MICHELE MASELLI FILHO

LIFE CYCLE ASSESSMENT OF BATTERY ELECTRIC AND INTERNAL COMBUSTION ENGINE VEHICLES IN THE CONTEXT OF SÃO PAULO

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To my family and friends.

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"The most incomprehensible thing about the world is that it is comprehensible."

– Albert Einstein

ABSTRACT

The consequences and the damages of human action on the environment is one of the main topics of interest of the last decades, and will continue to be in the foreseeable future. Among the numerous impacts, the high levels of Greenhouse Gases emissions (GHG) caused by humanity have received significant attention, especially due to its contribution to Global Warming. There are various emitting sources Greenhouse Gases that have received significant interest in the last decades, with multiple efforts towards reducing human impact on the environment. One of such sources are light duty vehicles, globally the main mean of individual transportation, currently facing an ever-growing transition movement, from internal combustion engine vehicles towards electric vehicles.

The study and research of the environmental impact of both powertrain technologies has been a significant topic of interest in literature in the past decade. However, despite a significant number of published studies, there is still a significant lack of understanding of the real impact of electric vehicles. Mainly, aspects such as automotive battery production and recycling, the influence of driving patterns and battery capacity fade are far from having a consensus among literature sources. In Brazil, the gap is even larger, as currently there is not a sufficient amount of studies that cover the topic on a satisfactory level.

The present thesis aims to contribute towards a deeper level of understanding of the environmental impact of electric vehicles versus internal combustion engine vehicles, assessing if the former is in fact the best option, considering the context of São Paulo, to substitute the latter, and, as a consequence, reduce the human impact on the environment. To do so, an introduction and contextualization of the problem is presented, followed by a review of the main studies in literature. Next, a Life Cycle Assessment of an electric vehicle and an internal combustion engine vehicle is performed, using the GREET database and software, so that the GHG emissions are evaluated on a cradle-to-grave basis. The scope of the study adopts as possible fuels for the ICEV both gasoline and sugarcane ethanol. For the EV, four scenarios of electricity generation mix are evaluated: Brazil, Europe, Italy, and 100% Natural Gas. Furthermore, other parameters often ignored are incorporated in the analysis, such as the driving cycle, the driving pattern, and automotive battery capacity fade. Results support the conclusion that EVs, given the evaluated conditions, are the best option for the reduction of GHG emissions, while sugarcane ethanol is also very beneficial. Gasoline fuelled ICEVs are shown to be by far the worst alternative among the three.

Keywords: Electric Vehicles, Life Cycle Assessment, Environmental Impact

RESUMO

Os danos ambientais causados pela ação humana é um dos principais tópicos de discussão das últimas décadas, uma tendência que deve se manter no futuro. Dentre os diversos tipos de impacto, as altas emissões de Gases Efeito Estufa (GEE), consequentes de ação humana, vêm recebendo grande atenção, dado o efeito de Aquecimento Global causados pelos mesmos. Várias fontes emissoras de GEE foram tópicos de discussão e ação nas últimas décadas, com diversos esforços dedicados para a redução de tal impacto humano. Dentre essas, pode-se citar os veículos de carga leve, os quais estão passando por um grande movimento de transição, de veículos motores à combustão para veículos elétricos.

O impacto ambiental de ambas as tecnologias foi um grande ponto de interesse para pesquisa na literatura, especialmente na última década. No entanto, apesar de um considerável número de estudos publicados, diversas lacunas ainda persistem quanto ao tópico. Em especial, pode-se citar campos como a produção e reciclagem da bateria, o impacto do estilo de direção e a perda de capacidade da bateria, ainda longe de um estágio de consenso literário. No caso específico do Brasil, existem ainda mais lacunas, afinal, poucos estudos tratam do assunto com nível suficiente de detalhe, com parâmetros-chave muitas vezes sequer sendo considerados.

O presente estudo almeja contribuir para o entendimento do impacto ambiental de veículos elétricos e à combustão, investigando se elétricos de fato representam a melhor alternativa para a redução do impacto da humanidade no meio ambiente, com ênfase para o contexto de São Paulo. Para tal, uma introdução e contextualização do problema é apresentada, seguida de uma revisão dos estudos da literatura. Em seguida, é performada uma Análise de Ciclo de Vida para um veículo elétrico e um à combustão, com uso da base de dados GREET, avaliando as emissões GEE "do berço à cova". Para o veículo à combustão, dois tipos de combustíveis são investigados, gasolina e etanol. Para o veículo elétrico, quatro cenários de geração de energia elétrica são analisados: Brasil, Europa, Itália e 100% Gás Natural. Além disso, outros parâmetros, muitas vezes desconsiderados, são incorporados, tal qual o estilo de direção, ciclo de direção, e perda de capacidade da bateria. Os resultados suportam a visão que veículos elétricos constituem a melhor alternativa, para as condições e escopo da análise, enquanto o etanol também se mostrou altamente benéfico. Veículos à combustão movidos à gasolina constituíram, por longa margem, a pior alternativa dentre os três.

Palavras-chave: Veículos elétricos, Análise de Ciclo de Vida, Impacto Ambiental.

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LIST OF ACRONYMS

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
GWP	Global Warming Potential

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1. Introduction

1.1 Motivation

The present document is the result of the author's knowledge acquisition throughout graduation at University of São Paulo and Politecnico di Torino, via the double-degree programme.

The last decades have been transforming in the way sustainability and the humanity impact on the environment are perceived by society and literature. This change has shaped several industries and technologies, and will continue to do so. One of the industries most affected by it is the car industry, which seemingly is going through a technological paradigm change, from internal combustion engines to electric. Faced with said movement of the industry and being increasingly interested on studying sustainability, I decided to further study and investigate the actual consequences of this movement, as the opportunity to do so arose from discussing the theme with my thesis advisors, both at University of São Paulo and Politecnico di Torino, providing me all the necessary support to develop this work, from the problem definition, to deciding on the approach to be taken and selecting the most relevant topics to be addressed in the report. The present work is not based on my internship experience, which makes their support even more important to its development.

Finally, the present thesis was an opportunity of developing a work centred around the city I grew up in, São Paulo, which has several questions and problems, one of which the road transportation and its consequential environmental impact.

1.2 Problem Introduction and General Objectives

The human influence on the environment is a topic that has received increasing concern in the past decades, as humanity's impact is as large as ever. One of the key issues to be addressed and dealt with is climate change, discussed in a number of the most important commissions and conferences around the globe, such as the Kyoto Protocol and, more recently, the COP26, which took place in 2021. One common topic among several of those conferences and commissions is the goal of reducing Green House Gases (GHG) emissions, due to its global warming potential. The COP26, for example, established as one of its goals to secure global net zero by 2050, and keep global warming across the century within the 1.5 ºC limit (UNFCCC, 1998; COP26, 2021).

Adhering to the environmental goals established requires concrete measures and strategies, that together, can amount to the overall goal of preserving environmental balance. In the specific case of the COP26, one of such measures is to speed up the switch to electric vehicles, credited as a more environmentally friendly alternative than the currently dominant internal combustion engine vehicles. 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 (IEA, 2022). In the Brazilian context, São Paulo signed the COP26 agreement, making the commitment of accelerating the substitution of light duty internal combustion engine vehicles by 2040 (O GLOBO, 2021).

Electric vehicles, differently than the often used Zero-Emission Vehicles (ZEV) denomination suggests, do in fact incur GHG emissions. On that matter, this study aims to assess the environmental impact, in terms of GHG emissions, of electric vehicles in the context of the city of São Paulo, comparing it to the currently dominant internal combustion engine vehicles. The end goal is to provide a comprehensive analysis that supports future decisions on road transportation technologies, keeping in mind the overall goal of contributing to a lower emitting society. Moreover, the incorporation of local factors into the analysis brings a deeper local understanding, that builds up on what has been studied in literature. Being so, potential parties interested in the study are government agents and policymakers in São Paulo and potentially Brazil, in general, car manufacturers, universities and light duty vehicle users, as the reduction of GHG emissions is of general interest.

Given the goal of studying the actual contribution of electric vehicles to the reduction of GHG emissions generated by road transportation in São Paulo, the full life cycle approach was adopted, so that emissions from the production phase, use phase and end of life are considered. A reference electric vehicle was chosen and analysed for different scenarios of electricity generation sources, accommodating more than just a single scenario. As a comparison mean, a reference internal combustion engine vehicle was also chosen and studied, with sugarcane ethanol and gasoline adopted as the fuel alternatives. Moreover, the impact of key parameters such as driving cycle, local temperature, driving style, battery capacity fade and recycling processes was also evaluated.

1.3 Structure

The present document is divided into 6 chapters, each of them containing subchapters as well. The first and present chapter introduces the general context and goal of the study, as well as the parties expected to have interest in it. The second chapter provides a more in-depth contextualization of the problem and the definition of the goal the study aims to achieve. The third chapter reviews the main studies currently available in literature that adopt a scope connected to the development of this study. The fourth chapter introduces the methodology through which the results of this study will be produced, the functional units adopted and also provides the basis for the calculation of the results of the study, more specifically the Production Phase, Use Phase and End-of-Life modelling. The fifth chapter presents the results, the life cycle emissions of the modelled vehicles, of the study as well as the discussion and comparison of such results with studies from literature. The sixth chapter provides the conclusion of the study, reviewing the key takeaways from the obtained results and suggests further topics to be explored in following studies.

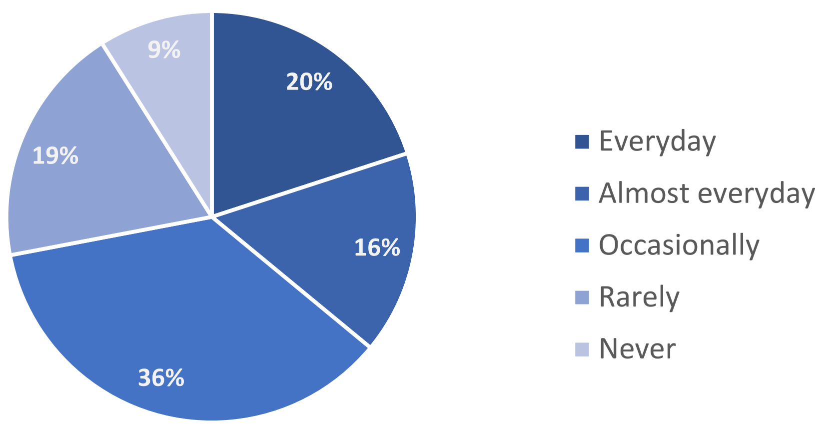
2. Problem Contextualization and Definition

2.1 The Transportation Sector in São Paulo

São Paulo is the most populated city in Brazil, with an estimated population of 12.4 million inhabitants (IBGE, 2021), that is spread over an area of around 1,521 km², resulting in a population density of 8,152.5 inhabitants/km². The city is also the largest economic centre of the country, with a GDP of R$ 763.8 billion in 2019, or USD 193.4 billion, accounting for roughly 10.3% of the national GDP in that year (IBGE, 2021; 2022). São Paulo has been growing both in terms of population and economically in the last decades, experiencing a 10.15% growth in population and a 69.5% GDP growth, in respect to 2010.

Urban mobility is a very relevant matter in São Paulo, as most people spend significant hours of their day moving around the city. On average, a person in São Paulo spends 1h57min of her day to go and come back from their main day-to-day activity, such as work or study. Taking into account all of the daily travels, not just the day-to-day activity, this number goes up to 2h43 min per day. This phenomenon is related to the main means of transportation used in the city, cars, which are the central theme of this study, and buses. Approximately 36% of the city's population uses the car with a high frequency, and another 36% uses it occasionally, as depicted in Figure 1. Therefore, approximately 72% of the city's population relies, to a considerable degree, on cars as their mean of transportation (MOBILIZE, 2018).

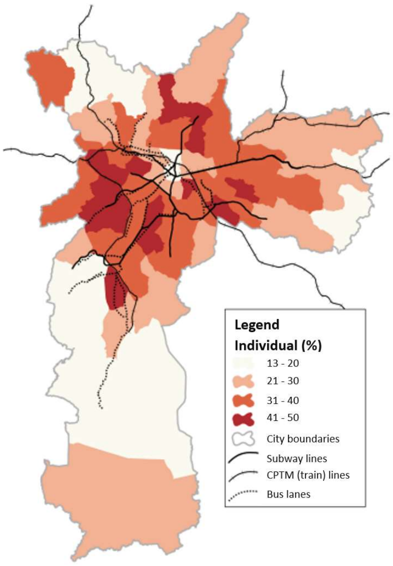
Figure 1 - How often do you use cars as a mean of transportation in São Paulo?



Source: MOBILIZE (2018)

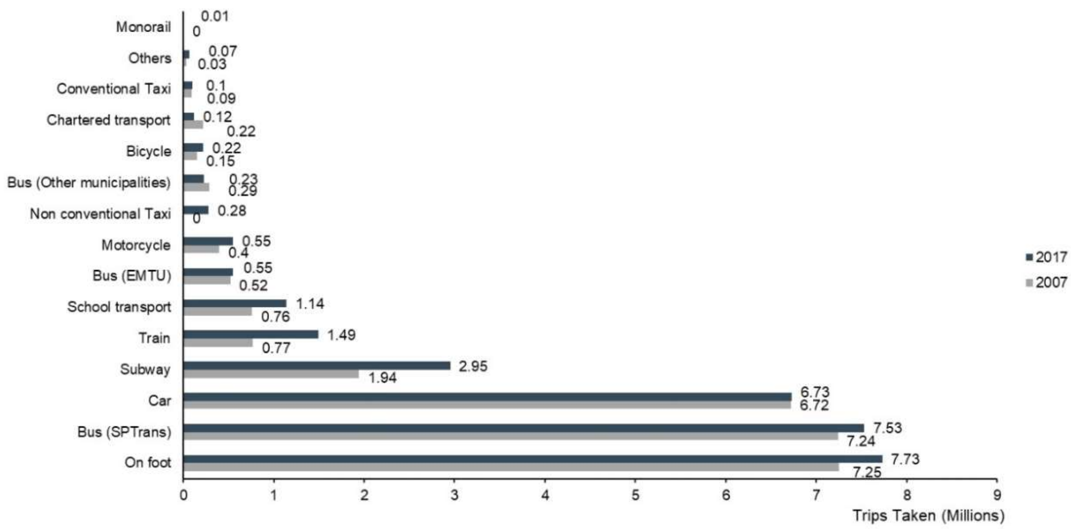
The zone of the city that is taken into consideration also has an important influence, as displayed in Figure 2, which shows the share of motorized transportation between public and individual. Central areas tend to use individual transportation more frequently, with most areas having an overall share of the trips higher than 31%, even reaching 50% of the overall trips that take place. When analysing the total of trips taken the participation is still very relevant. Figure 3 provides the total trips taken categorized by mean of transportation between 2007 and 2017 in the city of São Paulo, which shows that cars are the third most used mode of traveling, contributing to 19.3% of the total trips in 2017, only behind busses and walking, with a very large gap to the other options. However, it is important to note a slight decrease in the relative participation in the overall number of travels, from 25.4% in 2007 to 19.3% in 2017, mainly due to the introduction of non-traditional taxi services and the expansion of subways. (METRÔ, 2019). Nonetheless, the overall trend is that cars will still be used for years to come.

Figure 2 - Individual transportation share in respect to total motorized trips per city zone in São Paulo



Source: METRO (2019)

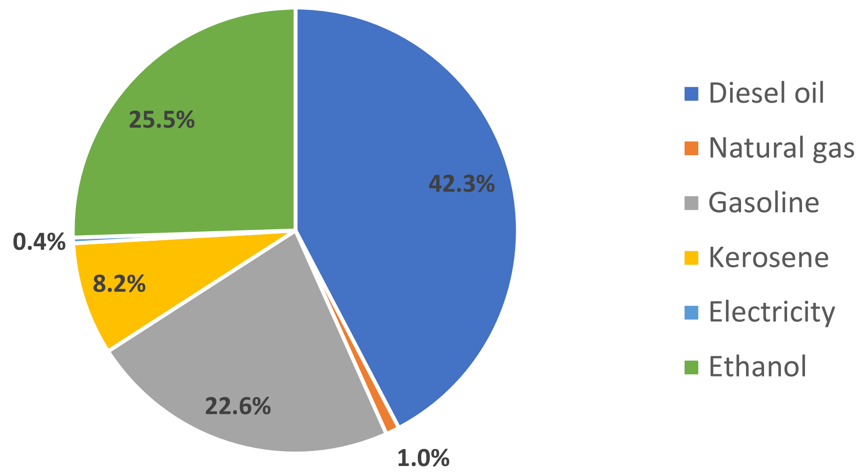
Figure 3 - Total trips by mean of transportation in São Paulo in 2007 and in 2017



Source: METRO (2019)

With such a high amount of people frequently using cars as mean of transportation, it is no surprise that São Paulo has the country's largest car fleet, with a total of 5.95 million road vehicles in 2020, a significant increase from the total of 4.61 million in 2010, representing almost 10.3% of the whole Brazilian car fleet (IBGE, 2021). When analysing the main sources of fuel in the in-use fleet, it can be seen that it is very flex dominant (vehicles that can be fuelled both by ethanol and gasoline), with 71.4% of cars being flex, followed by 17.4% gasoline-powered and 10.8% diesel powered. Unsurprisingly, only 0.1% of the fleet is composed by electric or hybrid cars (SINDIPECAS, 2021). Figure 4 presents the relative use of each fuel-type in the transportation sector, in the scope of the state of São Paulo. The data is aligned with the distribution of the car fleet, as gasoline and ethanol sum up to 48.1% of the total use. The high participation of diesel is due to the scope of the graph, that also includes trucks, which drives up the diesel consumption.

Figure 4 - Share of use by fuel-type in the transportation sector for São Paulo in 2021



Source: SINDIPEÇAS (2021)

Evidently, as it is expected from a scenario with intensive use of cars, the city currently faces an environmental problem regarding its elevated figures of GHG (Greenhouse Gases) emissions. Table 1 presents data from the Greenhouse Gas Inventory, conducted by the São Paulo City Hall, which provides information on the GHG emissions that occurred in São Paulo in 2018. In the first scope of analysis, which considers emissions that take place only inside city limits, the transportation sector was responsible for 8,401,286 tons of GHG, of which the road transportation contributed to 7,758,218 tons of CO_2 eq. Therefore, roughly 69.6% of the total emissions within city limits recorded in the year are attributed to road transportation, which is clearly a problem to be acted on. By broadening the scope, the share of attribution to transportation decreases, but still sits at an elevated 61.6% (SVMA, 2021).

Table 1 - GHG emissions in the city of São Paulo by source

Source of emission	**Scope 1**	**Scope 2**	**Scope 3**	**Total**
Stationary energy	2,043,402	1,941,958	-	3,985,360
Transportation	8,401,286	68,853	-	8,470,139
Roadway	7,758,218	2,179	-	7,760,397
Railway	628,777	66,674	-	695,451
Waterway	-	-	-	-
Air	14,291	-	-	14,291
Off-Road	-	-	-	-
Waste	686,492	-	605,302	1,291,784
Total	**11,700,710**	**2,010,811**	**605,302**	**12,747,293**

Source: SVMA (2021)

For comparison, in the state of Rio de Janeiro, a very important Brazilian economic pole, transportation and road transportation contribute to, respectively, 38.1% and 28.5% of the total reported emissions in 2015 (INEA, 2017). In Minas Gerais, another very relevant state to the Brazilian economy, transportation accounted for 15.1% of the state emissions and road transportation for 14.1% (FEAM, 2022). Clearly, change must happen in São Paulo, as elevated GHG emissions incur in several environmental problems. The Energy Balance of the State of São Paulo from 2021 also depicts a worrying image. When analysing data from GHG emissions divided by fuel, it can be seen that gasoline contributes to around 19.8% of the total emissions, only behind diesel oil, which has also a share of contribution from cars, strengthening the need of a structural change in the transportation sector, specifically road transportation (SIMA/SP, 2022).

2.2 Government Position and Initiatives

The government of the state and city is aware that the current situation demands change, as the impact of Greenhouse gases, such as causing respiratory diseases and increasing global warming are already known (MIKHAYLOV *et al.,* 2020). In this section the main programs, initiatives and public goals of the São Paulo government will be presented, so to demonstrate current and past efforts regarding the topic and, just as important, where the city plans to be in the future.

2.2.1 Proconve (Programa de Controle da Poluição do Ar por Veículos Automotores)

The Proconve is a governmental initiative instituted by the *Resolução Conama nº18,* in May 6th of 1986, controlled by IBAMA (*Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis)*, that acts upon vehicular emissions (IBAMA, 2021). The program acts with the goal of:

- Reducing pollutant emission levels by motor vehicles to meet air quality standards, especially in urban centres;
- Promoting the national technological development on both the automotive engineering and methods and procedures used to measure the emission of pollutants;
- Creating inspection and maintenance programs for the in-use vehicles;
- Promoting awareness on the air pollution caused by vehicles;
- To promote the improvement of the technical characteristics of the liquid fuels available for the national fleet of motor vehicles, aiming at the reduction of pollutants emitted into the atmosphere, and;
- Establishing conditions for evaluating the results achieved.

The program has had expressive results since its creation 36 years ago and has managed to be compliant with the goal of reducing pollutant emissions levels in the automotive sector. For example, before the program was created, a vehicle in Brazil would, on average, emit 54 grams of Carbon Monoxide (CO) per kilometre. Nowadays, the average vehicle emits 0.4 grams per kilometre.

The latest phase of the program is the L7, that came into force in the beginning of 2022. The L7 focuses on the reduction of emission of several gases that are harmful to the environment, such as the Carbon Monoxide (CO) and the Nitrogen Oxide (NOx). Additionally, the program also applies further restrictions on the EVAP (Evaporative Emission System), reducing the maximum daily emissions from 1.5 grams per day to 0.5 grams per day. Furthermore, catalysts will also have to be subject to improvements, as its lifespan requirements increase from 80,000 kilometres to 160,000 kilometres.

The ever-increasing requirements of the program constantly puts car manufacturers in a difficult spot, as significant investments are required to meet the demands imposed by the program. As a result of that, several manufacturers are forced to stop producing certain models, as was the case of Fiat, which due to the L7 stopped the production of four of its models, and Chevrolet, that removed two models from its production lines. The more severe requirements promote a scenario in which the production of vehicles that use renewable energy as fuel sources is increasingly more attractive to car manufacturers, of which are included the electric vehicles, potentially accelerating the diffusion of EVs in Brazil (IBAMA, 2021).

2.2.2 Pró Veículo Verde

In March 2022, the government of the state of São Paulo announced a new campaign, called *Pró Veículo Verde,* with the goal of incentivizing the production of cars fuelled by clean energy sources, mainly hybrid, electric or biofueled vehicles. To do so, a fiscal incentive of up to R$ 500 million in credit of the ICMS (*Imposto sobre Circulação de Mercadorias e Serviços),* a tax incurred on sales, will be offered to car makers that invest in the production of sustainable car models. As a result of said incentive, the state government aims to attract up to R$ 20 billion in investments in the segment for the next three years, accelerating the transition to a more sustainable automotive sector (INVESTESP, 2022).

2.2.3 COP26

In October 2021, the government of the city of São Paulo adhered to the COP26 declaration, that refers to an acceleration of the transition process from fossil fuelled vehicles to zero emission ones. The agreement establishes that signatories members will take actions so that, by 2040, all vehicles and vans in circulation are not fuelled by combustion engines, which cause harmful emissions to the environment (COP26, 2021). The city's adherence is a sign of the commitment the city and state are taking towards lowering the environmental impact of the transport segment, which accounts for 69.6% in the city and 61% for the whole state (SVMA, 2021; SIAM/SP, 2021). However, despite the agreement, the city hall did not further detail the plan of action it intends to follow to comply to the agreement (O GLOBO, 2021).

2.2.4 PlanClima SP

The PlanClima SP is a plan of action elaborated by the city of São Paulo in 2020 focused on the achievement of the city vision, that sets goals to be achieved by 2050 (CIDADE DE

SÃO PAULO, 2021). The whole scope involves achieving a more equalitarian city, more prepared to deal with the impacts of climate change, carbon neutral and able to promote access to public services with quality, generating welfare and economical development that is inclusive and sustainable. The plan started from 144 identified actions that would take the city to its vision, which then were prioritized and organized between 5 strategies, that guide the whole plan, the first one being the most interesting for this study:

- Carbon zero by 2050;
- Adapting the city of today for the tomorrow;
- Protect goods and people;
- Protecting the *Mata Atlântica;*
- Generate sustainable wealth and employment

The "Carbon zero by 2050" is heavily linked to the automotive segment, given the elevated emissions caused by mobility in the city, which must adapt itself so that the goal of reducing 50% of the liquid emissions by 2030 and 100% by 2050 can be reached. Within this strategy, several goals are established for different timeframes so that progress can incrementally increase and reach the end goal by 2050. Of those, these are the ones that directly influence the diffusion and use of electric cars in the city:

- By 2030, the city has the goal of developing a legislation that creates incentives to the distribution of zero emission vehicles in the city's territory;
- By 2030, promote and implement the regulation of electric car sharing in the city of São Paulo;
- By 2040, 100% of the vehicles used by the Military Police of the city will be zero emission;
- By 2040, 100% of the buses fleet will be electric.

In the Action 3, the plan commits to mobilizing efforts to foment the production and distribution of renewable source energy. This effort by the city if realized will help the carbon footprint of electric car use, as the electrical energy used to power the batteries will be generated by cleaner sources, contributing to the overall goal of lowering the impact in terms of emissions of the transportation sector.

Action 14 of the plan commits to perfecting the regulation on car-sharing, parking and recharge of electric vehicles or zero emissions vehicles in general. To do this, the city plans to develop a study for the instalment of a recharging infrastructure for electric vehicles and to also modify the legislation that concerns the use and occupation of land, as well as the building legislation, to favour the recharging of electric vehicles in residential and commercial buildings, further facilitating its use in the city. It is expected that the fraction of combustion vehicles in São Paulo decreases throughout the years, with goals to reach 35% by 2030, 20% by 2035 and 5% by 2050.

2.2.5 Investments by GWM

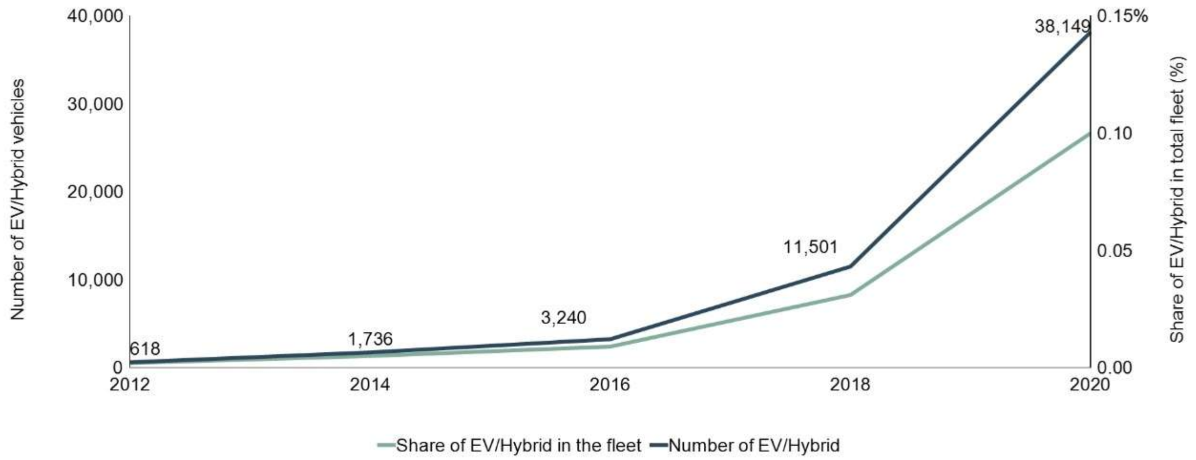
In March 2022, the government of the state of São Paulo announced that the Chinese car manufacturer GWM will build 100 new recharging points among cities of the state, in which is included the capital, São Paulo. The campaign will be part of a series of investments from the Chinese company that will sum up to R$ 10 billion, in which is also included the construction of a new factory in Iracemápolis, countryside of the state, which will produce exclusively electric vehicles, at a projected volume of one hundred thousand vehicles by 2025 (PORTAL DO GOVERNO DE SP, 2022).

