumption could be off by as much as 34.75%, depending on the chosen driving cycle. Finally, it is worth mentioning that further validation of those and other variables that influence the life cycle emissions of BEVs is still required, as a higher number of studies addressing the topic with primary data will contribute to a better understanding of such parameters.

Finally, in the specific case of Brazil, and to a broader level the Global South, the number of studies that adopt such scope is still small. On the Brazilian case, Souza et al. [27] and Sanches [28] have contributed to local literature, however, the influence of key parameters, such as driving behaviour, driving cycle and battery capacity fade was not investigated. Understanding the Global South conditions is also key, as we strive for a less environmentally harmful urban mobility on a global scale.

3. Methodology

The aim of this study is to evaluate and compare the life cycle GHG emission from a Battery Electric Vehicle (BEV) and an Internal Combustion Engine Vehicle (ICEV). To reach this goal, a Life Cycle Assessment (LCA) was carried out. This section presents the LCA method and studied phases as well as the explanation for the choice of vehicles used in our study. Figure 1 presents a summary of the methodology, presenting the parameters, sources and factors of the methodological framework adopted for development of the study.

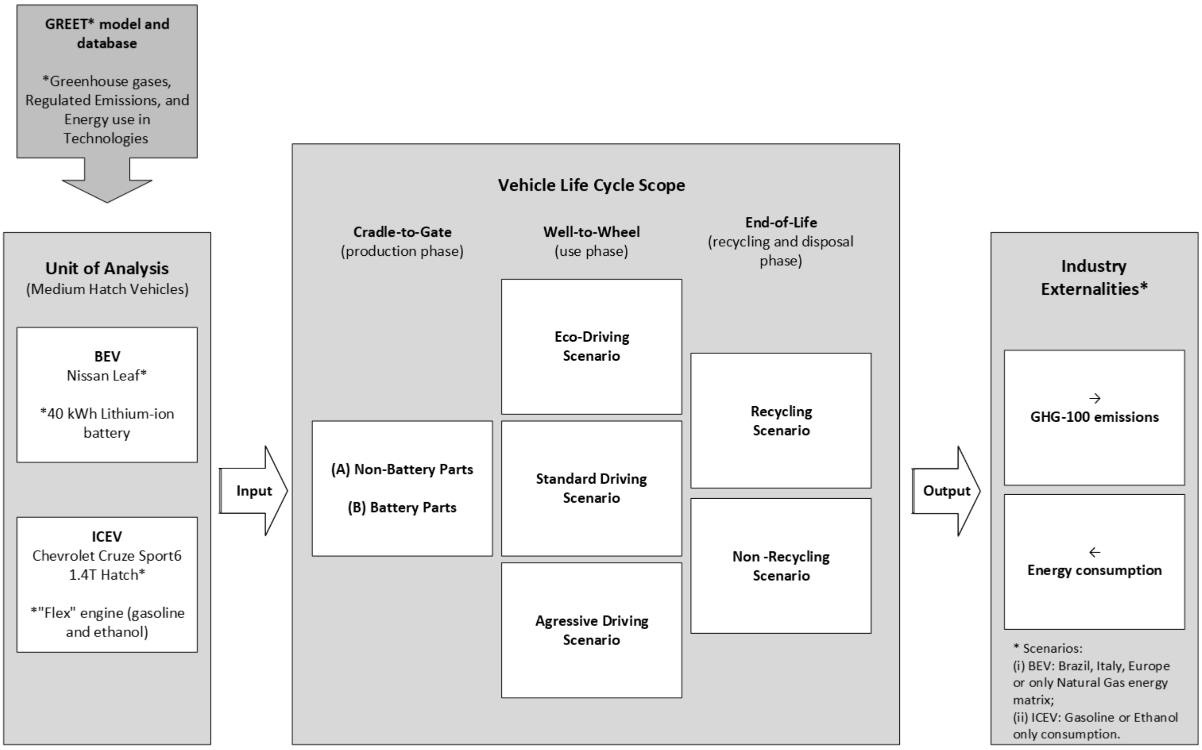

Figure 1- Methodological Framework

The goal of the LCA is to assess the Life Cycle Greenhouse Gas Emissions of two different powertrain vehicles, a Battery Electric Vehicle and an Internal Combustion Engine Vehicle, the dominant paradigm, in the context of the city of São Paulo. The purpose to do so is twofold: filling the gap in literature on BEV's contribution for GHG emission reduction in Global South contexts and provide further knowledge to policy makers and stakeholders on private transportation discussions. The boundaries are characterized as a Cradle-to-Grave, as further detailed in section 3.1. The functional unit of the study is one vehicle of each powertrain variety (BEV and ICEV), driven for 150,000 km. For the quantification of the environmental impact, the study adopted as impact measure the GHG-100 emissions, or IPCC greenhouse effects, measured in kg of CO_2 eq. The LCI for this study comprehends the GREET model and database, which will be further explored in section as well as other studies from literature. GREET was adopted for the majority of the assessment, except when clearly stated.

3.1 System Scope and Boundaries

The goal of analysing the whole life cycle of a vehicle implies including in the scope of the study the CtG (Cradle-to-Gate), WtW (Well-to-Wheel) and EoL (End-of-Life) phases. The CtG is the manufacturing phase, which includes, for the case of vehicles, the ore mining, the material transformation, the component manufacturing and the vehicle assembly. In this phase, emissions from tires, oil and parts replacement were also included. The WtW phase, also known as the Use phase, concerns the part of the lifetime in which the vehicle is being used, therefore involving the processes of fuel production and fuel usage. Finally, the End-of-Life phase involves the processes after the end of the product's life, which in this study is limited to landfill disposal and recycling. Figure 2 displays the main processes and flows in each phase for the two studied vehicles. Authors adopted the assumption that other emissions, such as factory construction or roads, are negligible when studying the production and impact of a single vehicle. Such an assumption is supported by other studies in the literature [29].

