

Louvain School of Management

Comparison of carbon footprint of (electric and thermic) vehicles.

Based on the Life Cycle Assessment method.

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Declaration

During the preparation of this master's thesis, we utilized DeepL and ChatGPT 3.5 for the following purposes:

- **Translation:** We used DeepL to translate some words and sentences.
- **Reformulation:** We used ChatGPT 3.5 to offer better phrasing and a more detailed and technical vocabulary in order to enhance the quality of the writing of this work.

After using DeepL and ChatGPT 3.5, we diligently reviewed and edited the content produced by the tool. We take full responsibility for the final content presented in this thesis.

By signing this declaration, we affirm that the content of this master's thesis reflects our original work, augmented by the responsible use of AI.

Chenut Juliette & Mathieu Maxime
15th July 2024

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Abstract

This master's thesis aims to compare the CO₂equivalent (CO₂eq.) emissions of Battery Electric Vehicles (BEVs) and Internal Combustion Engine Vehicles (ICEVs) fuelled with petrol and diesel over their entire life cycle (LC). The study seeks to identify which phases have the most significant impact on CO₂eq. emissions for each vehicle type. It addresses the question: 'Which type of car (ICEVs diesel/petrol and BEVs) emits the most CO₂eq. over its entire LC and which phases are the most impactful'? The underlying aim of this master's thesis is to provide a clear and comprehensive overview of the situation, given the number of divergent conclusions and findings in the literature.

This research employs the Life Cycle Assessment (LCA) methodology, as defined by ISO (International Organization for Standardization) 14040. LCA is chosen for its comprehensive evaluation of environmental impacts from raw material extraction, production, use, to end-of-life processes, providing a cradle-to-grave analysis. A literature review on the subject (LCA of BEVs and ICEVs) was carried out including data from scientific articles, industrial texts, and popular sources to ensure a broad and accurate perspective. The CO₂eq. emissions results of all these data sources are then pooled to obtain a single CO₂eq. emissions value for each phase and total LC for each type of car.

The findings indicate that BEVs have higher CO₂eq. emissions during the production phase, primarily due to battery manufacturing and during the origin and production of the fuel but with potential improvements when loaded with renewable energy. However, BEVs show significantly lower, even null, results during the use phase. ICEVs consistently emit CO₂ throughout their operational life due to fossil fuel combustion. The end-of-life phase reveals potential for emissions reduction through effective recycling, particularly for BEV batteries. The study also highlights regional variations, with different energy mixes and regulatory environments impacting overall CO₂eq. emissions.

The research concludes that BEVs offer a lower total carbon footprint compared to ICEVs, particularly as the electricity mix becomes greener. This underscores the need for advancements in renewable energy sources, battery production and recycling technologies. Policymakers and industry stakeholders should support these developments and promote the use of renewable energy for charging infrastructure. The study also supports the fact that the end consumer is a key point in this analysis via their driving behavior and their purchasing choices as a consumer. These findings provide valuable insights for making informed decisions towards sustainable automotive practices and highlight the importance of a holistic approach to evaluating vehicle environmental impacts.

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List of abbreviations

BEV: Battery Electric Vehicle

BiW: Body-in-White

CNG: Natural Gas

gCO₂eq./kWh: Gram of CO₂ equivalent per kilowatt-hour

TCO₂eq: tonne of CO₂ equivalent

Distrib.: Distribution

EoL : End-of-Life

EV: Electric Vehicle

FU: Functional Unit

GHG: Greenhouse Gas

GWP: Global Warming Potential

HEV: Hybrid Engine Vehicle

HRES: High Renewable Energy Scenario

ICEV: Internal Combustion Engine Vehicle

IE scenario: Electricity emission intensity scenario (amount of GHG produced per unit of electricity)

ISO: International Organization for Standardization

KTOE: Thousand Tonnes of oil equivalent

LC: Life Cycle

LCA: Life Cycle Assessment

LIB: Lithium-Ion Battery

LPG: Liquefied Petroleum Gas

Maint.: Maintenance

MJ: Megajoule

MEP: Marine Eutrophication Potential

MMTCDE: Million Metric Tonnes of Carbon Dioxide Equivalents

NMP: N-Methyl-2-Pyrrolidone (a type of solvent for lithium-ion batteries)

PHEV: Plug-in Hybrid Engine Vehicle

Prod.: Production

PVDF: PolyVinylidene Fluoride (used as a binder or separator in lithium-ion batteries)

RES: Renewable Energy Sources

WLTC: The Worldwide Harmonised Light Vehicle Cycle

WTW: Well-to-Wheel

WTT: Well-to-Tank

TTW: Tank-to-Wheel

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1 Introduction

Obviously the horse can still do things that the gas car can never do, and the gas car will always be able to do things the electric car can't do. But they have really different uses and advantages.

Chris Paine

We are living through a crucial phase in the world of mobility: fossil fuels are dwindling and climate issues are on the rise. This dual challenge has given rise to plenty of new solutions for the automobile sector but one of them seems to be the most popular in the eyes of the media: the electric car or Battery Engine Vehicle (BEV) (L'echo, 2022; Aramisauto, 2024). This possible key to the new industrial prowess is also extremely supported by European laws and regulations which propose the ban of the purchase of new thermic cars (called during this paper as Internal Combustion Engine Vehicle, (ICEV)) by 2035. The market adapted and anticipated those changes and ramifications have emerged from this duality such as Hybrid Engine Vehicle (HEV) or Plug-in Hybrid Engine Vehicle (PHEV) in response to a demand for a more ecological form of mobility that is not dependent on finite energies (L'essentiel, 2024). Indeed, the importance of this sector is unequivocal as it represents two-thirds of global greenhouse gas (GHG) emissions (Philippot et al., 2023).

In its current state and especially in this domain, information is abundant and diverse. Some advocate for one fact, and others for the opposite. It has become challenging to truly understand what is happening. The electric solution seems to be the rising response to this global crisis, but what is actually the reality of the sector?

Based on this duality, this thesis offers a meta-analysis of the CO₂equivalents (CO₂eq.) emissions of different types of engine (electric/diesel/petrol) to unveil the doubt about the real current situation.

Before starting the subject strictly speaking, it seems necessary to recall the context in which it operates and grows daily.

1.1 Market context

In June 2023, a significant milestone was reached for the European Union's automotive industry: for the first time ever, electric vehicles (EVs) outsold traditional internal combustion engine vehicles. This anticipated shift reflects a remarkable increase in EV market share, soaring from 10.7% to 15.1% within just one year. This sudden shift followed a period of skepticism among buyers, largely influenced by the fallout of the Diesel gate scandal, which eroded trust in conventional vehicle technologies. Despite these developments, gasoline-powered vehicles maintain their dominance, retaining a market share of 36.3% as of June 2023. This landscape underscores a pivotal moment in the automotive sector's evolution, marked by a transformative transition towards cleaner, more sustainable transportation options (L'essentiel, 2023; Babled, 2023).

Electric vehicles represent a real upheaval and are in extremely high demand by consumers to such an extent that they are reshaping the automotive sales sector. Indeed, for the first time, manufacturers are lowering their prices to become more competitive. For example, Tesla decreased its profit margin by 7%, dropping from 19% to 12% in just 2 years, while demand continues to increase (Klein, 2023). Meanwhile, China aims to become ultra-leaders by flooding the market in Europe with their new brand (BYD) which has a very unique business plan: undercutting everyone while remaining in the high-end quality (L'essentiel, 2023).

1.2 European contradictions about mobility

On the one hand, various initiatives are underway to decrease GHG emissions. Notable examples are the European Green Deal, an European Climate Law, which aims for net zero GHG emissions by 2050 or Euro 7 standards, designed to take effect in 2025, reflecting the EU's commitment to lower emissions. Additionally, the EU 'Fit for 55' package sets an interim target of a 55% reduction in GHG emissions by 2030 compared to 1990 levels. Achieving these climate objectives necessitates a significant increase in the proportion of Renewable Energy Sources (RES) in the EU's overall energy generation and consumption mix compared to current levels (Tran, 2023).

In Figure A.1 ¹, there is a table that represents the main guidelines and differences between Euro 5 and 6. One can observe a desire to reduce emissions of various gasses such as HC, CH₄C, PM, ... in order to improve air quality and limit fine particles. What is important to note from this table is that measures are becoming stricter over time, and the trend continues in this direction.

On the other hand, in early March 2023, Berlin made headlines by rejecting a proposed EU law

¹In appendix A: Euro V and VI, figure A.1: Maximum emissions allowed by Euro 5 and 6 (Tran, 2023)

aimed at reducing CO₂eq. emissions from newly manufactured vehicles. Despite this stance, the German capital remains deeply invested in exploring alternative solutions to mitigate carbon emissions in the automotive sector. Berlin's interest lies particularly in the development of synthetic fuels derived from CO₂eq. emissions generated by the industrial sector. Advocates of this technology envision it as a viable competitor to electric vehicles in the effort to decarbonize transportation. If successfully implemented, synthetic fuels could offer a promising pathway for the continued use of internal combustion engine vehicles beyond 2035, as their fuel would be carbon neutral. This underscores their commitment to exploring innovative strategies that align with both environmental sustainability and the automotive industry's long-term viability.

The problem here is to find an approach where the transition is as smooth as possible because straight up banning thermic cars would lead to a massive wave of unemployment at European levels. Indeed, around 12.5 million people are working in this precise sector (L'essentiel, 2023).

On the technological front, the automotive industry is constantly adapting, with discussions already underway about water-based batteries for smaller vehicles (Shen et al., 2023). There is a real debate about the emergence of new technologies and which path shall be taken over the others. The debate remains open, and all stakeholders are trying to gain the upper hand on their competitors.

All these externalities make the mobility horizon more difficult to define and enable certain behaviors that directly oppose the environmental crisis. This multidisciplinary problem affects everyone at different intensities and in several ways. It must therefore be treated with enormous vigilance and always oriented towards the future by planning arrangements in the present. This is how in this context, this constant contradiction between what we hear and what is done that the research question takes on its full meaning: "what are the CO₂eq. emissions of ICEVs and BEVs using the Life Cycle Assessment (LCA) approach and what are the life cycle (LC) phases that influence this result the most ?" because it will serve as a checkpoint about the whole process behind the mobility sector.

2 Methodology

2.1 Objectives

The primary objective of this master's thesis is to compare the CO₂eq. emissions of ICEVs with BEVs throughout their entire LC. This comparison aims to evaluate and contrast the CO₂eq. emissions of these vehicle types, providing insights into the most impactful LC phases in terms of CO₂eq. emissions for each vehicle category. The ultimate goal is to contribute to the understanding of the environmental impacts of these vehicle technologies and inform more sustainable choices in the automotive sector.

2.2 Choice and definition of the comparison method: Life Cycle Assessment

The comparison method chosen for this study is the Life Cycle Assessment. According to the ISO (International Organization for Standardization) standard 14040 (2006), "LCA addresses the environmental aspects and potential environmental impacts throughout a product's LC from raw material acquisition through production, use, end-of-life treatment, recycling, and final disposal (i.e., cradle-to-grave)."

In other words, according to Del Pero et al. (2018), LCA is: "an environmental accounting methodology which allows identifying, quantifying and assessing the impacts involved by the entire LC of a product/process basing on the inventory of all environmentally relevant flows (i.e. emissions, natural resources, material and energy, waste) exchanged with the ecosystem."(p. 523)

The ISO standards (from 14041 to 14045) also set different principles to detail the requirements and the processes for conducting a LCA. The list with the title of these different principles are presented in the figure B.1 ¹.

We selected this LCA method for several reasons:

- Comprehensive scope: LCA provides a holistic view of the environmental impacts (in our case CO₂eq. emissions) of ICEVs and BEVs, covering all stages from cradle to grave.
- Standardization: A lot of scientific articles use the ISO standards to perform their LCA, it allows easy comparison between them and ensures that the methodology is well established and widely accepted in the scientific community.

¹In appendix B: ISO standards 14040 - 14045, figure B.1: ISO series standards about LCA (Lai et al., 2022)

- **Comparability:** LCA allows for a detailed, easier and structured comparison of the different vehicle types and the phases that compose their LC.
- **Environmental relevance:** By focusing on the entire LC, LCA identifies the phases with the highest and the most complete environmental impact, enabling targeted improvement.

Here are the different steps that we are going to follow in order to perform our analysis and so to meet the objective of this master's thesis, we are going to develop them in more details later within section 2.5.:

1. **Define the LC phases.** This first step involves defining with precision and completeness the various phases of the ICEVs and BEVs LC based on rigorously selected and analyzed scientific articles and more informal sources.
2. **Quantify CO₂eq. emissions.** This second step is to quantify the CO₂eq. emissions for each LC phase of the vehicles. This quantification will be grounded in the results obtained from the selected literature.
3. **Comparative analysis.** In this final step, we will compare the CO₂eq. emissions results of each LC phase between vehicle types (vertical comparison) and within the same type (horizontal comparison). Subsequently, we will aggregate the results of all phases to enable a comprehensive comparison of the total LC CO₂eq. emissions of the studied vehicles.