The recharging stations will be mostly powered by photovoltaic panels, therefore contributing to the environmental impact of car usage in the city, and will be located in GWM dealerships and high circulation places, such as supermarkets and malls. The use of the recharging stations will be free of charge and accessible to vehicles of all car manufacturers, contributing to the diffusion of the electric car in the city, as it will make charging easier and cheaper.

2.3 Problem Definition

In face of the effort of lowering the transportations sector GHG emissions in São Paulo, more specifically the one regarding private means of transportation, one common theme of discussion that is usually regarded as a solution to this matter is the use and diffusion of electric cars. Several of the previously mentioned government initiatives refer to electric vehicles as the solution to this problem, being often referred to as “zero emission vehicles”. The commercial side, which can be assessed by the evolution in sales and representation of the car fleet, also seems to have adopted this idea. As represented in Figure 5, the number of electric or hybrid vehicles has had exponential growth in the last decade, from just 618 units in 2012 to 38,149 units in 2020, with a strong growth expected for the future as well. In terms of the participation in the overall car fleet of the city, in 2020, approximately 0.1% of the total cars in circulation were either electric or hybrid (SINDIPEÇAS, 2021).

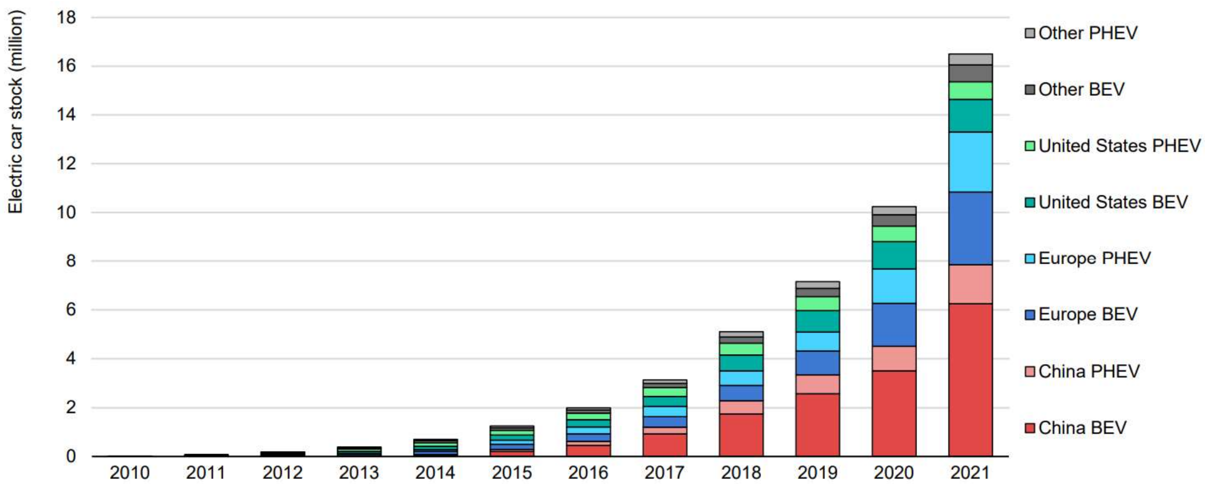
Figure 5 - Number and share of EV/Hybrid vehicles in the São Paulo fleet



Source: SINDIPEÇAS (2021)

Moreover, this scenario is definitely not particular to Brazil, as global sales of electric and hybrid vehicles are registering impressive growth. The latest publication of the Global Electric Vehicle Outlook, from 2022, points to a total stock of electric vehicles globally of more than 16 million vehicles, with a high concentration of those vehicles in China, Europe and the United States. The figure is particularly impressive, as the two million mark was reached as recent as 2016. The evolution of the electric vehicle fleet around the world is presented in Figure 6 (IEA, 2022).

Figure 6 - Global fleet of electric/hybrid vehicles



Source: IEA (2022)

However, despite being called “zero emission vehicles”, electric vehicles are definitely no such thing, as they have consequent emissions throughout all of its life cycle. Therefore, there is an evident need of understanding the actual environmental impact of the diffusion and use of electric vehicles as the dominant powertrain technology for cars in future society. So far, it is observed in literature an effort towards that direction, as more and more studies that aim to conduct such assessments are being published and developed, but despite that, very few of them adopt as their scope the Brazilian environment, and by consequence the environment of the city of São Paulo, as most of these studies have their scope focused on Europe, United States of America, Canada or China. The studies that do adopt a Brazilian-driven scope don't quite manage to get the full picture, as they often are focused on studying simply the Use Phase of the vehicle or do not provide a sufficient enough level of detail to the analysis.

Given the above mentioned, the focus of this study will be assessing and comparing the environmental impact, measured in terms of GHG emissions, of both an electric vehicle and an internal combustion engine vehicle in the São Paulo environment, and, as a consequence, the impact of changing the powertrain technology on vehicular emissions. The study will analyse all of the phases of both vehicles: manufacturing, use phase and end-of-life, as it performs a Life Cycle Assessment, following a methodology to be further explored later. It is important to state that there are limitations to this study, as important factors such as economic conditions, charging infrastructure, consumer acceptance of the product, and, environmental impacts other than GHG emissions, such as resource depletion, will not be considered in the analysis, which presents an opportunity for other studies as well, so that the understanding of the general impact continues to grow.

3. Literature Review

In order to achieve high level results for the goal of this study, assessing the environmental impact of the use of electric cars in the context of São Paulo, a literature review was conducted, prior to the development of the methodology and consequential results yet to be presented in this study. In doing so, several articles, reports and studies from published literature were analysed, in such a manner that the main conclusions relevant to the present study will be detailed in this section. The key objective of this literature review is to provide a better understanding of the topics that are relevant to the life cycle assessment of the environmental impact of electric cars, from the manufacturing and assembly, to the use phase, and, finally, to the End-of-Life.

3.1 Literature Review Methodology

The articles that were analysed in the literature review of this study are derived from four main online sources: Science Direct, Scopus, Research Gate and Google Scholar. The articles here discussed result from searches in the mentioned websites. The literature review is divided into four sections: articles that study battery production or complete vehicle production, articles that study the use phase only, articles that review the whole vehicle Life Cycle, and articles that study topics that do not directly fit into the three former categories, but were still very relevant to the analysis performed.

For the first one, the articles resulted from searches using key words such as: "LCA battery", "Lithium-ion battery", "Li-Ion battery", "automotive battery production", "automotive battery recycling". The second section results from searches using key words such as: "EV use phase", "electric vehicles WTT emissions", "WTW emissions", "Well-to-Wheels emissions". The third section results from searches using key words such as: "EV Life Cycle Assessment", "EV ICEV life cycle emissions", "BEV lifetime emissions". Moreover, the literature review from other studies was also a source of articles here reviewed.

3.2 Review of Battery and Vehicle Production Studies (Cradle-to-Gate)

Having selected the electric vehicle model to be used as the object of the analysis, the Nissan Leaf 2022, an effort to find relevant studies that would contribute to the end result of the assessment was required. In the case of evaluating the LCA results of the car battery, literature on Lithium-Ion batteries served as the main source of information and bibliographical reference, as this was the type of battery used in the reference car model.

Peters et al. (2017) conducted an extensive literature review on several articles published on the subject, reviewing studies dated from 2000 to 2016 and available in mainstream platforms such as Science Direct, Scopus and Google Scholar. However, it is important to note a limitation of the review, as only the impact of battery production was analysed, therefore excluding the recycling of batteries, which obviously limits the assessment of the potential impact of using recycled materials for the production of batteries, especially significant for the mining and resource extraction phases. The article reinforces an issue with most studies that address battery production, as of the 113 total publications that resulted from the literature search conducted, only 36 studies provided detailed results for LIB production and disclose sufficient information as to re-calculate these results on a per kg or per Wh of storage capacity basis.

Another important contribution of the review conducted by Peters et al. is the identification of LCA studies that make use of own LCI data, a total of 8 studies. Of those studies, 4 were judged relevant to the selected scope of this present report, as the battery chemistry studied by them corresponds to the one used in the Nissan Leaf (Nissan, 2022), and therefore will be included in this literature review. These studies are the ones conducted by Notter et al. (2010), Majeau-Bettez et al. (2011), Dunn et al. (2012), and Ellingsen et al. (2014).

In their study, Notter et al. (2010) obtained results that pointed to the conclusion that the extraction of lithium for the components of the Lithium-Ion battery isn’t a great contributor to the overall environmental impact of battery production. Conversely, the supply of copper and aluminium for the production of the anode and the cathode carry a considerable participation in the overall impact, as does the required cables or the battery management system. More specifically the study models a $LiMn_2O_4$ battery, which are especially relevant as magnesium has been frequently used in the automotive battery sector since the publication of the study and is expected to continue to be used (ARMAND; TARASCON, 2008; SCROSATI; GARCHE, 2010).

The LCA results presented by Notter et al. (2010) lead to the conclusion that the environmental impact of Lithium-ion batteries can be considered relatively small, when compared to the whole LCA of an EV. However, one has to keep in mind that changes in the electricity mix used to recharge the electric vehicle will heavily change the overall impact of the use phase, therefore changing the relative participation of the battery production.

According to the LCA analysis developed by Notter et al., the production of the Lithium-Ion battery incurs in the emission of 6 kg of CO_2 eq. per kilogram of battery. The greatest contributors to said emissions are the production of the Cathode (36.2% of the total), the Anode (14.5% of the total) and the Battery Pack (26.8% of the total), which indicates that metal supply is the key point to be addressed when trying to reduce the environmental impact of car batteries. Moreover, although lithium occurs in average concentrations of lower than 0.01% in the Earth's crust and hence can be considered to be a geochemically scarce metal (SKINNER, 1976), it can be said that lithium components are evaluated to not cause a very high ADP (Abiotic Depletion Potential).

One important aspect to be considered when analysing results from the study is the fact that authors did not consider the cell assembly process in their modelling. The process has to take place in a dry-room, which means that it is associated to very significant environmental impact and therefore shouldn't be neglected in the analysis. Following studies from literature support the relevance of impact of the cell assembly process (MAJEAU-BETTEZ; HAWKINS; STRØMMAN, 2011; DUNN et al., 2012; ELLINGSEN et al., 2014).

One of such, Majeau-Bettez et al. (2011), contributed to the assessment of the environmental impact of the batteries used in electric vehicles by performing the Life Cycle Assessment of three different batteries, a nickel metal hydride (NiMh) battery, a nickel cobalt manganese lithium-ion (NMC) battery, and an iron phosphate lithium-ion (LFP) batteries. The selection of the studied batteries reflects the state of the technology at the time, as at the time nickel metal hydride batteries were used in most hybrid electric vehicles and electric vehicles (AXSEN; BURKE; KURANI, 2008). The study is extremely valuable as it provides a new and original LCI inventory for the production of the mentioned batteries, something that as evidenced by Peters et al. (2017) could be considered quite scarce, enabling benchmarking with the existing literature, which directly contributes to the better understanding of the environmental impact of the technology. However, the study does not include the end-of-life scenarios in the analysis, a gap still to be filled in literature, as most studies follow the exclusion of that scope.

Results of the studied point to an impact by Lithium-ion battery production of 22 kg of CO_2 eq. per kg of battery. The major contributors to the overall emissions are the positive electrode paste, the battery components and manufacture, and the battery management system (BMS), with respectively 35%, 28% and 15%. Overall, the per kg of battery emissions calculated are above the overall average from literature, especially due to the contribution of the cell production (AICHBERGER; JUNGMEIER, 2020). Moreover, Majeau-Bettez et al.

(2011) concludes that the NiMH technology was found to have the highest environmental impact, followed by NCM and then LFP, which is important when assessing the future design of electric vehicles.

Ellingsen et al. (2014) performed a Life Cycle Assessment of a NMC Lithium-ion battery, with battery cells that uses $Li(Ni_xCO_yMn_z)O_2$ as the cathode material and graphite is used as the anode. The study divides the battery into four parts: battery cells, packaging, BMS (Battery Management System) and the cooling system. The report, along with the supporting information provided, offers a very complete and detailed LCI (Life Cycle Inventory) of the automotive battery in study, which, most importantly, is composed of original primary data, therefore contributing to the results and analysis to be presented in this report. Even more interesting, the assessment is made using battery manufacturer's data, as opposed to lab conditions, which is the case for most studies, resulting in the neglection of factors such as economies of scale.

Results of this study vary on the values of electricity use adopted, which were three different values, of which is only going to be considered the LBV (Lower Bound Value), as that was the value chosen for the analysis of results in the report by Ellingsen et al., therefore being the one suited for the purposes of this literature review. The CTG (Cradle-to-Gate) emissions of the studied battery were reported at 4580 kg of CO_2 eq. emissions for the whole pack, or 18 kg of CO_2 eq. per kg of battery or 172 kg of CO_2 per kWh of battery. From the results, it can be observed that the manufacture of battery cells is by far the greatest contributor to the emissions, a conclusion aligned with literature at the time but that has been disputed by recent studies (DAI et al., 2019). Other key contributors are the positive electrode paste, which confirms results by previous studies (NOTTER et al., 2010; MAJEAU-BETTEZ; HAWKINS; STRØMMAN, 2011), and the negative current collector. Nickel sulfate is reported as the causing factor for the high impact of the positive electrode paste, while copper plays that role in the negative current collector, which is in line with conclusions by Notter et al. (2010) on the big impact of metals in the emissions of battery manufacturing.

The importance of considering the electricity grid mix is also a factor analysed. Author's results show that using only coal to produce electricity would incur in an increase of more than 40% in total GHG emissions, while using hydroelectric powered electricity would reduce by more than 60%, which goes to show the important role of expanding the generation of clean electricity for the reduction of the impact of battery manufacturing.

Dunn et al. (2015) conducted an extensive study on the energy and material flows considering the cradle-to-grate system boundaries of Lithium-Ion batteries with several different types of cathodes: LMO, LFP, NMC, LCO and LMR-NMC. The first key point addressed is the environmental impact of the battery assembly step, as it is an important point of diversion between studies of literature, to the point that in some studies its reported energy requirements exceed those of the material requirements of the battery, whilst reports from other authors point to a practically negligible energy expenditure. The second key point addressed in the report is the role of recycling in lowering the environmental impact of the battery production, especially considering a scenario in which the battery assembly dominates the total environmental impact.

A first contribution of Dunn et al. (2015) is the analysis of the cause of such great variance regarding the battery assembly, that comes down to the choices, assumptions and modelling made by authors. Studies that use a bottom-up approach, meaning those that estimate the energy consumed in each individual step of the process and them sum them up to reach an overall value, tend to assign a low energy consumption to the assembly process, and usually assume that production facilities are operating at-capacity. On the other hand, studies that use a top-down approach, therefore assigning a share of the total corporate energy consumption to the assembly process or using sources from literature for primary fuel consumption related to the process, tend to have much higher energy requirements. Moreover, the effect of facility capacity is also shown to be extremely relevant, as conducting a study in a scenario of partial in-use capacity will result in much higher emissions in respect to a facility with high usage of capacity.

The relevance of recycling is also subject to the parameters of analysis of Dunn et al (2015). The view supported is that, at a high enough facility usage, recycling would grant considerable benefits. The main areas to focus on would be recycling materials from the cathode or wrought aluminium, which is used as a structural material. Furthermore, recycling of cathode material is presented as a big opportunity for emissions savings, as it accounts for 40% of the overall energy requirements of the battery. For this type of battery, the study evaluated the potential benefit of two recycling alternatives, an intermediate and a direct one. Results from the analysis pointed to a potential reduction in GHG emissions of around 20% for the intermediate method, and around 95% for the direct method. However, as authors themselves state, those figures should serve the purpose of indicating that recycling would grant positive benefits, and not be used as absolute results, as some probable steps of additional processing would be required so that the recycled materials would have a performance identical to virgin materials.

Another study, conducted by Dunn et al. (2012), focused on evaluating the discrepancy observed in the results of cradle-to-gate analysis of the energy consumption and GHG emissions of the production of batteries used in electric vehicles. In particular, the goal was analysing the battery assembly process, which is the main point of discussion, given the considerable differences in results between studies that adopt a top-down approach and a process-level approach. Results from the study are aligned with what was previously observed in literature, as authors obtained an energy consumption figure for the battery assembly process of 2.7 MJ/kg, which is expected as they made use of a process-level approach. In the sensitivity analysis, a decreased energy use share of the dry room and cycling in respect to the overall energy that the assembly plant uses was adopted, which resulted in an energy consumption figure of 8.1 MJ/kg, still far lower than what is observed in top-down approaches (MAJEAU-BETTEZ; HAWKINS; STRØMMAN, 2011; ZACKRISSON; BENGTSSON; NORBERG, 2010). Aluminium (58.33%), copper (8.66%) and the cathode material (9.74%) represented the largest contributors to the energy consumption.

Moreover, in their analysis, Dunn et al. (2012) reached the conclusion that, given the large contribution of recyclable materials to the environmental impact of the battery, it would be beneficial to assess viability and impact of recycling. Recycling via a hydrometallurgical process, an intermediate physical recycling process (with cobalt-containing cathodes) that recovers Li_2CO_3 and a direct physical recycling were analysed. The conclusion was that recycling of the main materials, aluminium, copper and $LiMn_2O_4$, is highly beneficial to lowering emissions and energy consumption.

Zackrisson et al. (2010) studied the impact both from the production, on cradle-to-gate boundaries, and the use phase of a 10 kWh Lithium-ion battery with $LiFePO_4$ as the cathode material. The study, aligned with other results from literature, concludes that under most electric grid mix conditions electric vehicles tend to have lower emissions than internal combustion vehicles. Additionally, authors investigated and validated the hypothesis that water can be used as a solvent of NMP in the slurry for the casting of cathodes and anodes for the batteries. Finally, in the conducted sensitivity analysis, results point that the battery internal efficiency is two to six times more relevant than the impact by weight, considering the parameters of the study. This motivates the conclusion that these are two key parameters to be analysed when designing or selecting a battery.

Kelly et al. (2020) analysed the environmental impact of the production of Lithium-ion batteries that use NMC (Nickel Manganese Cobalt oxide) as the cathode material, the most common currently in the world (PILLOT, 2018). Authors address an area of analysis that wasn't deeply explored in literature before, the effect of regional variability on the environmental impact. Having such goal in mind, the study explores the effect of region on the production of the key parts to the battery, from an environmental impact standpoint, those being alumina reduction (production of aluminium), nickel refining, NMC cathode, battery cells and the battery management system (BMS). Production of the reference battery was modelled for five chosen regions: United States, China, Japan, South Korea and Europe.

In their analysis, authors reached the conclusion that electricity mix and heat sources have a significant effect on the environmental impact of the battery production considering several measures of impact: energy expenditure, GHG emissions, SO_x emissions, water consumption and NO_x emissions. Referring to the most relevant results for the purposes of this report, reported GHG emissions for the best-case scenario were close to 40 kg of CO_2 eq. per kWh, while results for the dominant supply chain of the mentioned parts and materials amount to 100 kg of CO_2 eq. per kWh, a very significant difference. The gap between countries is smaller but nonetheless significant, with production in China being associated more than 30 kg of CO_2 eq. per kWh when compared to a European production. Such results are alarming due to the fact that most studies tend to adopt European conditions of electricity mix grid, whilst the production of several of the key components takes place outside of Europe. When comparing a US-centred production to a Chinese-centred one, an increase of 36% in GHG emissions is observed for the Chinese scenario.

In this study, Yuan et al. (2017) conducted a unit process-level energy analysis for the production of a Lithium-ion battery pack to be used in electric vehicles. The study contributes to the overall understanding of the topic by making use of directly measured data of a pilot industry production facility, on Johnson Controls' pilot scale dry room production facility.

Results from the study show that the electrode drying and the dry room facility are the two major energy consumers in the whole battery manufacturing process. Additionally, it is observed that material production accounts for approximately one third of the total energy demand, while the battery cell manufacturing is responsible for the remaining share, with the battery pack assembly being basically negligible from an energy expenditure standpoint. Moreover, it is reported that if production size is increased, from a pilot-batch scale to an industrial-scale mass production, energy requirements would be reduced by 72%, supporting the findings of Dunn et al. (2012).

Lutsey et al. (2018) provides a review on some of the main studies available in literature that covered the topic of battery production for electric vehicles. Despite very significant differences between the results from the studies, the general conclusion that electric vehicles have lower level of emissions than conventional internal combustion vehicles throughout its lifetime is validated. Furthermore, authors investigate the main opportunities for emission savings in several End-of-life scenarios, mainly battery second life and battery recycling, which would increase the benefit of adoption of electric vehicles. Finally, the tendency of a grid decarbonization comes into favour of battery production, as much of the emissions related to it are a consequence of the use of electricity.

Ellingsen et al. (2017) reviews LCA results and inventory data from literature regarding Lithium-ion automotive battery production. The main goal was trying to identify the cause to the significant discrepancy of results among the reviewed studies, that reported emissions from 38 to 356 kg of CO_2 eq/kWh. The study supports the view that the cell-manufacture process is energy intensive, as previously mentioned, a topic of strong disagreement in literature. Authors also go against results from bottom-up approach studies, characterized by a lower energy intensity, arguing that those probably underestimated or even omitted energy inputs for some production steps. Finally, the conclusions on the influence of production volume brought up by Dunn et al. (2015) are also disputed.

Dai et al. (2019) conducted a study envisioning to better assess the environmental impact of electric vehicles, in response to its increasing diffusion in the global vehicle market, this study adopts the scope of Lithium-Ion batteries, more specifically one based on NMC (Nickel Manganese Cobalt Oxide). The results of the article are particularly relevant to this report, as the type of battery studied corresponds to the one used in the Nissan Leaf 2022, the adopted vehicle in this report. Moreover, the LCA was conducted using the 2018 release of the Greenhouse Gases, Regulated Emissions and Energy Use in Transportation (GREET) model, which is a former version of the database used in the analysis to be presented in this study, therefore enabling even deeper comparisons.

The results of the analysis point to a total emissions figure of 72.9 kg of CO_2 eq. for a 1kWh NMC111 battery. The greatest contributors to the reported emissions are the NMC111 powder production, the cell production and the Aluminium production, with respectively 39.1%, 19.0% and 17.0%. The great share of emissions of the active cathode material is an expected result, aligned with the conclusions from the other studies featured in this literature review. Overall, results are more aligned with the bottom-up approach, as the cell production does not account for such high level of emissions as it usually is evaluated by top-down approaches.

In this study, Kim et al. (2016) perform a cradle-to-gate analysis on the environmental impact of a commercial electric vehicles Lithium-ion battery, using primary data from the battery industry, key to analysing real-world results. Considering the modelled battery, authors obtained reported emissions of 140 kg of CO_2 eq/kWh, a value within the range of the observed literature. Authors recognize the influence of production scale as a strong contributor to the considerable difference between results from literature. Results differ greatly from other analysis that adopted a bottom-up approach (NOTTER et al., 2010; DUNN et al., 2012). The main point of disagreement is the relevance of cell and pack manufacturing, which is usually considered neglectable for the majority of bottom-up approaches.

Kim et al. (2016) also investigated and compared cradle-to-gate environmental impact of the electric vehicle and the internal combustion vehicle version of the Ford Focus, the reference vehicle for the study. The production of the electric version is associated with a 39% increase in overall GHG emissions, but when including the use phase in the analysis, the electric version outperforms the internal combustion one.

In this study, Qiao et al. (2017a) conducts a cradle-to-gate study on the energy consumption and GHG emissions of a battery electric vehicle and an internal combustion engine vehicle, both being produced in China. Therefore, differently than the studies analysed so far, the article adopts a wider scope. The subject of the study is extremely relevant, as China is the largest automotive market in the world, with a fast-increasing electric car fleet. Since much of that market is supplied by national production, it is key to understand and assess the environmental impact of such production, especially considering that the majority of studies from literature usually are done with a European or USA-centric view.

The study outlays a complete cradle-to-gate system, being included in the considered boundaries the material production and transformation, component manufacturing, battery and other attachment production, assembling and replacements. The study adopts two-mid sized vehicles as reference for the study, which has become the standard for similar studies observed in literature. Two types of batteries were studies, one with a NMC cathode and the other LFP. The study uses own data for the dominant materials in the vehicles composition, while gaps of information were filled using reference results from other studies and databases.

As expected, considering the larger weight and inclusion of the battery, the electric vehicle was characterized by a larger environmental impact. The production of the NMC powered electric vehicle amounts to a total emission figure of 15,005 kg of CO_2 eq, a 50.3% increase when compared to the internal combustion electric vehicle. The production of the adopted battery amounted to a total emission figure of around 2896 kg of CO_2 eq. The production of the body and chassis also represented a big difference between the two types of vehicles, accounting for, respectively, 2810 kg of CO_2 eq and 1710 kg of CO_2 eq, in the case of the internal combustion engine vehicle, while 4460 kg of CO_2 eq and 2706 kg of CO_2 eq for the electric vehicle.

Authors discuss three main improvements opportunities, those being a gradual change in the electricity mix of China, characterized by being very carbon-intensive, the use of recycled materials in the input-stream of materials, and, finally, the improvement of manufacturing techniques. Despite the greater emissions observed in the production phase, the whole life cycle must be considered in order to assess the best alternative between the two technologies.

Qiao et al. (2017b) conducted a cradle-to-gate emissions analysis comparing the production of electric and internal combustion vehicles in China. Authors reached the consensus conclusion in literature that the production of the electric vehicles produces more emissions than that of the conventional vehicles, representing an increase of around 60%, according to their results. The study is valuable as it shows the significance of regional factors in the production phase, while literature tends to only focus on the impact in the use phase. When dealing with countries that use less renewable energy, the difference between the two vehicles is even greater, which can alter the final result on which vehicle is best at a life cycle point of view.

3.3 Review of Use Phase (WTW) only Studies

Orsi et al. (2016) conducted an energy-based WTW (Well-to-wheels) analysis that compared different types of fuel for passenger vehicles based on three different indicators: energy use, CO_2 emissions and economic cost. A total of eight types of combination of fuels, each representing a type of vehicle passenger, were analysed, those resulting from the use of one or the combination of more than one of the following: gasoline, diesel, ethanol, natural gas and electricity. The study is especially relevant as it also considers the regional influence in the results by running the analysis considering the different conditions of five selected countries: Brazil, China, France, Italy and the USA. Another important aspect considered in the analysis is the economic cost, which is often neglected in the majority of WTW of Life Cycle Assessment studies.

The results of the study show that, in terms of CO_2 emissions, the electric vehicle outperforms the other types of vehicles in the cases of Brazil, France and Italy, while it is the second best alternative in the case of the USA. The level of emissions of the electric vehicle is heavily dependent on the electricity grid mix, as it performs really well in a scenario in which a high share of renewable energy is used, a result supported by literature. For the purposes of this study, it is also interesting to point out that in the Brazilian case, electric vehicles outperform even vehicles fuelled with E85, which in Brazil's case has much lower level of emissions than the E85 from other countries, a result of the composition and processing of the fuel in the country.