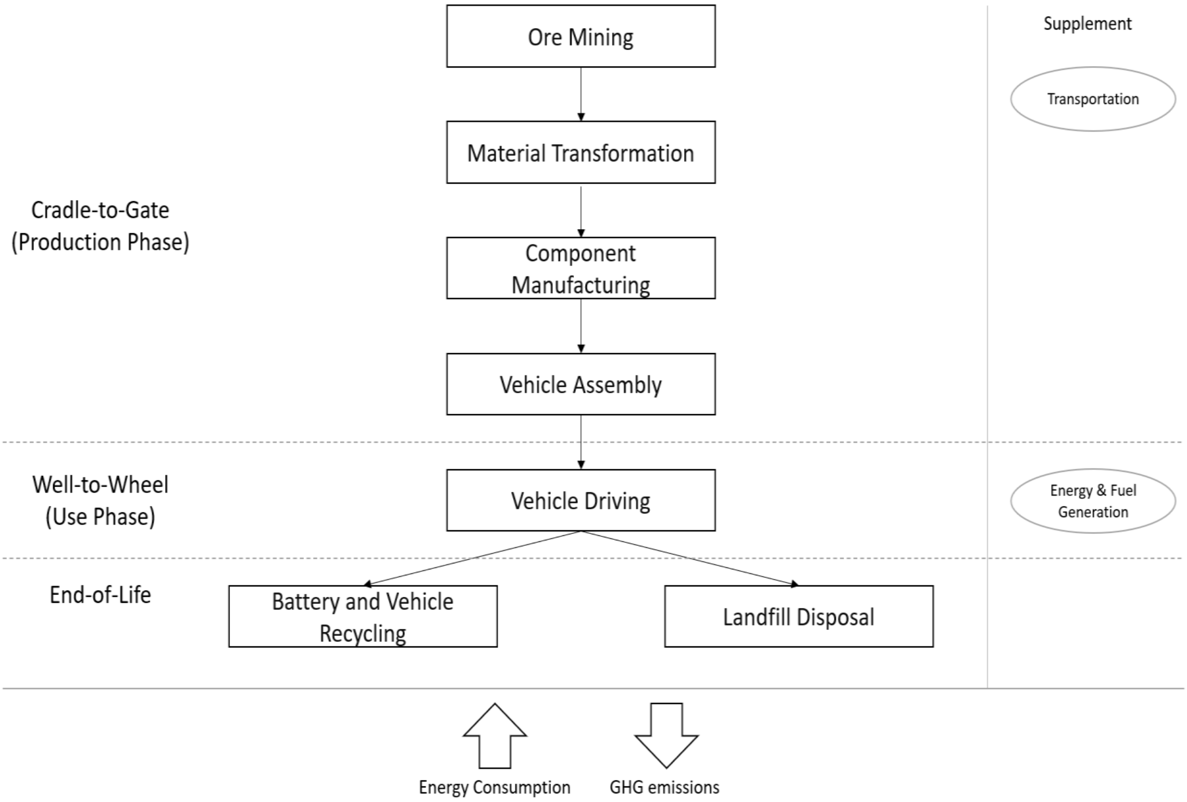

Figure 2 - Life Cycle Scope of the studied vehicles

The adopted measure of impact is the IPCC's GHG-100 emissions, which is the most commonly used way of calculating the Global Warming Potential (GWP). Therefore, other impacts such as acidification, ozone depletion and eutrophication were not calculated by the analysis developed in this study.

The main data source to be used in this study is the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) database. The GREET model and database is a Life Cycle Assessment tool built to support urban mobility studies, providing an extensive database for the modelling of vehicular LCAs, compiling energy requirements and greenhouse gases emissions for a variety of production processes, materials, fuels, and powertrain technologies. It was developed, and is continuously updated, by the Argonne National Laboratory, a United States of America multidisciplinary science and engineering research centre [30].

Several factors led to the decision of using GREET. Firstly, along with the Ecoinvent database, it has been widely used in literature as the data source when developing LCAs, in the case of secondary data studies [5]. Furthermore, the constant and frequent updates to the database, resulting from collection of primary data, were also a motivating factor, as literature trends are in constant evolution and change. Also, the use of a freely accessible database could facilitate the validation of the conclusions drawn in this study. For the sake of clarity, this paper adopts the definition of primary data as being “quantified data of a process or an activity obtained from a direct measurement, or a calculation based on direct measurements” [31]. Consequentially, secondary data is defined as “data which do not fulfil the requirements for primary data” [31].

3.2 Studied Vehicles

The vehicle model specification is a basic assumption for vehicle LCA analysis and has significant impact on the final results [10]. This assessment adopts two different vehicles that have a different underlying technology: a Battery Electric Vehicle (BEV) and an Internal Combustion Engine Vehicle (ICEV). BEVs are electric vehicles that use electrical power from a single source, the electrochemical battery, to power one or more electric motors, operating only on stored electricity. ICEVs are vehicles powered by a regular internal combustion engine that combusts fuel inside a combustion chamber with the help of an oxidizer, generating power [32], [33]. The ICEV environmental impact was assessed for two types of fuels, gasoline and ethanol.

The selected BEV is the 2022 version of the Nissan Leaf, as it represents the BEV with the largest commercial success in the Brazilian car market [34]. It is equipped with a 40 kWh Lithium-ion battery, with an approximate battery pack weight of 303 kg [35], [36]. The same vehicle was adopted in several other studies in literature, although a significant number of those adopted its previous version, equipped with a 24 kWh battery [24], [37]. In respect to the selected ICEV, a reference model that belongs to the same category as the Nissan Leaf, the modelled BEV was used, in this case a medium hatch. Among the available options in the Brazilian market, one that demonstrates significant commercial success is the Chevrolet Cruze Sport6 1.4T Hatch, which is the model adopted in this study [38]. The vehicle can run both on gasoline and on ethanol, which is fundamental for this particular analysis as both types of fuels are vastly used and diffused in Brazil [4].

3.3 Cradle-to-Gate Modelling

The Cradle-to-Gate, or production phase, modelling involves the assessment of the material requirements, material production processes, transformation processes and vehicle assembly processes. In the particular case of BEVs, there is the additional need of detailing the battery production, as it is a key factor in terms of emissions.

In the case of both vehicles, although data on general specifications for both vehicles is available, a more detailed description of the vehicle composition is not available. To overcome this problem, data on vehicle composition by component and by material available on public sources was used, following what has been done on the main reports and studies [5], [6]. More specifically, whenever reliable and precise information on either vehicle is not available, data from the GREET2 2021 spreadsheet and software was used [30] . Data was used without any transformation, except when clearly stated. The rationale on choosing GREET as the main data inventory for this analysis was explored in section 3.1. As previously discussed, several studies are based on the same dataset [39], [21], [24], [40] and, most importantly, the overall goal of the study was not affected, as the differences between real and adopted data are not likely to significantly change the final conclusions.

3.3.1 Non-Battery Parts

The first step of the production phase modelling was to define the material requirements to produce the vehicle. To do so, it was first necessary to define how the total weight of the vehicle is distributed among its different parts, those being powertrain system, transmission system, chassis (without the battery), traction motor, electronic controller, body (including the BIW , interior, exterior and glass), the Lithium-Ion battery (exclusive to the BEV), the Lead-acid battery and fluids. Due to the lack of official data on the actual mass of most of these parts, the mass distribution provided by the GREET2-2021 spreadsheet was adopted. It is to be mentioned, however, that in the case of the BEV, the weight of the Lithium-Ion battery was known, specifically 303 kg, and so this value was adopted. The material composition of each subcomponent followed the same rationale, resulting in the material requirements. The weight division by subpart, as well as the material composition of each subpart for both vehicles followed what was reported in the database with no further modifications. The specific case of the Lithium-Ion battery production, responsible for powering the BEV, is later explored in further detail, since it is still a heavy point of discussion in literature, therefore requiring a deeper analysis.

One modification to the original GREET2-2021 spreadsheet that must be highlighted is the share of recycled materials being used in the production of the vehicles. Recycled materials often have a lower embodied energy than virgin materials, which would imply lower emissions and energy requirements in the cradle-to-gate phase, so that for the baseline scenario the assumption that no recycled material is used was made. This decision leads to a more transparent baseline scenario and allows a better degree of comparison of the results here derived and those from literature.

Finally, non-including the Lithium-Ion battery of the Nissan Leaf, the next step of the analysis was modelling the assembly of the parts, deriving the energy requirements and GHG emissions. The GREET 2021 software has a pre-existing pathway that models the assembly of a vehicle, which was chosen as the solution to that matter on this study. The pathway is the same for all types of vehicles, as the detailed processes do not differ between vehicles that use different powertrain technologies. The processes and resources included in the pathway are: paint production, painting, HVAC & Lighting, heating, material handling, welding, compressed air.