2.3 Data sources

The data for this study are drawn from three main types of sources: scientific articles (54), industrial texts (20), and newspaper or internet articles (13), totaling 87 sources. This multi-tiered approach ensures a comprehensive understanding of the current situation and minimizes research bias. By incorporating diverse types of sources, we aim to present an accurate and current picture of the CO₂eq. emissions associated with different vehicle types, reflecting both scientific research and general public discourse.

2.4 Scope of the analysis

2.4.1 Types of vehicle

This study focuses on passenger cars as defined by the Regulation (EU) 2018/858 of the European Parliament and of the council of May 30, 2018: "motor cars designed and constructed primarily for the carriage of passengers and their luggage."(p.14)

Within passenger cars, the study will examine BEVs and ICEVs using petrol and diesel fuels.

For electric vehicles (EVs), the scope is limited to BEVs, even if there exists 2 other types of electric vehicles: PHEVs and HEVs. It was decided as such because hybrids are only seen as a transitional stage in the automotive spectrum. We will focus on BEVs' LC in China and Europe to analyze the differences of their respective electricity mixes to fuel the battery of the car and the impact of these differences.

While for ICEVs, the focus will be on diesel and petrol vehicles, as these are the most widely used fuels globally. According to the European Automobile Manufacturers' Association, in 2019, 58.9% of new cars produced are ICEVs petrol and 30.5% are ICEVs diesel (figure C.1 ¹) (European Automobile Manufacturers' Association, 2021). Natural gas (CNG), Liquefied Petroleum Gas (LPG), and biofuels have been excluded from our scope for conciseness and due to their lower consumption worldwide.

2.4.2 Functional unit and TCO₂eq.

When carrying out a LCA, it's essential to establish and define what we assess with a functional units (FU). According to Nordelöf et al. (2014), the FU of a complete LCA is: "a vehicle LC, which is specified by a total number of driven kilometers." (p. 1880). This FU could be 1 km, 100,000 km, 150,000 km, 200,000 km etc and all the CO₂ emissions of each LC phase are expressed according to this FU.

It is also essential to define the unit in which results are expressed: it could be gCO₂eq./km, kgCO₂eq./km, kgCO₂eq. or TCO₂eq. for the corresponding FU. When the study considers a FU of 1km (the results are expressed per km), the value of the mileage independent phases depend on the driving mileage of the car considered in the study.

For our comparison in this report, we have chosen TCO₂eq. (tonnes of carbon dioxide equivalent) with a FU of 150,000km as the measure of comparison.

According to the European Environment Agency (EEA), carbon dioxide equivalents (CO₂eq.) are commonly expressed as "million metric tonnes of carbon dioxide equivalents (MMTCDE)". The carbon dioxide equivalent for a gas is calculated by multiplying the tonnes of the gas by the associated Global Warming Potential (GWP). So, we obtain the following formula: MMTCDE =

¹In appendix C: Types of cars produced in Europe in 2019, figure C1: Types of new cars produced in Europe in 2019 (European Automobile Manufacturers' Association, 2021)

(million metric tonnes of a gas) $\times$ (GWP of the gas) (EEA, n.d.).

We choose these parameters given that in most of the studies we analyzed, this mileage driving was chosen (it represents an average of 5 years of driving approximately) and in our sense, $\text{TCO}_{2\text{eq}}$ are more meaningful figures than the other possible units.

2.5 Methodological process

2.5.1 Definition of the life cycle phases

So, the first step of our analysis will be the definition of the LC phases for each type of vehicle. To enable an analysis and a future comparison of the 2 types of vehicle (BEV and ICEV), they are treated in a comparable manner (same LC phases) to enable the ability to benchmark them while respecting their respective specificities.

Here are the different LC phases we have selected based on the LC Structure and Boundaries of these following authors, M. Hirz, A. Nordelöf, etc. (Figure D.1, D.2, D.3 and D.4 ²):

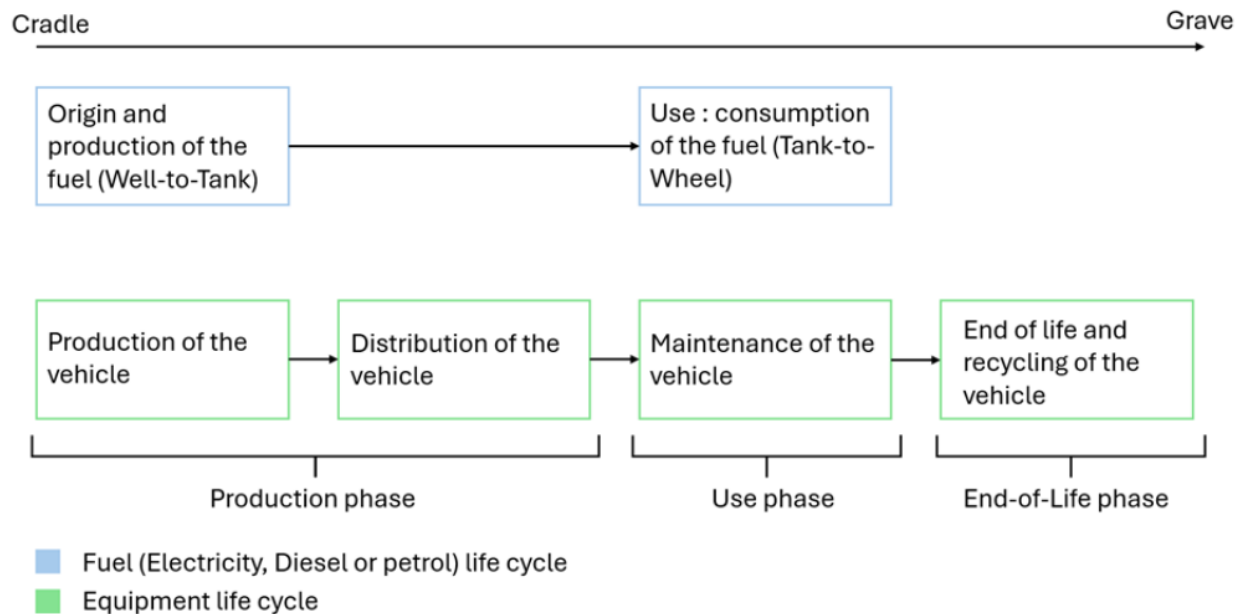


Figure 1: LC structure and boundaries

As you can observe on this graph, the LC is divided into two main sections. The fuel LC, also known as the Well-to-Wheel (WTW) LC and the equipment LC.

²In appendix D: LC structures and boundaries references

The fuel LC corresponds to the LC of the fuel (electricity for BEVs, petrol for ICEVs fuelled with petrol and diesel for ICEVs fuelled with diesel). It is composed of:

- The origin and production of the fuel phase also known as the Well-to-Tank (WTT) phase: the extraction of raw materials to produce the fuel, to the distribution of fuel into the vehicle's tank or the battery.
- The use phase also known as the Tank-to-Wheel (TTW) phase: the consumption of the fuel within the vehicle (Hirz & Nguyen, 2022, Nordelöf et al., 2014).

The equipment LC corresponds to the LC of the entire vehicle, this includes the LC of the glider (the structure of a vehicle without its motor or powertrain components) and the powertrain system. It includes:

- The production phase: it goes from material production (including raw materials extraction), through parts manufacturing to vehicle assembly (Yang et al., 2021).
- The distribution phase: the movement of the final vehicle from the production factory to the point of use (Tashtoush et al., 2023).
- The maintenance phase: the replacement of certain vehicle parts at more or less regular intervals.
- The End-of-Life (EoL)/recycling phase.

Once the LC structure and boundaries used for our work have been delimited, the next step is to define clearly and completely these different phases constituting the LC thanks to the lecture and analysis of our selected data (cfr 2.4: data sources). To analyze the data, we have created the following analysis grid:

- | | | |
|--|--|--|
| • APA reference | • Type of data (database, primary, secondary data) | • EoL phase |
| • LCA : yes or no | • Origin and production of the fuel phase | • Impact categories |
| • Others ? | • Production phase | • Particularities of the study (location, lifetime considered, vehicle model + features, etc.) |
| • BEVs : yes or no | • Distribution phase | • Main conclusions |
| • ICEVs : yes or no (if yes, petrol or diesel ?) | • Use phase | • Results (CO2 emissions) |
| • Entire vehicle ? Yes or no | • Maintenance phase | |
| • Specific component ? | | |

Figure 2: Analysis grid for the document analysis

2.5.2 Quantification of the CO₂eq. emissions

The second step is the quantification of the CO₂eq. emissions for each phase. To do this we can aggregate the results from the different data sources and so allocate a CO₂eq. emission value for the corresponding phase.

Firstly, we need to aggregate all the results of the studies analyzed for each of the phases: Origin and production of the fuel (WTT), use (TTW), production, distribution, maintenance, EoL and the total LC (addition of all the phases) to obtain a final value for each of these categories and be able to compare them. Indeed there are fairly wide variations in the results of the studies due to several possible reasons:

- Variation in scope delimitation
- Differences between energy sources (especially for our case)
- Use of different quantitative tools (database, LCA simulation software...)
- Assumptions about different arbitrarily chosen values: lifespan, driving mileage or type of battery production, etc (Nordelöf et al., 2014; Horne, 2009).

The median was chosen to aggregate all the results, as outliers have less influence than the average. Mathematically the median can be defined as the 0.5 quantile ($\phi(0.5)$) of the random variable Y (in our case, $Y = Y_x$ = the CO₂eq. emissions results for the LC phase x). $\phi(0.5)$ can be defined as follows : The smallest value such that $P(Y \leq \phi(0.5)) = F(\phi(0.5)) \geq 0.5$. If Y is continuous, $\phi(0.5)$ is the smallest value such that $F(\phi(0.5)) = P(Y \leq \phi(0.5)) = 0.5$ (Wackerly et al., 2008).

Before calculating it, it is essential to put all the results in the same unit (in TCO₂eq. for a FU of 150,000 km, cfr section 2.4.2).

Using the same units is a matter of simple mathematics, but there are certain special cases when the driving mileage or the FU considered in the study is different from 150,000 km:

- If the results of the mileage independent LC phases (phases that do not depend on the number of km driven by the car) ; Production, distribution, EoL ; are expressed per km and the driving mileage considered is other than 150,000 km. The results of the fixed phases per km cannot simply be multiplied by 0.15 (gCO₂eq./km -> TCO₂eq./150,000km). They must be multiplied by the driving mileage considered in the study.
- When the driving mileage is: 100,000km, 200,000km etc with results in kgCO₂eq. or TCO₂eq. The mileage dependent LC phases (phases depending on the number of km driven

by the car) ; Usage, origin and production of the energy (WTT), maintenance ; must undergo a rule of three. The results must be divided by the driving mileage to obtain a result per km and then multiplied by our FU of 150,000 km.

- When a study only includes CO₂eq. emissions for the total LC as a result and has one of the two cases above as its driving mileage considered. We do not know what percentage of mileage dependent and independent LC phases per km is included in the total result. We therefore have to make assumptions about the percentage of each phase in relation to all the studies we have analyzed.

Once all of this has been done, we will calculate the median defined previously. In practical terms, we will sort the results of each LC phase in ascending order, if the number of results is odd we take the middle result, if the number of results is even we take the two middle results and calculate the average of the two. After this, we will obtain a single value of CO₂eq. emissions for each phase of the LC of BEVs and ICEVs petrol and diesel. To make everything more visual, we also used the "boxplot" tool (figure E.1: "How to read a boxplot" ¹). This allows us to highlight where the median is located within the statistical range and have a representation of the results' distribution.

In addition to this, we will add an externalities section for BEVs. We are going to take into account some externalities (the weather, the electricity mix of countries, the driving behavior etc.) that could increase the median in order to obtain the "worst case" possible for BEVs and then compare this scenario with the others results.

2.5.3 Comparison analysis

We will first make a vertical comparison: comparison of the CO₂eq. emissions results of each LC phase between vehicle types. We will also aggregate the results of all phases to enable a comprehensive comparison of the total LC CO₂eq. emissions of the studied vehicles.

And then, a horizontal comparison: comparison of the CO₂eq. emissions results of each LC phase within the same vehicle type.

Finally, we are going to make a break-even analysis with the median calculations we found in order to see the dependence of impact on LC mileage (Del Pero et al., 2018).

¹In appendix E: How to read a boxplot ?

3 The Internal Combustion Engine Vehicle

The scope of this analysis is based on:

- A classic ICEV passenger car
- Mileage of 150,000 km
- Driven across the world but with a focus in Europe

As previously mentioned, we will focus on two types of fuels: diesel (or gas oil) and petrol. These are the primary fuels consumed worldwide.

For this part, we based our analysis on 34 studies (22 about ICEV petrol, 1 about ICEV diesel and 10 about both petrol and diesel).

Each phase of the LC described below comprises various stages, but we will only provide an overall distribution of the results (based on the results of the data sources we analyzed) for the entire phase based on the analyzed data sources. However, we will detail what these different stages entail and include figures to give a sense of scale. Due to the limited data available in the studied articles, more detailed results cannot be provided.

3.1 Origin and production of the fuel

This section focuses on the WTT phase of the fuel LC, which is part of the WTW analysis. This phase encompasses the extraction of raw materials to produce the fuel, to the distribution of fuel into the vehicle's tank (figure D.1 ¹).