In the economic analysis, however, results are not favourable to the electric vehicle, as it has a high cost per km in comparison with other alternatives. In Brazil's case, it has the second-highest cost per km, only being cheaper than PHEV (Plug-in Hybrid Electric Vehicles). This obviously can be an important factor in the velocity of diffusion of the electric vehicle, as the higher costs, especially concentrated in the initial investment, can be a barrier to some customers.

Challa et al. (2022) conducted a well-to-wheel study on both electric vehicles and internal combustion vehicles, assessing its GHG emissions. In their study, authors analysed the effect of several factors on the level of emissions, those being climate, miles driven on average, fuel economy, road type, electricity grid mix and vehicle type. The incorporation of the influence of temperature is especially interesting, as it hasn't been much explored in literature. In order to analyse different combinations of those factors, the study was conducted considering five different regions: US average, Arizona, California, New York and Oregon. Each region was assigned to a specific vehicle, the most sold vehicle in that region, and he parameters relevant to the analysis were based on the observed scenario for that specific region. The evolution of technology through time was also considered in the study, with the analysis considering the period from 2018 to 2030.

Results of the study show that, on a well-to-wheel basis, the electric vehicle demonstrates a lower level of GHG emissions for all regions considered, with the exception of New York, even when considering the evolution in fuel economy of internal combustion vehicles. The results for the case of New York are expected, as numerous studies from literature depict the significant increase in electric vehicles emissions when electricity is generated through fossil fuels, which is the case of future New York, as nuclear energy is replaced with natural gas power plants. Results from the study also show the significant influence of vehicle type, as a higher use of heavier and larger vehicles, the case of Arizona, are characterized by having larger emission figures.

Woo et al. (2017) conducted a well-to-wheel analysis of the emissions of both electric vehicles and internal combustion vehicles, comparing the two alternatives. For the analysis, authors decided to explore the effect of the geographical location on the emissions, as each country has its own electricity grid mix. To do so, the analysis involved a total of 70 countries, therefore constituting one of the largest studies, considering this scope, in literature. Furthermore, as size and weight also play a heavy influence on the overall level of emissions of both powertrain technologies, results were analysed for four vehicle categories: subcompact, compact, full-size luxury and SUV.

Although it offers a really important perspective, the study relies solely on secondary data to estimate the emissions. In doing so, factors such as climate, type of roads, fuel quality, fuel composition, driving patterns are ignored, meaning that there is room for a significant amount of variance of results if those were to be considered. Nonetheless, the study offers an unique global perspective and includes in the analysis countries that very rarely are addressed in the literature.

Results of the study show very clearly the effect of the electricity grid mix on the level of GHG emissions across all categories of electric vehicles. Countries high extremely high share of non-renewable energy, such as China, India, Indonesia and Australia, are the only observed cases in which the electric vehicle yields higher emissions. The highest frequency of larger emissions by the electric vehicle occurs in the subcompact category, which are vehicles characterized by great fuel consumption efficiency and dedicated efforts on its improvement. For the remainder of the categories, composed of larger vehicles, the electric vehicle only has higher levels of GHG emissions when considering the maximum emission factor. For the specific case of Brazil, in none of the categories the electric vehicle is estimated to generate higher GHG emissions than either diesel or gasoline vehicles, even when adopting the maximum emission factor. This can be attributed to the high share of renewable energy in the country's mix, mainly hydroelectric.

3.4 Review of Full Life Cycle Assessment Studies

Hawkins et al. (2012) conducted a full Life Cycle Assessment of an electric vehicle and an internal combustion engine vehicle, comparing the two alternatives on several impact measures. Authors developed a life cycle inventory for both vehicles, contributing to literature with new data, better supporting the understanding of the two technologies. Furthermore, the End-of-life impacts are considered, an aspect that is often neglected in literature.

Results of the study point to a better performance of the electric vehicle when taking into consideration the GHG emissions, even though its production produces roughly twice the amount of GHG emissions than the production of the ICEV alternative, to which a great contributor is the battery production. Overall emissions for the electric vehicle are basically split between the production phase and the use phase, while for the ICEV the use phase is far more dominant.

The environmental benefit of the electric vehicle is subject to some key factors, mainly the adopted lifetime of the vehicle and, especially, the electricity mix used to power it. When powered by natural gas, electric vehicles are shown to provide only a 12% benefit in respect to gasoline powered ones. For coal, the situation is even inverted, with total emissions of the electric vehicle representing a 17% increase when compared to the ICEV. Therefore, the study shows that in normal conditions the electric vehicle is a better alternative, environmentally, however, conditions of use must be considered. Furthermore, other aspects such as battery replacements in the lifetime can decrease the performance of the technology.

Tagliaferri et al. (2016) conducted a life cycle assessment study to compare the environmental performance of internal combustion vehicles and electric vehicles. Two types of electric vehicles are analysed, as well as one hybrid electric vehicle and one internal combustion engine vehicle model. The study follows a cradle-to-grave approach, therefore being an important contributor to the full understanding of the life cycle emissions of the different powertrain type vehicles mentioned, as the disposal phase is often neglected by other studies. However, the inventory used by authors is not constituted of primary data, which would increase even more the value of the study to literature. As measures of impact the study uses the GWP (Global Warming Potential), ADPf (Abiotic Depletion Potential – fossil fuels) and HTP (Human Toxicity Potential).

Results of the study point to a reduction in GWP for both types of electric vehicles in respect to the internal combustion vehicle. The hybrid electric vehicle outperforms the latter in this criterion as well, but with a smaller margin. Aligned with the vast majority of results from literature, the production phase for electric vehicles has a greater impact than the production of ICEV, however, due to the use phase impacts, the electric powertrain has a better overall performance in its whole life cycle. However, when looking at the HTP measure of impact, as electric vehicles are characterized by the largest impact in the category, due to the materials used in the production of the electric battery. On the battery production, cathode production and battery assembling were the most significant emission factors, accounting for 61% of the total battery emissions in the cradle-to-gate phase.

Nanaki et al. (2013) conducted a Life Cycle Assessment study in which authors considered both the production and the use phase of electric vehicles, internal combustion vehicles and hybrid electric vehicles (HEV), considering the case of Greece. Results show that the electric vehicle is a better alternative in the three different scenarios considered: a low carbon scenario, a medium carbon scenario and a high carbon scenario. In the latter, the difference in results between the three types of powertrain vehicles are practically negligible. Although the study brings important results considering the sensitivity of electric vehicles to the electricity grid mix, data used for calculation for the production phase were based on other studies. Moreover, the study does not consider the End-of-life impacts.

Poovanna et al. (2018) conducted a full Life Cycle Assessment, therefore including production phase, use phase and end-of-life, on an electric vehicle and a internal combustion engine vehicle, powered by gasoline, with the goal of comparing the two alternatives in terms of GHG emissions. The study adopts the scope of vehicle use in Canada. To assess the use phase, three different electricity grid mixes are considered, the Canada mix, the Alberta mix and the British Columbia mix. Authors made use of an already available database, the 2017 version of the GREET model.

Results from the study clearly show the sensitivity of electric vehicle emissions in respect to the electricity grid mix. While for low-carbon mixes the electric vehicle quickly compensates its higher impact in the production phase, in the case of Alberta, characterized by a grid dominated by coal (67%), the benefit of using an electric vehicle is only observed after 50000 km. However, it is important to note that the electric vehicle had lower life cycle emission in all of the scenarios considered. The results for the British Columbia scenario display a carbon-emission reduction potential that wasn't much explored in literature, as the majority of studies adopt the European electricity mix.

Qiao et al. (2019) developed a full Life Cycle Assessment of the environmental impact, measured by GHG emissions, of both an electric vehicle and an internal combustion engine vehicle, comparing the two alternatives, under the perspective of the Chinese scenario. The study, as it is a full assessment, includes in its scope the production phase, the use phase and the end-of-life, which is often neglected. The study contributes to literature as it provides a regional perspective to the impact assessment of the mentioned vehicles, the key aspect being the use of a city-specific driving cycle, Beijing's, something uncommon to the vast majority of studies in literature, that usually adopt the NEDC (New European Driving Cycle). The distinction is of particular importance as the consumption by electric vehicles in the Chinese city conditions is much higher, 35% more. The study also provides results for two different periods of time, 2015 and 2020.

In the results of the study, the electric vehicle is showed to outperform the internal combustion vehicle in terms of life cycle GHG emissions, even under the conditions of an electricity grid mix characterized by a high carbon intensity. The difference is even higher considering the results in 2020, as due to technological advancements in the electric vehicle and a tendency of increased renewable energy in use, life cycle emissions will be reduced by 20%, while reductions for the ICEV are only 2%. As it is observed in the majority of the studies in literature, the production of the electric vehicle has a higher level of GHG emissions, but the difference in the use phase of the two compensates this disadvantage. The study also shows the important role of recycling in reducing the environmental burden of the electric vehicle production, pointing to a potential reduction of the cradle-to-gate emissions of up to 50%.

Girardi et al. (2015) conducted a Life Cycle Assessment of an electric vehicle and an internal combustion engine vehicle, comparing the two under several different measures of impact. The goal of the study is to make the assessment under regional conditions, as many studies from literature tend to adopt averages. The geographical variable is of key influence as it defines the electricity grid mix, which heavily influences results, as well as driving behavior, which in some cases is not well modelled by average scenarios. For the purposes of the study, the Italian scenario was adopted, which is dominated by fossil fuel power plants. The assessment is made for two periods of time, 2013 and 2030, as the latter is much more representative of when the diffusion of electric vehicles will be at a much more advanced stage.

Considering the 2013 scenario, results show that the electric vehicle is associated to a lower level of impact, the key one for this study being the GHG emissions, however, for the eutrophication and human toxicity measures, the electric vehicle has a higher impact, mainly due to the battery. Similar results are observed in 2030, with a higher difference between the alternatives being observed. The study follows the pattern from literature in which the production phase is associated with a higher impact, when compared to the ICEV, while the opposite behaviour is observed in the use-phase. Still, the study highlights the need for improvement in the battery production, in the sense of reducing its impact.

Wu et al. (2019) conducted an emissions study, adopting as scope the production and the use phase, in which the effect of lightweighting and regional heterogeneity is assessed. The study offers an important contribution on that matter as it takes into account on the analysis the effects of the electricity grid emission intensity, driving pattern, local climate, share of urban and road driving, comprising a significant amount of regional variance, coupled with the effect of vehicle lightweighting. The study uses an extensive amount of on-road collected data, so that final results can be composed of real-life data, providing an important perspective.

Their results support the conclusion that lightweighting further accentuates the regional differences. As a result, it is observed that for rural areas that have a high share of their electricity generated by non-renewable energy the observed emissions for electric vehicles are larger, in some cases by a vast margin, than those of usual and a lightweight internal combustion vehicle. For 20% of the analysed counties, located in the US, the observed emissions for the lightweighted vehicle were lower than those of battery electric vehicles. Conversely, for urban areas, especially those with a less carbon-intensive electricity grid, the battery electric vehicle was far more beneficial.

Ellingsen et al. (2016) investigated the effect of increasing battery size and driving range on the life cycle emissions of both battery electric vehicles and internal combustion vehicles. The topic is relevant to literature as most studies that conduct a Life Cycle Assessment study tend to adopt smaller and more compact vehicles, which results in a somewhat lack of understanding of the subject when dealing with larger vehicles. In the study, hypothesized vehicles of four different segments are analysed, for both internal combustion and electric powertrain: A (mini car), C (medium car), D (large car) and F (luxury car). It is important to note, however, that the energy consumption per km adopted by the study resulted from a regression curve, a decision that, although does not affect the conclusions to be drawn from the study, limits the influence of some technological features of more efficient vehicles.

Results of the study show that under the adopted conditions of an average European electricity grid mix the life cycle emissions of the electric vehicle are always lower than those of the traditional vehicle in the same segment. The break even point, in terms of driving distance, is smaller the larger the weight of the vehicle, which is expected, since the small vehicle market is extremely focused on fuel efficiency. Results are only inverted in scenarios in which electricity is generated mostly by coal. The analysis of the study illustrates important results, however, a more real-case scenario could have been analysed as well, as the study limited itself to average vehicles and use conditions.

Souza et al. (2016) performed a Life Cycle Assessment of a conventional, a battery electric vehicle and a plug-in hybrid vehicle in Brazilian conditions. Their study evaluated each of the three powertrains in terms of global warming potential, acidification and human toxicity. The inventory used by the authors is not composed of primary data, as for all necessary data required to perform the LCA data from other studies from literature was used. For the production of the battery, researchers adopted the data provided by Majeau-Bettez et al. (2011). Results from the analysis indicate that the BEV is the best option in terms of GWP, followed by the plug-in hybrid vehicle and then the ICEV, fuelled with gasoline. In terms of numerical emissions, the calculated GHG emissions for the BEV were 0.118 kg of CO_2 eq/km, while for the ICEV authors reported figures of 0.229 kg of CO_2 eq. /km. For the other measures, the worst performer in terms of acidification was the vehicle fuelled with ethanol, while the BEV performed the worst in terms of human toxicity.

Sanches (2021) also performed a Life Cycle Assessment study comparing an electric vehicle and an internal combustion engine vehicle, considering Brazilian conditions. The impact measures analysed by the author were primary energy demand, global warming potential and abiotic depletion of both technologies. As factors that could influence the end results, the author considered only the electricity grid mix as a variation parameter. The GaBi database was used as the main data source for the study, which was supplemented by results from literature when fitting, therefore, the study does not make use of primary data.

Overall results point to the conclusion that EVs are potentially beneficial for all three impact categories when compared to ICEVs, with global warming potential the category with the highest impact difference. The study also addressed the benefit of producing the vehicles in Brazil, as the cleaner electricity grid mix would allow for considerable reductions in the overall life cycle emissions.

3.5 Review of Studies Complementary to the Analysis

Lewis et al. (2014) conducted an assessment of the effects on life cycle energy and GHG emissions of vehicle lightweighting, applied to three powertrain technologies: internal combustion engine vehicles, hybrid electric vehicles and plug-in hybrid electric vehicles. The lightweighting of the reference vehicles is done by using either aluminium or advanced/high strength steel (A/HSS).

For all powertrain technologies, results point to a reduction in energy consumption and GHG emissions, with greater difference being observed as the mass reduction increases. Internal combustion vehicles have a higher sensitivity to mass reductions when analysing the effect on GHG emissions and energy consumption. Results show that on a per unit mass reduced basis, A/HSS leads to greater reduction in GHG emissions, however, the maximum amount of reduction is reached with an aluminium-intensive 35% BIW (Body-in-white) mass reduction.

Marques et al. (2019) assessed the impact, under a number of impact measures, of the production and use of Lithium-ion batteries for automotive applications. The focus of the study was to evaluate the impact of capacity fade in the observed impact of the reference batteries, as this would define the need for battery replacement during a battery electric vehicle lifetime. To evaluate the speed of capacity fade, the conditions of use, modelled as the driving style, were considered in the analysis, as well as the comparison of performance between two battery cathodes. Furthermore, authors also evaluated the influence of the regional electricity grid mix in the overall impacts.

Results of the study show that both the electricity grid mix and the driving style have a great influence on the overall emissions of a battery electric vehicle. The former is aligned with the general conclusion from literature and goes to support the existing trend. The latter contributes to understanding yet another factor to be considered in life cycle assessment studies, as under moderate and intensive use conditions, the number of batteries needed in the lifetime ranged from 2 to 3, if we consider the upper integer value that results from the model. It is important, however, to note that the lifetime adopted was 200,000 km, a higher value than the usual standard in literature, which is 150,000 km (PETERS et al., 2013; NOTTER et al.; 2010; ELLINGSEN et al., 2014; DUNN et al., 2015; DAI et al., 2019).

Karabasoglu et al. (2013) performed a comparative analysis on cost and emissions between hybrid electric vehicles, plug-in electric vehicles, battery electric vehicles and conventional vehicles, evaluating the influence of driving patterns on the performance of each technology. Results of the study show that different driving patterns result in very different results, displaying the significance of the variable in the analysis. Under urban conditions of driving, in the studied case that of New York, battery electric vehicles generated 50% less emissions than conventional vehicles, while hybrid vehicles demonstrated a reduction of 60%. However, under the HWET driving cycle, characterized by free-flow traffic on highway, differences in emissions were marginal.

3.6 Takeaways from the Literature Review

Several conclusions can be drawn regarding the state of literature on the environmental impact of electric vehicles, compared to internal combustion engine vehicles. For instance, the vast majority of studies supports the view that electric vehicles have lower life cycle emissions than internal combustion engine vehicles, when considering most scenarios assessed. This view is only overturned when scenarios of high use of coal to electricity generation are considered, which largely increases the use phase impact of the EV, diminishing its benefits. On that matter, it is consensual in literature that the Use Phase is by far the main contributor to GHG emissions by ICEVs, while for EVs the impact is better distributed among the three different phases. Finally, it is consensual that when considering electricity generated by renewable sources, EVs can lead to very significant GHG savings across the life cycle of the vehicles.

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 views, as some authors estimate an impact up to six times larger than what is estimated by other sources in literature. The difference is especially significant when comparing studies that adopt a bottom-up approach to those that adopt a top-down approach. 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. Moreover, the effect of the driving behaviour, driving cycle, battery capacity fade and the study of other environmental impacts still needs investigation, as a higher amount of studies addressing the topic with primary data will contribute to a better understanding of such parameters.

Finally, the specific case of Brazil and its regions still requires further investigation, as the number of studies that adopt such scope is still small. Moreover, the studies that do adopt the Brazilian case as their scope neglect the influence of key parameters, such as driving behaviour, driving cycle and battery capacity fade. Given that scenario, this thesis aims at contributing to the mentioned gaps in literature, building upon what has been done so far, as the understanding of the environmental impact of EVs continues to develop.

4. Methodology

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, in the context of the city of São Paulo. By doing so, the results of this study can serve as a support for future decisions on private mobility and for other future studies that adopt similar goals.

To reach this goal, a Life Cycle Assessment was developed. A LCA is 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 ISO 14044 Environmental management – Life Cycle Assessment – Requirements and guidelines is the main source for guidelines on conducting a LCA study, but it does not define exactly how it should be done (ISO, 2006). In accordance to the ISO 14044 (ISO, 2006), which states "The scope, system boundary and level of detail of an LCA depend on the subject and intended use of the study. The depth and breadth of LCA may differ considerably depending on the goal of a particular LCA", the scope of this study will have its limitations that should be noted. Such limitations include the range of impact measures here assessed, as only GHG emissions are taken into account, and also limitation of data, which will be addresses whenever necessary.

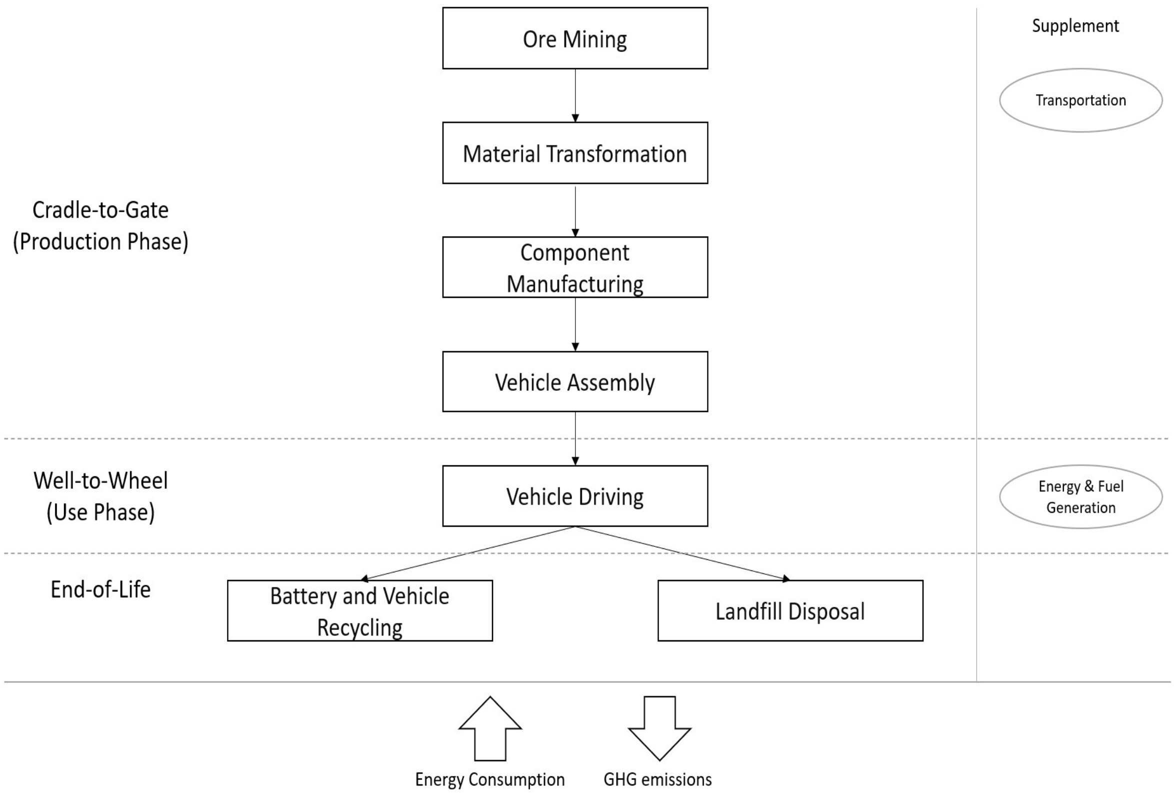
4.1 Functional Unit

As previously mentioned, the goal of the study is to assess the environmental impact of both a BEV and an ICEV throughout their respective lifetime. The functional unit for the study is one unit of the reference vehicle, to be further detailed, for each technology, both with an assumed lifetime mileage of 150,000 km, as it is the most frequent adopted value in literature (PETERS et al., 2013; NOTTER et al.; 2010; ELLINGSEN et al., 2014; DUNN et al., 2015; DAI et al., 2019; HAWKINS et al., 2012).

4.2 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-Wheels) 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. 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 will be limited to landfill disposal and recycling. Figure 7 displays the main processes and flows in each phase for the two studied vehicles.

Figure 7 - Life Cycle Scope of the studied vehicles



Source: The author

As the main focus of the present study is to address the GHG emissions of the automotive sector in the context of São Paulo, the measure of impact to be assessed here is the GHG-100 emissions, which is the most commonly used way of calculating the Global Warming Potential. Therefore, other impacts such as acidification, ozone depletion and eutrophication will not be calculated by the analysis developed in this study, as previously stated in the problem definition section.

Given the selected scope and boundaries above presented, it is fundamental to justify the main data source to be used in this study, the GREET database. The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) 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 (GREET, 2021).

The GREET database was chosen as the main data source for this study for several reasons. First, it is widely used in several studies from literature with the same purpose, being, along with the Ecoinvent database, the author's preferred option when developing LCAs, in the case of non-primary data studies (AICHBERGER; JUNGMEIER, 2020). 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. Finally, all of the GREET resources can be accessed free of charge, a decisive factor in relation to the Ecoinvent database, which has several paid-only resources. The main benefit of using a free database is the fact that it facilitates the validation of the conclusions drawn in this study and, most importantly, better enables future literature to build on the results here produced, contributing to the overall comprehension of literature regarding the environmental impact of both powertrain technologies.

4.3 Studied Vehicles

In this section, the reference vehicles chosen for the study are going to be specified and characterized on the relevant aspects to the goal of the study. The 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 (NIEUWENHUIS; CIPCIGAN; SONDER, 2020; DELUCCHI; LIPMAN, 2020). The ICEV environmental impact will be assessed for two types of fuels, gasoline and ethanol.

4.3.1 Battery Electric Vehicle – Nissan Leaf

A variety of factors influence the environmental impact of an electric vehicle. First, there are a lot of different types of electric vehicles, such as hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) and battery electric vehicles (BEV), each one with a functioning principle and, as a consequence, different performance under a set of metrics. Therefore, there is a need for adopting a vehicle that is aligned with the desired scope, as the choice of vehicle will heavily influence the final results. As previously mentioned in the methodology section, this study will focus on BEVs.

For the purposes of this study a BEV model will be adopted as reference, as key factors such as weight, type of battery, range, power, material composition and others can vary greatly between different models, which also plays an important part on the final results. Therefore, by establishing a reference model for the study, more precise results can be derived, enhancing the significance of the conclusions to be drawn here and in future reports, as a better basis of comparison is created.

Taking into consideration the goal of the analysis of assessing the impact of electric vehicles in the Brazilian context, more specifically in the city of São Paulo, the model adopted is the 2022 version of the Nissan Leaf, as it was the most sold BEV (Battery Electric Vehicle) in Brazil in 2021, with 439 units sold (ABVE, 2021). Table 2 contains the main characteristics of the model (NISSAN, 2022), which shares most of its technical characteristics with the 2017 version, the first one to adopt the 40 kWh battery, differing from the previous standard batteries of 24 kWh. Another factor that favours the choice of the Nissan Leaf as the studied model is the fact that it has been used by several other studies, although most of them used the previous version, equipped with a 24Kwh battery, which enables better comparisons of results and, as a consequence, better conclusions (POOVANNA; DAVIS, 2018; MARQUES et al., 2019).

Table 2 - Characteristics of the Nissan Leaf assumed as BEV in this analysis

Nissan Leaf 2022	
Weight	1626 kg
Length	448 cm
Width	179 cm
Height	156.5 cm
Electric Motor	110 kW
Battery (Li-Ion)	40 kWh

Nissan Leaf 2022	
Range (EPA)	240 km
Range (NEDC)	350 km

Source: Nissan (2022)

As it is displayed in Table 2, the 2022 version of the Nissan Leaf uses a 40 kWh Lithium-ion battery, with an approximate battery pack weight of 303 kg, as it has been since the 2017 model, the first one to use such battery size, result of an effort by Nissan to better address its customers range demands (MARKLINES, 2018). Previously, as already mentioned, the model used a 24 kWh battery, allowing a range of 199 km, considering the NEDC (EV DATABASE, 2022a). Further details and characteristics of the battery pack will be explored when assessing the environmental impact of its manufacturing.

The use of a Lithium-Ion battery is important, as this type of battery has become the most used in battery electric vehicles, as it offers the greatest electrochemical potential, allowing great performance on power, energy density, as well as superior performance on functional aspects (e.g. long service life, low self-discharge rate), and, finally, the fact that lithium is a light metal compared to other alternatives (HE et al., 2012; NOTTER et al., 2010; WANG et al., 2011).

There are several types of Lithium-ion batteries, as several different materials are used as cathode. The main ones used in the market are: LiMn2O4 (LMO), $LiFePO_4$ (LFP), $Li(NiCoAl)O_2$, and $Li(Ni_xCo_yMn_z)O_2$ (NCM) where x,y,z denotes different possible ratios. For the anode material, the most commonly used material is graphite (CAMEÁN et al., 2010; PARK et al., 2013). In the specific case of the Nissan Leaf 2022, the NMC111 is used as the cathode material.