3.3.2 Lithium-Ion Battery and Lead-acid Battery

The next step was modelling the production of the battery that powers the Nissan Leaf, a 40 kWh Lithium-ion battery. The battery uses NMC 111, $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$, as the cathode material and graphite as the anode [35], [36]. Battery production has been a well-researched topic in the literature over the last decade, but the results of different studies have shown a very high degree of diversity [17]. The main difference between studies has been the cell production process, as for some authors it is just moderately energy intensive while for others, it is one of the biggest contributors to the overall emissions and energy demand. Moreover, both the selected BEV and ICEV make use of a Lead-acid battery, also modelled in this study.

For the modelling of the cradle-to-gate emissions of the battery production the GREET 2021 database and software was used, as it was the case for the other vehicles subcomponents. The database is built around the works of Dunn et al. [41-43] and Dai et al. [21], which was based on primary data collected from large-scale commercial battery manufacturers, which incorporates the development of production processes.

The adopted material composition of the 40 kWh Lithium-ion NMC111 battery that is used by the Nissan Leaf follows the weight distribution reported in the GREET 2021 spreadsheet, as there were no necessary modifications. The same applies for the Lead-acid battery of the BEV and ICEV.

The Lithium-Ion battery production is quite a complex process characterized by disagreements on the energy requirement estimations for some of the production steps, such as the calcination, co-precipitation, which compose the NMC powder production [21]. The energy-intensiveness of the cell production is also very disputed, as the energy expended by the dry room still represents a point of uncertainty. Ellingsen et al. [19] reported a very high energy intensity in their study, which made use of monthly electricity consumption data from a cell manufacturer, with an observation period of eighteen months. Similar conclusions were obtained by Kim et al. [44], which used energy use data from Ford Motor Company's cell supplier, however, the original energy use data was not entirely disclosed. Conversely, Dai et al. [21] conducted a study in which data from a leading Chinese Lithium-Ion battery manufacturer was used, collected in an on-site visit of the facilities. Their results point to a much less energy-intensive process than the one suggested by Ellingsen et al. [19] and Kim et al. [44], that reported respectively 2318 MJ/kWh and 525 MJ/kWh of battery. Meanwhile, Dai et al. [21] reported figures of approximately 170 MJ/kWh.

Overall, some factors tend to explain such differences. Mainly, the year the studies were conducted, which heavily influences battery volume production, factory idle capacity, and, consequently, energy saving economies, as well as the production facilities in which data was collected, as some only had access to smaller, pilot-scale facilities.

In this scenario, considering the uncertainty in data, the values reported by the GREET 2021 Database, congruent to those presented by Dai et al. [21], were used in the assessment. Moreover, the fact that the database is constructed with primary data from the industry increases reliability, as volume of production, methods used and production efficiency can change drastically through time and the use of most recent sources is suggested.

3.4 Use Phase

The Use Phase, commonly referred to as the Well-to-Wheel (WtW), comprises emissions from the source of the fuel that is used by the car to the emissions that result from the use of that fuel by the vehicle. The Well-to-Wheel is divided into two phases, the Well-to-Tank (WtT) and Tank-to-Wheel (TtW). The first represents all of the emissions that result from the processes needed to produce and transform the fuel to a form that it can be used by the vehicle and also the transport emissions to reach the point in which the vehicle is going to be fuelled. The TtW phase involves all of the emissions that result from the use of the fuel, which takes place when driving the vehicle [10].

In the case of the electric vehicle, four scenarios of electricity generation mix were explored are: the Brazilian case, the average European case and an all-non-renewable energy case. For the case of the internal combustion vehicle the following fuel types were explored: E27 and hydrous ethanol (Brazilian sugarcane ethanol).

Another important point to be mentioned is the consumption ratings adopted in the study for both vehicles. Doing so is of key importance since consumption figures can greatly vary between different rating sources. In the particular case of this study, the EPA rating [45-47] was adopted as a baseline, which was then adapted to fit the selected scope of the study.

3.4.1 Use Phase – Battery Electric Vehicle

A variety of factors influence BEV consumption, the one most explored in literature being the electricity mix, i.e. how the electricity that is being used by the vehicle is produced, either via natural gas, hydropower, coal, solar, wind, nuclear, biomass, geothermal and eventually even others. Studies show that the electricity generation mix is the most important factor when determining consumption [40], [13], justifying the focus on that theme in literature, and the choice of assessing three different electricity generation scenarios.

Despite the existence of a significant structure electricity generation, the State of São Paulo is far from self-sufficient, as local production only amounts to 34.1% of the Gross Supply, with the most significant share of the supply coming from imported energy [48], mainly from four countries: Paraguay, Argentina, Venezuela, and Uruguay [49]. However, there is no accessible information on how much energy is imported from each country and from what sources of production. Such large contribution from unknown energy sources results in a situation in which just the generation of São Paulo can’t be assumed as a good representation of the sources used to power the electric vehicle.

To overcome this problem, the Brazilian electricity mix was adopted, as a sufficient level of data clarity and reliability is available, and, to the point of the relevance of imports, in the national case for Brazil, the share of imported electricity is a lot less significant [50]. Finally, the European scenario will use the source distribution of the continent [51].

3.4.2 Use Phase – ICEV

Several fuels are used to power ICEVs in São Paulo’s car fleet, such as gasoline, diesel, sugarcane hydrous ethanol, VNG (Vehicular Natural Gas) among others. Nevertheless, the vast majority of the city's car fleet is composed by flex vehicles, around 71.4% of the total fleet, as such technology has experienced substantial commercial growth in the last decade, while other fuels either significantly dropped or simply maintained their participation [4].

Considering this scenario and the selected regional scope, the assessment considers two scenarios of fuel use: gasoline (E27) and sugarcane Brazilian hydrous ethanol. Government resolutions currently establish that the concentration of anhydrous ethanol in the type C gasoline (common gasoline) should be 27%, with a ± 1% tolerance [52], [53]. To model the gasoline emissions, the GREET 2021 software is used, as it provides a simulation tool for the Well-to-Wheel emission.

In regard to the sugarcane hydrous ethanol, the ANP Resolution No. 19 from 15th of April of 2015 states that its density at 20°C should be between 802.9 and 811.2 kg/m^3. Furthermore, its alcohol content, expressed by the share of alcohol mass, should be between 92.5% and 95.4% [54]. To model the GHG emissions of the Brazilian sugarcane hydrous ethanol, the Ecoinvent database was be used. Here, the choice of not using the GREET 2021 software is motivated by the fact that Ecoinvent provides a more in-depth rationale of how the data for the Brazilian ethanol was obtained, therefore enhancing the quality of this specific data. Unfortunately, the GREET database does not provide the same level of detail for the Brazilian sugarcane ethanol, which motivated the choice here [55].

3.5 End of Life (EoL) Phase

The final phase of the analysis is the End of Life (EoL). This phase of the life cycle composes the processes of disposal, recycling or reuse of the vehicle.

In the case of the vehicle itself, there is a great opportunity for recycling, as large quantities of steel, aluminium and other valuable materials are used in the composition of a car, as shown in the Cradle-to-Gate phase. As previously stated, the initial assumption of the analysis is that no material used for the construction of the vehicle was used, but a scenario in which recycled materials are used is not only possible, but already happening to some degree. The main factor influencing the resulting GHG emissions therefore is the share of recycled materials being used to build the vehicle. As a reference, the remission savings of 2.93 kg of CO_2 eq./kg of vehicle reported by Qiao et al. [56], in one of the latest studies, is adopted in this one, aligned with others as well [17], [18].