Before getting to the heart of the matter, it's important to understand how petrol differs from diesel. Both fuels are derived from the distillation of crude oil, with their differences lying in the hydrocarbons they originate from and the ignition process in their respective engines.

Diesel is derived from heavier hydrocarbons compared to petrol. Petrol consists of a mixture of alkanes and cycloalkanes with chains containing between 5 and 12 carbon atoms, with boiling points between 40 and 205°C. While diesel consists of alkanes with 12 or more carbon atoms, which have boiling points ranging from 250 to 350°C. So both diesel and petrol come from crude

¹In appendix D: LC structures and boundaries references, figure D.1: Sequences of energy provision and conversion for vehicle propulsion (Hirz & Nguyen, 2022)

oil but are different in the refinery process they require and the resulting hydrocarbons (figure F.1¹) (European Automobile Manufacturers' Association, 2016).

For the consumption of the fuel within the engine, we will focus on this part in the Usage/Tank-to-Wheel section.

The various phases included in the WTT part of the fuel LC are as follows:

1. Recovery or production of the feedstock
2. Transportation of the feedstock
3. Conversion of the feedstock to the final fuel (refinery - high and low conversion capacity refineries) and subsequent storage
4. Distribution and delivery to the vehicle tank (Del Pero et al., 2018).

In summary, these are all the processes involved in transforming the fuel before its consumption in the vehicle's engine (Del Pero and al., 2018).

Emissions associated with construction facilities (machinery, buildings, etc.) are generally excluded from studies.

Several additional factors can affect CO₂eq. emissions from fuel production:

- The type and quality of crude oil
- Upstream fuel production technologies.
- Variations in transportation and distribution (transport type such as maritime or railway, distance, whether the country is a producer or not) (Hirz & Nguyen, 2022).

In general, WTT emissions amount to between 10% and 20% of TTW emissions for conventional fuels, with a higher impact for petrol and a lower impact for diesel (Hirz & Nguyen, 2022). For Masnadi et al. (2018), the WTT emissions account for 15% to 40% of the total WTW cycle.

The transport, distribution, and storage stages are quite variable and have a smaller impact compared to oil extraction and refining.

¹In appendix F: Fractional distillation in oil refining, figure F.1: Fractional distillation in oil refining (European Automobile Manufacturers' Association, 2016)

Masnadi et al. (2018) made an inventory of the upstream CO₂eq. emissions produced by the oil extraction, refining and transportation across the world. The global volume-weighted-average upstream carbon intensity estimate is 10.3 g CO₂eq./megajoule (MJ) crude oil, with Denmark in last position (3.3 gCO₂eq./MJ) and Alegria with the top position (20.3 gCO₂eq./MJ) (Masnadi et al., 2018).

Gopinathan (2020) found that 1t of crude oil exported to India causes 0.48235t of CO₂eq. emissions in the extraction sites, and 8g CO₂eq./km is emitted per kg of refined fuel. According to him, the CO₂eq. emissions from WTT phase for diesel and gasoline would be approximately 27g CO₂eq./km (a bit more than 20% of the TTW phase, and approximately 19% of the WTW cycle). The highest contribution comes from the oil extraction (approximately 19g CO₂eq./km), followed by the oil refining (approximately 8g CO₂eq./km) and a small impact from the oil transportation has to be taken into account (figure G.1¹).

Quantification

Once we aggregated all the results we found in the data sources, we obtain the following results:

- **Petrol** (TCO₂eq.):

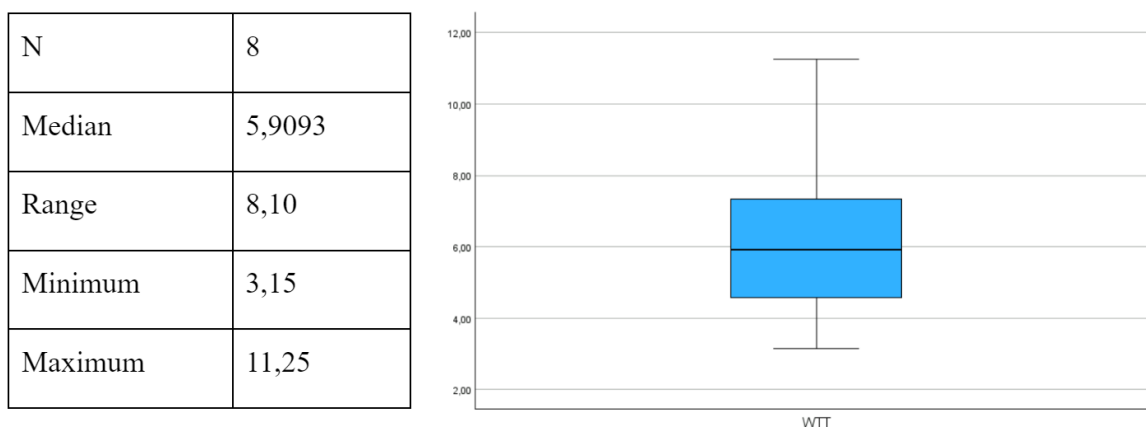


Figure 3: Median results for the WTT phase of an ICEV petrol in TCO₂eq. and boxplot

- **Diesel:** We only found a single observation, 31.2 TCO₂eq. in Joshi et al., (2022).

There are very few results from studies on the WTT phase (especially for diesel) because this is an extremely variable phase for which it is difficult to find reliable and actual sources of information. These studies differ in parameters such as location, whether the country is an exporter or importer,

¹In appendix G: Emissions of WTW LC of BEVs and ICEVs, figure G.1: Emissions per kilometer of operation of vehicles in 2030 in HRES (Gopinathan, 2020)

and the system boundaries in the LCA. Many studies exclude the extraction of raw materials or the transportation of fuels due to a lack of data. In addition, many authors use a common calculation for the complete LC of the fuel (WTW LC) and not for the WTT and TTW parts separately. We have therefore also calculated a median and a boxplot for the WTW LC of petrol and diesel fuels (origin and production of the fuel + use) to give an order of magnitude ¹. The median for petrol is 33.75 TCO₂eq. (21 observations) and for diesel, 30.00 TCO₂eq. (9 observations).

3.2 Production

We can combine two different distinction criteria to split the production phase:

Decomposition of the vehicle:

- Glider (chassis, exterior, interior, wheels, etc.)
- Powertrain system

Decomposition of the production process:

- Material production (including raw materials extraction)
- Parts manufacturing
- Vehicle assembly (Yang et al., 2021).

This also includes the transport of products between each stage.

The production phase for diesel and petrol ICEVs is quite similar. The glider is the same, and the petrol and diesel ICEV powertrains have approximately the same composition (Habermacher, 2011; Naranjo et al., 2021).

The typology and quantity of materials, as well as manufacturing processes for each vehicle component, are determined through a breakdown analysis of the vehicle. The vehicle consists of several units, which can be subdivided into smaller units down to the individual component (de Souza et al., 2018).

Typically, the compositions and mass distributions in studies are based on specific models using confidential industrial information or databases such as Ecoinvent, GREET or GaBi.

¹In appendix N: Median results and boxplots, figure N.1 for petrol and N.2 for diesel

First, in terms of materials contained in the vehicle:

Shafique and al. (2022) use the composition in figure G.2 ¹. with sources from Ecoinvent data, GREET 2019, and confidential industry data, with a total car's weight of 1395 kg. (Shafique and al., 2022). This is the most precise breakdown analysis that we found in our comparison analysis.

With this mass, materials and energy breakdown analysis, we can see that the most demanding part of the ICEV for materials is its vehicle body and chassis (glider) , followed by the lead acid battery, then the powertrain system (+ transmission system). The glider is mainly composed of steel and plastic, the powertrain and transmission system of steel, aluminum and iron.

To understand the only difference in the composition of petrol and diesel ICEVs, it's necessary to take a closer look at the composition of the powertrain system. Hirz & Nguyen (2022) propose a structure for diesel and petrol powertrains (figure I.1 ²). The only difference between petrol and diesel ICEVs lies in the exhaust system. The exhaust system of an ICEV is a series of components designed to direct and manage the gasses produced during combustion. For petrol engines, it consists of a three-way catalyst, whereas for diesel engines, it includes an oxidation catalyst and NOx reduction (Hirz & Nguyen, 2022).

Now, let's review the various processes involved in the production of an ICEV:

The most comprehensive description of the different processes in the studies we reviewed is found in the study by Yang et al. (2021).

Material Production Phase: Several processes are carried out during the material production phase. We have mining extraction, enrichment, smelting, and refining of metals. For polymer production, the processes include oil and gas recovery, refining, and synthesis of raw materials.

Parts Manufacturing: Parts manufacturing involves molding, rolling, stamping, and drawing (Sullivan et al., 2013 & Wang et al., 2012 as cited in Yang et al., 2021). It is important to consider the consumption of primary fuels associated with these processes, such as natural gas, coal, and electricity, as they are the primary source of CO₂eq. emissions during this phase (Kim et al., 2016 & Wang et al., 2013 as cited in Yang et al., 2021). Additionally, residual oil, diesel, liquefied natural

¹In appendix H: Mass breakdown analysis, figure H.1: Mass and energy balance of ICEV and BEV's vehicle production (Shafique et al., 2021)

²In appendix I: Powertrain system ICEVs petrol and diesel, figure I.1: Powertrain structure of conventionally driven cars diesel and petrol (Hirz & Nguyen,2022)

gas, and thermal energy are also consumed, though their emissions are relatively low compared to the primary fuels.

Vehicle Assembly: Finally, vehicle assembly includes painting, material handling, heating, welding, and other processes (Sullivan et al., 2013 as cited in Yang et al., 2021).

Once this decomposition of materials and processes is performed, each unit of the vehicle and each process must be associated with CO₂eq. emissions. For this, the authors of the different studies once again use databases and LCA simulation software.

To calculate the CO₂eq. emissions related to a production process, Farzaneh & Jung (2023) proposes this equation: (Energy per mass × Vehicle mass × Carbon footprint coefficient) / 1 000 000

With:

- Energy per mass: quantity of energy required to make the process for each kg of materials
- Carbon footprint coefficient: the quantity of CO₂eq. emissions produced per unit of energy required in gCO₂eq./kWh (Farzaneh & Jung, 2023).

For the material production, they found 13.77 TCO₂eq. for an entire ICEV and for the manufacturing, 3,405 TCO₂eq. We see that the process of raw material extraction has much more impact than the manufacturing of the car. These numbers depend on the carbon footprint coefficient specific to a country or a region, so the production phase's CO₂eq. emissions can vary across countries and their specific electricity mix generation (Farzaneh & Jung, 2023).

According to Qiao et al. (2017), assembling a vehicle consumes 852 MJ of electricity and 5568 MJ of natural gas per vehicle. We can have a closer look to the results of Del Pero et al. (2018), they made a contribution analysis by vehicle assembly (figure J.1 ¹). With approximately 23% for Body-in-White (BiW: assembly part before painting etc), 16% for door and closures, 24% for drivetrain (powertrain), 6% for electrics/electronics, 13% for interior and 18% for suspension and chassis (Del Pero et al., 2018).

Hirz & Nguyen (2022) provide a synthetic version of the contributions of material production and the different parts constituting the vehicle. They do not base it on a particular car model but on

¹In appendix J: CO₂eq. emissions during production phase for ICEVs, figure J.1: Contribution analysis by vehicle assembly of production impacts (ICEV), (climate change for CO₂eq. emissions) (Del pero et al., 2018)

general mean characteristics (figure J.2 ¹).

Thanks to this graph, we can see that according to Hirz & Nguyen (2022) 's works, the total CO₂eq. emissions for the production phase is 7,5 tonnes. Regarding the main modules of the vehicle, we observe that the main contribution in terms of CO₂eq. emissions is the car bodywork with 28%, closely followed by the powertrain and the interior with 22% and 20% respectively. Then we have electrics and electronics with 17%, chassis with 9% and finally exterior with 4%. In terms of materials used, the most polluting would be steel, followed by aluminum, electrics and electronics, polymers and finally other materials.

Steel is in first position due to its large quantity in the glider's composition, but aluminum remains the most polluting material: As already explained in the BEV's part, steel accounts for approximately 2 tonnes of CO₂eq. emissions per tonne of finished product and aluminum between 10 to 15 tonnes of CO₂eq. emissions per tonne of finished product (Hirz & Nguyen, 2022).

We can also have a look to the results of Shafique et al. (2022) (figure J.3 ²). In this study 35% of the CO₂e emissions come from the production of the vehicle body (glider), 21% from the vehicle assembly, 18% from the production of the powertrain system, 14% from the production of the chassis (glider), 7% from the production of the transmission system (powertrain), 4% from the vehicle fluids and 1% from the lead acid battery.

So, in general authors agree to state that the glider emits more CO₂eq. emissions than the powertrain system during the production phase for an ICEV and the production of raw materials emits more CO₂eq. emissions than the manufacturing and the assembly part.