Table 3 - Nissan Leaf 2022 battery specs

Number of modules	24
Number of cells	192 (2 in parallel and 96 in series)
Battery capacity	40 kWh
Length	1547 mm
Width	1188 mm
Height	264 mm

Weight	303 kg
Weight energy density	132 Wh/kg

Source: Nissan (2022), Marklines (2018)

4.3.2 Internal Combustion Engine Vehicle – Chevrolet Cruze Sport6 1.4T Hatch

As already discussed, to properly evaluate if the adoption of electric vehicles is beneficial or not regarding GHG emissions and environmental impact it is necessary to compare the upcoming powertrain technology with the one that is currently the most used, which are Internal Combustion Engine Vehicles (ICEV).

In the specific case of this study a reference ICEV model will be used to conduct the environmental impact assessment. There are obviously multiple different models of ICEVs currently being sold in the Brazilian market from which one could choose from, however, in an attempt to compare "apples to apples" a reference model that belongs to the same category as the Nissan Leaf, the modelled EV, will be used, in this case a medium hatch. Such decision is important for the quality of the comparison of results to be made, as choosing a smaller hatch, for example, wouldn't be totally accurate, as the level of performance, weight and size between the two reference models would not be compatible. Among the available options in the Brazilian market, one that demonstrates significant commercial success is the Chevrolet Cruze Sport6 1.4T Hatch, the model adopted in this study. Table 4 presents the main characteristics of the reference ICEV model adopted (CHEVROLET, 2022).

Table 4 – Characteristics of the Chevrolet Cruze Sport6 1.4T Hatch

Chevrolet Cruze Sport6 1.4T Hatch	
Weight	1331 kg
Length	444 cm
Width	181 cm
Height	148 cm
Engine	1.4 L turbo
Tank Capacity	52 L
Horsepower	153/152 @5.200 rpm

Source: Chevrolet (2022)

The vehicle is "flex", which means that it 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. Table 5 the data of consumption and range of the vehicle under urban, highway and mixed conditions.

Table 5 – Chevrolet Cruze Sport6 1.4T Hatch consumption and range data

	Consumption (Km/L)		Range (Km)	
	Ethanol	Gasoline	Ethanol	Gasoline
Urban	7.6	11.3	395.2	587.6
Highway	9.3	13.6	483.6	707.2
Mixed	8.1	12.0	421.7	623.5

Source: Chevrolet (2022)

4.4 Cradle-to-Gate Modelling

In this section, the detailed modelling of the cradle-to-gate phase of each vehicle will be provided. To do so, the material requirements, material production processes, transformation processes and vehicle assembly will be addressed. Furthermore, in the case of the BEV, the battery production will also be detailed, as it is a key factor in terms of emissions.

4.4.1 Nissan Leaf (BEV) Production Phase

The first aspect to be modelled in the Nissan Leaf cradle-to-gate phase is going to be the material production. The general specifications of the Nissan Leaf 2022 were already addressed in the vehicle description section, however, more detailed data on the composition of the vehicle is not available. To overcome this problem, data on vehicle composition by component and by material available on public sources will be used, following what has been done on the main reports and studies from literature (HAWKINS; MAJEAU-BETTEZ; STRØMMAN, 2012; AICHBERGER; JUNGMEIER, 2020). There are several databases available that provide data on vehicle composition and mass distribution between components, among which the GREET model by the Argonne National Laboratory, that, as previously stated, will be the adopted source for this study. Therefore, in situations where reliable and precise information on the Nissan Leaf was not available, data from the GREET2 2021 spreadsheet and software will be used, with due modifications to the original spreadsheet being made whenever valid. The choice is well supported by literature, as several studies are based on the same dataset (NOTTER et al., 2010; DUNN et al., 2015; DAI et al., 2019; MARQUES et al., 2019), and, most importantly, won't affect the overall goal of the study of comparing BEVs to ICEVs, as the differences between real and adopted data are not likely to affect the final conclusions. All modifications to the original spreadsheet will be mentioned and explored, so that the study can be transparent.

The first step to calculate the material requirements for the production of the Nissan Leaf was to find the weight of each subpart of the vehicle, which is divided in powertrain system, transmission system, chassis (without the battery), traction motor, electronic controller, body (including the BIW, interior, exterior and glass), the Lithium-Ion battery, the Lead-acid battery and fluids. All of the mentioned sum up to a reported weight of 1626 kg, with the battery having a known weight of 303 kg (NISSAN, 2022). The remaining parts did not have a reported weight by the manufacturer, so the mass distribution of the components excluding the battery was adopted according to the GREET2-2021 spreadsheet, as well as the weight of the Lead-acid battery. The relative weight and absolute weight of each of the mentioned subparts is presented on Table 6.

Table 6 - Nissan Leaf 2022 weight distribution by component

Component	Relative Weight (%)	Weight (kg)
Powertrain system	3.60%	58.5
Transmission system	4.43%	72.0
Chassis (without battery)	19.18%	311.9
Traction motor	7.38%	120.0
Electronic Controller	4.67%	76.0
Body	39.94%	649.4
Lithium-ion battery	18.63%	303.0
Lead-acid battery	0.62%	10.0
Fluids	1.55%	25.2
Total	**100%**	**1626**

Source: The author, GREET (2021)

Based on the calculated weight displayed on Table 6, the next step was to model the material composition of each subpart. Once again, the data available on the GREET2-2021 spreadsheet was used to find the relative weight contribution of each material to the overall mass of the subcomponents. The material composition of the two batteries will be further detailed later on. The relative weight and absolute weight of each material for the body, powertrain system, transmission system, chassis, traction motor, electronic controller and fluids is presented on, respectively, Table 7, Table 8, Table 9, Table 10, Table 11, Table 12 and Table 13.

Table 7 - Nissan Leaf 2022 Body material composition

Component	Relative Weight (%)	Weight (kg)
Steel	65.3%	423.9
Wrought Aluminium	3.1%	19.9
Cast Aluminium	0.2%	1.1
Copper/Brass	1.9%	12.3
Glass Fibber-reinforced plastic	0.8%	5.5
Glass	7.3%	28.8
Average Plastic	21.7%	140.8
Rubber	1.8%	11.5
Others	0.9%	5.6
Total	**100%**	**649.4**

Source: The author, GREET (2021)

Table 8 – Nissan Leaf Powertrain System material composition

Component	Relative Weight (%)	Weight (kg)
Wrought Aluminium	30.0%	17.6
Copper	28.3%	16.6
Average Plastic	40.7%	23.8
Others	1.0%	0.6
Total	**100%**	**58.5**

Source: The author, GREET (2021)

Table 9 - Nissan Leaf transmission system material composition

Component	Relative Weight (%)	Weight (kg)
Steel	60.5%	43.6
Copper	18.9%	13.6
Wrought Aluminium	20.0%	14.4
Average Plastic	0.2%	0.1
Others	0.4%	0.3
Total	**100%**	**72.0**

Source: The author, GREET (2021)

Table 10 - Nissan Leaf chassis material composition

Component	Relative Weight (%)	Weight (kg)
Steel	34.3%	107.0
Cast iron	9.2%	28.7
Wrought Aluminium	2.0%	6.2
Cast Aluminium	34.7%	108.2
Copper/Brass	1.8%	5.6
Glass Fibber-reinforced plastic	8.3%	25.9
Average Plastic	2.6%	8.1
Rubber	6.4%	20.0

Component	Relative Weight (%)	Weight (kg)
Others	0.7%	2.2
Total	**100%**	**311.9**

Source: The author, GREET (2021)

Table 11 - Nissan Leaf traction motor material composition

Component	Relative Weight (%)	Weight (kg)
Steel	36.1%	43.3
Cast Aluminium	36.1%	43.3
Copper	27.8%	33.4
Total	**100%**	**120.0**

Source: The author, GREET (2021)

Table 12 - Nissan Leaf electronic controller material composition

Component	Relative Weight (%)	Weight (kg)
Steel	5.0%	3.8
Cast Aluminium	46.9%	35.6
Copper	8.2%	6.2
Rubber	3.7%	2.8
Average Plastic	23.8%	18.1
Others	12.4%	9.4
Total	**100%**	**76.0**

Source: The author, GREET (2021)

Table 13 - Nissan Leaf fluid weight by type of fluid

Fluid	Relative Weight (%)	Weight (kg)
Brake fluid	3.6%	0.9
Transmission fluid	3.2%	0.8
Coolant	28.4%	7.2
Windshield fluid	10.8%	2.7
Adhesives	54.0%	13.6
Total	**100%**	**25.2**

Source: The author, GREET (2021)

One modification to the original 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. Alternative scenarios that include the recycling benefits will be address later on the sensitivity analysis. Table 14 displays the materials assumed by the reference spreadsheet to have a recycled content, and the corresponding original values assumed by it.

Table 14 – BEV share of recycled materials originally adopted by the GREET2-2021 model

Material	Virgin content (%)	Recycled Material (%)
Steel	73.6%	26.4%
Wrought Aluminium	89.0%	11.0%
Cast Aluminium	15.0%	85.0%
Lead	27.0%	73.0%
Nickel	56.0%	44.0%
Magnesium	47.9%	52.1%

Source: The author, GREET (2021)

Having defined the material requirements of the non-battery parts 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. The pathway is the same for all types of vehicles, as the detailed processes does not differ between vehicles that use different powertrain technologies. The processes included in the pathway are: paint production, painting, HVAC & Lighting, heating, material handling, welding, compressed air. The software uses as default the United States electricity mix as the electricity grid composition supplying vehicle assembly, however, the Nissan Leaf units that supply the Brazilian market are produced in the United Kingdom (NISSAN, 2022). To accommodate this specific aspect of the reference vehicle, the adopted electricity grid mix for vehicle assembly was that of the United Kingdom, as displayed in Table 15.

Table 15 - Share of electricity generation by source in the UK

Source	Share (%)
Coal	2.0%
Oil	0.3%
Natural gas	36.5%
Biofuels	11.2%
Waste	3.2%
Nuclear	16.1%
Hydro	2.5%
Wind	24.2%
Solar PV	4.1%
Tide	0.0%

Source: IEA (2022)

Having finished the modelling of the cradle-to-gate emissions of the car, the next step was modelling the production of the battery that powers the Nissan Leaf, and, in addition to that battery, the Lead-acid battery that is also used in the vehicle, which its material composition presented in Table 16. As briefly mentioned in the definition of the reference battery electric vehicle, the 2022 version of the Nissan Leaf is equipped with a 40 kWh Lithium-ion battery. The battery uses NMC111, $LiNi_{1/3}Mn_{1/3}Co_{1/3}O_2$, as the cathode material and graphite as the anode (NISSAN, 2022; MARKLINES, 2018). The production of the battery has been well explored topic by literature in the past decade, however, results from different studies have presented a very significant degree of diversity (PETERS et al., 2013). The main point of diversity 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 expenditure.

For the modelling of the cradle-to-gate emissions of the battery production the GREET 2021 database and software will be used, as it was the case for the car itself. Several other authors also made use of the same database, so the decision is supported by literature. The database is constructed around the works of Dunn et al. (2012, 2014, 2015), that conducted several studies on behalf of the Argonne National Laboratory. Moreover, the database received an update in 2019, as explored by Dai et al. (2019), which was based on primary data collected from large-scale commercial battery manufacturers, which incorporates the development of production processes. However, in order to obtain broader results, that incorporate the results from other authors from literature, a sensitivity analysis will be carried, so that conclusions can be drawn analysing different scenarios. This is a necessary step in the direction of having valid results in the future, as the most relevant results from the main authors from literature are considered in the analysis.

Table 16 provides the material composition of the 40 kWh Lithium-ion NMC111 battery that is used by the Nissan Leaf, with the weight distribution being equal to that reported in the GREET 2021 spreadsheet, as there were no necessary modifications.

Table 16 - NMC111 Nissan Leaf Lithium-Ion battery material composition

Material	**Weight contribution (%)**	**Weight (kg)**
Active Material (NMC111)	38.2%	115.6
Graphite/Carbon	20.2%	61.1
Silicon	0.0%	0.0
Binder	1.8%	5.5
Copper	7.2%	21.8
Wrought Aluminium	17.3%	52.3
Cast Aluminium	0.0%	0.0
Electrolyte: $LiPF_6$	1.4%	4.2

Material	Weight contribution (%)	Weight (kg)
Electrolyte: Ethylene Carbonate	3.9%	11.7
Electrolyte: Dimethyl Carbonate	3.9%	11.7
Plastic: Polypropylene	0.7%	2.0
Plastic: Polyethylene	0.2%	0.6
Plastic: Polyethylene Terephthalate	0.2%	0.6
Steel	0.6%	1.8
Thermal Insulation	0.3%	1.0
Coolant: Glycol	2.6%	7.9
Electronic Parts (BMS)	1.7%	5.1
Total	**100%**	**303.0**

Source: The author, GREET (2021)

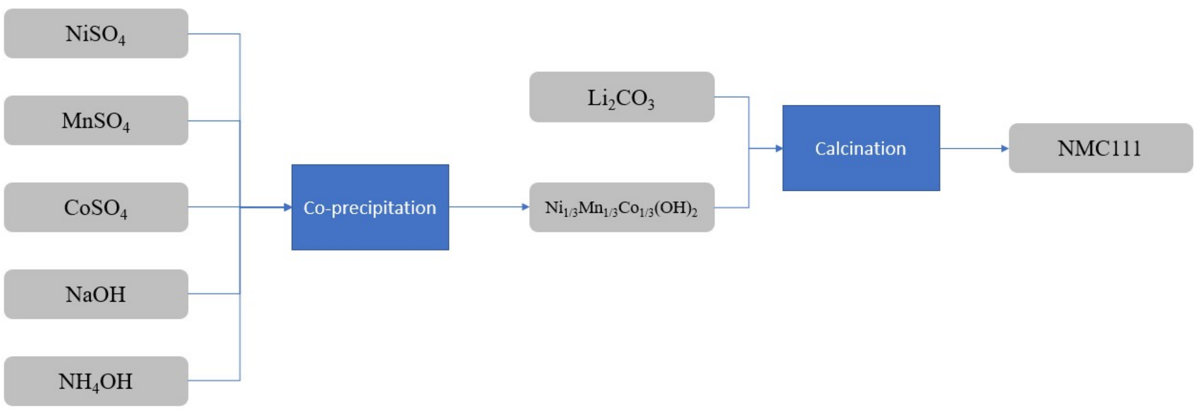
Table 17 - Nissan Leaf Lead-acid battery material composition

Component	Relative Weight (%)	Weight (kg)
Plastic: Polypropylene	6.1%	0.61
Lead	69.0%	6.9
Sulfuric Acid	7.9%	0.79
Fiberglass	2.1%	0.21
Water	14.1%	1.42
Others	0.8%	0.08
Total	**100%**	**10.0**

Source: The author, GREET (2021)

The NMC111, cathode material, results from the combination of two processes. Firstly, $NiSO_4$, $MnSO_4$, and $CoSO_4$ are reacted with NaOH and NH_4OH to produce $Ni_{1/3}Mn_{1/3}Co_{1/3}(OH)_2$ in a co-precipitation process. After that, a calcination process of $Ni_{1/3}Mn_{1/3}Co_{1/3}(OH)_2$ and Li_2CO_3 is performed, finally obtaining the cathode powder (QIAO et al., 2019a). The process is illustrated in Figure 8.

Figure 8 - NMC 111 production



Source: Qiao et al. (2019a)

There are three Life Cycle Inventories for the production of the NMC powder in literature reviewed in this study, reported by Majeau-Bettez et al. (2011), Ellingsen et al. (2014) and Dai et al. (2019). The LCI by Dai et al. (2019) corresponds to the one used in the GREET 2021 spreadsheet, which differs from the other two inventories. Another important point to be mentioned are the reported energy requirements for the calcination and co-precipitation. Table 18 provides the energy and material requirements reported on each study or database. By analysing the provided data, it is clear that there are some key differences in terms of the energy expenditure required to produce the NMC powder, even when dealing with the same ratio between the atoms, comparing the two NMC111 inventories. Differences can probably be attributed to the origin of the data, with the inventories by Majeau-Bettez et al. (2011) and Ellingsen et al. (2014) deriving from pilot-scale processes, while Dai et al. (2019) obtained the inventory from bench-scale industry sources. In the latter, processes such as water treatment and multiple-stage calcination are usually necessary, therefore increasing energy demands. The consequences to the calculated results will be analysed later on.

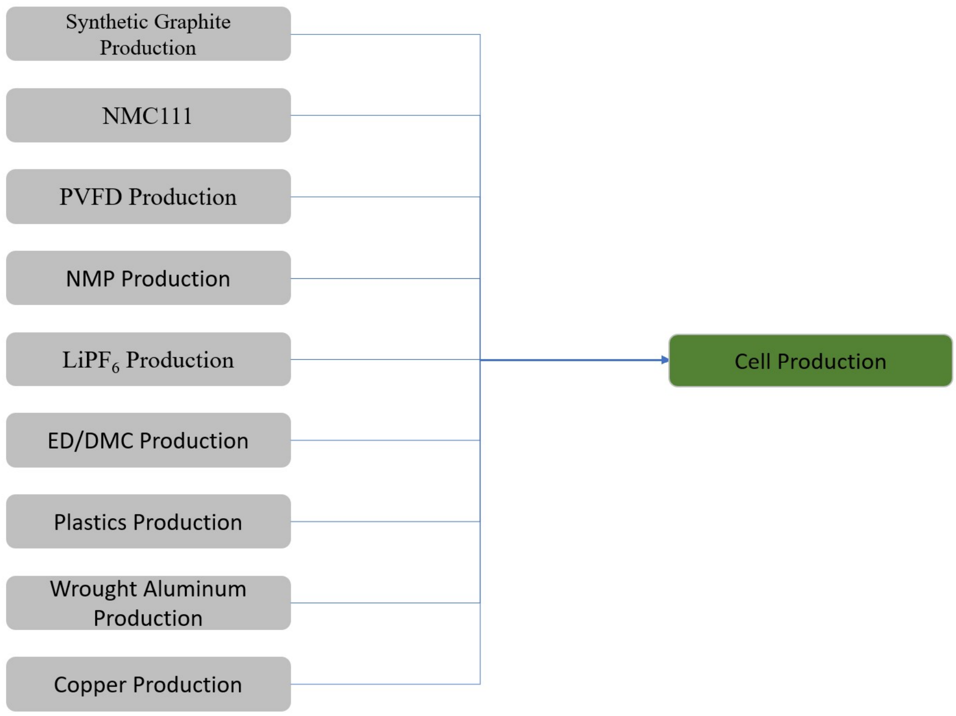
Table 18 - Material and energy requirements for the production of NMC

	Majeau-Bettez et al. (NMC442)	**Ellingsen et al. (NMC111)**	**GREET 2021**
Calcination			
Material inputs (kg/kg NMC)			
$NMC(OH)_2$	0.95	0.95	0.95
LiOH	0.25	0.25	
Li_2CO_3			0.38
Energy inputs (MJ/kg NMC)			
Heat	0.55	0.55	
Electricity			25.2
Co-precipitation			
Material inputs (kg/kg NMC(OH)2)			
NiSO4	0.68	0.57	0.56
MnSO4	0.66	0.55	0.55
CoSO4	0.34	0.57	0.56
NaOH	0.88	0.88	0.89
NH4OH			0.12
Energy inputs (MJ/kg NMC(OH)2)			
Heat			42.6

Source: Majeau-Bettez et al. (2011), Ellingsen et al. (2014), GREET (2021)

The next step of the process involves the cell production, which is a process composed of slurry preparation, electrode production, cell assembly and cell conditioning. The general flow of the process is depicted in Figure 9. The electrode production consisting of coating the slurry onto the current collectors, drying, calendaring, and slitting (KWADE et al., 2018). In literature, a very intense debate is observed regarding the degree of energy-intensiveness of the cell production process. The debate arises due to the fact that the process has to occur in a dry room, as controlling the moisture levels is fundamental to the electrochemical performance of the produced battery, which brings up the need to analyse how much energy is being used by the process. However, performing this measurement is definitely not trivial, as it heavily depends on the methodology or approach to how perform the measurement or calculation of the energy requirements, resulting in the highly different reported results in the literature.

Figure 9 - Lithium-Ion battery cell production scheme



Source: Dai et al. (2019)

Some of the most important studies in literature, discussed in the literature review, report a very energy-intensive cell production when discussing Cradle-to-Gate analysis or Life Cycle Analysis of Lithium-Ion Battery production. For instance, Ellingsen et al. (2014) 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. Another study that obtained similar conclusions was conducted by Kim et al. (2016), 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. (2019) 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. Results of the article point to a much less energy-intensive process than the one suggested by Ellingsen et al. (2014) and Kim et al. (2016). Table 19 presents the reported values from the study, which helps illustrate the difference in results.

Table 19 - Energy intensity of the cell production process by different sources in literature

	Ellingsen et al. (2014)	Kim et al. (2016)	Dai et al. (2019)
Energy Intensity	2318 MJ/kWh	525 MJ/kWh	170 MJ/kWh

Source: Ellingsen et al. (2014), Kim et al. (2016), Dai et al. (2019)

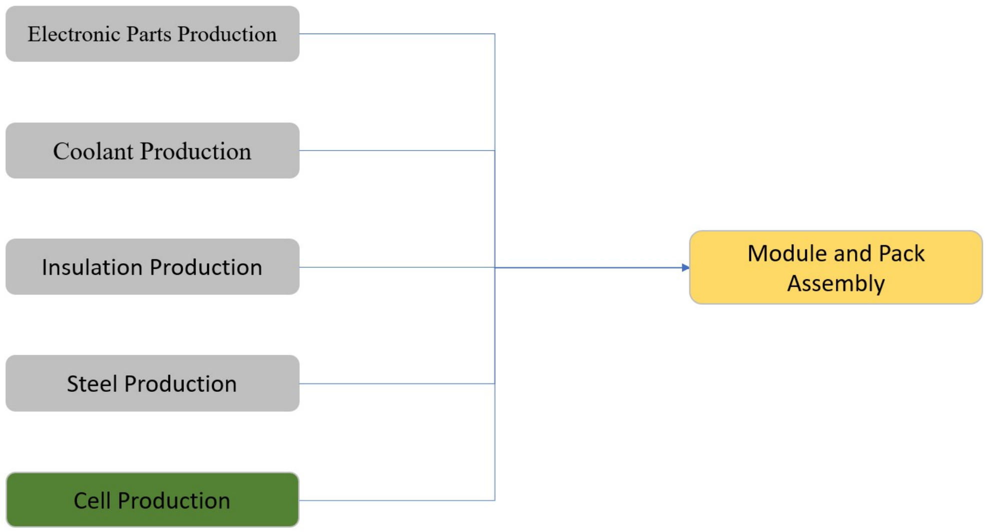
Given the great gap between results of the studies the causes of such disparity have to be taken into consideration. Firstly, the date of publication of the studies should be regarded, as the data from Dai et al. (2019) is considerably more recent, 2017, than the other two mentioned studies, Ellingsen et al. (2014) was published in 2014, and Kim et al. (2016), in 2016, but the precise date of the data source is not disclosed. This factor is particularly relevant as the volume of production of batteries greatly changed between the time of collection of data of the studies. According to figures reported by Pillot (2018) the sum of Lithium-Ion batteries produced amounted to a total figure around 5 GWh and didn’t surpass 10 GWh in 2013. By contrast, the production facility analysed by Dai et al (2019) had production values, by itself, of 2 GWh per year. The higher volume can generate better energy saving economies, due to the scale of production, which could explain at least part of the difference. Additionally, the weather can also play a role, as more facilities located in more humid regions would require a heavier use of the dry room.

As for the results reported by Kim et al. (2016), the fact that idle capacity was observed in the facility can help explain the reported values. The studied plant, called Ochang, had a production capacity in 2014 of around 200,000 batteries per year (BUSINESS KOREA, 2015), a very high amount, however, only 70,000 batteries were produced in the whole of South Korea in 2014 (LUTSEY; GRANT, 2018), which goes to show the idle capacity at the time.

Therefore, always having in mind that the precision of data is not absolute, this study will use as a reference the values reported the GREET 2021 Database, congruent to those presented by Dai et al. (2019). The choice is justified by the fact that the database is constructed with primary data from the industry, which is important, as volume of production, methods used and production efficiency can change drastically through time.

Finally, the last step of the battery manufacturing is the Module and Pack assembly. This final step involves the assembly of the electronic parts of the battery, the coolant production, the insulation production, which serves the purpose of thermally insulating the battery, the steel production and the battery cell, which the production was just explored. Figure 10 presents a schematic of the process.

Figure 10 - Battery Module and Pack Assembly



Source: Dai et al. (2019)

4.4.2 Chevrolet Cruze Sport6 1.4T Hatch (ICEV) Production Phase

After having finished the modelling and presenting the production phase of the Nissan Leaf in terms of the materials requirements for each of its parts, the next step of the analysis involved modelling the selected ICEV, the Chevrolet Cruze Sport6 1.4T Hatch. Similarly to what was done in the modelling of the Nissan Leaf, as to keep a level of alignment between the two modelling procedures, the analysis of the production phase for the Chevrolet Cruze will make use of the GREET2-2021 Spreadsheet to complement gaps of information from the material requirements and production steps that were not available.

The first step of the modelling process was to establish the contribution of each subpart of the vehicle to the overall reported weight of 1331 kg. The data contained in Table 20 that depicts such distribution is based on the GREET2-2021 Spreadsheet. One aspect that deserves to be noted is the weight difference between the two vehicles, with the Nissan Leaf having an exceeding weight of 295 kg in regard to its ICEV benchmark (NISSAN, 2022; CHEVROLET, 2022). Of course, this is heavily linked to the battery contained in the Nissan Leaf, which amounts to 303 kg. The observed weight difference suggests that the material requirements and, most importantly, the GHG emissions for producing the electric vehicle are higher than those of the other powertrain technology, an aspect to be verified at the end of the analysis.

Table 20 - Chevrolet Cruze Sport6 1.4T Hatch weight distribution by subpart

Component	Relative Weight (%)	Weight (kg)
Powertrain system	14.6%	194.7
Transmission system	6.1%	81.4
Chassis	24.3%	323.2
Body (including BIW, interior, exterior and glass)	50.6%	673.1
Lead-acid battery	1.2%	16.3
Fluids	3.2%	42.4
Total	**100%**	**1331.0**

Source: The author, GREET (2021)

From the overall weight of each subpart that composes the vehicle, the next step was depicting the material requirements for each of the mentioned subparts: powertrain system, transmission system, chassis, body, fluids and lead-acid battery. Once again, data from the GREET2-2021 spreadsheet was used to assess the relative weight contribution for each material in the composition of the listed subparts. The weight contribution by material for each of the mentioned subparts is presented on, respectively: Table 21, Table 22, Table 23, Table 24, Table 25 and Table 26.