In the case of the Lithium-Ion battery, however, things are not so clear. Aichberger and Jungmeier [5] reviewed 50 publications from the years 2005 and 2020 that analysed and discussed the life cycle impacts of automotive batteries. They found that only the minority of the reviewed studies included the recycling step in the analysis, as there is today a lack of inventory data on recycling. Dunn et al. [41], Qiao et al. [57], Amarakoon et al. [58] and Gaines et al. [59] highlights the potential for recycling of cathode materials, such as cobalt and nickel, or the aluminium, present in the collector for the battery case. Therefore, the main opportunities for recycling discussed are centred on the use of recycled materials for the production of the batteries.

Two methods of recycling, pyro metallurgical and hydrometallurgical, are the ones most discussed in literature, with the possibility of direct recycling being less explored [5]. Gaines et al. [59] defines the pyro metallurgical process as a high-temperature smelting process to reduce metals like cobalt and nickel from oxides to metals and is currently the common process for Li-ion battery recycling. However, the energy demand is high, and mostly only nickel and cobalt are recovered, while additional processes to recover other metals are needed. The process, however, is still very limited, as, firstly, the lithium in the recycled batteries ends up in a slag, being energy intensive and even economically unfavourable to recover it, which means that nickel and cobalt are recovered. Secondly, the scalability of the process is also an issue, as authors from literature evaluate that performing the process in large scale, which would be necessary considering an expansion of the use of electric vehicles, seems unlikely [43].

The hydrometallurgical process is a technique used to recover the metals in a battery's active materials, the cathode and anode. The process is vastly applied to recover $LiCoO_2$ batteries from laptops, and its use for electric vehicles has been discussed. Dunn et al. [42] studied the process application to spent $LiMn_2O_4$ batteries and concluded that the process would yield savings in terms of energy expenditure and GHG emissions. Present studies in literature did not yet assess the energy expenditure and savings for the specific case of NMC111 batteries, however, it seems reasonable to assume that at least the lithium and cobalt contained in the cathode could be recovered, as it is the case for the battery studied by Dunn et al [42].

As for the direct recycling approach, it is still only performed in a lab-scale. The great advantage is that it tries to extract the cathode without breaking its chemical structure. This would yield a higher economic value in performing the process, which makes it more attractive [5]. Another opportunity discussed by Dai et al. [21] is the recovery of the aluminium present in the batteries, as the use of non-virgin aluminium would significantly decrease the environmental impact.

Another promising opportunity that still needs to be further investigated in literature is of a second life of the battery. Neubauer et al. [60] analysis showed that discarded BEV batteries can still provide 70% of their initial capacity after around 15 years of service. Utility scale peak-shaving is presented as the most promising opportunity for the battery second life, as the required charge cycles per day are considerably lower and longer discharge durations can be addressed by the lower capacity battery, which is not the case for the use in electric vehicles. However, it is important to note that the actual performance of batteries in such state has not yet been sufficiently investigated.

Given current scenario of uncertainty and lack of accuracy in defining the actual environmental benefit, or impact, of battery recycling, this study adopted reference values from literature. Among the studies reviewed and analysed by Aichberger et al. [5] a median recycling benefit of 20 kg of CO_2 eq./kWh of battery capacity is observed. Buberger et al. [12] reports a more advantageous scenario, based on the studies of Qiao et al. [10, 56], with a recycling benefit of 48.4 kg of CO_2 eq./kWh. A factor relevant to be noted is that the latter is a more recent study, meaning that the effectiveness of the processes have increased, yielding better results. For the base scenario, the average of the two values was adopted, i.e., 34.2 kg of CO_2 eq. of emission savings per kWh. The significance of this parameter to the overall conclusion of the study will be discussed in the results and sensitivity analysis section.

Finally, addressing a scenario in which neither the vehicle or the battery are recycled is also important, as these practices might not be available in some cases, due to possible causes such as lack of companies able to perform these activities, lack of economic interest or others. In this scenario, where end vehicle parts are assumed as disposed, the estimate of carbon emissions of 0.01 kg of CO_2 eq. /kg of material disposed provided by Ashby [61] will be adopted.

3.6 Additional Factors of the Analysis

In addition to the already addressed, other factors have been shown to have a significant role in the life cycle emissions of vehicles: capacity fade of the battery, temperature and driving cycle.

3.6.1 Capacity Fade for Electric Vehicle Batteries

The battery that powers the electric vehicle has a considerable impact in the overall emissions. Given such relevance, it is reasonable to consider that the number of batteries used in a vehicle’s lifetime plays a key role in its environmental impact, an hypothesis validated by both Hawkins et al. [6] and Marques et al. [24]. In literature, capacity fade models have been used to estimate the number of batteries required along the entire lifetime of the electric vehicle (e.g., Ouyang et al. [62], Torai et al. [63]).

This study adopted the results obtained by Marques et al. [24], in which an analysis was conducted considering three possible scenarios of use, or driving style: light use, moderate use and intensive use. In their assessment, two types of batteries were considered, one using a $LiMn_2O_4$ cathode and the other a $LiFePO_4$ cathode. Researchers reached the conclusion that in both cases, for a lifetime of 150,000 km, both a moderate and an intensive driving style would yield the need for a second battery at some point during the lifetime of the vehicle.

3.6.2 Temperature

The weather conditions have also been explored in literature, as researchers investigate the effect that it has on the consumption of electric vehicles. Allen [64] investigated the effects of cold weather in the consumption of a Nissan Leaf model and concluded that such conditions tend to increase consumption, due to a reduction in battery efficiency. Furthermore, battery performance is also affected by the weather, as the efficiency, discharge capability and available energy all decrease. On the other hand, an increase in battery performance is observed in warmer environments, however, only up to a point, as very high temperatures also decrease battery performance [65].

Yuksel et al. [66] made use of real-world data from vehicle monitoring services that allowed to associate the effect of consumption and temperature. In their study, more than 7000 trips through North America were considered, all of them made using a Nissan Leaf, powered by a 21kWh battery, a former version of the vehicle here studied. Results from the study point to a considerable increase in consumption when driving at extreme temperatures, either cold or warm, with optimal consumption being reached around 18 $^{\circ}$C.

For the specific case of São Paulo, the temperature effect does not seem to be of great significance, due to the weather pattern of the city, which can be considered very mild. Being so, the effect of temperature in vehicle consumption was not included in this study, as the impact of the variable would be far smaller than the one observed from other variables considered.

3.6.3 Driving Cycle

The driving cycle, or driving pattern, is another factor that has been assessed in literature, with studies mostly agreeing on the conclusion that under different driving patterns, the benefit of using electric vehicles instead of internal combustion vehicles is modified. Factors such as share of urban driving considered, average speed and amount of stops during, all of which are integrated in the driving cycle, have been shown to be important aspects when assessing the environmental benefits of electrified vehicles and will therefore be incorporated in the analysis.

In this study, the focus is to model real-life conditions of the city of São Paulo. Factors such as traffic, terrain and driving style must be considered. However, differently than what is observed in some other global metropolis, such as New York or Beijing, where a driving cycle specific to the city is available, in the case of São Paulo a lack of data is observed, in particular referring to BEV consumption.

Carvalho et al. [67] provided a methodology proposal for a real driving cycle in the city of São Paulo (SP04), comparing it to the FTP-75. Results from the study shows an increase in GHG emissions per km of 18% in the SP04, when compared to the emission levels of the EPA FTP-75. The behaviour can be mainly credited to the smaller average speed of the São Paulo driving cycle. Such results were adopted as to adjust the original EPA rating of the ICEV to the conditions of São Paulo. However, the study was conducted using only internal combustion engine vehicles, so that results cannot be completely translated to electric vehicles.