Quantification

Once we aggregated all the results we found in the data sources, we obtain these results:

¹In appendix J: CO₂eq. emissions during production phase for ICEVs, figure J.2: CO₂eq. emissions of the production of the parts and the materials constituting an ICEV (Hirz & Nguyen, 2022)

²In appendix J: CO₂eq. emissions during production phase for ICEVs, figure J.3: Contribution of the components of each vehicle during the production phase (Shafique et al., 2022)

- **Petrol** (TCO₂eq.):

N	21
Median	5,3400
Range	13,82
Minimum	3,30
Maximum	17,12

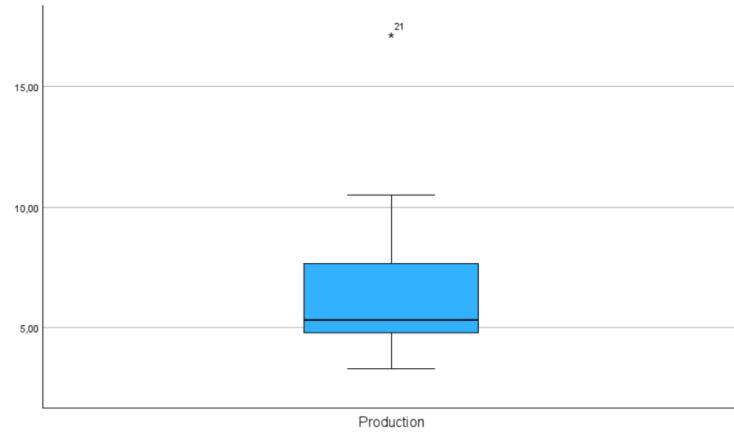


Figure 4: Median results for the production phase of an ICEV petrol in TCO₂eq. and boxplot

- **Diesel** (TCO₂eq.):

N	9
Median	5,2900
Range	5,70
Minimum	3,30
Maximum	9,00

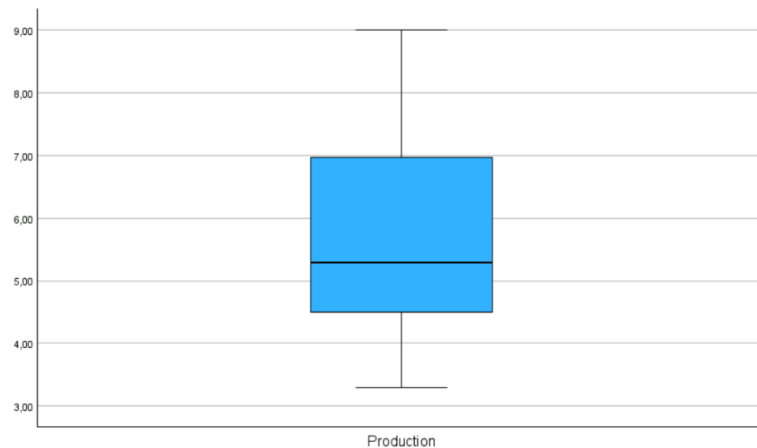


Figure 5: Median results for the production phase of an ICEV diesel in TCO₂eq. and boxplot

3.3 Distribution

The distribution phase for petrol and diesel ICEVs is minimal compared to other phases of the LC. This transportation phase is defined by the movement of the final vehicle from the production factory to the point of use. CO₂eq. emissions during this phase are primarily derived from the fuel consumption of the vehicle transporting the merchandise (Tashtoush et al., 2023).

Several factors can influence these emissions: the distribution distance, the mass of the vehicle,

the type of transport vehicle (ship, railway etc.), the energy consumption coefficient, and the emission factors. These elements determine fuel consumption and, consequently, the CO₂eq. emissions during the distribution phase (Wang et al., 2013 as cited in Yang et al., 2021).

Quantification

Once we aggregated all the results we found in the data sources, we obtain these results:

- **Petrol** (TCO₂eq.):

N	6
Median	0,4125
Range	0,64
Minimum	0,01
Maximum	0,65

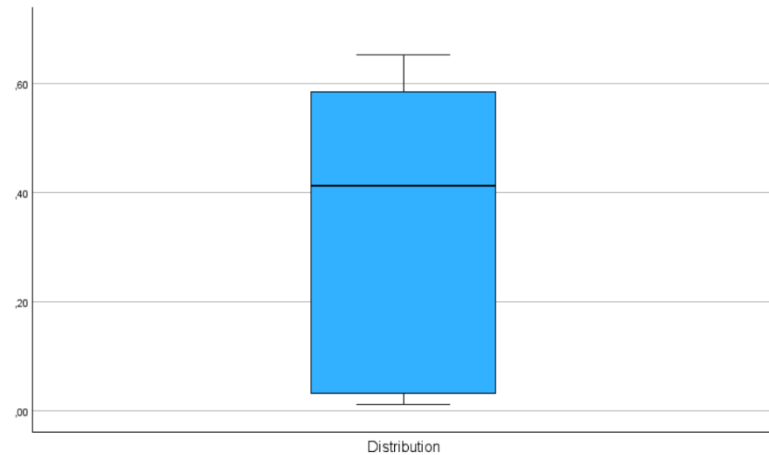


Figure 6: Median results for the distribution phase of an ICEV petrol in TCO₂eq. and boxplot

- **Diesel** (TCO₂eq.): We only found 2 observations, 0.45 and 0.49 TCO₂eq.

3.4 Use

The operational phase of the vehicle has the most significant impact on CO₂eq. emissions in the LC of both petrol and diesel ICEVs.

This phase corresponds to the TTW part of the fuel LC (WTW). It involves the conversion of energy within the vehicle, including the combustion process of the fuel. This combustion is the primary source of CO₂eq. emissions during the vehicle's usage phase (Hirz & Nguyen, 2022).

The difference between diesel and petrol during this phase lies in the way the fuel is consumed within the engine. Diesel engines ignite fuel by compressing air at very high pressure, generating heat that ignites the diesel, thus powering the engine. In contrast, petrol engines use a spark plug to produce a spark, igniting the petrol-air mixture. Petrol comes in two types: SP95 and SP98, with the numbers indicating the octane rating. A higher-octane rating means easier ignition and less

engine wear (Proxi-TotalEnergies, 2024).

The factors determining the CO₂eq. emissions produced by fuel combustion in petrol and diesel ICEVs during their use are:

- Fuel efficiency (fuel consumption)
- Fuel emission factor
- (Driving mileage) (Yang et al., 2021).

Fuel efficiency refers to the amount of fuel consumed by a vehicle (in kilograms or liters) to travel a distance of 100 km. In our selection of studies, the average fuel consumption for petrol ICEVs is 6.9 l/100 km and for diesel ICEVs is 5.9 l/100 km. This value, specific to a car, depends on the fuel type, the car features and the user behavior (driving pattern and style). In many studies they define the user behavior according to the World harmonized Light vehicle Test Cycle (WLTC) and average user-behavior schemes (Hirz & Nguyen, 2022).

The fuel emission factor refers to the amount of CO₂eq. emissions (grams) produced by the vehicle per liter of fuel consumed. Many studies in our selection are conducted in Europe and are based on EURO 5 and EURO 6 standards ¹. The emission factor depends on the properties of the fuel used by the vehicle, including the region, country, and ambient temperature. It can be calculated using two factors: the density of the fuel (g/l) and the carbon content of the fuel (kgCO₂eq./kg fuel). According to the European Commission, the average fuel emission factor is:

- 22.78 (100 gCO₂eq./l) for petrol ICEVs (with an average fuel density of 749.5 g/l and carbon content of 0.03039 kgCO₂eq. /kg fuel)
- 26.31 (100 gCO₂eq./l) for diesel ICEVs (with an average fuel density of 835.0 g/l and carbon content of 0.03151 kgCO₂eq./kg fuel) (European Commission, 2024).

For Hirz & Nguyen, 2022, the emission factor equals to 23.2 for gasoline and 26.2 for diesel. These figures are very similar to those given by the European Commission. The difference between petrol and diesel is due to their slightly different ratio of hydrogen and carbon content. (Hirz & Nguyen, 2022).

The Worldwide Harmonised Light Vehicle Test Procedure (WLTP) is used to test and establish the official fuel consumption and CO₂eq. emissions of passenger cars. This has been mandatory

¹See appendix A: EURO V and EURO VI

since September 2018 and focuses on calculating these figures based on "real-world" consumption (Vehicle Certification Agency, 2021).

Finally, driving mileage refers to the total distance covered by the vehicle during its LC as considered in the study. This choice can significantly impact the results of the LCA. The longer the vehicle can drive, the more CO₂eq. emissions it produces over time and the more maintenance it requires. Conversely, the shorter the vehicle's lifespan, the less the emissions from production, distribution, and End-of-Life phases are amortized.

Fuel consumption and the fuel emission factor together form the following equation to obtain the amount of CO₂eq. emissions in grams per kilometer traveled: CO₂eq. emissions (g/km) = (Fuel consumption (l/100km) × Emission factor (gCO₂eq./l)) / 100

To calculate the total CO₂eq. emissions in kilograms over the entire lifecycle of the vehicle, multiply this equation by the driving mileage and divide by 1000: Total CO₂eq. emissions (kg) = (CO₂eq. emissions (g/km) × Driving mileage (km)) / 1000 (European Commission, 2024).

Quantification

Once we aggregated all the results we found in the data sources, we obtain these results:

- **Petrol (TCO₂eq.):**

N	16
Median	30,6915
Range	40,62
Minimum	12,08
Maximum	52,7

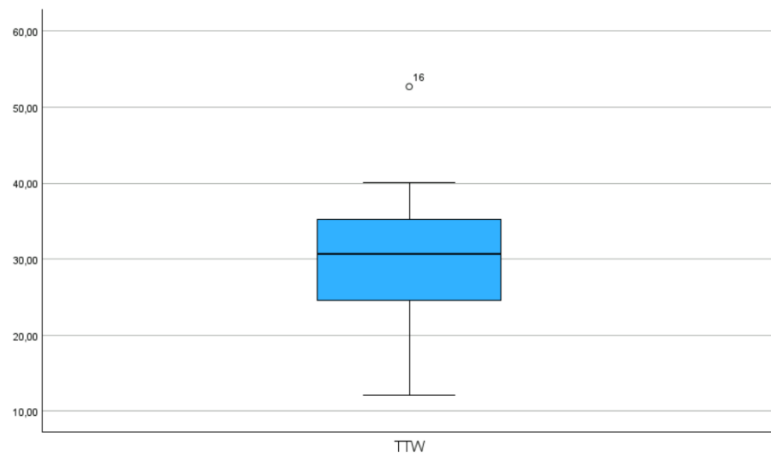


Figure 7: Median results for the use phase (TTW) of an ICEV petrol in TCO₂eq. and boxplot

• **Diesel** (TCO_{2eq.}):

N	6
Median	32,2943
Range	28,18
Minimum	7,67
Maximum	35,85

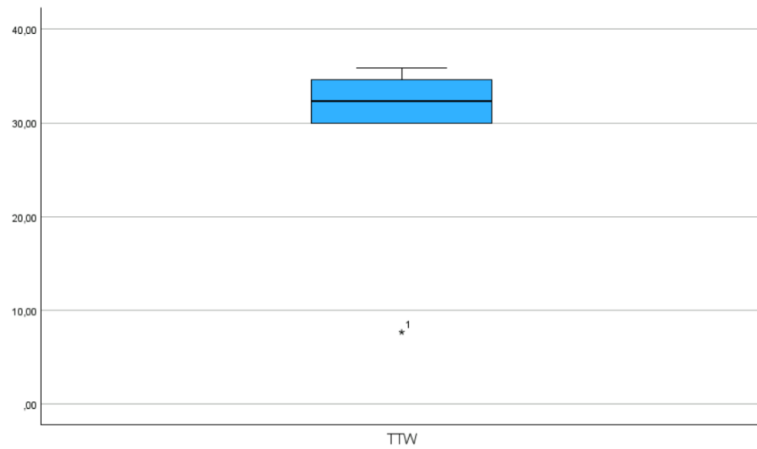


Figure 8: Median results for the use phase (TTW) of an ICEV diesel in TCO_{2eq.} and boxplot.

3.5 Maintenance

Within the use phase of the ICEV petrol and diesel, some maintenance is required. The maintenance phase involves the replacement of certain vehicle parts at more or less regular intervals. We have the maintenance and replacement of tires, lead-acid batteries, vehicle fluids like oil, coolant and transmission fluid etc.

For example, in the study by Kawamoto et al. (2019), they consider these intervals for the replacement of tires, lead-acid batteries, engine oil, and radiator coolant for diesel and petrol ICEVs, along with the corresponding CO_{2eq.} emissions, (these CO_{2eq.} emissions are related to the production of these consumable parts) :

Part Name	Maintenance Interval [km/Maintenance]	CO ₂ Emission [kg-CO ₂ /Maintenance]	Reference	Applied Vehicles
Tire	40,000	108	JLCA [27]	GE, DE, BEV
Lead-acid battery	50,000	19.5	JLCA [27]	GE, DE, BEV
Engine oil	10,000	3.22	JLCA [27]	GE, DE
Radiator coolant	27,000	7.03	JLCA [27]	GE, DE
Li-ion battery	160,000	6337	Table 4	BEV

Figure 9: Assumptions for the maintenance phase (Kawamoto et al., 2019)

In the studies by Kosai et al. (2022) and Tashtoush et al. (2023), tire replacement is also set at 40,000 km. This interval is strongly influenced by tire quality as well as the quality of the roads traveled by the vehicle. For engine oil consumption, Tashtoush et al. (2023) set the maintenance

interval at 5,000 km, windshield fluid at 12,000 km, powertrain coolant at 60,000 km, and brake oil at 60,000 km. It is also established that the transmission fluid will be replaced only once over the entire LC of the car.