Table 21 - Chevrolet Cruze Sport6 1.4T Hatch Powertrain System material composition

Component	Relative Weight (%)	Weight (kg)
Steel	42.4%	82.6
Wrought Aluminium	4.8%	9.3
Cast Aluminium	22.3%	43.4
Copper	6.8%	13.2
Glass-Fiber Reinforced Plastic	2.5%	4.9
Average Plastic	19.0%	37.0
Rubber	2.2%	4.3
Total	**100%**	**194.7**

Source: The author, GREET (2021)

Table 22 - Chevrolet Cruze Sport6 1.4T Hatch Transmission System material composition

Component	Relative Weight (%)	Weight (kg)
Steel	30.0%	24.4
Cast Iron	30.0%	24.4
Wrought Aluminium	30.0%	24.4
Average Plastic	5.0%	4.1
Rubber	5.0%	4.1
Total	**100%**	**81.4**

Source: The author, GREET (2021)

Table 23 - Chevrolet Cruze Sport6 1.4T Hatch Chassis material composition

Component	Relative Weight (%)	Weight (kg)
Steel	66.8%	215.9
Wrought Aluminium	1.5%	4.8
Cast Aluminium	18.6%	60.1
Copper	1.3%	4.2
Magnesium	0.1%	0.3
Glass-Fiber Reinforced Plastic	0.2%	0.6
Average Plastic	2.3%	7.4
Rubber	9.2%	29.7
Total	**100%**	**323.2**

Source: The author, GREET (2021)

Table 24 - Chevrolet Cruze Sport6 1.4T Hatch Body material composition

Component	Relative Weight (%)	Weight (kg)
Steel	65.3%	439.5
Wrought Aluminium	3.1%	20.9
Cast Aluminium	0.2%	1.3
Copper	1.9%	12.8
Glass-Fiber Reinforced Plastic	0.8%	5.4
Glass	4.4%	29.6
Average Plastic	21.7%	146.1
Rubber	1.8%	12.1
Others	0.9%	6.1
Total	**100%**	**673.1**

Source: The author, GREET (2021)

Table 25 - Chevrolet Cruze Sport6 1.4T Hatch Fluid weight by type of fluid

Component	Relative Weight (%)	Weight (kg)
Engine oil	9.1%	3.9
Brake fluid	2.1%	0.9
Transmission fluid	25.7%	10.9
Powertrain Coolant	24.6%	10.4
Windshield coolant	6.4%	2.7
Adhesives	32.1%	13.6
Total	**100%**	**42.4**

Source: The author, GREET (2021)

Table 26 - Chevrolet Cruze Sport6 1.4T Hatch Lead-acid battery weight composition by material

Component	Relative Weight (%)	Weight (kg)
Plastic: Polypropylene	6.1%	1.0
Lead	69.0%	11.2
Sulfuric Acid	7.9%	1.3

Component	Relative Weight (%)	Weight (kg)
Fiberglass	2.1%	0.3
Water	14.1%	2.3
Others	0.8%	0.1
Total	**100%**	**16.3**

Source: The author, GREET (2021)

Finally, a modification to the original spreadsheet data was made, in order to obtain better results for the base scenario of analysis, which was altering the share of virgin and recycled materials used, adopting a scenario of no recycled materials being used. As previously mentioned in the Nissan Leaf production phase analysis, recycled materials have a far lower embodied energy and level of emissions when compared to the use of virgin materials, which would have great consequence in the resulting emissions for the production phase. So, to build a base scenario that is easier to replicate and clearer to understand and compare to other sources of literature, this modification was done. Alternative scenarios that include the recycling benefits will be addressed later on the sensitivity analysis. Table 27 displays the materials assumed by the reference spreadsheet to have a recycled content, and the corresponding original values assumed by it.

Table 27 - ICEV share of recycled materials originally adopted by the GREET2-2021 model

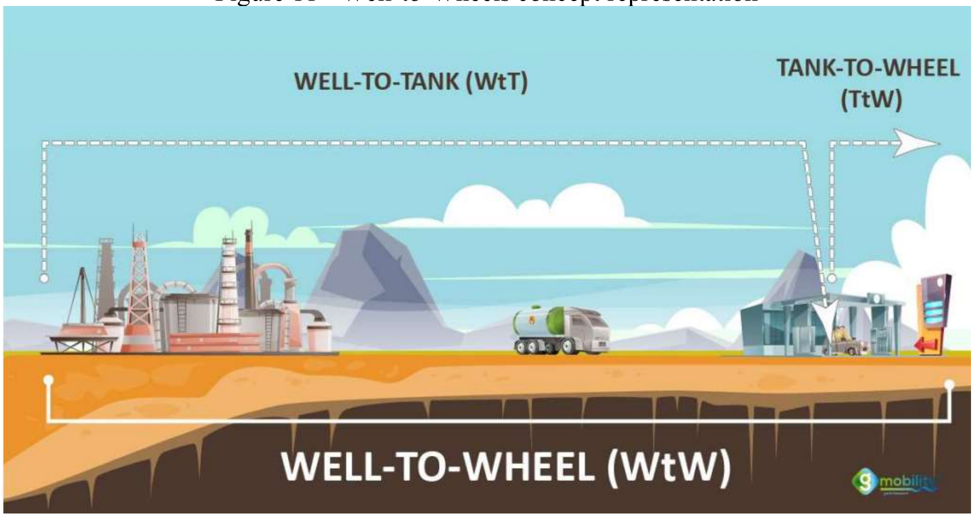
Material	Virgin content (%)	Recycled Material (%)
Steel	73.6%	26.4%
Wrought Aluminium	89.0%	11.0%
Cast Aluminium	15.0%	85.0%
Lead	27.0%	73.0%
Nickel	56.0%	44.0%
Magnesium	47.9%	52.1%

Source: The author, GREET (2021)

4.5 Use Phase

In this section the use phase modelling for both vehicles will be described and explored. In literature, the Use Phase is commonly referred to as the Well-to-Wheel (WtW) scope of the lifetime of a vehicle, as it 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, so to give a better understanding of the main factors influencing the emissions being analysed, 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 (QIAO et al., 2019a). Figure 11 presents an illustration of the described concepts.

Figure 11 - Well-to-Wheels concept representation



Source: Gmobility (2022)

The section of the methodology dedicated to the Use Phase will only explore the effect of different sources of electricity, with a total of four being considered, or fuels, as other parameters that influence it will be analyzed later on a dedicate segment.

Following that rationale, in the case of the electric vehicle, the four scenarios of electricity generation mix explored are: the Brazilian case, the Italian case, the average European case and an all non-renewable energy case. For the case of the internal combustion vehicle the following fuel types will be explored: E27 and hydrous ethanol (Brazilian sugarcane ethanol). The reasons for the described selection will be explored in the section destined to the scenario. Moreover, in this section the baseline fuel consumption for both types of vehicles will also be analysed, as it also represents a decisive factor to the analysis.

4.5.1 Use Phase – Electric Vehicle

The first powertrain technology that will be explored is the electric vehicle. A variety of factors influence the consumption of the EV, the one most explored in literature in literature being the electricity mix, which is basically 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 from literature show that the electricity generation mix is the most important factor when determining the consumption (NOTTER et al., 2010; WOO; CHOI; AHN, 2017), which is the reason that motivates the focus on that theme in literature.

Given the importance of the electricity generation mix there is the evident need of assessing a variety of scenarios when performing the analysis of the use phase. More specifically, the scenarios here analysed will be the current Brazilian electricity mix, the Italian electricity mix, the average European mix and a scenario in which exclusively non-renewable energy sources are used.

4.5.1.1 Electric Vehicle – Consumption

The electricity consumption and range of the electric vehicle has a considerable influence on the emissions of the vehicle, therefore being an important factor in the analysis. There are several drive cycles that analyse the consumption of the 2022 Nissan Leaf. Table 28 presents some of the main conducted studies on the range of the 2022 Nissan Leaf. NEDC rates the highest autonomy for the vehicle, while the American EPA and the WLTP (Worldwide Harmonised Light Vehicles Test Procedure) have a smaller rating for the estimated autonomy.

Table 28 - Studied ranges for the 2022 Nissan Leaf

Source	**Range (km)**
NEDC	350
EPA	240
Green NCAP	306
EVDB	235
WLTP	270

Sources: GREEN NCAP (2021), EV DATABASE (2022b), EPA (2022a)

The EVDB (EV-Database) is an organization that focuses on providing estimations on real scenarios, as to provide more accurate data on the actual consumption of electric vehicles. Their evaluation consists of measuring the range under a variety of scenarios, combining conditions such as driving on city conditions, highway or a combination of the two. Moreover, the weather is taken into consideration, analysing mild and cold weather scenarios. The Green NCAP follows a similar methodology, however, it is important to note the considerable difference between the final ratings of the two.

Initially, the results from the EPA rating will be used as a reference, as the studies from literature make use of official tests, generally the NEDC, EPA or WLTP, as the baseline consumption, altering it, in some cases, based on the assumptions and analysis being made. That will be the case for this study as well, as specific driving conditions from São Paulo will be incorporated later on. Moreover, the impact of the consumption will be discussed and assessed in the sensitivity analysis. Finally, it is important to note that the EPA assumes as a standard relative participation of urban drive of 55%, therefore 45% on highways.

4.5.1.2 Brazilian Electricity mix

The first electricity generation mix scenario that will be addressed is the Brazilian case. As mentioned earlier on, the goal of this study is to assess and compare the environmental impact of both an electric vehicle and an internal combustion engine vehicle in a Brazilian context, more specifically the city of São Paulo. Therefore, it is only natural that the electricity that is going to power the electric vehicle is analysed and considered in the analysis.

The state of São Paulo has a significant electricity production, mainly using sources such as hydro, thermal, wind, nuclear and photovoltaic. Table 29 displays the installed capacity for electricity production in the state of São Paulo as of December 2021. As displayed in the table, most of the capacity for electricity production is concentrated in hydro (60.9%) and thermal generation (36.7%). For Hydro, the number of units is well distributed among the different categories of hydroelectric plants. CGHs are plants with an installed capacity of up to 1 MW, PCH are plants with an installed capacity between 1 and 30 MW and UHE are plants with an installed capacity that exceeds 30 MW. UTE BIOMASSA are thermal plants that make use of biomass as fuel for electricity production, while UTE FÓSSIL are pants that use fossil sources as fuel. When faced with the whole Brazilian installed capacity, the sum of the plants in São Paulo represents 13.5% of the total installed capacity in the country. The main hydroelectric producers in the state are CTG (China Three Gorges), with 4995.2 MW, followed by AES Tietê S/A with 2658.4 MW and CTG – Rio Paranapanema Energia with 2297.8 MW, among others (SIAM/SP, 2022).

Table 29 - Installed Capacity in the state of São Paulo per source

Electricity source	Number of units	Installed capacity (kW)
Hydro	128	14.897.947
CGH	47	53.970
PCH	33	307.598
UHE	48	14.536.379
Thermal	935	8.992.411
UTE BIOMASSA	233	6.620.312
UTE FÓSSIL	702	2.372.099
Photovoltaic	33	587.064

Electricity source	Number of units	Installed capacity (kW)
UFV	33	587.064
Wind	1	2
EOL	1	2
Thermonuclear	0	0
UTN	0	0
TOTAL	**1.097**	**24.477.425**

Source: SIAM/SP (2022)

Despite the existence of a significant structure for generation of electricity, the State of São Paulo is far from self-sufficient in that matter. Table 30 presents data on the supply of electricity throughout the years. As displayed, although a significant production of electricity exists, it only amounts to 34.1% of the Gross Supply, with the most significant share of the supply coming from imported energy, at 78.1% and more than twice the figure for internal production. The electricity is imported from four countries: Paraguay, Argentina, Venezuela, and Uruguay (ANEEL, 2017). 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 that will be used to power the electric vehicle. The solution to address this matter will be explored later in this very topic.

Table 30 - Supply of electricity in the State of São Paulo (GWh)

	2016	2017	2018	2019	2020	2021
Production	67414	74899	69374	67942	64908	51788
Public utilities	53150	60421	55101	54244	52010	38874
Self-production Power Plants	14264	14478	14273	13698	12898	12914
Import	112595	100479	106581	108115	109905	118535
Export	-18265	-15642	-14466	-15021	-18907	-9536
Losses in Distribution and Storage plus Losses	-16229	-11415	-11137	-9916	-10455	-9058
Gross Supply	**145515**	**148321**	**150352**	**151120**	**145451**	**151729**

Source: SIAM/SP (2022)

The state of São Paulo needs to import electricity, as the domestic supply is a lot smaller than the consumption figures. As displayed in Table 31, the internal production, ignoring all kind of losses, wouldn't be sufficient to supply the industrial segment alone, and hardly sufficient to supply electricity to the residential sector.

Table 31 - Consumption of electricity in the State of São Paulo (GWh)

	2016	2017	2018	2019	2020	2021
Final Consumption	145515	148321	150352	151120	145451	151729
Final Energy Consumption	145515	148321	150352	151120	145451	151729

	2016	2017	2018	2019	2020	2021
Energy Sector	3090	3252	3003	3032	3030	2423
Residential	38114	38988	39703	40791	42027	42235
Commercial	27963	28185	28385	29530	26071	27052
Public	11376	11532	11697	11976	11209	11516
Agriculture and Livestock	3102	3276	3431	3628	3793	3799
Transportation	1097	1097	1097	1097	1097	1097
Industrial	60773	61991	63036	61066	58224	63607
Cement	1502	1588	1628	1651	1802	1910
Pig-Iron and Steel	591	630	648	601	578	642
Iron Alloys	321	350	370	355	365	387
Mining/Pelletization	495	496	505	479	441	473
Non-Ferrous/Others Metals	7681	7935	8090	7954	8312	9143
Chemical	8475	8653	8835	8185	7424	8263
Foods and Beverages	8602	8946	9186	9253	11135	11803
Textiles	3170	3224	3291	3275	2968	3294
Paper and Pulp	7145	7417	7862	7414	7656	8123
Ceramics	2457	2518	2546	2546	2329	2576
Others	20334	20234	20075	19353	15214	16993

Source: SIAM/SP (2022)

Given the scenario previously displayed, simply using the electricity production in the State of São Paulo would not be sufficiently representative when trying to estimate the sources to the electricity that would power electric vehicles in the city. Being so, an alternative must be used so to estimate the electricity energy mix of the city of São Paulo. For this study, it was decided to use the Brazilian electricity mix, 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. Table 32 provides the Brazil's external dependence on electricity, the difference between the internal demand for electricity and internal production. As displayed, the dependence is far inferior than what is observed in the case of the state of São Paulo, which makes data on national production far more relevant and significant.

Table 32 - Brazil's external dependence on electricity

Year	GWh	Relative dependence (%)
2015	34422	5.6%
2016	40795	6.6%
2017	36355	5.8%
2018	34979	5.5%
2019	24957	3.8%
2020	24718	3.8%
2021	23103	3.4%

Source: MME (2022)

When analysing the regional internal electricity production in the country, the Southeast Stands out as the highest producing region, followed by Northeast, North, South and finally the Midwest. Nonetheless, the production among regions is well distributed, with the only standout being the Midwest, which is expected given the area of the region compared to the others.

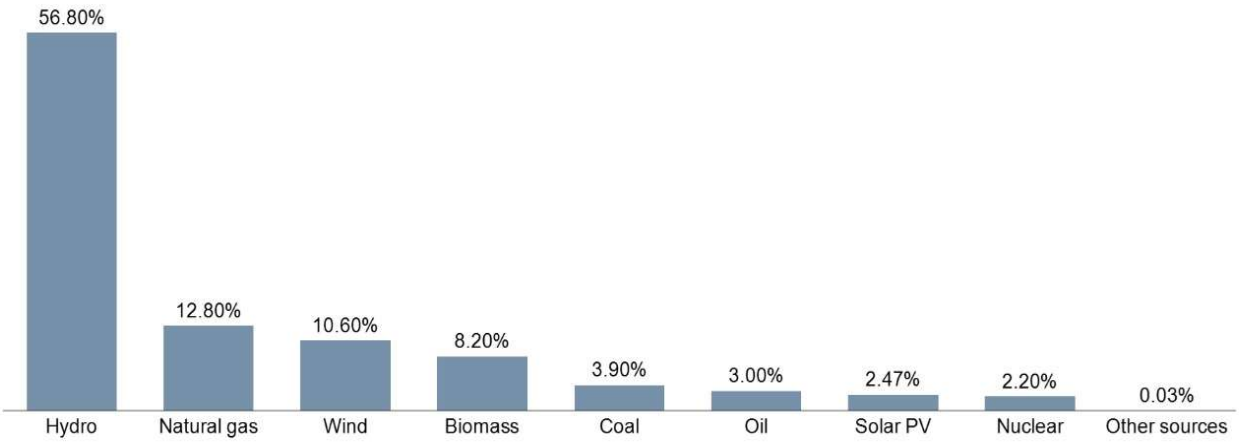
Table 33 - Brazilian electricity production by region and by source in 2021

	North	Northeast	Southeast	South	Midwest
Hydro	122047	29956	70342	89322	51153
Wind	0	65826	56	6404	0
Solar	495	7280	5450	2015	1513
Nuclear	0	0	14705	0	0
Thermal	13617	44476	93921	21490	16044
Sugar cane	294	2400	22681	1478	7489
Firewood	63	103	636	1039	384
Total	**136159**	**147538**	**184473**	**119230**	**68710**
Relative contribution (%)	**20.8%**	**22.5%**	**28.1%**	**18.2%**	**10.5%**

Source: MME (2022)

Finally, to assess the carbon intensity of the generation of electricity in Brazil, expressed in kg of CO_2 eq. per kWh produced, the relative contribution of each source in the country's general picture is necessary. The electricity generation mix is expressed in Figure 12, and, as expected, hydro generation is the source with the highest share. The next two major contributors are natural gas and wind, the latter being a confirmation of the potential in the country, that still is vastly unexplored, as the expectation for the following years is that the production continues to significantly increase (BARROS; PIEKARSKI; DE FRANCISCO, 2018).

Figure 12 - Share of electricity generation by source in Brazil in 2021

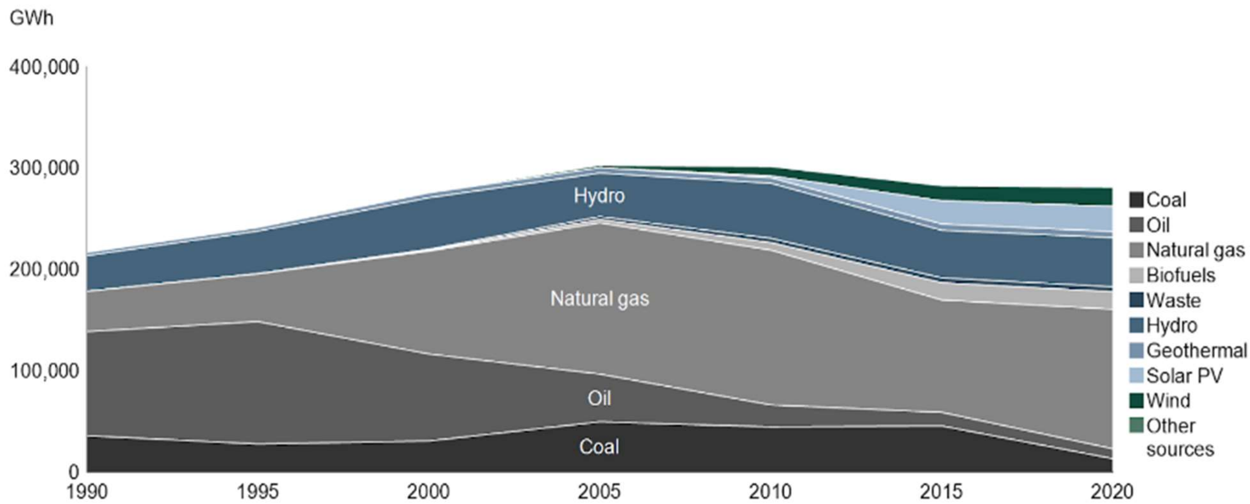


Source: MME (2022)

4.5.1.3 Italian Electricity mix

The second electricity mix scenario that is going to be assessed is the Italian case scenario. When conducting the analysis it is important to contemplate a vast amount diversity of scenarios, so that results can be more conclusive by comparison between each of the assessed scenarios and also literature comparison is facilitated as well. Given the mentioned goals, the Italian case represents a valuable scenario when considering an electricity generation mix that is considerably different than the one observed in the Brazilian or São Paulo case. In terms of the reference for the composition of the electricity generation mix the country's average will be used, as it provides data on a granularity that is sufficient for the purposes of the analysis.

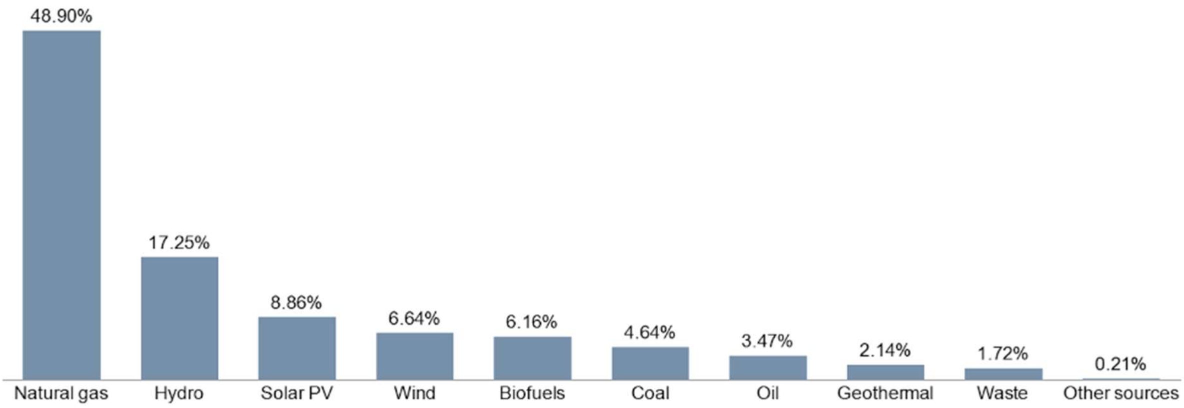
Figure 13 - Italian electricity generation by source (GWh)



Source: IEA (2022b)

Figure 13 provides the Italian electricity generation divided by source throughout the years. By looking at the graph, it is clear that the country is very reliant on non-renewable sources, in particular natural gas. Figure 14 displays the share between sources for 2020, in which is very clear the vast dependence on natural gas. However, it is valid to note that the following four most relevant sources are renewable energy, which has grown over the years, as presented in the historical series.

Figure 14 - Share of electricity generation by source in Italy in 2020

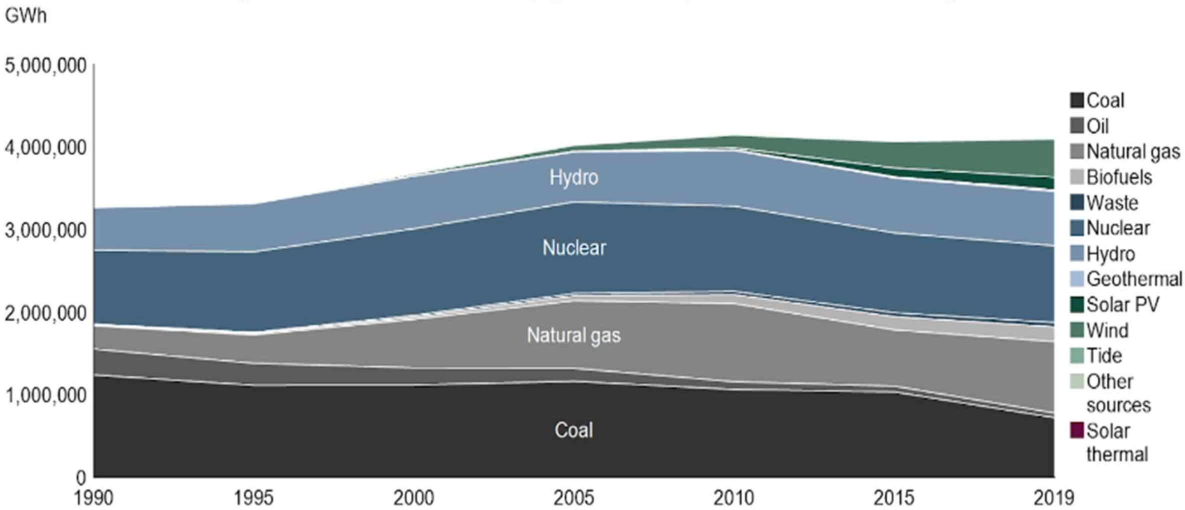


Source: IEA (2022b)

4.5.1.4 European Electricity mix

Once again, by analysing several scenarios the quality of results is enhanced, as comparisons with present and future studies from literature is facilitated. With such goal in mind, it is extremely valuable to analyse the scenario of the average European electricity generation mix, as several studies from literature have done in the past (NOTTER et al., 2010; HAWKINS et al., 2012; TAGLIAFERRI et al., 2016). This is due to a very high number of studies that look to assess the environmental impact of EVs being made by European universities as well as a very significant growth in the use of electric vehicles in the continent. Having such reasons in mind, this study will also explore the average European scenario.

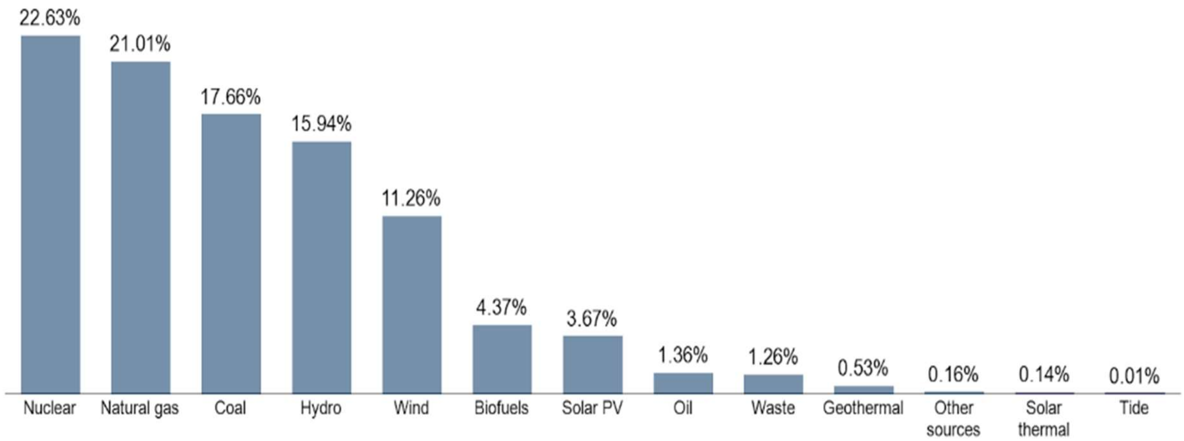
Figure 15 - Share of electricity generation by source in 2019 in Europe



Source: IEA (2022c)

Figure 15 presents the cumulative electricity generation in Europe throughout the years up until 2019, the total being divided by the individual contribution of each different source. It is interesting to compare this graph to the others previously presented as, for example, Italy uses a mix a lot more reliant on natural gas than Europe as a whole, as the two graphs demonstrate. Also, nuclear energy is also a lot more utilized than what is observed in both the Italian and the São Paulo (Brazilian) case. Figure 16 presents the share of electricity generation for the European case in 2019, in which a very well distributed generation mix is observed. Nuclear is the largest contributor but there is not a very considerable gap to the other 4 most relevant sources: natural gas, coal, hydro and wind. Finally, it is easy to conclude that although there is relevant electricity generation by renewable sources, the share held by non-renewables is still very considerable.