To overcome this issue, a benchmark city, which has the necessary data available, was considered. Such practice is observed in literature when referring to the scope of São Paulo by Costa [68], as Shanghai was used as a basis for studying GHG emission mitigation policies in the context of road transportation of São Paulo. Being so, results from Gong et al. [26], that provides a real-world evaluation of the driving cycle in crowded cities in China, were incorporated in this study, as a basis to adapting the EPA rating to São Paulo like conditions. Incorporating the mentioned adjustments, the assumed range for the Nissan Leaf here studied was 230 km, instead of the original EPA rating of 240 km.

Finally, it is also necessary to incorporate different driving styles to the analysis. Faria et al. [69] studied the impact in consumption between a normal driving style and Eco-driving and aggressive driving. Their results are especially valuable to the BEV analysis, as real-world data obtained from a former version of the Nissan Leaf, a BEV, characterized the study. Therefore, this study adopted their results in evaluating the impact of driving styles for EVs, resulting in a 27% reduction in consumption, expressed in kWh/km, being adopted in an eco-driving scenario, and an 18% increase adopted in the aggressive driving scenario.

For the internal engine combustion vehicle, studies from literature support the conclusion that the driving style does have a significant influence on the consumption rate, and consequently range. Miotti et al. [70] evaluated the effect of eco-driving for ICEVs in a variety of scenarios in the USA, using real-world data, and concluded that, on average, consumption is reduced by 6% when adopting a lighter style of driving. Fonseca et al. [71] conducted similar research, evaluating that eco-driving can reduce consumption by up to 14%. On the other hand, an aggressive driving style is also shown to contribute significantly to increase consumption. Fonseca et al. [71] evaluates the increase in consumption by aggressive driving at around 40%, a figure similar to the results obtained by Szumska et al. [72], that pointed to an increase of around 30% to 40%. Finally, Huang et al. [73] evaluated the effect on consumption for ethanol-fuelled vehicles, concluding that a 35% increase is expected. Following such results, a reduction of 10% in consumption, expressed in L/km, was adopted for the Eco-driving scenario and an increase of 35% in consumption for the aggressive style driving, both applying to the ICEV powered by the two fuel types, gasoline and ethanol.

The resulting total ranges for each combination of vehicle type and style of driving are summarized in Table 1. The influence of such parameters to the results will be evaluated in the sensitivity analysis.

Table 1 - Assumed range for the studied vehicles under different driving styles

Vehicle type	Eco-driving	Standard driving	Aggressive driving
BEV (Nissan Leaf)	315 km	230 km	195 km
ICEV (Chevrolet Cruze) – Gasoline	711 km	640 km	474 km
ICEV (Chevrolet Cruze) – Ethanol	485 km	437 km	323 km

3.7 Limitations

Given the goals of the study, and the methodology used to reach them, it is also important to clarify its limitations. Firstly, the analysis is conducted considering only GHG emissions as the studied impact measure. In the future, as to provide a deeper understanding of the environmental impact of both powertrain technologies, further assessments that incorporate other impact measures should be conducted, as to evaluate, among others, resource depletion, soil acidification and human toxicity. Furthermore, researchers only had access to public information on the production of the reference vehicles, which can lead to a less precise modelling of the material composition of the vehicles, for example, as an exact list of suppliers for the many parts was not available. Finally, the work is limited to analysing the environmental impact of the selected scope, not detailing or

discussing economic, political and structural conditions that relate to São Paulo or Brazil in general.

4. Results and Discussion

4.1 Isolated Phase Results of the LCA

As expected, the total emissions for producing the Nissan Leaf, of 10,356 kg of CO_2 eq., are considerably higher, by 48%, than the required to produce the Chevrolet Cruze Sport6 1.4T Hatch, 6977 kg of CO_2 eq., as it is expected when comparing a BEV to an ICEV of comparable size. Moreover, the general consensus that the battery is a very significant influence when assessing the emissions for producing a BEV is also confirmed, with the 40 kWh Li-Ion battery being the most significant contributor in the BEV case (37%).

The per kg of vehicle impact of both the EV and the ICEV is aligned with the results from literature. The production of the ICEV yields 5.24 kg of CO_2 eq./kg of vehicle. Buberger et al. [12] estimates this value at 4.56 kg of CO_2 eq./vehicle, Qiao et al. [57] estimates it at 6.96 kg of CO_2 eq./kg of vehicle and Hawkins et al. [6] obtained an estimation of 5 kg of CO_2 eq./kg of vehicle, providing an expected range for future studies of 4 to 6.5 kg of CO_2 eq./kg of vehicle. For the BEV, this study estimates an emission level of 4.93 kg of GHG/kg of vehicle for non-battery parts. Buberger et al. [12] provide an expected range from 4.17 – 4.82 kg of CO_2 eq. kg/kg of vehicle, whilst Qiao et al. [57] obtained 6.94 kg of CO_2 eq./kg of vehicle for their studied vehicle, modelled in China.

When looking at the contribution of each battery component to the overall emissions of the BEV production phase, the positive electrode paste, NMC111, the battery assembly and the cell production are the largest contributors to the overall emissions of the battery, together amounting to 68.2% of the total emissions. Majeau-Bettez et. al [20], Ellingsen et al. [19], Dai et al. [21], Zackrisson et al. [18], Kelly et al. [22], Dunn et al. [43], Wu et al. [74], Aichberger et al. [5] and Peters et. al [17] all mention the positive electrode paste and the cell production as the most significant contributors to battery emissions, however, there is a level of disagreement on the level of that contribution, as some studies, such Majeau-Bettez et al. [20] and Ellingsen et al. [19], estimate a higher emission factor for the cell production than others.

In terms of emissions measured on a per kWh of battery basis, the estimated impact of the battery is 95.8 kg of GHG/kWh. Such figure, when compared to the results of other studies from literature, is positioned around the middle, with results from Majeau-Bettez et al. [20] and

Dunn et al. [41] being on the extremities, among the reviewed studies. Aichberger et al. [5] provides a median value of 120 kg of CO_2 eq./kWh, with 50 studies taken into consideration, and boundaries of 70 kg of CO_2 eq./kWh and 175 kg of CO_2 eq./kWh for the 25% and 75% quantiles, respectively, which reinforces the results from this study.

In the Use Phase modelling, three driving behaviours, or styles, were considered: eco-driving, standard driving and aggressive driving. Moreover, different types of fuels were considered for the two vehicles. In the case of the EV, three electricity mixes were analysed: Brazil, European average and Natural Gas (NG). In the case of the ICEV, two fuels were considered, E27 (73% gasoline and 27% ethanol), which is currently the standard for gasoline in Brazil, and Brazilian sugarcane ethanol. Figure 3 presents the estimated emissions of all of the mentioned scenarios.