The different studies also assume that there will be no manufacturing defects during vehicle production, no major repairs, and no accidents.

As we can see, in the above table the maintenance phase has a relatively low impact on the carbon footprint of ICEVs compared to the entire LC (Hirz & Nguyen, 2022).

In general, ICEVs have a higher maintenance phase than BEVs, with a greater demand for services and replacement of consumable parts (filters, engine oil, brakes, tires, clutches, etc.) throughout their LC. This is mainly due to the maintenance of the powertrain and brake system (Hirz & Nguyen, 2022).

Finally, this phase depends on the lifetime mileage of the vehicle: the longer the lifetime considered, the more certain parts will need to be replaced.

Quantification

Once we aggregated all the results we found in the data sources, we obtain these results:

- **Petrol** (TCO_{2eq.}):

N	7
Median	0,75
Range	0,71
Minimum	0,48
Maximum	1,19

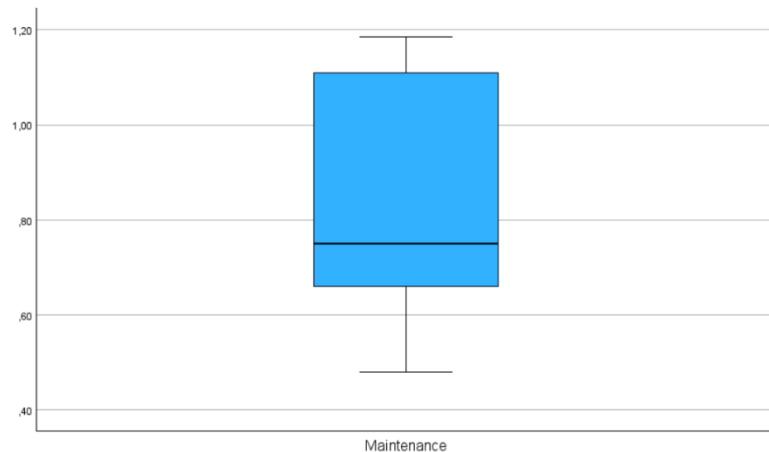


Figure 10: Median results for the maintenance phase of an ICEV petrol in TCO_{2eq.} and boxplot

- **Diesel** (TCO_{2eq.}): We only found 2 observations, 0.5685 and 1.185 TCO_{2eq.}

3.6 End-of-Life

Firstly, it can be observed that this stage is similar for both diesel and petrol ICEVs. Furthermore, the EoL of the glider of both ICEVs and BEVs are approximately the same, so this section (except the aggregated results) can also be applied to the EoL of the BEVs' glider (the Lithium-ion battery EoL is not included).

The EoL phase of an ICEV or a BEV depends on the regulations and measures taken in the respective countries. The EoL stage can be based on different principles and directives. In the EU, the following directives apply:

Directive 2000/53/EC: This directive establishes various rules for the end-of-life stages, focusing on the overall management of end-of-life vehicles.

- Prevention: Limiting the use of hazardous substances in vehicle design to facilitate recycling and prevent hazardous waste disposal.
- Collection: Collecting vehicles.
- Treatment: This includes dismantling, depollution, cutting, shredding, recovery, and preparation for waste disposal.
- Encouraging reuse of vehicle components: Setting reuse and recovery targets of at least 85% by weight per vehicle by 2006, and 95% by 2015.
- Information and coding: Producers must provide information on vehicle dismantling and use coding standards to facilitate the identification of reusable and recoverable components (European Commission, 2023).

There is also the directive 2005/64/EC and the directive 2018/858 of the European Parliament.

Globally, there is the ISO standard 22628:2002 "Road vehicles — Recyclability and recoverability — Calculation method" which defines a method for calculating the recyclability and recoverability rates of a new vehicle, expressed as a percentage of the vehicle's mass. The vehicle can be either recycled, reused, or both (recyclability rate), and it can also be recovered, reused, or both (recoverability rate). This calculation is performed by the vehicle manufacturer when a new vehicle model is introduced to the market. It divides the EoL into four steps: depollution, dismantling, shredding, and post-shredding (ISO 22628:2002).

Therefore, different studies are based on various principles to analyze the EoL. The application

of these regulations worldwide significantly affects the emissions of this LC stage since each country or organization has its own rules.

Here are the different steps of a complete EoL process:

- **Dismantling:** First, the vehicle is disassembled, particularly separating the glider from the powertrain. This can result in waste flows (rubber, glass, and mineral oil) which are incinerated.
- **Shredding the glider:** The glider is then sent to a shredding facility where recyclable materials (Al, Fe, and Cu scrap) are separated from waste fractions.
- **Shredding the powertrain:** The ICEV powertrain is also sent to a shredding facility where some elements that could be recycled (Al, Fe, Cu scrap) are withdrawn.
- **Recycled elements and reuse:** All these recycled or reused elements are removed from this system and integrated as secondary materials in the cradle-to-gate phase (from car production to its sale).
- **Landfilling and incineration:** All the waste (the remaining residues, plastics etc) from the shredding of the glider and the powertrain that cannot be recycled or reused, are sent to landfills or municipal incineration (Del Duce cited by Bicer et al., 2018; Naranjo et al., 2021).

As with every stage, transport between each process must also be considered, but these are negligible compared to the main stages of the EoL.

Electricity is the dominant energy source in the EoL phase, thus the environmental impact and the CO₂eq. emissions for this phase are calculated through the energy consumption required to make each EoL process (Wang cited by Yang et al., 2021; Del pero et al., 2018).

To calculate the CO₂eq. emissions corresponding to a process in the EoL phase, Farzaenh & Jung (2023) use the following equation : (Process Energy per mass × Vehicle mass × Carbon footprint coefficient)/1 000 000

With:

- **Process energy per mass:** the quantity of electricity needed to make the process per kg of material processed in kWh.
- **Carbon footprint coefficient:** the quantity of CO₂eq. emissions generated per kWh of electricity generated in gCO₂eq./kWh (Farzaneh & Jung, 2023).

For shredding for example: $= (0.43 \times 0.277778 \times 2261 \times 405.8) / 1000000 = 0.105 \text{ TCO}_2\text{eq.}$

Kawamoto et al. (2019) provide these figures for the disassembly, shredding, transport and land-filling processes of the body part, interior, and exterior (In sum, it corresponds to the glider) of the ICEV petrol and diesel and the BEV (They consider that these are the same figures for the 3 types of vehicle):

Process Name	CO ₂ Emission [kg-CO ₂]
Disassembly *	-
Shredding and sorting	24
Transport	4
Landfilling	38
Total	65

*: Energy consumption in disassembly is relatively lower than the other treatment

Figure 11: CO₂eq. emissions from EOL treatment for BEVs and ICEVs petrol, diesel (Kawamoto et al., 2019)

We can see that the landfilling phase is the most significant with 38 kg of CO₂eq. , and the disassembly phase is much smaller compared to the others.

In the recycling and reuse phase, these steps can actually reduce the carbon footprint of vehicles, potentially resulting in negative CO₂eq. emissions for the EoL phase. This is observed in the study “Comparative environmental LCA of electric and conventional vehicles in Lithuania” by Petrauskiene et al. (2020), with approximately minus 3250 kg of CO₂eq., “Total CO₂eq. life cycle emissions from commercially available passenger cars” by Burberger et al. (2022) with minus 5000 kg of CO₂eq. and in “Life Cycle Assessment in the automotive sector: a comparative case study of Internal Combustion Engine (ICE) and electric car” by Del Pero et al. (2018), with minus 95 kg of CO₂eq.

According to Del Pero et al. (2018), many of the car’s components (BEVs and ICEVs) can be recycled or reused: Tyres at 66%, catalytic converter, batteries, bumpers at 66%, glasses, bonnet, brakes disc, steel at 98% and Al at 98% too (they take into account the 2000/53/EC Directive and ISO standard 22628:2002) (figure K.1 ¹).

Quantification

¹In appendix K: EoL phase of ICEVs and BEVs, figure K.1: Allocation of components and materials to EoL processes for ICEVs and BEVs (Del Pero et al., 2018)

Once we aggregated all the results we found in the data sources, we obtain these results for the ICEVs petrol and diesel exclusively:

- **Petrol** (TCO₂eq.):

N	13
Median	0,6000
Range	6,55
Minimum	-3,25
Maximum	3,30

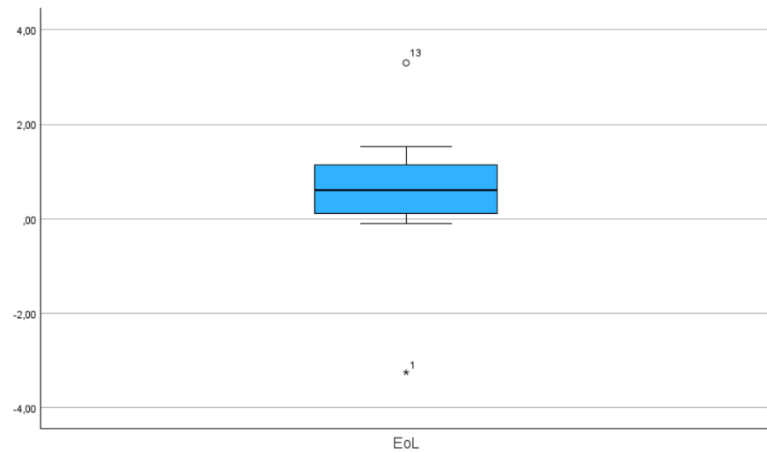


Figure 12: Median results for the EoL phase of an ICEV petrol in TCO₂eq. and boxplot

- **Diesel** (TCO₂eq.):

N	5
Median	0,840
Range	4,64
Minimum	-3,25
Maximum	1,39

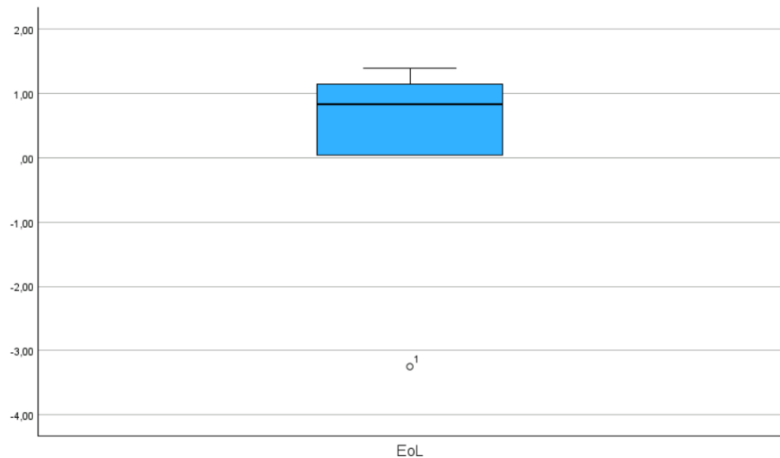


Figure 13: Median results for the EoL phase of an ICEV diesel in TCO₂eq. and boxplot

3.7 Total life cycle

We also aggregate the results for the total LC of an ICEV petrol and an ICEV diesel from our data sources and we obtain these results (this section does not correspond to the addition of the previous ones (LC phases) but to a median calculation of all the "Total LC results" from our data sources):

• **Petrol** (TCO₂eq.):

N	22
Median	40,5000
Range	54,58
Minimum	15,79
Maximum	70,37

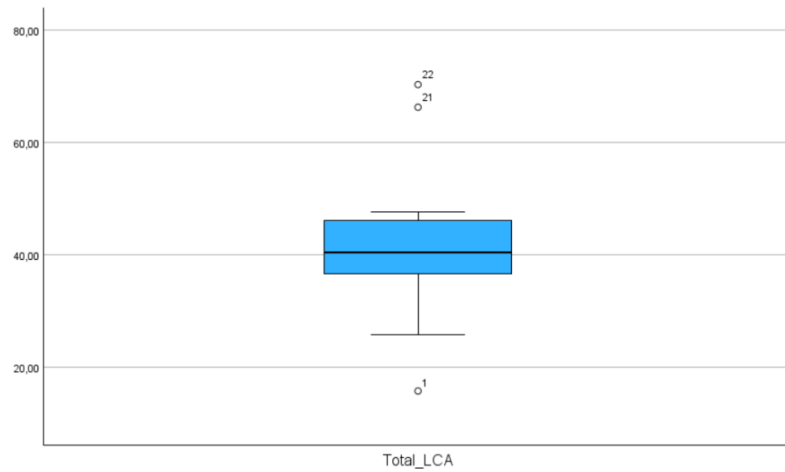


Figure 14: Median results for the total LC of an ICEV petrol in TCO₂eq. and boxplot

• **Diesel** (TCO₂eq.):

N	9
Median	36,0000
Range	64,66
Minimum	11,39
Maximum	76,05

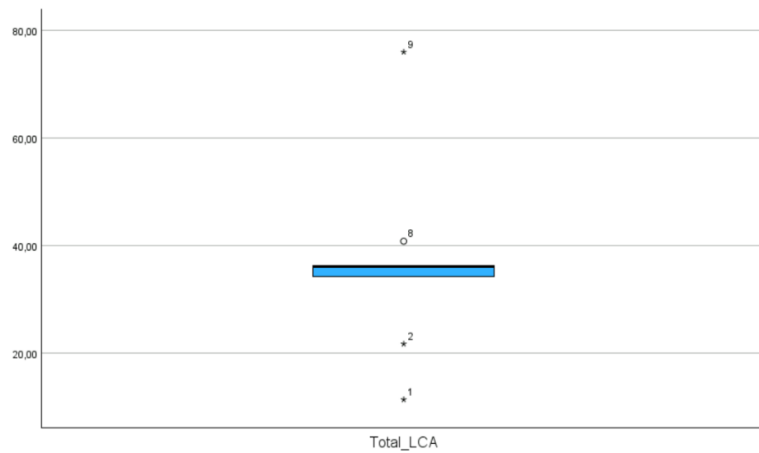


Figure 15: Median results for the total LC of an ICEV diesel in TCO₂eq. and boxplot

4 The Battery Electric Vehicle

Let's now perform the same analysis for BEVs.