Figure 16 - Share of electricity generation by source in 2019 in Europe



Source: IEA (2022c)

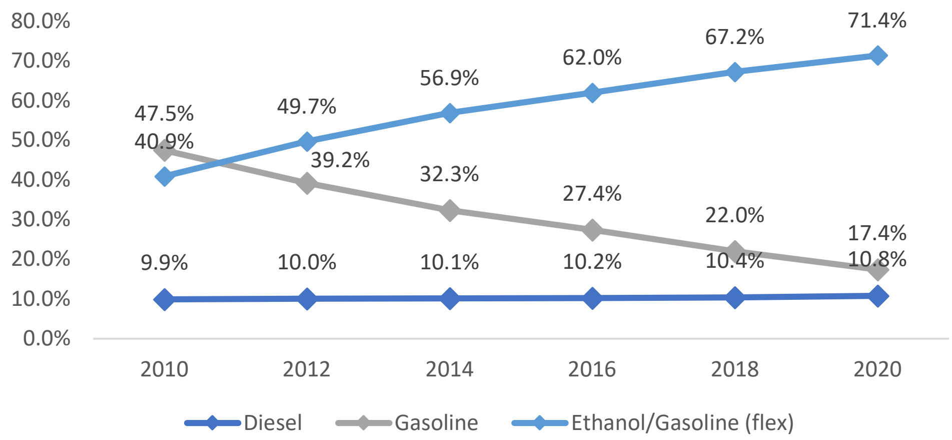
4.5.1.5 Fully Now-renewable Electricity mix

The final scenario of electricity generation mixes to be considered in the analysis is a fully non-renewable electricity mix. As it has been demonstrated in literature, non-renewable sources such as natural gas, hard coal and oil are characterized by having the highest carbon footprint, emissions of CO_2 eq. per kWh, among the different electricity generation sources GREET (2021). Nevertheless, in case of sudden needs, due for example to an electricity shortage, it is common to use such sources to generate electricity. Therefore, it is important to assess the projected environmental impact of having electrical vehicles being powered by non-renewable source electricity, which in the case of this report will consist of natural gas.

4.5.2 Use Phase – Internal Combustion Engine Vehicle

Having explored the use phase modelling for the electric vehicle, the next step is to define what scenarios will be assessed for the internal combustion engine. Given the scope of São Paulo, a variety of fuels are used to power internal combustion engine vehicles, such as gasoline, diesel, sugarcane hydrous ethanol, VNG (Vehicular Natural Gas) among others. Figure 17 provides the participation of each type of vehicle, sorted by fuel used, in the São Paulo car fleet. It is clear that in the last decade, the participation of vehicles that can be powered with both gasoline and ethanol expressively increased, substituting vehicles that can only be fuelled with gasoline, which means that both types of fuel should be considered in the analysis. Vehicles powered by VNG never constituted more than 0.2% of the fleet, not representing a significant enough share to be assessed. In terms of diesel use, the share of the fleet has remained fairly stable, as the fuel is yet to be a dominant presence (SINDIPEÇAS, 2021).

Figure 17 - Distribution of São Paulo car fleet between type of fuel



Source: SINDIPEÇAS (2021)

Given the presented scenario of fuel use by internal combustion engine vehicles and the scope of studying the specific case of São Paulo, the assessment will consider three scenarios of fuel use: gasoline (E18), gasoline (E27) and sugarcane Brazilian hydrous ethanol. According to the Pub. Law No. 9478, from the 6th of August of 1997, the concentration of anhydrous ethanol in the type C gasoline, which is the one sold if gas stations, must be established between 18% and 27.5% (PLANALTO, 1997). The latest resolution on the subject, the Portaria MAPA No. 75, from 05/03/2015, establishes that the concentration of anhydrous ethanol in the type C gasoline (common gasoline) should be 27%, with a ± 1% tolerance. For the premium gasoline, the concentration should be 25%, with the same ± 1% tolerance (MAPA, 2015). To model the emissions of the two different concentrations of gasoline, the GREET 2021 software will be used, as it provides a simulation tool for the Well-to-Wheel emission.

For the sugarcane hydrous ethanol, the ANP Resolution No. 19 from 15th of April of 2015 states that its density at 20ºC 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% (ANP, 2015). To model the GHG emissions of the Brazilian sugarcane hydrous ethanol, the Ecoinvent database will 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 (ECOINVENT, 2016).

The fuel consumption rating for the Chevrolet Cruze Sport6 1.4T Hatchback assumed in this study is presented in Table 34. The first thing to note is that differently than what was done for the electric vehicle, the source of data is not the EPA, as a rating for sugarcane hydrous ethanol is not published. Moreover, there is a difference to be noted on the consumption rating for gasoline between the EPA and what is published in Brazilian sources. The difference can probably be attributed to the type of gasoline in the US, used in the EPA measurement, and the Brazilian gasoline, which has a higher concentration of ethanol, on average 10% in the US and 27% in Brazil (EIA, 2022). Given that the goal is studying the case of São Paulo, the decision to adopt the figures adopted and published in Brazil was made. It is important to note that the final value results from a share of 55% and 45% of urban and highway driving, respectively, following the procedure for the EPA and the initial assumption made for the electric vehicle.

Table 34 - Adopted fuel consumption and EPA rating for the Chevrolet Cruze Sport6 1.4T Hatchback

	Ethanol (Km/L)	**Gasoline BR (Km/L)**	**Gasoline EPA (Km/L)**
Urban	7.6	11.3	11.9
Highway	9.3	13.6	16.2
Mixed	8.4	12.3	13.8

Source: EPA (2022b), CHEVROLET (2022)

4.6 End of Life (EoL) Phase

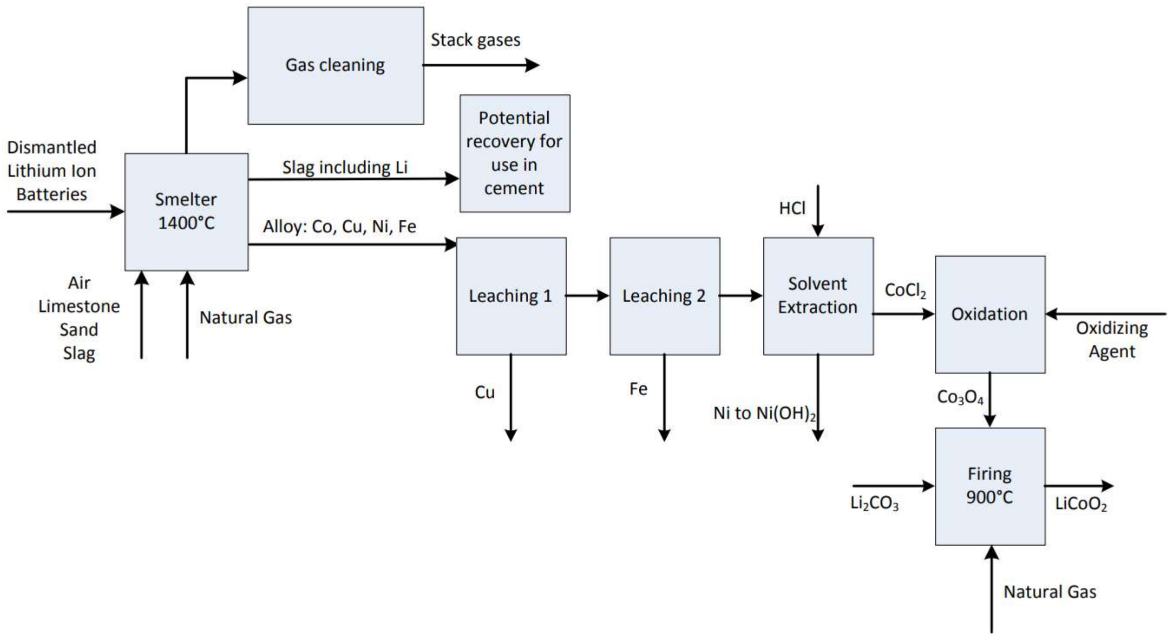
The final phase of the analysis is the End of Life (EoL). After the production phase and the use phase, this phase of the life cycle composes the processes of disposal, recycling or reuse of the vehicle, after its use life has ended. In this section, the end of life processes and impacts of both the vehicle itself and the Lithium-Ion battery will be analysed, each with its own particularity.

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 depicted 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. (2019a), in one of the latest studies from literature, will be adopted in this study, as it is aligned with other studies from literature as well (PETERS et al., 2017; ZACKRISSON; AVELLAN; ORLENIUS, 2010).

In the case of the Lithium-Ion battery, however, things are not so clear. Aichberger et al. (2020) reviewed and compiled 50 publications from the years 2005 and 2020 that analysed and discussed the life cycle impacts of automotive batteries. Despite the significant number of studies currently available in literature, only 16 of the 50 reviewed studies included the recycling step in the analysis, as there is today a lack of inventory data on recycling. Dunn et al. (2012), Qiao et al. (2017), Amarakoon et al. (2013) and Gaines et al. (2015) highlight 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 in literature are centred around the use of recycled materials for the production of the batteries.

Two methods of recycling, pyrometallurgical and hydrometallurgical, are the ones most discussed in literature, with the possibility of direct recycling being less explored (AICHBERGER; JUNGMEIER, 2020). Gaines et al. (2015) defines the pyrometallurgical 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. A graphical representation of the process, given by Tytgat (2011), is presented in Figure 18. 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 (DUNN et al., 2015).

Figure 18 - Representation of the pyrometallurgical recycling process



Source: Tygat (2011)

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. (2014) 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 safe 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 (2014).

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 (AICHBERGER; JUNGMEIER, 2020). Another opportunity discussed by Dai et al. (2019) 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 investigates in literature is the potential for battery second life. Lutsey et al. (2018) briefly discusses the possibility, as Neubauer et al. (2012) analysis showed that discarded EV 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 hasn't yet been sufficiently investigated, as a significant number of studies from literature that discuss the topic do not currently exist.

Given current scenario of uncertainty and lack of accuracy in defining the actual environmental benefit, or impact, of battery recycling, this study will adopt reference values from literature. Among the studies reviewed and analysed by Aichberger et al. (2020) a median recycling benefit of 20 kg of CO_2 eq./kWh of battery capacity is observed. Buberger et al. (2022) reports a more advantageous scenario, based on the studies of Qiao et al. (2019a, 2019b), 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 will be adopted, 34.2 kg of CO_2 eq./kWh of emission savings. 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. To this purpose, this study will assume that the vehicles, or parts, will be disposed in landfill, in the case that they do not go through recycling processes. In this scenario, the estimate of carbon emissions of 0.01 kg of CO_2 eq. /kg of material provided by M. F. Ashby (2013) will be adopted.

4.7 Additional Factors of the Analysis

In this section, other factors that have been shown to be significant in recent studies from literature will also be analysed. Such factors are complementary to the traditional analysis of production, use phase and end of life that characterized the first studies from literature that assessed via a LCA the emissions of an electric vehicle. More specifically, the influence of three main factors will be taken into consideration here: capacity fade of the battery, temperature and driving cycle. These three characteristics have been studied by recent literature, and their significance will be here investigated as well, in addition to the electricity grid mix and remaining parameters, already discussed previously.

4.7.1 Capacity Fade for Electric Vehicle Batteries

As previously discussed and highlighted in the cradle-to-gate analysis, 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. (2012) and Marques et al. (2019). In literature, capacity fade models have been used to estimate the number of batteries required along the entire lifetime of the electric vehicle. Some of the studies from literature that can be mentioned are Ouyang et al. (2016), Torai et al. (2016) and Lim et al. (2016).

The minimum required capacity for a battery powering an electric vehicle is not a complete consensus in literature. The United States Advanced Battery Consortium (USABC) suggests that automotive batteries for electric vehicles should be replaced at 80% capacity, while some automotive manufacturers recommend the substitution at 70% capacity (TONG et al., 2013; VAN DE BOSSCHE et al., 2006).

Marques et al. (2019) conducted an analysis considering three possible scenarios of use: 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. Table 35 provides the results obtained by Marques et al. in their analysis.

Table 35 - Capacity fade and energy consumption by driving style

	$LiMn_2O_4$			**$LiFePO_4$**		
	Light	Moderate	Intensive	Light	Moderate	Intensive
Total distance travelled (km)	180047	100541	79192	214703	124086	98544
Energy consumption (kWh/km)	0.105	0.178	0.214	0.114	0.187	0.223
Number of cycles per battery	1555	1472	1394	2022	1914	1812

Source: Marques et al. (2019)

Results from the study highlight the very significant impact of the driving style when estimating the number of batteries required in the lifetime of an electric vehicle. For instance, when considering a moderate or an intensive driving style and a lifetime of 150,000 km, which is the assumption for this study, in the case of both cathodes a second battery would be needed. In the case of the $LiMn_2O_4$ cathode being used intensively, the second battery is barely enough, with its capacity reaching only around 160,000 km.

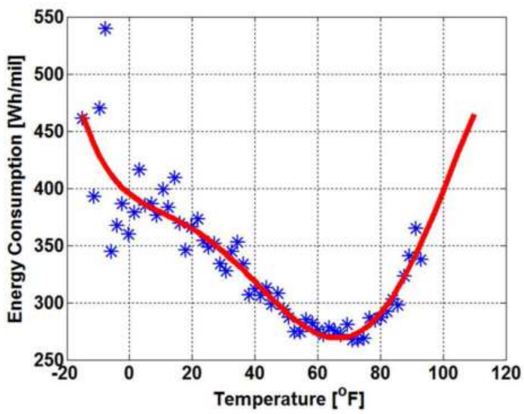
4.7.2 Temperature

The weather conditions have also been explored in literature, as researchers investigate the effect that it has on the consumption of electric vehicles. Allen (2013) investigated the effects of cold weather in the consumption of a Nissan Leaf model and concluded that such conditions tend to increase consumption. 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 (REDDY, 2010).

The decrease in performance can be attributed to several functionalities that increase energy consumption as they are activated, such as electric cabin heating and air conditioning. Those, together with the impact on the battery performance itself amount can amount to considerable changes in the estimated performance and emissions.

Yuksel et al. (2016) 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 are displayed in Figure 19.

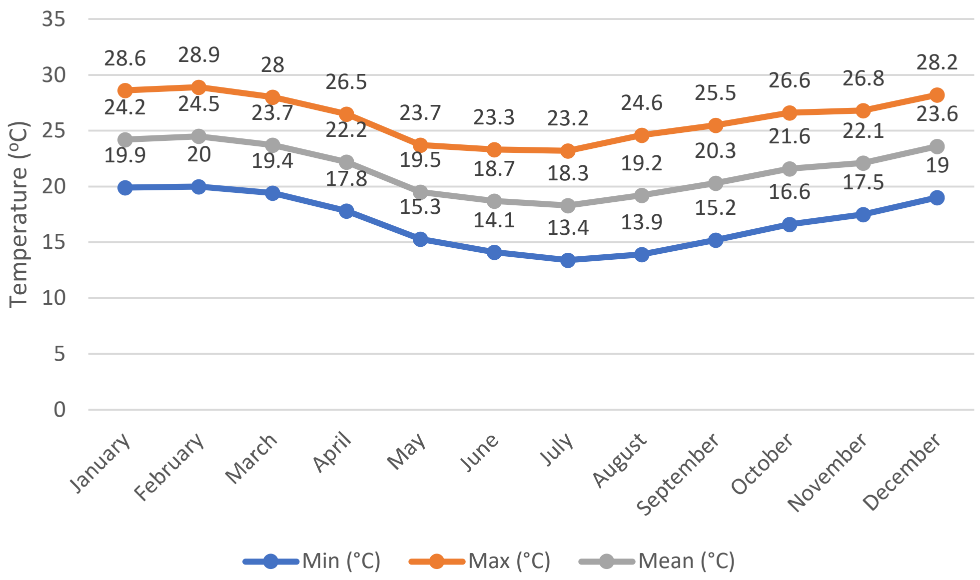
Figure 19 - Consumption versus temperature for electric vehicles



Source: Yuksel et al. (2016)

Data from the study suggests that the optimal region for consumption efficiency is around 15 ºC (60 ºF) and 26 ºC (80 ºF), where consumption is at its lowest. For temperatures outside the mentioned range consumption starts to increase significantly, although it is worth mentioning that there is no available data for temperatures above 100 ºF. The significant impact of the cold is also very well displayed by the results of the study.

Figure 20 - Temperature for São Paulo (1991-2020)



Source: Climates to travel (2022)

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. Figure 20 provides the average temperatures for each month taking into consideration the period from 1991 to 2020. The average monthly temperature never exits the mentioned range of 15 ºC to 26 ºC, however, the max temperatures can exceed those boundaries and, in June, July and August, the lower bound limit is also crossed. Nonetheless, the effect of temperature, considering the results from Yuksel et al. (2016), should not yield increases in consumption that are large enough to have significant influence in the overall results of the analysis, considering the whole year.

4.7.3 Driving Cycle

The driving cycle, or driving pattern, is another factor that has been studied 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 a driving cycle all have been shown to be important aspects when assessing the environmental benefits of electrified vehicles.

The importance of further investigating driving patterns and conditions comes to the fact that the initial basis estimation for the majority of studies in literature makes use of driving tests conducted in lab conditions, as they must be performed under controlled and repeatable conditions. However, when trying to assess emissions on real life conditions, factors such as traffic, terrain and driving aggressiveness must be considered. In the particular case of the EPA, used as the baseline reference test in this study, a five-cycle testing method is adopted. The five cycles of testing are: aggressive (US06), air conditioning on (SC03), cold weather (Cold FTP), city driving (FTP) and highway (HWFET) (EPA, 2006).

One of the studies that addressed the subject was performed by Karabasoglu et al. (2013), in which several driving patterns were assessed. Data from the study shows that the EPA rating models with accuracy, to a significant degree, the driving conditions of New York. The consumption for NYC, expressed in mi/kWh was the highest among the studied driving cycles, which yielded the highest GHG emission per mile travelled. The elevated consumption can be mainly credited to the amount of stops and time at rest.

Gong et al. (2018) conducted an evaluation of how well the traditional driving cycles represent real-world data on the driving cycle of crowded cities, more specifically Beijing. Researchers compared the real-world data obtained, which was collected using electric vehicles, and compared it to the NEDC, the FTP-75 (one of the five tests used in the EPA rating) and the JP10-15, a Japanese test. Results show that the FTP-75 is the one that represents the Beijing driving cycle the best, among the three, with a SAFD (Speed Acceleration Frequency Distribution) of 8.16%. The NEDC was shown to be far from accurate as a standard to be used in crowded cities, with an SAFD of around 34.75%.

For the specific case of São Paulo, there is a lack of data in a consolidated driving cycle. De Carvalho et al. (2005) 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 behavior can be mainly credited to the smaller average speed of the São Paulo driving cycle. However, the study was conducted using only internal combustion engine vehicles, so that results cannot be completely translated to electric vehicles.

Table 36 – Summary of comparisons between SP04 and FTP-75 cycles

Parameters	EPA FTP-75 (with 600s turned off	EPA FTP-75 (without 600s turned off)	SP04
Average speed (km/h)	25.85	34.12	27.94
Trip Length (km)	23.97	23.97	22.35
Trip Time (min)	55.63	45.63	51.00
Cold Start	Yes	Yes	No
Preconditioning	At least 12 hours before test		Immediately before test

Source: De Carvalho et al. (2005)

Faria et al. (2013) also studied real-life consumption of electric vehicles under urban conditions and also following different driving styles. Researchers used real-life data to estimate the impact of the driving style in consumption, for which three scenarios were used: aggressive, normal and eco-mode. Moreover, the use of air-conditioning was also evaluated, both for cooling and heating. Results from the study indicate that an aggressive style of driving increases consumption by an average of 18%, while the ECO-mode reduces consumption by an average of 27%, both compared to a normal style of driving. The use of AC for cooling also yields an increase in consumption, by an average of 18%. Heating is shown to have the largest impact, increasing consumption by 45% on average. When comparing driving on ECO-mode without air conditioning and scenarios of aggressive driving with air condition for cooling and heating, an increase of 69% and 103% is observed, respectively. Therefore, it is safe to conclude that both aspects are of key influence to the overall consumption of an electric vehicle, and therefore to their environmental impact. For internal combustion engine vehicles, results from literature show that the increase in consumption from the use of air conditioning for cooling ranges from 16% to 29%, for the FTP-75, depending on the intensity of the air conditioning.

For the electric vehicle adopted in this study, as previously mentioned, a baseline scenario for the consumption and range of the Nissan Leaf assumed the EPA rating, which yielded a range of 240 km. In an effort to check if that range is really applicable to the case of São Paulo, two views will be merged. Firstly, in a previous study from literature, Costa (2019) used Shanghai as a basis for studying GHG emission mitigation policies in the context of the road transportation of São Paulo. Therefore, results from Gong et al. (2018), that provides a real-world evaluation of the driving cycle in crowded cities from China, could be used as a basis. The NEDC range rating for the Nissan Leaf, adopted in this study as the EV, is 350 km. Following the results from Gong et al. (2018), under real-world conditions of driving, the estimated range for a crowded city, Beijing, would be around 230 km, which given the characteristics of São Paulo and the scope defined by researchers, is applicable to São Paulo to a good enough degree. De Carvalho et al. (2005) obtained results that indicate that the range in São Paulo is slightly smaller than the one provided in the conventional rating of the EPA, although it is worth mentioning that the evaluation was made for internal combustion engine vehicles, which do not have the benefit of regenerative braking, as do electric vehicles, a factor that is specially significant in driving characterized by frequent stops and braking (KARABASOGLU; MICHALEK, 2013). Given the factors presented, the assumed range for the Nissan Leaf will be adjusted to 230 km, instead of the original EPA rating of 240 km.

Another aspect to be addressed is the assumed consumption for all three scenarios of driving style to be considered. The range of 230 km corresponds to conditions in which the AC is on and of normal driving. From that range, results from Faria et al. (2013) will be used to calculate the range figures, as they were obtained using real-world data and also using a former version of the Nissan Leaf, with a smaller battery. Therefore, a 27% reduction in consumption, expressed in kWh/km, is adopted in an eco-driving scenario, and an 18% increase is 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. (2021) 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. (2010) 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. (2010) evaluates the increase in consumption by aggressive driving at around 40%, a figure similar to the results obtained by Szumska et al. (2020), that pointed to an increase of around 30% to 40%. Finally, Huang et al. (2021) 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, will be 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.

Following the above-discussed, the ranges for the different scenarios and vehicles assumed in the present Life Cycle Assessment are displayed in Table 37. The influence of such parameters to the results will be evaluated in the sensitivity analysis.

Table 37 - 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

Source: The author

5. Results and Discussion

In this section, the results of the LCA analysis will be exposed and discussed, via analysis of the resulting data and comparison to other studies from literature. Moreover, a sensitivity analysis will also be presented, as to detect the key parameters that influence the results.

5.1 Isolated Phase Results of the LCA

The Life Cycle Assessment, as previously explored, accounts for the whole life of the product. To calculate the GHG emissions of both an electric vehicle and an internal combustion engine vehicle the Cradle-to-Gate, Use Phase and End-of-Life phases were modelled according to the base literature review and databases, mainly the GREET 2021, following the procedures and assumptions detailed in the methodology presentation. Here, only the results from that methodology and the comparison to the current state of literature on such results will be explored.

The overall GHG emissions referring to the Cradle-to-Gate phase of both the Nissan Leaf and the Chevrolet Cruze Sport6 1.4T Hatch are presented in Table 38. As expected, the total emissions for producing the Nissan Leaf are considerably higher, by 48%, than the required to produce the Chevrolet Cruze Sport6 1.4T Hatch, as it is expected when comparing an EV to an ICEV of comparable size. Moreover, the general consensus that the battery is a very significant influence when assessing the emissions for producing an EV is also confirmed, with the 40 kWh Li-Ion battery being the most significant contributor in the EV case.

Table 38 - Cradle-to-Gate emissions GHG emissions (kg) for each vehicle by component

Vehicle Component	**EV**	**ICEV**	**EV (%)**	**ICEV (%)**
Body	2128	2206	21%	32%
Powertrain System	187	936	2%	13%
Transmission System	289	322	3%	5%
Chassis (without battery)	1749	1799	17%	26%
Traction Motor	620	0	6%	0%
Electric Controller	429	0	4%	0%
Assembly (body)	919	905	9%	13%
Battery (Li-Ion) Materials	2915	0	28%	0%
Battery (Li-Ion) Assembly	919	0	9%	0%
Battery (Lead Acid)	18	44	0%	1%

Vehicle Component	EV	ICEV	EV (%)	ICEV (%)
Fluids	183	764	2%	11%
Total (C2G)	**10356**	**6977**	**100%**	**100%**

Source: The author

The per kg of vehicle impact of both the EV and the ICEV is aligned with the results from literature. This study estimates an emission level of 4.93 kg of GHG/kg of vehicle for the EV, excluding emissions and weight of the battery, and an emission level of 5.24 kg of GHG/vehicle for the ICEV. Buberger et al. (2022) estimates this value at 4.56 kg of GHG/vehicle while Qiao et al. (2017) estimates at 6.96 kg of GHG/kg of vehicle for the ICEV and 6.94 kg of GHG/kg of vehicle for the modelled EV. In their study, Hawkins et al. (2012) obtained an estimation of 5 kg of GHG/kg of vehicle, providing an expected range for future studies of 4 to 6.5 kg of GHG/kg of vehicle.

Table 39 presents the contribution of each battery component to the overall emissions of the EV 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 (2011), Ellingsen et al. (2014), Dai et al. (2019), Zackrisson et al. (2010), Kelly et al. (2020), Dunn et al. (2015), Wu et al. (2019), Aichberger et al. (2020) and Peters et. al (2017) 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. (2011) and Ellingsen et al. (2014), estimate a higher emission factor for the cell production than others. Moreover, the significance of the battery assembly is also a point of dispute, as some studies find that it has a significant impact to the overall emissions, as does the assessment conducted in the present study, while others claim that it practically does not produce emissions. The non-alignment among the different sources of literature is expected, as explored in the literature review and also on the battery cradle-to-gate emissions calculation methodology. The impact of Aluminium is also very significant, at 12.9%, a conclusion promoted by Notter et al. (2010) that is aligned with the results from this study.

Table 39 - Nissan Leaf 40 kWh Li-Ion battery production and assembly emissions

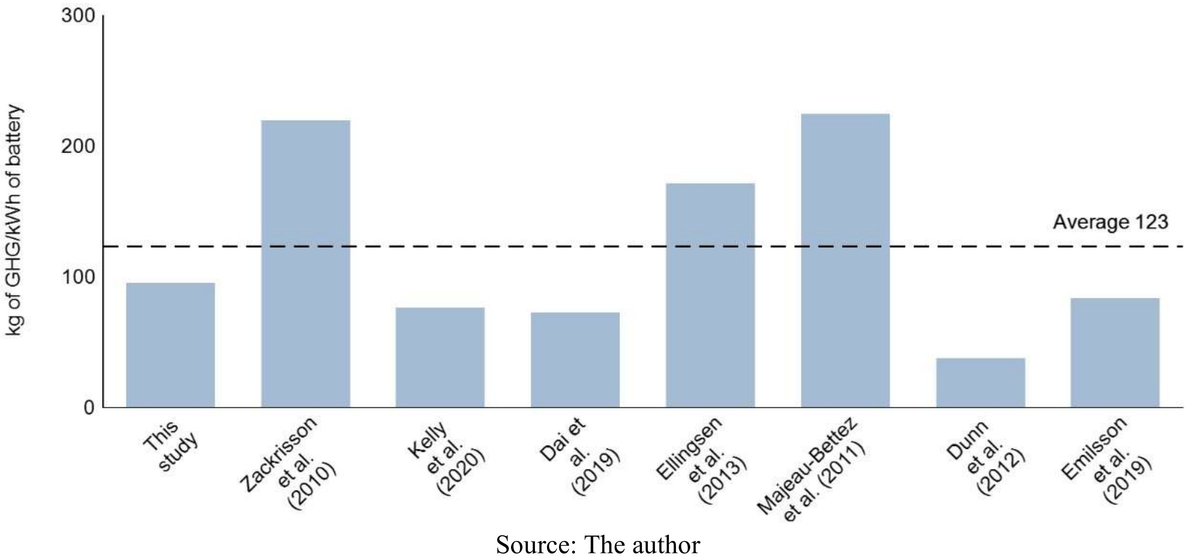
Battery Component	GHG emission (kg)	Relative contribution (%)
NMC111 Powder	1139.6	29.7%
Graphite/Carbon	214.8	5.6%
Binder	14.4	0.4%
Copper	101.6	2.7%
Wrought Aluminum	495.6	12.9%

Battery Component	GHG emission (kg)	Relative contribution (%)
Electrolyte: LiPF6	54.8	1.4%
Electrolyte: EC	6	0.2%
Electrolyte: DMC	21.6	0.6%
Plastic: PP	8	0.2%
Plastic: PE	2.8	0.1%
Plastic: PET	2	0.1%
Steel	4.8	0.1%
Thermal Insulation	2.4	0.1%
Coolant: Glycol	21.2	0.6%
Electronic Parts	271.6	7.1%
Cell Production	554	14.5%
Battery Assembly	918.6	24.0%
Total	**3833.8**	**100.0%**

Source: The author

The common practice in literature when trying to compare the battery production results with results from other studies is to use a per kWh basis. As previously presented, the EV modelled in this study has a 40 kWh battery, which results in an emission figure of 95.8 kg of GHG/ kWh of battery. Figure 21 presents the GHG emission level for different studies in literature.