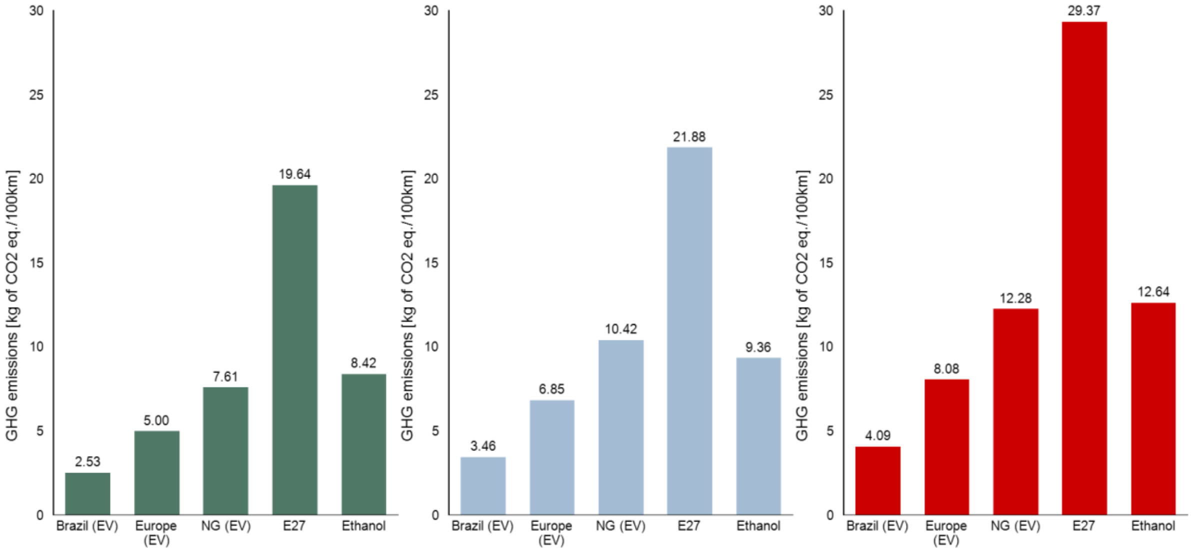

Figure 3 - Level of GHG emissions (kg of CO2 eq.) for the Use Phase for the different scenarios considered

Results are aligned with literature's general consensus, with the use phase of a gasoline powered ICEV incurring more emissions than the use phase of a BEV. Orsi et al. [15] also conducted a WtW analysis comparing the emissions of an EV and an ICEV considering different scenarios of electricity generation mixes. Their results support the results of this study, with the emissions for an E10 (gasoline) powered ICEV in Brazil being almost seven times higher than the value observed for a Battery Electric Vehicle. Woo et al. [13] results also support the conclusion that when considering the Use Phase, the EV performs better than a corresponding ICEV for Brazilian and average European scenarios. Furthermore, results point to the conclusion that the share of renewable energy is a key factor to the Use Phase emissions, as also defended by Marques et al. [75]. When comparing natural gas powered EVs and ICEVs, Hawkins et al. [6] also reached results that supported the conclusion that an EV powered with only natural gas yields less emissions than an ICEV fuelled with gasoline.

Finally, the End-of-Life GHG emissions were estimated based on current sources from literature, so comparing it to those sources of literature, as was done for the other phases of the life cycle, is not as beneficial. Nevertheless, as a reminder, the values assumed for the two different scenarios considered in the analysis were 0.01 kg of CO_2 eq./kg of material when the disposal in a landfill occurs and a credit (savings) of 34.2 kg of CO_2 eq./kWh of battery recycled and 2.93 kg of CO_2 eq./kg of vehicle (battery excluded) for the recycling of the remaining parts of the vehicle, BEV or ICEV.

4.2 Life Cycle Assessment Results

By combining the emissions of each isolated phase of the life cycle of each vehicle, obtained using the methodology described above, the full results of the Life Cycle Assessment are obtained. Table 2 presents the results for individual phases of the Life Cycle for different electricity mix scenarios, while Table 3 depicts the results that refer to the BEV and ICEV comparison in São Paulo.

Table 2 - Single Phase emissions for different assessed scenarios (kg of CO2 eq.)

	Brazil	Europe	Natural Gas	Gasoline	Ethanol
Production Phase					
Non-Battery	6,522	6,522	6,522	6,977	6,977
Li-Ion Battery	3,834	3,834	3,834	-	-
Use Phase					
Eco-Drive	3,795	7,497	11,415	29,460	12,637
Standard	5,190	10,275	15,630	32,820	14,041
Aggressive	6,135	12,120	18,420	44,055	18,955
EoL					

Vehicle Recycling	-3,772	-3,772	-3,772	-3,727	-3,727
Li-Ion Battery Recycling	-1,368	-1,368	-1,368	-	-
Vehicle Landfill	13	13	13	13	13
Li-Ion Battery Landfill	3	3	3	-	-

The displayed results clearly show the overall prevalence, in the context of São Paulo, of the BEV when compared to its traditional counterpart, the ICEV. Such prevalence is sustained in all of the assessed scenarios, even when adding a second battery that is not recycled in the EoL, which significantly increases the BEV emissions impact. It is to be mentioned that despite the gap between the modelled BEV and the gasoline ICEV being of considerable size, a narrower, although still significant, difference separates the EV from the ethanol ICEV.

Analysing the data with a mileage perspective, the BEV larger emissions in the production phase are quickly compensated when compared to the gasoline ICEV, already having a lower total calculated emissions at around 20,000 km, for all driving behaviours. The BEV becomes more beneficial than the ethanol ICEV from 50,000 km to 60,000, for all driving behaviours. When considering capacity fade, and the consequent need of a second battery, to be replaced at the half point of the total lifetime, i.e., around 80,000 km, the BEV will start having a lower total GHG emissions figure than the ethanol ICEV at around 110,000 km, for the Eco-drive scenario, at around 120,000 km, for the standard driving scenario, and only at around 135,000 km for the aggressive driving scenario. It is important to note, however, that the recycling benefits are only credited at the end of the lifetime of the vehicle, which can distort, to a degree, this per mileage view, in favour of the ICEV.

Table 3 - EV and ICEV Life Cycle GHG emissions in São Paulo (kg of CO2 eq.)

			EV	ICEV (Gasoline)	ICEV (Ethanol)
Recycling	Without 2nd Battery	Eco-drive	9,010	32,709	12,886
		Standard	10,405	36,069	17,290
		Aggressive	11,350	47,304	22,204
	With 2nd Battery	Standard	12,871	36,069	17,290
		Aggressive	13,816	47,304	22,204

Landfill Disposal	Without 2nd Battery	Eco-drive	14,167	36,449	19,626
		Standard	15,562	39,809	21,030
		Aggressive	16,507	51,044	25,944
	With 2nd Battery	Standard	19,398	39,809	21,030
		Aggressive	20,343	51,044	25,944

Another aspect to be analysed is the contribution of each phase to the overall emissions. As expected, for ICEVs, the Use phase is the phase with the largest contribution, while for BEVs, the overall share is more distributed between the Production and Use Phase. In the particular case of the EV with a Brazilian electricity mix, the Production Phase produces practically twice the emissions of the Use Phase. Looking at results from literature, a dominant use phase is the standard for ICEVs. Qiao et al. [10] reports that the Use Phase contribution to the overall emissions of the ICEV is larger than 70%. Buberger et al. [12] reports its contribution at almost 80%. For this study, not considering the benefit of the recycling phase, the contribution of the Use Phase of the gasoline ICEV emissions were around 76%.

Results of the LCA analysis also reinforce some of the main positions from literature. For instance, the electricity energy mix was shown to be a key parameter to the analysis of BEV emissions, as, for example, the percentual increase in total emissions from the Brazilian case for the European and Natural Gas is, respectively, 41% and 85%, considering the eco-drive with recycling scenario. Being so, it is clear that generating and making use of clean electricity is fundamental to optimizing the potential benefit of EVs. Moreover, the role of recycling was also shown to be of key significance to the overall reduction of lifetime emissions of vehicles, especially BEV. For instance, when analysing the Brazilian EV scenario, and adopting standard driving, a net difference of 5157 kg of CO_2 eq. is observed, or a 49.6% increase, between recycling and not recycling scenarios. Considering the need of a second battery, due to capacity fade, the observed increase is 50.7%. Finally, it should be noticed that the gasoline ICEV was evaluated as the worst option in all of the combined assessed scenarios, a result usually reached by fellow researchers [12].