The scope of our analysis is as follows:

- a classic BEV passenger car
- Mileage of 150,000 km
- Driven in Average Europe / Poland / Norway / China
- 50 kWh lithium-ion battery approximately
- Battery range of 300 km per recharge approximately

We recognize that our aggregated figures do not accurately summarize the whole situation (it's impossible to take into account everything) but provide an overall idea of the current trend and try to be as accurate as possible.

For this part, we based our analysis for BEVs on 38 scientific studies and other more informal sources as previously explained in the data sources section.

As for the ICEVs, each phase of the LC developed below is made up of different stages, but we will only give a complete distribution of the results for the entire phase. However, we will explain what these different stages consist of, with figures to give an order of magnitude. Based on the articles studied, there is not enough data to give more detailed results.

4.1 Origin and production of the fuel

This section corresponds to the whole process behind the production of electricity in order to charge the battery of BEVs. We're going to take into account all the CO₂eq. emissions linked to the production of electricity needed by the BEV to cover a distance of 150,000 km (our FU). This phase is entirely dependent on the electricity mix concept.

The electricity mix is the concept that explains the origin of electricity. Often used on a national scale, it allows us to understand, using percentages, the proportion of renewable energy used per kilowatt-hour. Thus, we have an easy-to-use and comparable calibration.

Additionally, this indicator provides knowledge of carbon intensity expressed in grams of CO₂ equivalent per kilowatt-hour. In order to correctly provide a representation of what the electricity mix is and why it is so important in our analysis, below are four examples of 4 different countries. Each country is constrained to power itself and must find solutions that are specific to its circumstances. Since each entity is unique, they face their own challenges where there is no one-size-fits-all solution (Boisseleau, 2022).

We have focused on various regions (Europe average, Poland, Norway and China). This desire to have a diverse range of origins provides a broader understanding of the current situation and how significantly it varies between different countries and sometimes even between different regions within the same geographical area. This specificity makes the work more challenging as it is necessary to tailor each response to the research question with a pre-established territory.

According to Andersson & Börjesson (2021), the 2020 electricity mix in Europe would emit 139 g CO₂eq./km. and are expecting for 2050 an impact of 77g CO₂eq./km (Figure L.1¹). This reduction in the carbon footprint can easily be explained by the numerous European laws and legislations (Fit for 55 or Euro 7) imposing increasingly strict constraints regarding pollution and the origin of electricity. This provides tangible and quantitative evidence of Europe's desires to reduce its ecological footprint (L'essentiel, 2023).

4.1.1 Example of countries

Our sample of regions is composed as such for the following reasons: Poland, often cited as a bad example of the European continent, Norway at the opposite end of the spectrum. Europe is taken as an aggregated value of the overall tendency and China as a country to explain the divergences of values between different areas within the same territory. Indeed, while remaining a very powerful country, this country struggles with the energetic transition and suffers from huge disparities among it. For example, an electric vehicle fuelled with electricity from China in the Yunnan region emits 104.4 gCO₂eq./km, while the same vehicle emits 265.7 gCO₂eq./km in Shandong. This difference is directly related to the regional dependence on coal, which is still widely used in China (Wu et al., 2019).

Thus, with this sample, there is already a good idea of the entire spectrum: the worst in Europe, the best one, the aggregated value, and a special case with a lot of variations within the same country.

¹In appendix L: Electricity mix per country, figure L.1: Life Cycle CO₂eq. emissions from the HEV, PHEV and BEV model when using 2020 and 2050 european electricity (Andersson & Borjesson, 2021)

The numbers presented below come from the database of the group "Lowcarbonpower.org" and are all from the year 2023 (Figure L.2 to L.5 ¹).

Poland (Figure L.2)

Poland is highly reliant on fossil fuels (coal especially), with a percentage over 70%. However, it has a proportion of low-carbon energy (wind and solar) of 26%. This country has among the worst results in terms of carbon footprint for its electricity in the European Union because of how hard they still rely on high-carbon electricity.

The carbon intensity is 273.30 gCO₂eq./kWh.

Norway (Figure L.3)

Norway is known for having already solved its energy transition. With naturally occurring energy sources (hydraulic and wind), it represents what all countries aspire to in terms of energy independence. Indeed, their proportion of low-carbon energy stands at 99%.

The carbon intensity is 27.94 gCO₂eq./kWh.

Europe (Figure L.4)

This is an aggregated value of all European countries, offering a low-carbon intensity of nearly 70%, with a predominance of nuclear power (23.3%). Next come the various alternatives, ranging between 8.6% and 15% presence.

The carbon intensity is 210.89 gCO₂eq./kWh.

China (Figure L.5)

China still heavily relies on its coal mines, with a dependence rate of up to 63.57% on fossil fuels. However, it has a proportion of low-carbon energy of 36.33% (hydropower 13.7%, wind 10.6% and solar 5.8%)

The carbon intensity is 523.65 gCO₂eq./kWh.

The conclusion of this part is to inform and put into perspective that every region is truly unique and rely on different solutions leading to disparities among them. Each has found, according to the predispositions of its territory, a relatively ecological and adequate suitable solution for energy

¹In appendix L: Electricity mix per country

transition. It is capital to really grasp and use the carbon intensity to benchmark the real impact of every electricity mix.

In our case, this represents an additional challenge and adds another dimension to understanding the real impact of an electric car. Indeed, in light of this data, it becomes evident that the solution with the lowest emissions must be implemented in the right geographical area. Otherwise, we are limited to cardinal amounts and information without context.

Nevertheless, having those numbers will allow a comparative approach on how a BEV behaves in those respective regions. Here is the recapitulative table of those numbers:

	Poland	Norway	Europe	China
Electricity mix (g CO ₂ eq/kWh)	273.3	27.94	210.89	523.65

Table 1: Recapitulative table of the electricity mix of Poland, Norway, Europe and China

It is now time to transform these results expressed in gCO₂eq./kWh in TCO₂eq. for a FU of 150,000km.

The following example only shows the figures for the European electricity mix. To find out the origin of the other numbers, simply replace 210.89 with the amount for the desired region.

This vehicle's electricity consumption is 50kWh/300km = 0.1667kWh/km. In CO₂eq. emissions per km, we obtain: $0.1667 \times 210.89 = 35.13$ gCO₂eq./km.

Multiply this value by 150,000 to obtain the total emission for this distance and then it must be divided by 1 000 to have the result in TCO₂eq.

	Poland	Norway	Europe	China
Total Emissions for 150,000 km (TCO ₂ eq.)	5.2695	0.624	6.8325	13.092

Table 2: Electricity mix for Europe, Poland, Norway and China in TCO₂eq.

This table above is just a representation of one of our sources (lowcarbonpower.org), the aggregated calculations based on all our data sources can be found further down in this section. But this table serves as evidence of the root cause of such a huge range between results: if the electricity comes from a low CO₂eq. emission source, the final emission factor is up to 20 times lower as seen between the two extremes (Norway and China).

It's important to note that these numbers don't take into account the distribution of the electricity into the charging infrastructure and the battery of the vehicle.

We have chosen to base our future results on China and the European average only, in order to have a clearer vision.

Quantification

Once we aggregated all the results we found in our data sources, we obtain these results for the origin and production of the electricity needed to recharge the vehicle's battery to enable it to cover 150,000 km:

- **Europe** (TCO₂eq.): ¹

N	13
Median	9
Range	25,14
Minimum	3,375
Maximum	28,515

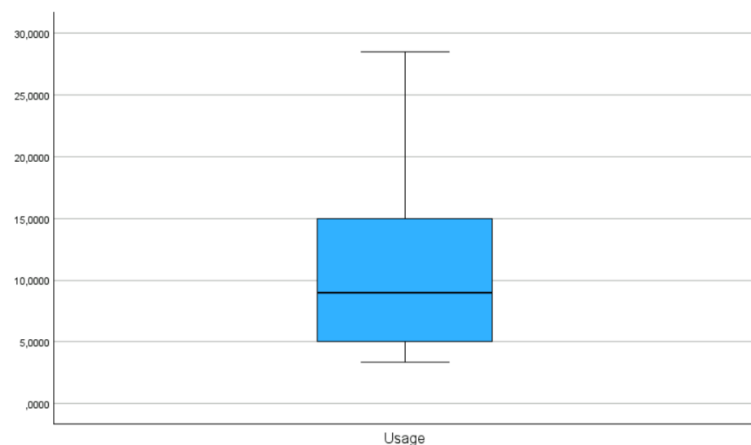


Figure 16: Median results for the Origin and production of the fuel for BEVs in Europe in TCO₂eq. and boxplot

- **China** (TCO₂eq.): We only found an interval from 9.525 to 49.2. The Chinese interval is immense due to significant disparities between regions in terms of energy dependency on coal. In order to compare these values with the other section of our work, we are going to take into account the mid-value of this range: 29.3625.

4.2 Production

The following graph (Figure 17) provides us a comparison of CO₂eq. emissions in tonnes per vehicle produced. It becomes very easy to understand that BEVs are the highest emitters during

¹The "N" in the table corresponds to the number of data sources' results

this step, with values nearing 17 tonnes per unit produced (Luk et al., 2018). Those numbers depend on a lot of parameters: type of ore, recycled or not, the mileage, origin of the electricity used, ... Production of batteries is highly dependent on the technology used, since BEV is highly subject to change and technological advances.

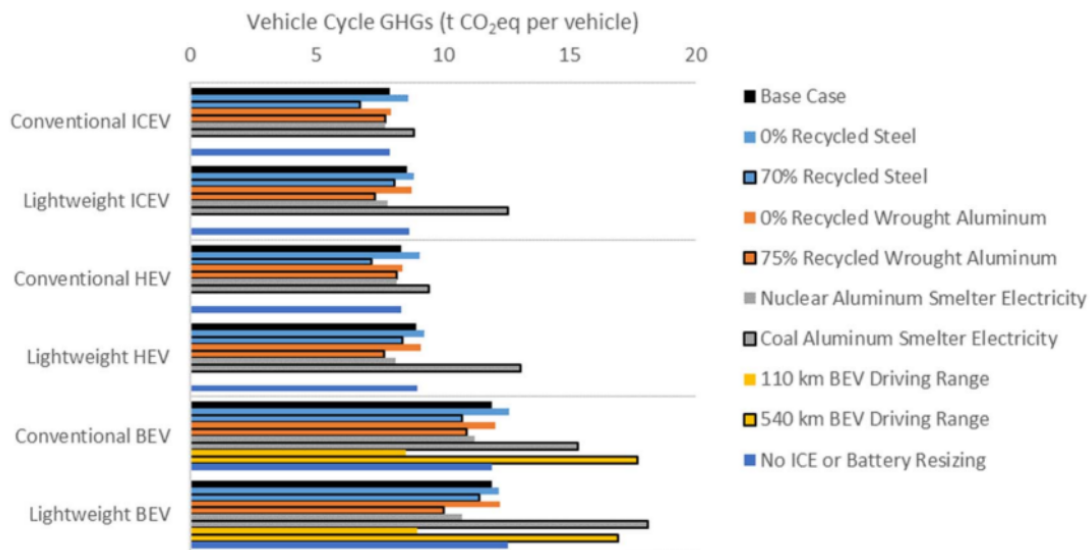


Figure 17: Sensitivity analysis results for vehicle cycle GHG emissions (Luk et al., 2018)

It is important to note that there are many ways to design an electric vehicle and that each unit is unique due to its options or supply chain. This diagram offers a visual representation of the current situation:

- There is a significant link between the driving range of the BEV and their emissions.
- The source of electricity (electricity mix) plays a crucial role in the CO₂eq. emissions during production.