Figure 21 - Figures of kg of GHG/ kWh of battery for different studies

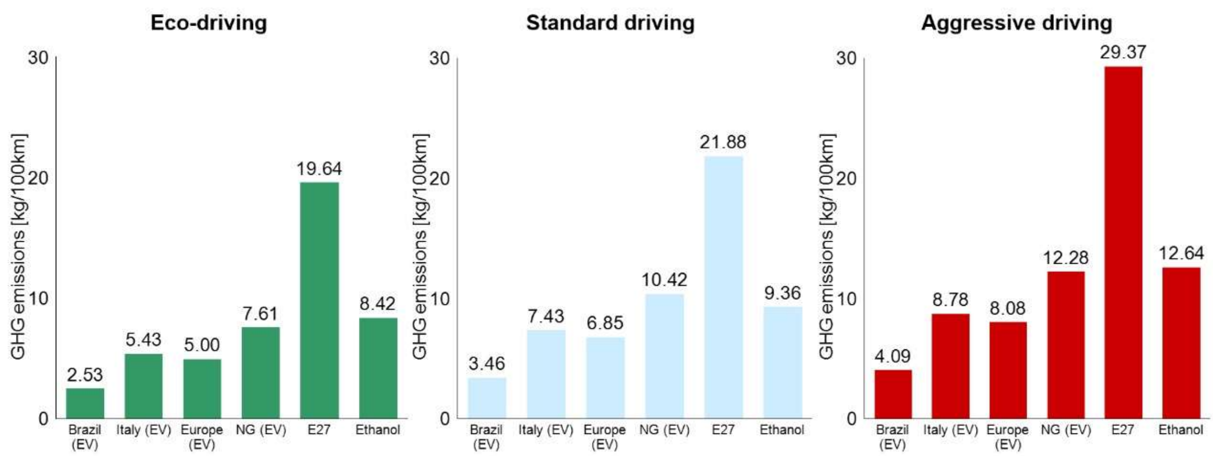


Source: The author

Results vary greatly, mainly due to the value attributed to the cell production, as previously explored. Recent studies, such as Dai et al. (2019), Kelly et al. (2020) and Emilsson et al. (2019) have attributed smaller values to the cell production, and consequently to the overall kg of GHG that result from the battery production. The assessment of this study, it can be said, is more in line with such studies and also with the direction of literature in recent years in that regard. Aichberger et al. (2020) 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. The observed value of 95.8 kg of GHG/ kWh of this study is well within those boundaries.

Following the presentation of the results from the Cradle-to-Gate scenario, the next step is to present and discuss the results from the Use Phase. For the purposes of this study, three driving behaviours 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, four electricity mixes were analysed: Brazil, Italy, 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 22 presents the emission figures for all combinations of the mentioned scenarios. As expected from the literature review, the EV presents a lower level of emissions when compared to a gasoline powered ICEV for all the different scenarios. Even more significant, even when eco-driving, an ICEV will produce more emissions than an EV being driven aggressively and powered by natural gas. However, when compared to the sugarcane ethanol, there is not a clear advantage for all the considered scenarios. Considering the main goal of this study, which is to investigate if EVs are a better alternative than ICEVs in the context of São Paulo, the scenario in which the EV is powered by the Brazilian electricity grid mix is very superior when compared to all other scenarios, even when considering aggressive driving.

Figure 22 - Level of GHG emissions for the Use Phase for the different scenarios considered



Source: The author

Another important conclusion is the significance of the amount of coal used to generate electricity to the emissions level of the EV. The Italian case uses a very high amount of natural gas (48%) and a not very high amount of non-GHG intensive sources (about 39%), while Europe, on average, uses less GHG intensive sources (about 58%), but a very high amount of coal (18%), which results in very similar scenarios of emissions, even though there is a considerable difference in the amount of renewable sources used.

Orsi et al. (2016) also conducted a well-to-wheels 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. For the Italian case, the EV also showed considerably lower emissions than the E10 alternative, but when compared to an E85 scenario, the advantage is not so expressive. Woo et al. (2017) results also support the conclusion that when considering the Use Phase, the EV performs better than a corresponding ICEV for a Brazilian and average European scenarios. However, in their study, the Brazilian scenario yields emissions of 1.66 kg of GHG/100km, which are smaller figures when compared to the ones in this study, which can be attributed to differences in the electricity grid mix, as different years were used, and also consumption estimations, as their study adopts the NEDC with no adjustment based on driving behavior or driving cycle. Marques et al. (2013) is also aligned with the general result that higher share of renewable energy will yield better emissions levels when compared to scenarios with lower share. Hawkins et al. (2012) also reached results that supported the conclusion that an EV powered with only natural gas yields less emissions than an ICEV fuelled with gasoline.

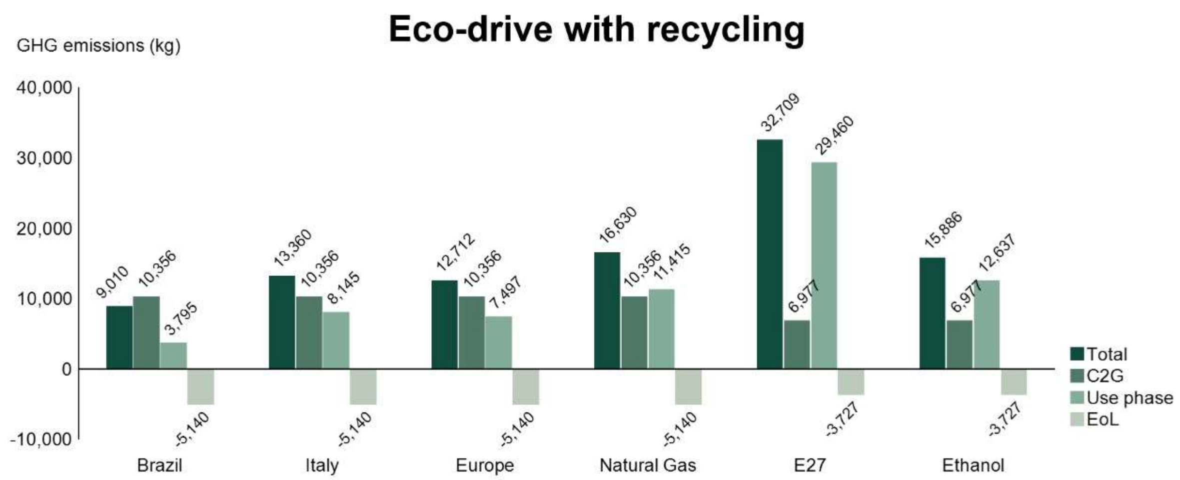
Finally, the End-of-Life GHG emissions were estimated based on current sources from literature, so comparing it to those sources of literature, as was done for the other phases of the life cycle, is not as beneficial. Nevertheless, as a reminder, the values assumed for the two different scenarios considered 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, EV or ICEV.

5.2 Life Cycle Assessment Results

From the above-explored isolated view of each one of the three phases of the life cycle, we obtain the results of the full Life Cycle Assessment of both the modelled EV and ICEV, for the different scenarios considered. First are presented the results for the scenario in which recycling of both the battery and remainder of vehicle parts occurs. The need for additional batteries in the case of EVs will be addressed shortly, but the first presentation of results will not consider it, as most studies in literature do not include this parameter in the analysis.

Figure 23 presents the Life Cycle GHG emissions of the Eco-drive with recycling scenario. As displayed in the graph, considering the Brazilian electricity mix, the EV offers a much better performance than the ICEV, for both types of fuels, as ethanol life cycle emissions are 76% higher and gasoline emissions are approximately 3.6 times higher. As the share of renewable sources in electricity production increases, so does the GHG emissions. The percentual increase in total emissions from the Brazilian case for the Italian, European and Natural Gas is, respectively, 48%, 41% and 85%, supporting the conclusion that the electricity mix is a key parameter in the life cycle emissions analysis of a BEV. It is interesting to note that the gasoline ICEV is by far the worst option among the different scenarios assessed. Ethanol fuelled vehicles, on the other hand, are significantly competitive in terms of life cycle GHG emissions, especially when compared to EVs powered by electricity mixes with lower shares of renewable sources.

Figure 23 - LCA GHG emissions for Eco-drive with recycling



Source: The author

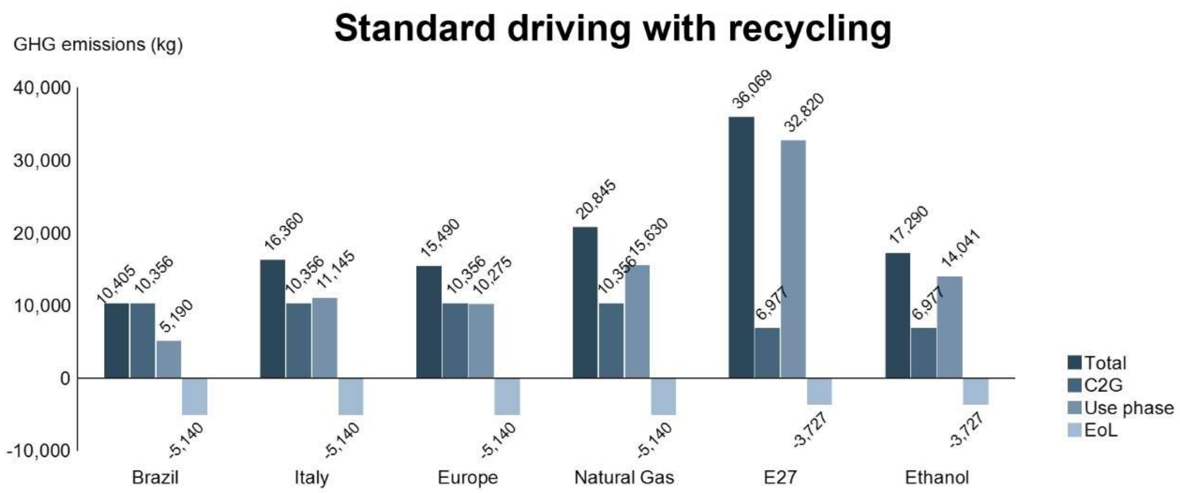
Figure 24 and Figure 25 present the life cycle results for the standard driving and aggressive driving scenarios, both with recycling being considered. Independent of the driving style, the EV calculated emissions for Brazil are lower than the ICEV emissions, fuelled with either ethanol or gasoline, supporting the case of the high benefit of adopting EVs in the São Paulo context. When considering standard driving, the gap between sugarcane ethanol and Italian and Europe electricity mixes is reduced, with the EV still holding a small advantage. Meanwhile, Natural Gas calculated emissions are higher than those of Ethanol.

In an aggressive driving scenario the order in terms of GHG emissions is not affected, with Brazil still being the clear best performer and gasoline the worst, by a wide margin. Changes in the driving style are shown to have significant influence in life cycle emissions. In the Brazilian scenario, the change from Eco-drive to Standard driving results in a 15.5% increase in life cycle emissions, while the change from Standard driving to Aggressive driving results in a 9.1% increase. The higher the GHG emissions per km driven the higher the influence of the driving style. For example, the mentioned increases for the Europe scenario are 21.8% and 11.9%. For ethanol, the respective increases are 8.8% and 28.4% and, for gasoline, 10.2% and 31.1%.

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 EVs, 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. Finally, the role of recycling in reducing the emissions for both powertrain technologies is fundamental, as displayed in the results that consider recycling, which reinforces the need for continuous improvement of recycling and reuse processes for the overall goal of reducing worldwide GHG emissions.

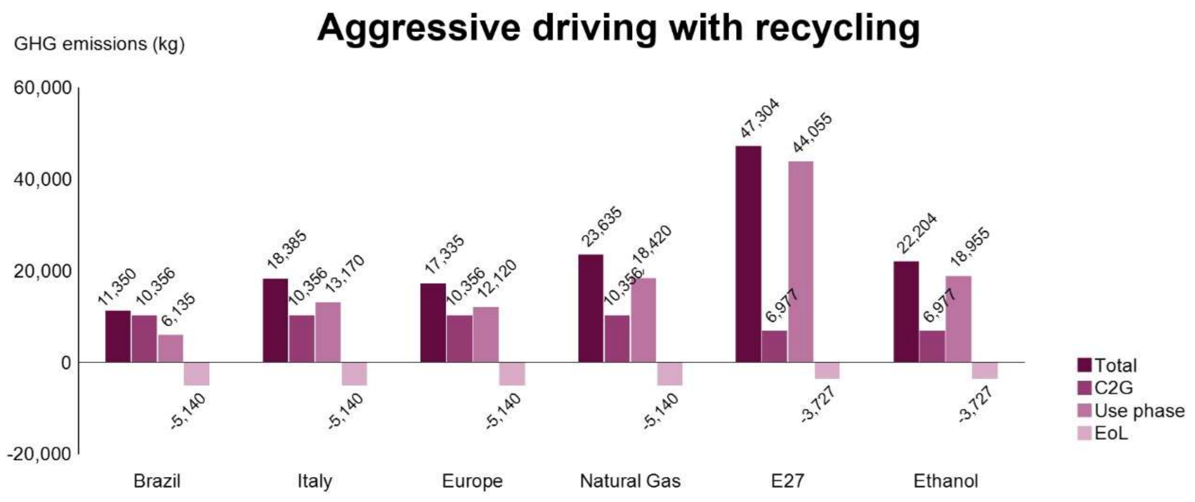
Looking at results from literature, a dominant use phase is the standard for ICEVs. Qiao et al. (2019) reports that the Use Phase contribution to the overall emissions of the ICEV is larger than 70%. Buberger et al. (20220 reports the same contribution at almost 80%. For this study, not considering the benefit of the recycling phase, the contribution of the Use Phase of the gasoline ICEV emissions were around 76%.

Figure 24 - LCA GHG emissions for standard driving with recycling



Source: The author

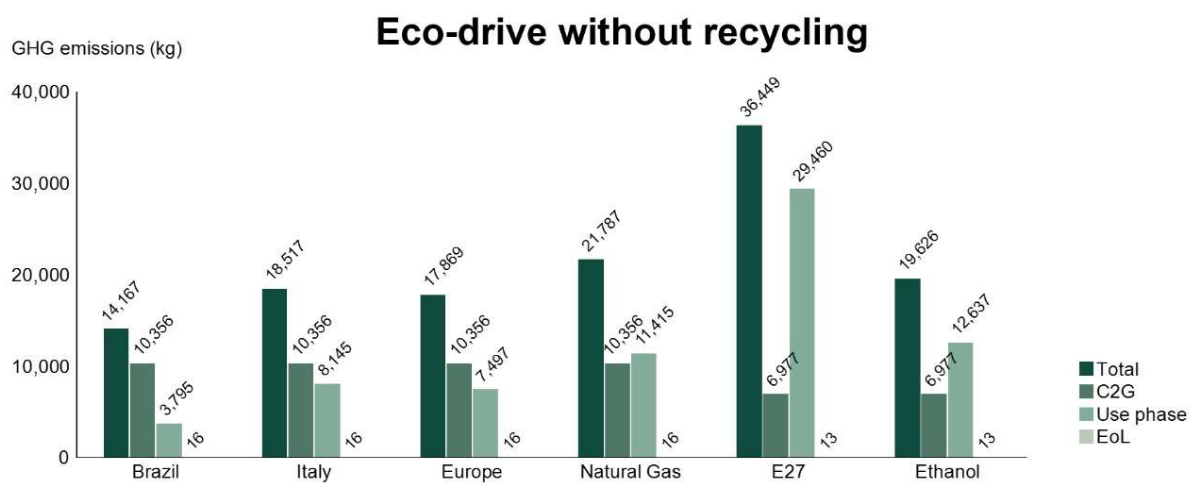
Figure 25 - LCA GHG emissions for aggressive driving with recycling



Source: The author

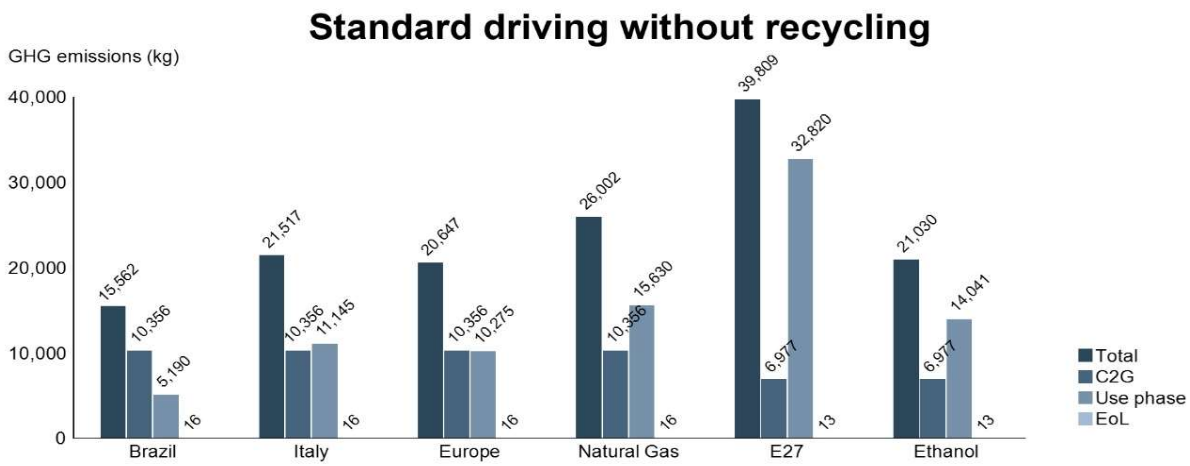
The scenario in which recycling is not performed and instead, landfill disposal is the End-of-Life scenario of the vehicles, was also assessed in this study. The emissions for the three different driving styles are presented in Figure 26, Figure 27, Figure 28. As displayed in the graphs, the landfill disposal itself does not produce a significant level of GHG emissions, however, the lack of emissions credit does have a decisive impact, especially for the battery, as its high production emission intensity is not compensated. As a result, Italy and Europe scenarios become less attractive, but still overall better than ethanol. Natural Gas is worse than ethanol for all three driving styles, again, due to the impact of the battery. The Brazil scenario is still the best overall by a considerable margin, while gasoline is the worst by an even wider margin, not being advantageous in any of the studied scenarios.

Figure 26 - LCA GHG emissions for Eco-drive without recycling



Source: The author

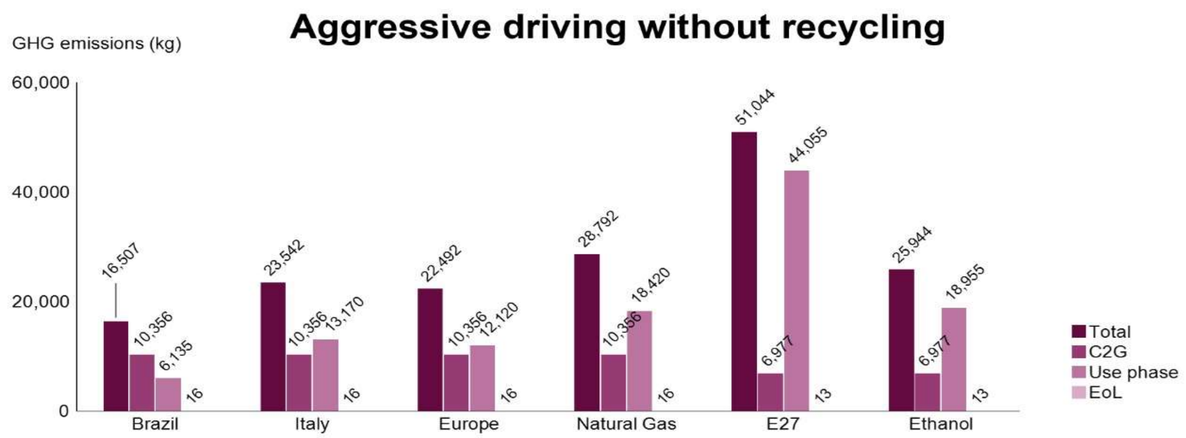
Figure 27 - LCA GHG emissions for standard driving without recycling



Source: The author

Therefore, even though recycling is not fundamental to determining how each scenario ranks in relation to others for overall emissions, it does offer a big contribution, for both types of vehicles, in reducing the life cycle emissions. For example, considering standard driving and Brazil electricity generation mix, not recycling increases life cycle GHG emissions by 49.6%, or around 5,157 kg of CO_2 eq. This of course, means that recycling is a key parameter when analysing vehicles life cycle emissions, which reinforces the need for a more detailed study of the topic in literature.

Figure 28 - LCA GHG emissions for aggressive driving without recycling

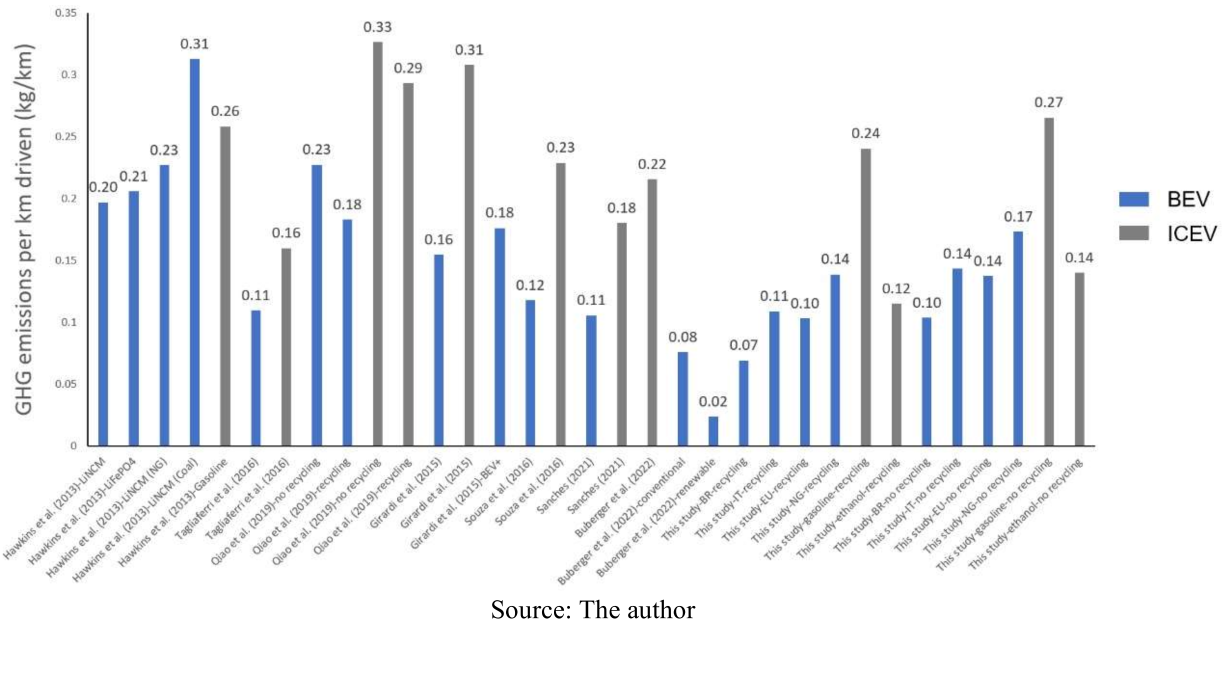


Source: The author

Finally, it is also important to incorporate the view of literature in the results discussion. Figure 29 provides the life cycle GHG emissions per km driven, expressed in kg of GHG/km, reported by several sources from literature. Overall, analysing the BEV assessments, results from this study are within what is expected from literature, with the overall results being more similar to those of recent studies, such as Qiao et al. (2018), Girardi et al. (2015) and Buberger et al. (2022). Results by Hawkins et al. (2012) tend to be above what is expected from the current view from literature. The main differences that amount to such result is the evaluation of the 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. Such difference can be attributed to the higher concentration of hydrous ethanol in the Brazilian gasoline. Results for the ethanol fuelled vehicle are also aligned with the overall expectation, as the fuel is considerably less intensive than gasoline in terms of GHG emissions.

When comparing the present study results for the Brazilian electricity grid mix scenario with figures reported by Souza et al. (2016) and Sanches (2021), 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. (2016) adopted the inventory published by Majeau-Bettez et al. (2011), which as shown in the literature review, provides one of the highest estimates for battery production emissions in literature. Sanches (2021) adopted the inventory published by Yin et al. (2019), 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. (2016) and Sanches (2021). 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.