When compared to other BEV LCAs from literature, results from this study are within expectations, as displayed in Figure 4. This applies especially regarding recent studies [12], [8], [57]. Earlier studies, such as Hawkins et al. [6], tend to be above what is expected from the current view from literature mainly due to the evaluated battery production impact and the technological progress of BEVs in the past decade, resulting in better consumption rates and less emissions-intensive production processes. In respect to the observed ICEV results, the gasoline fuelled vehicle life cycle emissions are in line with what is expected from literature, especially studies conducted considering Brazilian conditions, that tend to have slightly lower estimations than studies that consider European or North American conditions, which pertains to higher concentration of hydrous ethanol in the Brazilian gasoline.

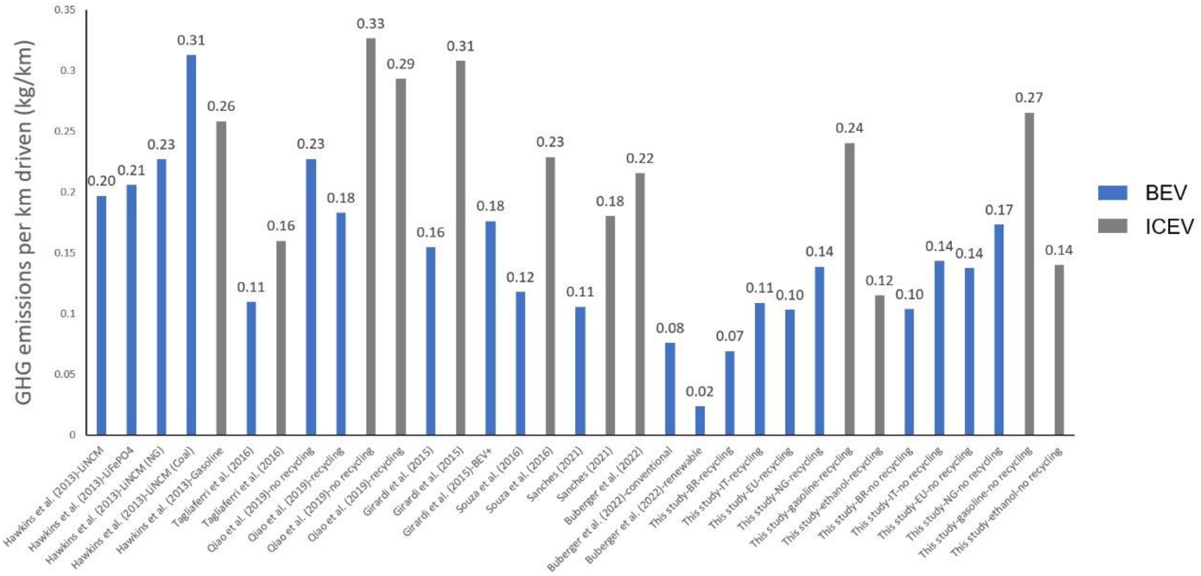

Figure 4 – Life cycle emissions per km driver (kg of CO2 eq./km) reported by several studies in literature

When comparing the present study results for the Brazilian electricity grid mix scenario with figures reported by Souza et al. [27] and Sanches [28], which adopt Brazilian conditions, there is a quite significant difference that can be attributed to some parameters. First, battery production emissions among the three studies are considerably different. Souza et al. [27] adopted the inventory published by Majeau-Bettez et al. [20], which as shown in the literature review, provides one of the highest estimates for battery production emissions in literature. Sanches [28] adopted the inventory published in a previous study, which reports higher emissions for battery production than the GREET 2021 Database. Secondly, recycling benefits estimated by this study are higher than the reported values by Souza et al. [27] and Sanches [28]. Those two factors are the main contributors to the observed difference, and the impact of both parameters will be further evaluated in the sensitivity analysis.

4.3 Sensitivity Analysis

In the sensitivity analysis section, the effect in results from varying the parameters of battery production, vehicle lifetime, fuel or electricity consumption, and battery recycling were investigated. To do so, the life cycle emissions of the modelled BEV and ICEV were accounting for a number of scenarios, in which the value of each of the above-mentioned parameters is modified. It is important to note that all calculations adopted as baseline the standard driving behaviour and that recycling of both the vehicle and battery occurs.

For the battery production, fuel or electricity consumption and battery recycling, a total of five scenarios were compared and analysed. For battery production and consumption, the baseline scenario adopts the same value from the analysis. Scenario “A” adopts 80% of the value assumed in the analysis, scenario “B” adopts 125%, scenario “C” adopts 150% and, finally, scenario D adopts 200% of the value assumed in the analysis. For battery recycling, “baseline”, scenario “A”, scenario “B”, scenario “C” and scenario “D” adopted, respectively, 100%, 120%, 80%, 50% and 10% of the recycling benefit calculated in the LCA.

For vehicle lifetime, a total of four scenarios were compared and analysed. The baseline scenario, as explored in the methodology, adopts a lifetime of 150,000 km. Scenario “A” adopts a lifetime of 250,000 km, scenario “B” adopts a lifetime of 200,000 km, and scenario “C” a lifetime of 100,000 km.

Looking at the sensitivity analysis results, available at Figure 5 for the EV Brazilian case, it is noticeable that changes in the consumption rate have a growing impact, as the source of electricity becomes less renewable. Such behaviour is also observed for the other electricity generation scenarios analysed. For the Brazilian scenario, doubling the BEV consumption yields a 50% increase in lifetime emissions, while the same increase in a scenario in which electricity is generated by natural gas yields a 75% increase. Another conclusion is that the impact of variation in parameters such as battery production and battery recycling decrease as the share of non-renewable sources in the electricity grid mix increases. The adopted vehicle lifetime also has a significant impact in the overall life cycle emissions of both an EV and an ICEV, particularly if the Use Phase is associated with high emissions, as it is the case for both ICEV fuels and Natural Gas electricity.