We can also have a look to the results of Del Pero et al. 2018: in this study, BEV requires 8.9 tonnes to be produced. This result is completely different from the one of the graph above. This proves once again the enormous variation in results across the literature of this subject.

We'll now take a closer look at the production phase. To facilitate the isolation of the root cause there has to be a separation in the manufacturing process into 2 main parts: the powertrain system and the glider. The first term refers to everything that generates, stores and transfers energy to the road to set the vehicle in motion (mainly the battery in this case), while the second one refers to everything else (interior, chassis, etc.).

4.2.1 Lithium-ion battery production

As a starting point for this part, we have unilaterally chosen to show the LCA of Shu et al. (2021) only and use it as our reference. Indeed, it is the most comprehensive and representative. However, all the insights given originate from other authors Lavigne Philippot, Lavis, ... were used in the computations of the aggregated values. Even though the focus was made on this example, many others are just as good as this one, another LC structure example can be found in figure D.3 ¹.

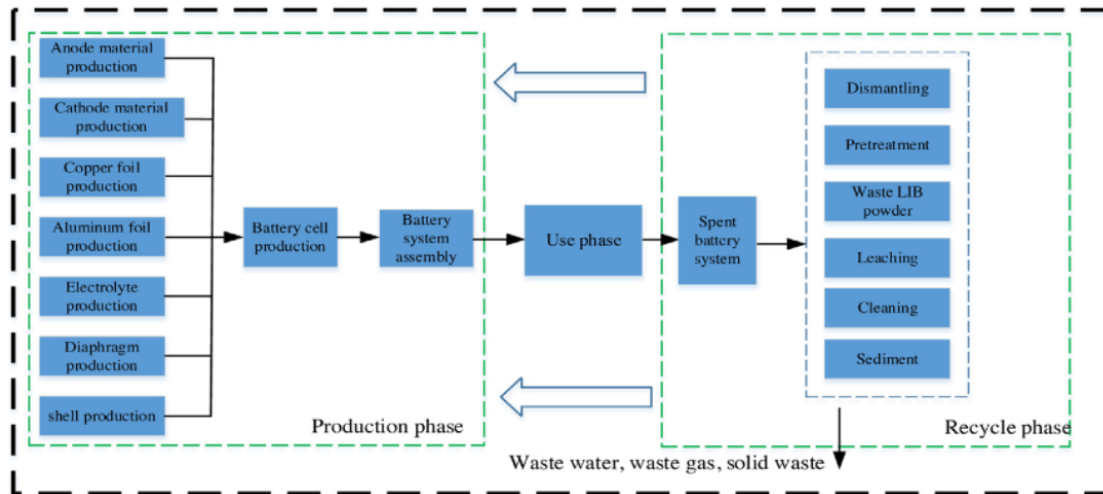


Figure 18: System boundaries for the LCA of the batteries of interest (Shu et al., 2021)

Before discussing the CO₂eq. emissions related to the production of Lithium-ion batteries (LIBs), it is important to understand how they work. Like any other type of battery, they are composed of:

- Anode: the negative electrode of the battery
- Cathode: the positive electrode of the battery
- Electrolyte: the area between the anode and cathode that allows the movement of lithium ions
- Separator: a thin separation between the anode and cathode that allows ions to pass through
- Current Collectors: thin films that collect the current and direct it outside the cell
- Casing: external protection
- Performance Enhancers: additives to increase battery performance

¹In appendix D: LC structures and boundaries references, figure D.3: System boundaries (Lavigne Philippot et al., 2023)

Here is a table representing a contribution analysis of the emissions per production of parts making up a battery:

	Cells in modules	Casing	Cooling circuit	Power elec.	Powerbox
% of emissions per part	74%	11%	7%	7%	1%

Table 3: Percentage of emissions per production of parts making up a battery (Romare & Dahllöf, 2017)

The cells in the modules refer to the sum of the anode, cathode, electrolyte, and separator. A module is a group of cells, and a battery pack is a group of modules. The battery pack is what powers an electric vehicle (Romare & Dahllöf, 2017).

The aggregated value from the median computations is 3.05 tonnes of CO₂eq. per unit produced in Europe and 3.81 tonnes in China. The distribution of results and boxplot can be found in figure N.3 for Europe and N.4 for China ¹.

4.2.2 Glider production

The production of the BEV glider is significantly simpler than the one of an ICEV. Indeed, due to their absolute dependence on battery packs and the electric motor, there is no longer any need to manufacture other classic components of the thermal engine such as exhaust systems or fuel tanks (The Aluminium Association, 2024; World Steel Association, 2024).

An estimation of the CO₂eq. emissions to produce a glider composed of steel, aluminum and plastic mainly (95%), is computed as follows:

- Steel: around 2 tonnes of CO₂eq. emissions per tonne of finished product.
- Aluminum: between 10 to 15 tonnes of CO₂eq. emissions per tonne of finished product.
- Plastic: between 1,7 to 3.2 tons of CO₂eq. emissions per ton of finished product depending on the different types of plastic: polyéthylène, polystyrène, ...

For example, let's consider our 5-door electric car glider weighing 2 tonnes, with a glider composed of 1,125 tonnes made of steel and 0.375 tonnes made of aluminum:

1. Steel emissions: $1.125 \times 2 = 2,25$ tonnes of CO₂eq.
2. Aluminum emissions: $0.375 \times 12.5 = 4,6875$ tonnes of CO₂eq.

¹In appendix N: Median results and boxplots

3. Plastic emissions: $0.1 \times 2.3 = 0.23$ tons of CO₂eq.

Total CO₂eq. emissions for the glider: $2.25 + 4.6875 = 6.9375$ tonnes of CO₂eq. per glider. (We do not include plastic in this equation, given its very low impact and its wide variability depending on its type).

These results found by computations have to be challenged with the numbers found from our data sources. Once it is done, the aggregated value (median) for this part is 6 tonnes of CO₂eq. per unit (figure N.5 ¹) (European Aluminum, 2024; World steel Association, 2024).

Quantification

For the total production, once we aggregated all the results we found in our data sources, we obtain these results:

- **Europe** (TCO₂eq.):

N	11
Median	9,0000
Range	12,504
Minimum	8,800
Maximum	21,304

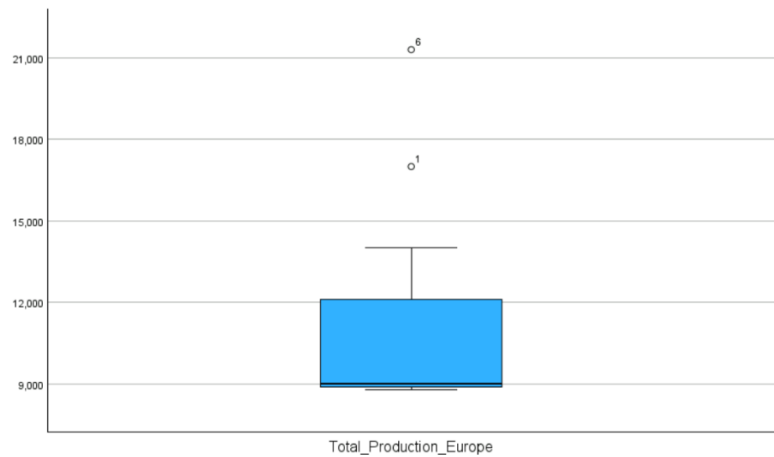


Figure 19: Median results for the total production in Europe in TCO₂eq. and boxplot

- **China** (TCO₂eq.):

¹In appendix N: Median results and boxplots

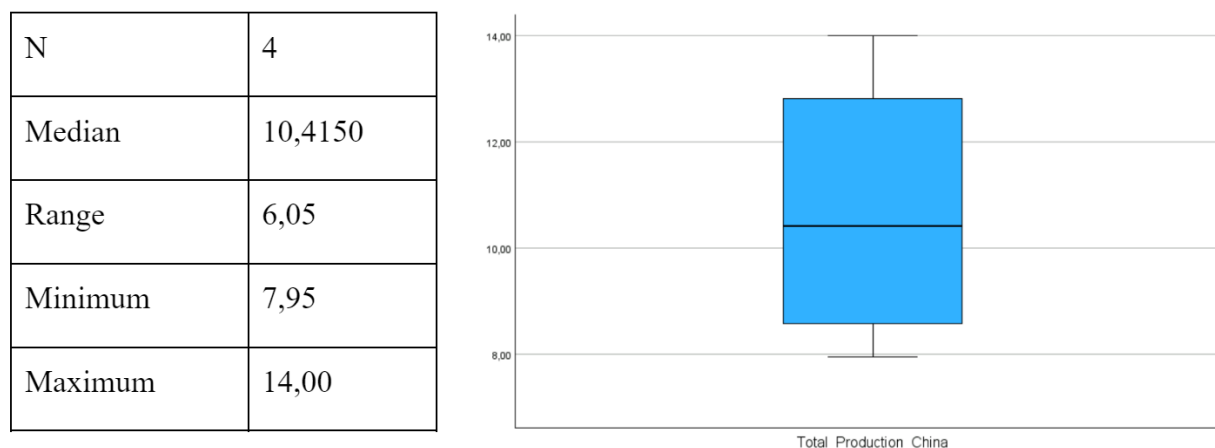


Figure 20: Median results for the total production of BEVs in China in TCO₂eq. and boxplot

4.3 Distribution

Despite a notable difference in weight between the two types of vehicle (BEV has a factor around 1.4 times the weight of a thermic car), there isn't a huge difference in CO₂eq. produced during this phase. For example, the difference of weight between a Peugeot 208 has a weight of around 1100 kg, whereas in its electric version, called the e-208, it is around 1500 kg (Noël, 2023). An aggregated version of the differences lying in the mass breakdown analysis of BEVs and ICEVs may be found in figure G.1 and figure G.2¹.

So, it was decided to simply apply the value found for the ICEV to the BEV due to the difficulty to find those numbers exclusively for electric cars and their relatively low impact on the total emissions. So, 0.4 TCO₂eq. per unit is the amount found for this section. For the origin of this number, it is available on section 3.3.

4.4 Use

A huge strong point of the BEV is the fact that it does not emit CO₂eq. during the use phase (the consumption of the fuel : electricity). We can simply state that this phase is equal to 0 for BEVs.

However, electricity consumption can be strongly influenced by external factors during the BEV's usage phase. If electricity consumption increases, the car needs more electricity, so more has to be generated. This will increase CO₂eq. emissions in the origin and production of the fuel phase,

¹In appendix G: Mass breakdown analysis, figure G.1: Mass breakdown analysis of ICEV and BEV modelled in LCA (Del Pero et al., 2018) and figure G.2: Mass and energy balance of ICEV and BEV's vehicle production (Shafique et al., 2021)

given that more electricity needs to be produced to drive the 150,000 km distance. These external factors could be: driving behavior, type of driving (urban area, agglomeration, etc.), vehicle weight, weather, etc. These factors will be discussed in the discussion section of this work, but we can say that they're encountered during the use phase but they influence the emissions from the origin and production of the fuel (electricity) phase.

4.5 Maintenance

Regarding maintenance, one of the major advantages of electric vehicles is their relative independence on these repair and replacement costs. Due to, for example, the absence of small, easily breakable parts or the fact that there are no fluids to change (coolant or oil) (Consumer Report, 2024), the CO₂eq. costs can be considerably lowered.

Nevertheless, there are two particularly unique maintenance expenses for electric motors: battery replacement after 5 to 10 years of use and tire wear. The aging of a battery is explained in the next section called "Recycling / End-of-Life". About the second one, due to the absence of gear shifting and significantly higher starting power compared to its internal combustion counterpart, it is important to note that if we combine this particularity with a more aggressive driving, the tires are more likely to become smooth even faster (Thaux, 2024). According to Michelin France (2020), a new tire emits 25 to 30 Kg CO₂eq. per unit, so 100 to 120 kg for a set of 4.

The tires must be changed after 29,000 km for electric vehicles (Piot, 2023).

	Reference mileage	Tire wear	Emissions per set	Nb of swap	Total emissions
BEV	150,000 km	+/- 29,000 km	100 to 120 kgCO ₂ eq.	+/- 5	0.55 TCO ₂ eq.

Table 4: Tires replacement for BEV (Piot, 2023)

So, for the maintenance phase of BEVs we obtained a value of 0.55 TCO₂eq with our two data sources (Michelin France, (2020) and Piot, (2023)).

4.6 Recycling/End-of-Life

4.6.1 Glider recycling

The recycling process for a BEV or ICEV glider does not differ in the common areas (chassis, passenger compartment, etc.)

In order to limit repetition, this is only explained once in section 3.6. However, the figures calculated here represents an example vehicle, the specifics of it have already been introduced earlier in the glider production section.

	Steel	Aluminium
Weight distribution	1.125 tonnes per unit	0.375 tonnes per unit
CO ₂ eq.per recycling	0.4CO ₂ eq./tonne	0.5 CO ₂ eq./tonne
Effective amount	0.45 TCO ₂ eq.	0.1875 TCO ₂ eq.

Table 5: Steel and Aluminium breakdown of a model vehicle (European Aluminium association, 2024; World Steel Association, 2024)

The total amount is 0.6375 TCO₂eq. per unit for a 2 tonnes BEV. (Once again we do not take into account the plastic because of its minimal impact during the recycling process (0.0007 TCO₂eq. per unit)).