Figure 29 – Life cycle emissions per km driven (kg/km) reported by several studies in literature

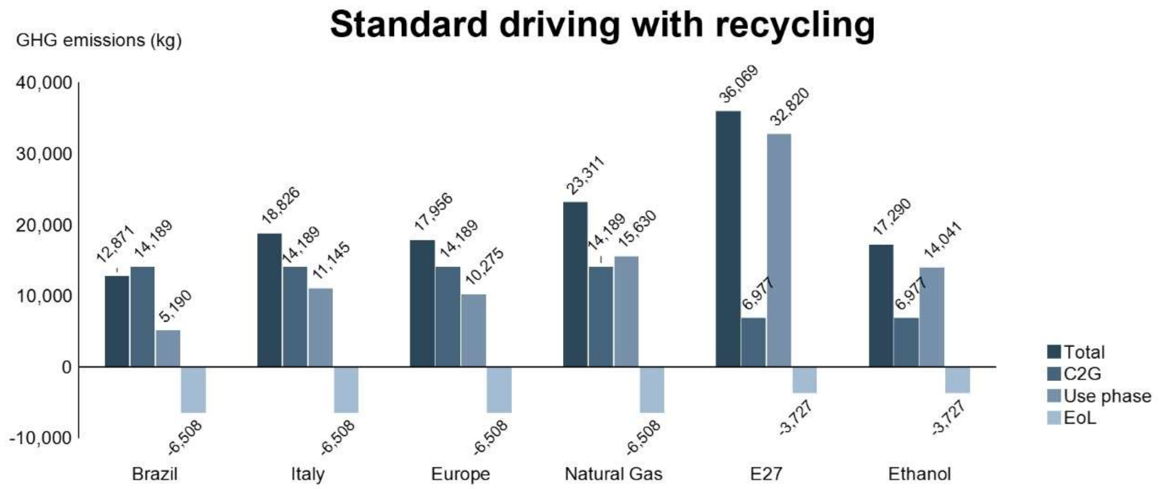


Source: The author

5.3 Life Cycle Assessment Results accounting for Capacity Fade

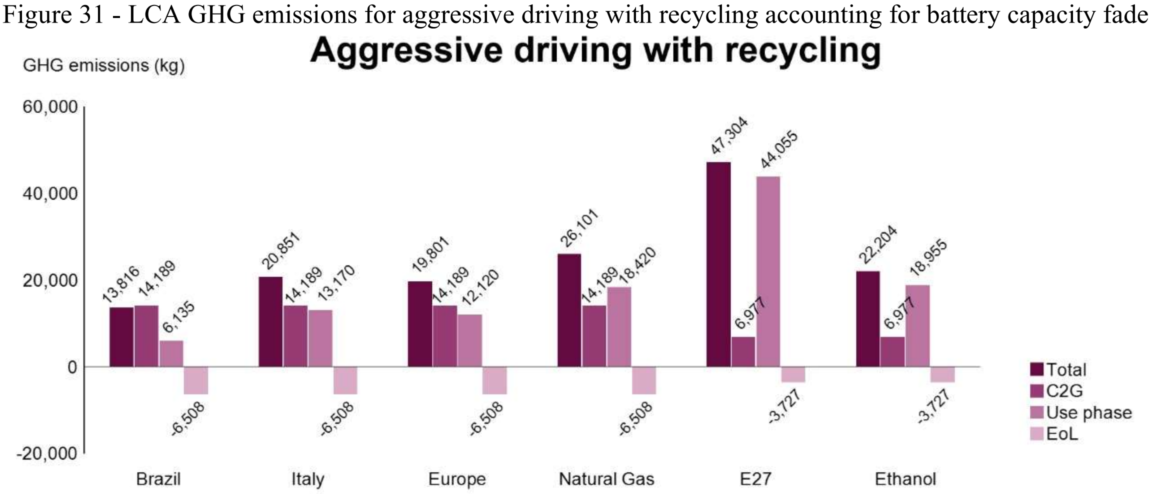
The next step in the results discussion is to evaluate the parameter of battery capacity fade. As addressed in Section 4.8.1, a second battery might be necessary for a standard and an aggressive driving style with a lifetime of 150,000 km, which, of course, increases the life-cycle emissions of the modelled EV. Figure 30 and Figure 31 present the results of the analysis in a scenario in which a second battery is used, and recycling of the battery and vehicle occurs. Results show that for the Brazilian electricity mix, life cycle emissions are still lower than those for the ethanol and gasoline scenarios. However, EVs powered with natural gas generated electricity produce significantly more GHG emissions than the ethanol vehicle, while Italy and Europe present similar performance to ethanol, the best alternative depending on the driving style

Figure 30 - LCA GHG emissions for standard driving with recycling accounting for battery capacity fade



Source: The author

Figure 31 - LCA GHG emissions for aggressive driving with recycling accounting for battery capacity fade

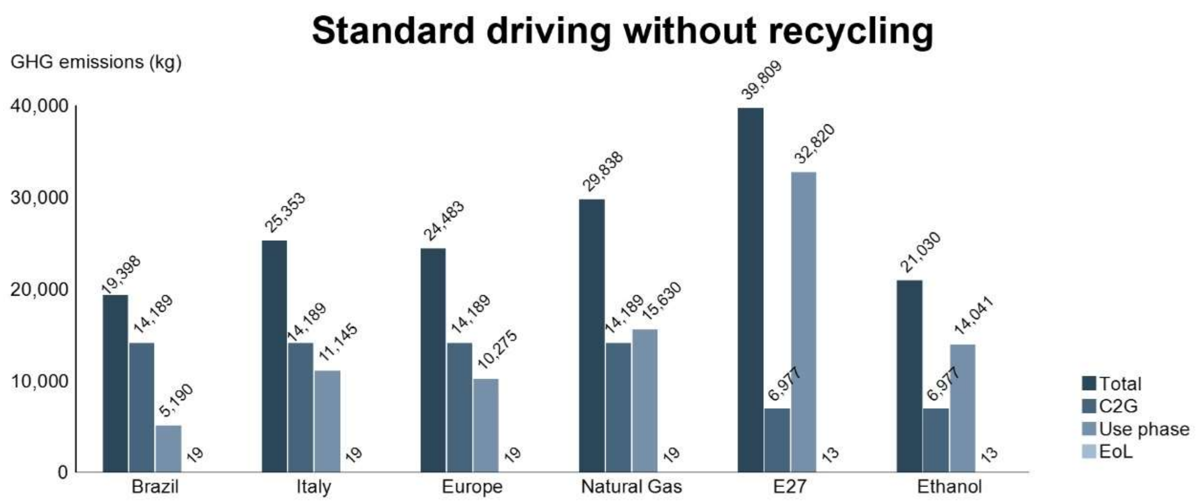


Source: The author

Meanwhile, if recycling does not occur, results are changed significantly. As displayed in Figure 32 and Figure 33, the EV powered by the Brazilian electricity mix is still be best option, in terms of GHG emissions, but now with a smaller margin to the ethanol option, a gap a little smaller than 2,000 kg of GHG for standard driving. For aggressive driving, the difference is enlarged, probably due to the regenerative breaking of the EV (KARABASOGLU; MICHALEK, 2013). Italy and Europe scenarios are worse by a considerable margin when compared to ethanol when considering standard driving, while the difference between the three is a lot smaller for aggressive driving, being practically equivalent. The gasoline ICEV is still by far the worst option, even after the addition of the second battery and its disposal in landfill, leading to the conclusion that, at least for the considered scenarios, a gasoline fuelled ICEV is never the best option in terms of GHG emissions. In the worst scenario possible for the EV, aggressive driving without recycling, using natural gas generated electricity and a second battery, the life cycle emissions are similar to the best-case scenario for the ICEV, eco-drive with recycling, both at around 32,000 kg of GHG.

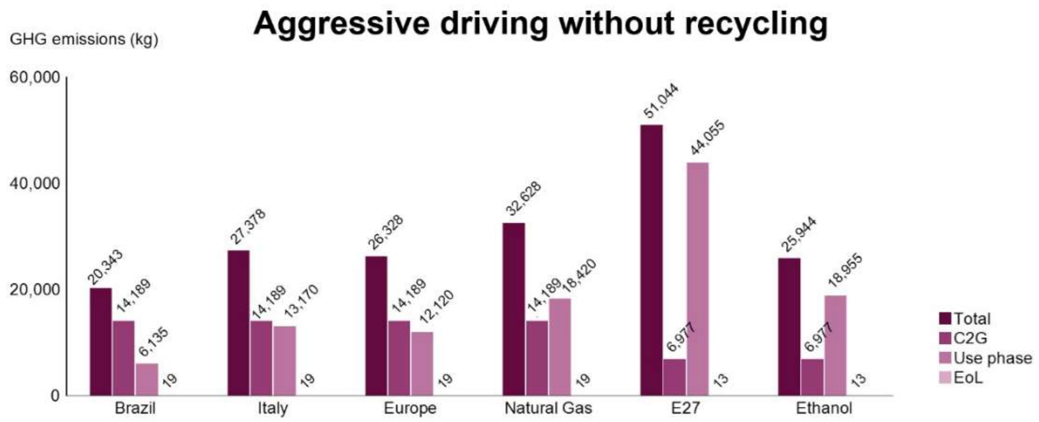
Moreover, battery capacity fade is proven to be a key parameter to the life cycle emissions of electric vehicles, so that its inclusion as a parameter in future analysis is practically mandatory. For example, considering the Brazilian scenario for standard driving, it results in a 23.7% increase when assuming recycling and a 24.6% increase when assuming landfill disposal.

Figure 32 - LCA GHG emissions for aggressive driving without recycling accounting for battery capacity fade



Source: The author

Figure 33 - LCA GHG emissions for aggressive driving without recycling accounting for battery capacity fade

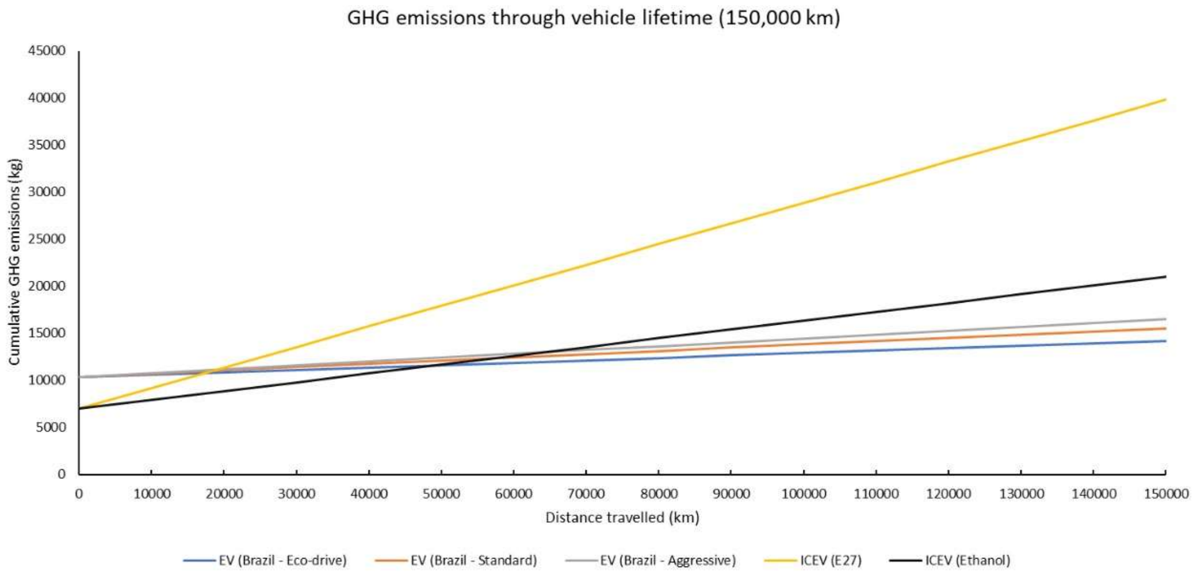


Source: The author

5.4 In-depth view of the Brazilian Electricity Mix Scenario

As the goal of this study is to provide a comparison between a BEV and an ICEV in the context of São Paulo, the results referring to the Brazilian case will be explored with further detail. Figure 34 provides a more in-depth view of the lifetime emissions of both vehicles for the scenario in Brazil, comparing all three driving behaviours for the EV with standard driving for the ICEV. As displayed, the EV 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 EV becomes more beneficial than the ethanol ICEV from 50,000 km to 60,000, for all driving behaviours. Under such conditions, there is a clear benefit in adopting battery electric vehicles as the dominant powertrain technology for light-duty vehicles, in terms of GHG emissions.

Figure 34 - Lifetime GHG emissions comparison between EV in Brazil and ICEV (no second battery included)

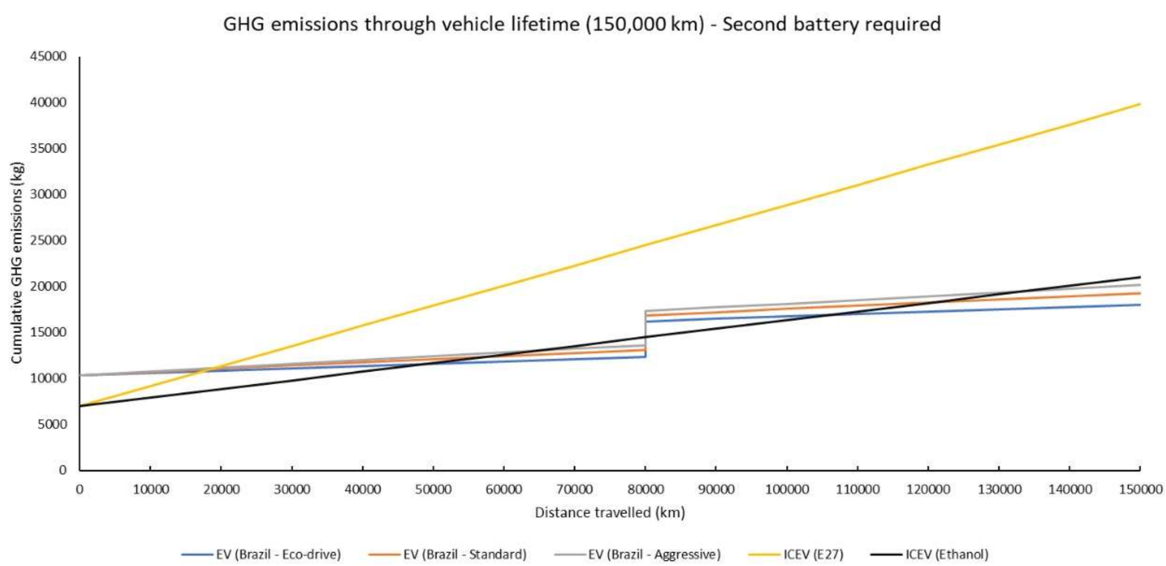


Source: The author

However, there is a strong possibility that a second battery is required in the lifetime of the BEV. As discussed in the previous section, even in such conditions, the BEV would produce the least amount of GHG emissions in its lifetime, but it is important to note exactly when the turning point occurs.

If we consider that the battery will be replaced after half of the estimated lifetime mileage, at around 80,000 km, the meeting of the lines is delayed, as presented in Figure 35, meaning that the mileage at which the EV starts to be beneficial is a considerably higher one. 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. The gasoline remains as clearly the worst option, in terms of GHG emissions, but the ethanol ICEV compares considerably well to the EV. However, it is important to note that in this representation of the GHG emissions throughout the lifetime mileage the effect of recycling is not considered, which was shown to be a key parameter to the overall emissions of both the BEV and ICEV. If recycling is performed, the burden of the second battery would be reduced, so that the benefit at the very end of the life of the BEV will be larger.

Figure 35 - Lifetime GHG emissions comparison between EV in Brazil and ICEV (second battery included)



Source: The author

5.5 Sensitivity Analysis

In the sensitivity analysis section, the effect in results from varying the parameters of the analysis is analysed. More specifically, the influence of the battery production, the vehicle lifetime, fuel or electricity consumption, and battery recycling will be investigated. To do so, the life cycle emissions of the modelled EV and ICEV will be calculated 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 will adopt as baseline the standard driving as the driving behavior 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 will be 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” will adopt, respectively, 100%, 120%, 80%, 50% and 10% of the recycling benefit calculated in the LCA.

For vehicle lifetime, a total of four scenarios will be 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.

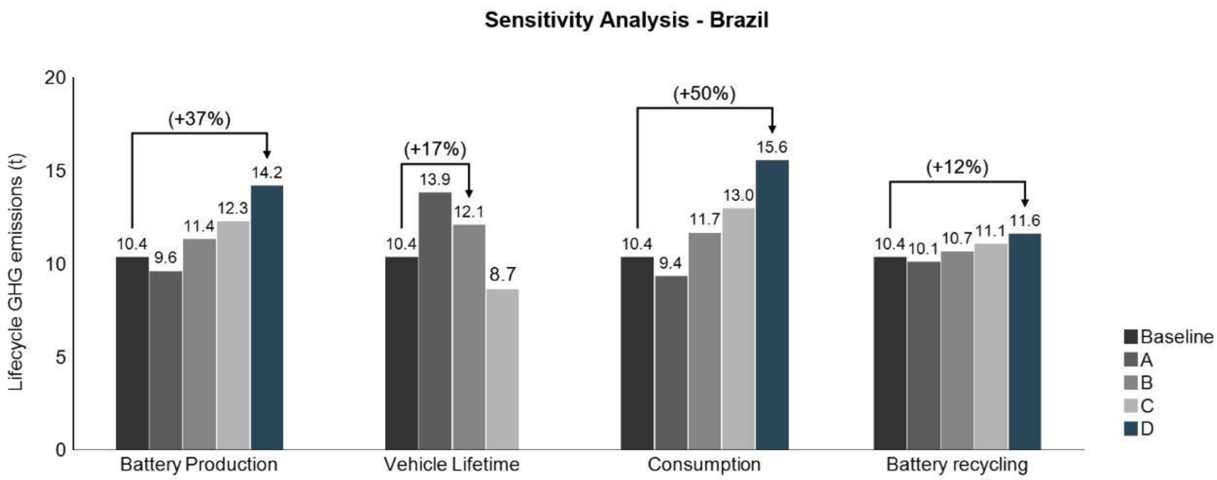
The results of the life cycle emissions for the described scenarios are presented in Figure 36, Figure 37, Figure 38, Figure 39, and Figure 40. Several conclusions can be derived from the results of the different scenarios. First, it is noticeable that changes in the consumption rate have a growing impact, as the source of electricity becomes less renewable. For the Brazilian scenario, doubling the EV consumption will yield 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.

By looking specifically at the case of the EV 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. (2016) and Sanches (2021), as both authors adopted much higher estimates for battery production. Nevertheless, even when doubling the impact of the battery production, the EV 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.

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%.

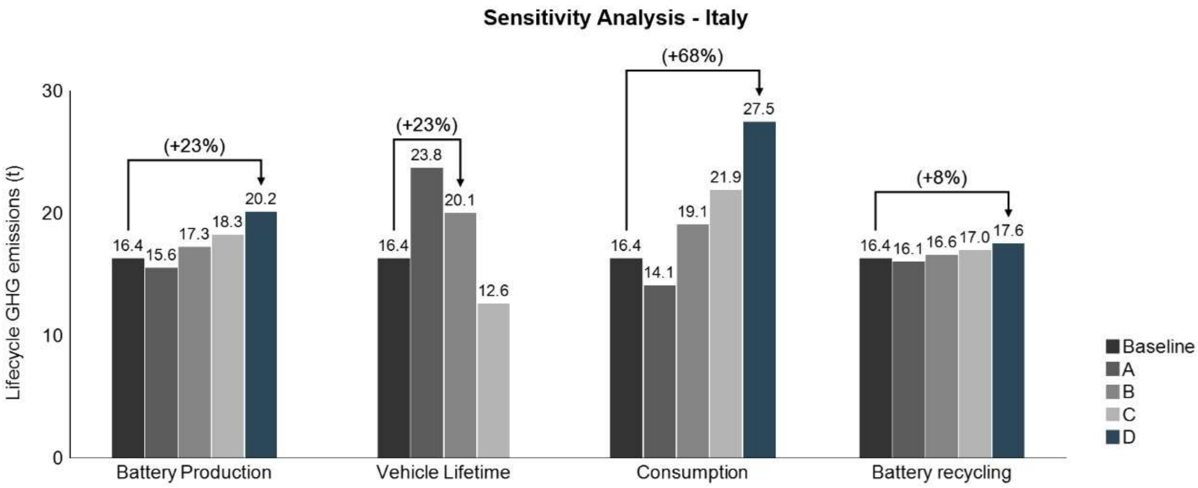
Finally, the ICEV is much more affected from changes in consumption than the EV, which was expected, considering that the Use Phase was shown to be much more dominant for ICEVs than EVs.

Figure 36 - Sensitivity analysis for Brazil electricity grid mix



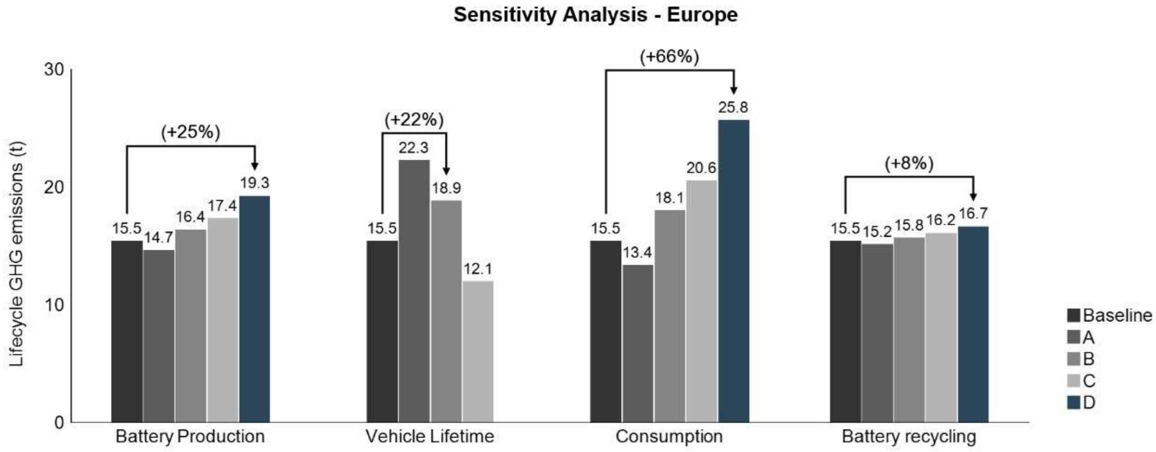
Source: The author

Figure 37 - Sensitivity analysis for Italy electricity grid mix



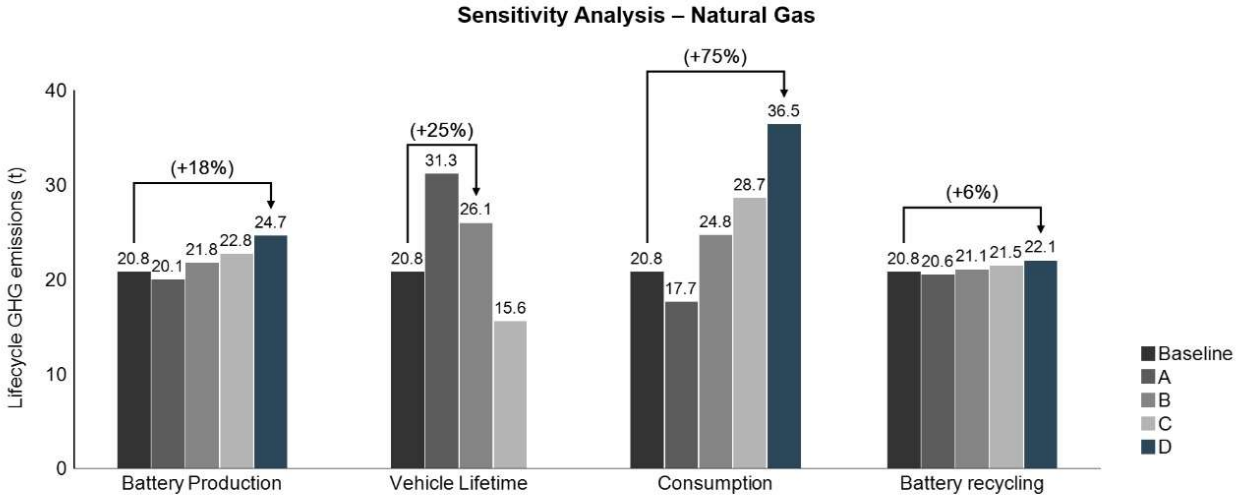
Source: The author

Figure 38 - Sensitivity analysis for Europe electricity grid mix



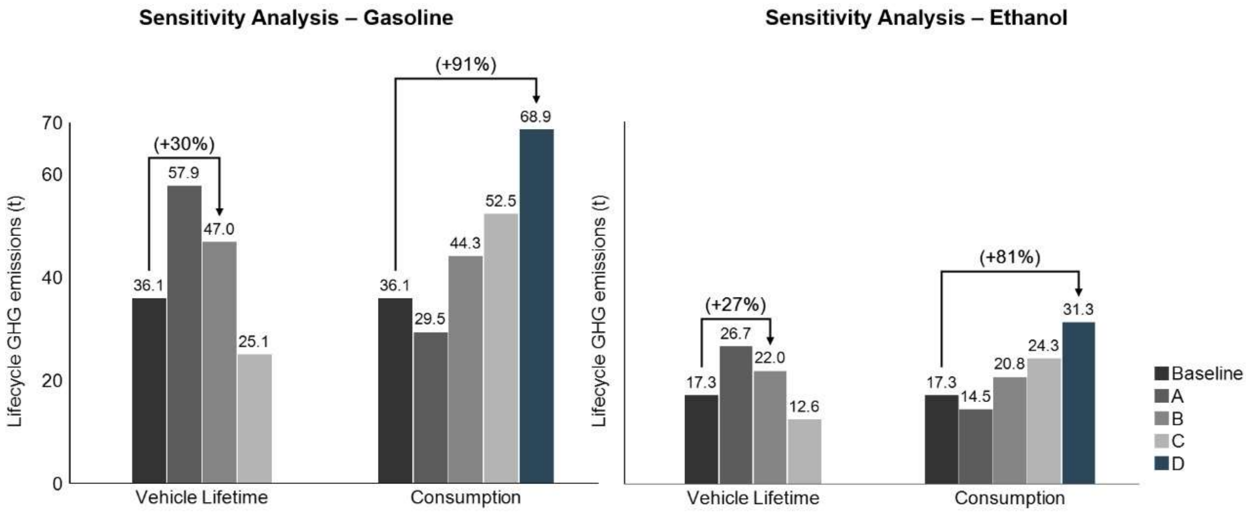
Source: The author

Figure 39 - Sensitivity analysis for Natural Gas electricity grid mix



Source: The author

Figure 40 - Sensitivity analysis for the ICEV with E27 (Gasoline) and Ethanol



Source: The author

6. Conclusion

The goal of this study consisted of evaluating and comparing the environmental impact, measured by GHG emissions, of both an Electric Vehicle and an Internal Combustion Engine Vehicle 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-Wheels) 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 EV, 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. However, 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 EV and the ethanol ICEV is comparable to a considerable degree.

In addition to the pure comparison between powertrain alternatives and different fuels, key parameters to determining the emissions of EVs were also identified. The electricity mix that powers the EV 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.

As for the diffusion of EVs in a São Paulo context, or even in general for Brazil, several public policies are applicable, given the shown benefit of EVs over ICEVs, following what has been done in the main cases of success around the world. In China, for instance, where EVs had a reported 15.4% market share, considering all light-duty vehicles sales, measures such as a strong subsidy scheme policy are pointed as key actions to such relevant figures. Canada's government has also been highly participative, implementing purchase subsidies and strongly investing in EV infrastructure, with approximately USD 769 million invested, to date. The European Union, complementarily to subsidies and infrastructure investments, has also progressively tightened legislation on vehicles CO_2 emissions (IEA, 2022). Moreover, investing in research can be highly beneficial, as it accelerates the development of better production and recycling processes. All of the before mentioned measures, implemented through a structured long-term plan of car fleet electrification, can promote a faster transition to EVs, and, as a consequence, a less environmentally harmful light-duty vehicle based mobility. Finally, public-private partnerships can also be a valuable way of accelerating transition and creating a vast recharging structure, as it was the case with the investments by GWM (PORTAL DO GOVERNO DE SP, 2022).

Finally, 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. First, other impact measures should be assessed in the future, as to provide a more complete picture of the environmental impact of both powertrain technologies. Other impact measures that should be subject of future studies 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 economical, political and structural conditions is fundamental for a complete understanding of the real impact electric vehicles can have in reducing the GHG emissions in São Paulo and Brazil in general.

Directly addressing the discussion that originated this work, it is clear that EVs can play an important role in the general effort of trying to reduce GHG emissions generated by road transportation in São Paulo. However, there are some key aspects that require attention, so that the best results from the use of EVs can be obtained. First, it is essential that the electricity powering EVs derives from clean and renewable sources, such as hydro, wind and solar, as this is one of, if not the most, important factor to the lifetime emissions of the EV, a conclusion reached by this study that reinforces the current view from literature. The development of recycling processes is also key for the long-term success of the technology, given its benefits for both GHG emissions savings and better resource usage, and the possible need of multiple batteries used in the lifetime of the EV. In conclusion, EVs are a valid alternative to the overall goal of reducing GHG emissions from light duty vehicles in São Paulo, but certain conditions must be met so that its full potential benefits are explored.

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