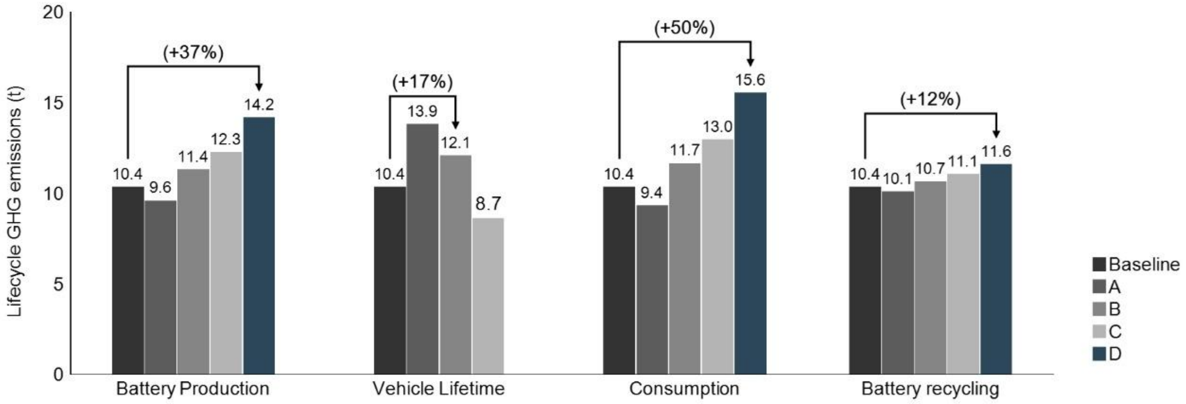

Figure 5 - Sensitivity Analysis: BEV in the Brazilian electricity mix

By looking specifically at the case of the BEV in Brazilian electricity generation conditions more conclusions can also be drawn. First, battery production is very relevant to the life cycle emissions, as by doubling the estimated emissions from the baseline scenario, an increase of 37% is observed. This scenario is closer to the modelled by Souza et al. [27] and Sanches [28], as both authors adopted much higher estimates for battery production. Nevertheless, even when doubling the impact of the battery production, the BEV still has lower life cycle emissions than the ICEV, fuelled with either E27 (gasoline) or ethanol, supporting the conclusions from the LCA analysis performed. Even more importantly, even if the consumption of the vehicle were to double, the EV would still be the best option in terms of life cycle GHG emissions, adopting Brazilian electricity generation conditions. Once again, the results analysis corroborates the reliability of the main result of the study, the prevalence of the BEV as the best powertrain alternative for the Brazilian case, in terms of GHG emissions, especially when compared to a gasoline vehicle.

When analysing the other electricity grid mixes, however, such prevalence was not fully observed. In scenario D, which doubles the battery production emissions, the EV the presents larger lifetime emissions than the ethanol ICEV, when considering the European and Natural Gas mixes. On the other hand, even in such scenario, the gasoline vehicle remains the worst option among the studied powertrain and fuel combinations. The same behaviour is observed when analysing the sensitivity of consumption, which yields an even greater increase than the battery production, in respect to the base scenario. It is worth noticing that when EV consumption is doubled, and the electricity is generated by Natural Gas, the lifecycle emissions are almost equivalent to the lifecycle emissions of the gasoline vehicle.

The variation of the benefit of recycling the battery was also investigated. The data supports the conclusion that even in a scenario of decreased benefits from recycling, the EV would still be a good alternative, if not the best, when trying to reduce life cycle GHG emissions of light duty vehicles. Even when adopting only 10% of the original benefit, the observed increase in life cycle emissions was not larger than 12%.

Finally, the ICEV is much more affected from changes in consumption than the EV, which was expected, considering that the Use Phase was shown to be much more dominant for ICEVs than EVs.

5. Conclusions and outlooks

The goal of this study consisted of evaluating and comparing the environmental impact, measured by GHG emissions, of both a BEV and an ICEV in the context of São Paulo. To achieve this goal, a Life Cycle Assessment was performed, in which the Production Phase (Cradle-to-Gate), the Use Phase (Well-to-Wheel) and the End-of-Life Phases were assessed and explored. Additionally, other factors that influence said life cycle emissions were incorporated in the analysis, a gap from previous studies found in literature that adopted a similar scope, those including the battery capacity fade, the driving style, and the driving cycle.

To that end, results from the analysis reinforce some previous conclusions from literature but also add other aspects to the analysis. Firstly, considering the scenarios here approached, it is clear that the gasoline fuelled ICEV is by a considerable margin the worst option in terms of GHG emissions, as discussed and presented in the results. The BEV, on the other hand, especially when powered by a clean electricity grid mix, like the current Brazilian case, is shown to be of great value for the reduction of the light duty vehicles emissions. Total lifecycle emissions reduction ranges from 7.8% to 48.9% in respect to the ethanol fuelled vehicle, and, from 51.3% to 76.0% in respect to gasoline fuelled vehicles, among the different scenarios considered. Being so, the use of ethanol to power vehicles can be an interesting practice, especially in a transition phase between the two technologies, as it was shown that if a second battery is required and recycling processes do not occur at a desirable frequency, the level of emissions between the BEV and the ethanol ICEV is comparable to a considerable degree. This result is especially relevant for contexts where resources for implementing the necessary infrastructure to recharge EVs is not available. In this scenario, ethanol could be an interesting option to reduce GHG emissions.

In the sensitivity analysis, the significance of the above-mentioned conclusions was enhanced. Results indicate that even in scenarios in which total emissions from battery production and fuel consumption are larger than originally estimated, the BEV powered with the Brazilian electricity mix continues to be the best option. The same applies to studied changes on vehicle lifetime and battery recycling.

In addition to the pure comparison between powertrain alternatives and different fuels, key parameters to determining the emissions of BEVs were also identified. The electricity mix that powers the BEV represented a key parameter in the analysis, as was expected from the results and conclusions of other studies from literature. Capacity fade, an aspect that was often neglected in a considerable number of studies, was also shown to be a key parameter to the overall emissions, as a consequence of the GHG emissions intensive production process of the battery. The local driving cycle was also shown to be very relevant to the overall results, especially when comparing estimations based on the NEDC with studies that made use of real-world data. The influence of the driving style was also assessed, with the conclusion that it can have a significant impact in two ways, by directly influencing consumption, and, affecting battery capacity throughout the lifetime of the vehicle. Local temperature, considering the conditions from São Paulo, did not play a very significant role in the analysis, which can be attributed to the fairly soft weather of the city. Finally, the role of recycling of both the vehicle and the battery, and also the potential for secondary use of the latter, manifested as a key parameter to the overall emissions in the different assessed scenarios but also to define which powertrain or fuel was more advantageous.

These empirical findings could support policy makers to develop more efficient strategies and public policies towards GHG emission reduction from vehicles, and thus, contributing to SDGs 11 (Sustainable cities) and 13 (Climate Action). Results show that EVs can play an important role in the general effort of trying to reduce GHG emissions generated by road transportation in São Paulo, but with integrated policies regarding energy (electricity supply mix from clean and renewable sources) and Circular Economy (battery and vehicle recycling play an important role). These recommendations are valid not only to the city of São Paulo, but other cities that already has a cleaner energy mix.

It is important to note and recognize the limitations of this study, which should be addressed by future research, as well as next steps from literature, so as to build on the conclusions here drawn. Firstly, the analysis focuses exclusively on GHG emissions as the primary impact measure. Future studies should incorporate additional impact measures, such as resource depletion, soil acidification, and human toxicity, to provide a more comprehensive understanding of the environmental impact of both powertrain technologies. Furthermore, the researchers relied solely on publicly available information regarding the production of the reference vehicles, which may result in less precise modelling of the material composition due to the unavailability of detailed supplier lists. Finally, this study is confined to examining the environmental impact within the specified scope, without delving into the economic, political, or structural conditions pertinent to São Paulo or Brazil as a whole

As recommendations for further studies, other impact measures should be assessed, as to provide a more complete picture of the environmental impact of both powertrain technologies. These other impact measures include, but are not limited to, resource depletion, soil acidification and human toxicity. Moreover, the present study made use of databases and other studies from literature as the sources of data for the analysis performed. To build on the analysis performed, a possible next step would be incorporating primary data, ideally collected from the industry to the inventory of the assessment, as such type of data is still lacking at an adequate volume in literature. Additionally, aspects other than the purely environmental side should be subject of future analysis. For instance, assessing economic, political and structural conditions is fundamental for a complete understanding of the real impact electric vehicles can have in reducing the GHG emissions in cities with clean electricity mixes, similar to São Paulo and Brazil in general, and its implications for the national energy policies.

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