4.6.2 Battery first recycling

This part, eagerly awaited by skeptics of electric vehicles, is very promising and provides a real guideline for what needs to be done to make an end-of-life battery viable again. Indeed, the lifespan of a battery varies between 5 to 15 years. This difference is due to many factors such as usage, type of LIB used or even the quality of the product itself (Xia & Li, 2022).

A battery is defined as aging and could be recycled when it has lost between 20 and 30% of its initial capacity. Despite this state, it remains more profitable to reuse it than to replace it. In this case, 2 main guidelines are possible:

- Remanufacture: this involves repairing and refurbishing the LIB to reuse it in an electric vehicle. Such a process leads to a reduction in GHG and a monetary gain of 40%. However, a problem remains, there is no large-scale network or direct application.
- Repurposing used batteries: this does not involve putting them back into another electric vehicle but rather placing them in systems requiring a lower voltage: energy source for a secondary network, auxiliary system, etc. This alternative is very interesting because it requires very little adjustment between the worn battery and the one that can be used again (Xia & Li, 2022).

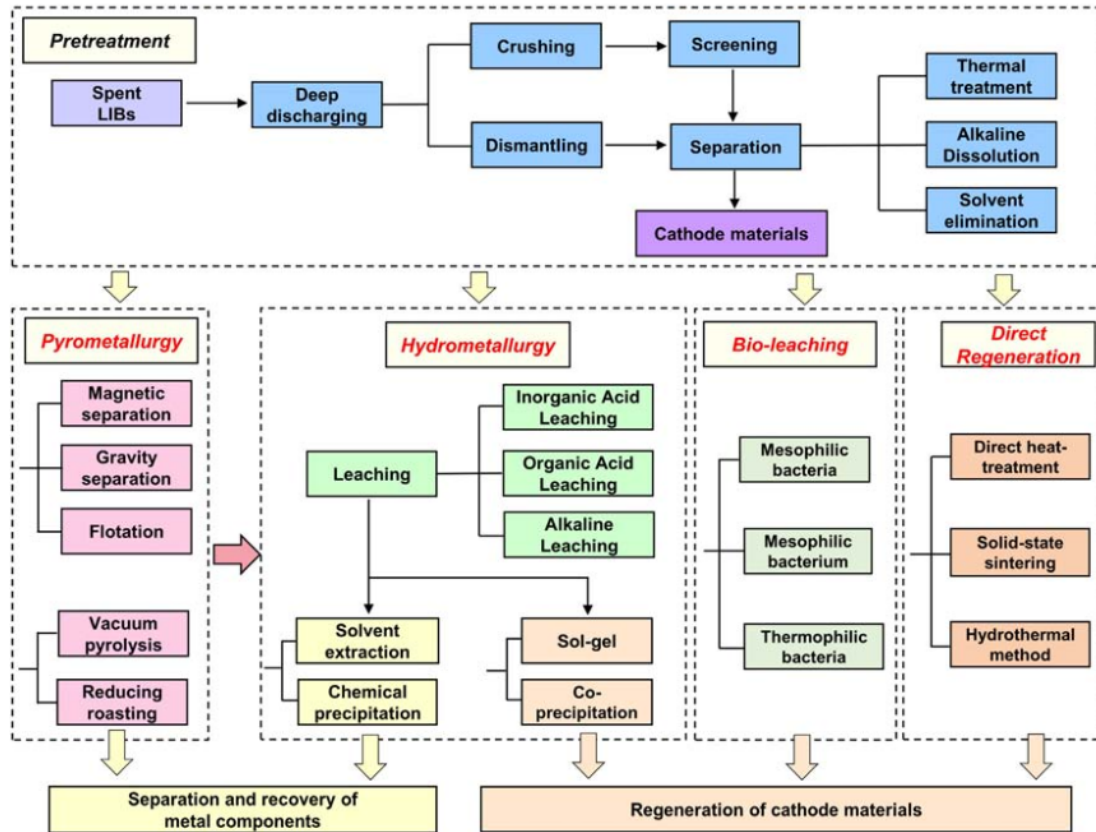


Figure 22: General processes and main approaches for recycling the cathode of spent LIBs (Roy et al., 2021 & Tan et al., 2021 as cited in Xia & Li, 2022)

4.6.4 Limitations of the recycling

Nevertheless, the reality on the field is more difficult to grasp. On one hand, it seems very favorable for recycling with, for example, Umicore, European leader in its sector, claiming to have technology capable of recycling up to 95% of cobalt, copper, and nickel while asserting that they can recycle lithium on an industrial scale (Umicore, 2024).

On the other hand, despite the already established existence of applicable LCAs (14) regarding the end-of-life of these batteries, a problem persists. The recycling network is still in a very juvenile stage and sorely lacks experience on the field. The process is ready and usable, but it still needs to be implemented under real conditions. Currently, 50% of batteries are recyclable, and the goal is to reach 85/90% in the coming years. In reality, only 5% of them are truly recycled because there are still limitations in the implementation of the process:

- There are not enough end-of-life batteries to really put the process into practice.
- There are constant legal changes regarding the treatment of Co, Pb, Li, and Ni.

Despite a certain interest in managing the EoL of the product, the network is therefore faced with externalities where it has no power other than to wait and hope when changes are made in their favor (Baranna, 2023).

Nevertheless, not all batteries are recyclable or recycled, and it is necessary to manage the different possibilities for handling their end-of-life: stationary storage or landfill disposal, research and development, and reuse. Various methods exist, each with a different environmental impact:

- Storage or landfill disposal: This does not emit anything in itself but merely postpones the problem of end-of-life management and exposes humans to heavy metals.
- Research and development: The battery can be used for laboratory research purposes.
- Reuse: A battery that has reached the end of its life can be used in another device that requires lower power, thus giving it a second life and extending its overall lifespan (Sahle-Demessie, 2023).

For our final calculations, we have retained a value of 0 TCO₂eq. for the EoL of a LIB. We decided to use Baranna (2023), as a reference, who states that there is not yet a real and mature recycling network. Moreover, the only plausible solutions are those presented above and they do not emit CO₂eq.

4.6.5 Aging of a battery

Another aspect that must be quoted is that during the lifespan of a conventional battery, its capacity to store energy drops over the years. Indeed, at first the fall is exponential during the first 5 years then becomes linear thereafter. At 10 years old, the battery is only 71.2% efficient of its initial potential (Lavissee et al., 2023; Baranna & Hache-Vinceno, 2023).

Moreover, another externality that the BEV must face is that the battery is subject to performance loss depending on the temperature it is exposed to. Indeed, in their work, Lavissee et al. (2023), show us the difference in efficiency between an electric car used in a mild climate (Lyon, France) and in a cold one (Stroheim, Norway). The results are as follows:

Performance	France	Norway
After 5 years	-20%	-40%
After 10 years	-25%	-60%
After 20 years	-47%	-80%

Table 6: Percentage of battery loss over time for France and Norway

The visual representation may be found in figure M.1 ¹.

This completely changes the game regarding the synergy between low carbon electricity mix and driving in Norway. Indeed, Nordic countries are known for their reliance on green energy (wind, hydraulic and geothermal), making them perfect potential users of electric cars with very low environmental costs. However, with their cold climate, the lifespan of the powertrain is lowered by 20, 35 and 33% in terms of performance each 5 years. In light of this externality, it is mandatory to reconsider the electric mobility solution that seemed so suitable for this region of the world.

4.7 Total life cycle

Quantification

For the total LC of BEVs Europe, once we aggregate all the result from the data sources, we obtain these results in TCO_{2eq.} for a FU of 150,000km (this section does not correspond to the addition of the previous ones (LC phases) but to a median calculation of all the "Total LC results" from our data sources):

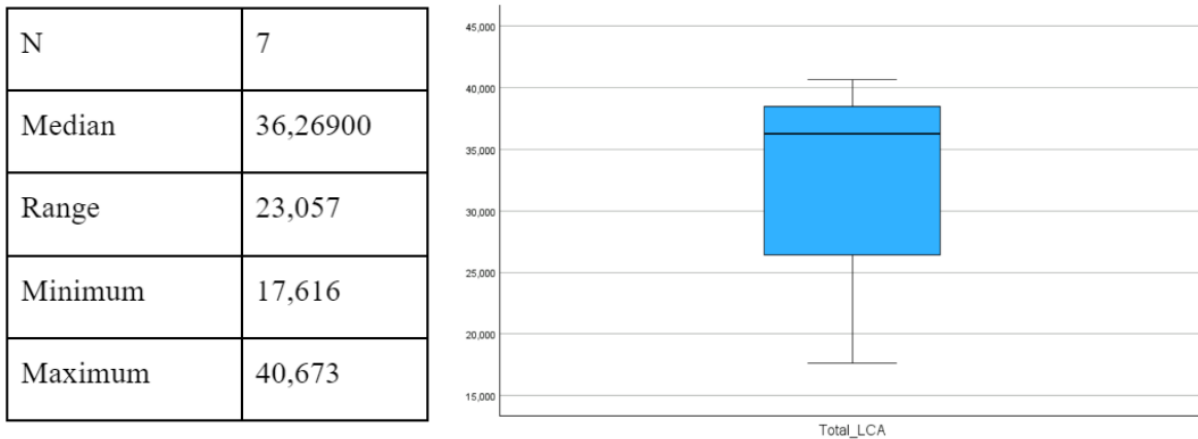


Figure 23: Median results for the total LC of BEVs Europe in TCO_{2eq.} and boxplot

¹In appendix M: Aging of a battery, figure M.1: Capacity loss of a 33.3 kWh (26.6 kWh usable) during 20 years in Lyon and in Trondheim (Lavis et al., 2023)

5 Externalities of BEVs

By revisiting the results found in part 1: The Battery Electric Vehicle and associating it with the following externalities:

- If the electricity mix comes from Poland, +28% emissions
- If the battery production is done in China, +25% emissions
- If the driver decides to drive aggressively, +20% emissions
- If the driver drives in a cold country, -20% life expectancy in 5 years
- No consideration of battery recycling because the network is not yet mature

We obtain these results for the CO₂eq. emissions of BEVs with externalities for each phase of their LC:

	Origin and prod. of the fuel	Prod. LIB	Total prod.	Distrib.	Use	Maint.	EoL	Total LC
Europe	9	3.05	9	0.4	0	0.55	0.6375	19.5875
Externalities	+28% if Polish +20% if fast driving (need + electricity)	+25% if Chinese	+25% of LIB production if Chinese battery	/	/	Cold weather, -20% lifespan	Only glider, battery recycling = too early	+0.8105 +4.824 +3.6 = 9.2345
Final numbers	13.824	3.8105	9.8105	0.4	0	3.05 (New battery) +0.55 (New tires) = 3.6	0.6375	19.5875 +9.2345 = 28.822

Table 7: BEVs externalities results in TCO₂eq.

6 Comparison analysis

Now that all the phases have been analyzed and the calculations have been made in order to assign a CO₂eq. emissions value for each of them, it is now time to compare them.

Here are the summary tables with all the values we have calculated (all values shown in this section are derived from the data sources collected for this thesis):

BEVs:

	WTT	Prod. LIB	Total prod.	Distrib.	Use	Maint.	EoL	Total	Total LC
Europe	9	3.05	9	0.4	0	0.55	0.637	19.587	36.269
China	29.362 ¹	3.81	10.415	0.4	0	0.55	0.637	41.09 ²	
Externalities	13.824	3.81	9.81	0.4	0	3.6	0.637	28.822	45.503

Table 8: Recapitulative table of median results for BEVs in europe, china and externalities in TCO₂eq.

The figures above are for the current year (2024). However, for EoL, 50% of battery production emissions can be avoided by recycling them and, by 2027, these figures are expected to increase to 85-90%. Nevertheless, only 5% of batteries are currently recycled. Therefore, only the glider recycling is considered in this work for BEVs (Baranna & Hache-Vinceno, 2023).

ICEVs petrol and diesel:

	WTT	Prod.	Distrib.	Use	Maint.	EoL	Total	Total LC
Petrol	5.9	5.34	0.4	27.28	0.75	0.6	40.27	40.5
Diesel	31.2 ³	5	0.47	32.29	0.88	0.84	45.38	36

Table 9: Recapitulative table of median results for ICEVs petrol and diesel in TCO₂eq.

You can observe that there are 2 total columns, the first one (Total) correspond to the addition of the results from the other columns and the second one (Total LC) corresponds to a calculation in its own right, using the same method as for the other columns (LC phases columns).

¹mid-value of the interval : [9.525;49.2]

²mid-value of the interval : [21.5275;60.6525]

³This number is derived from only one scientific article (Joshi et al., 2022) and seems to be an extreme value, we are not going to take it into account for further analysis but we are going to replace it by the value of petrol, given that the amount of CO₂eq. emissions produced by the production of the two is quite similar (Hirz & Nguyen, 2022).

6.1 Vertical comparison between ICEVs (petrol and diesel) and BEVs

We are able now to compare the CO₂eq. emissions results of each LC phase between vehicle types. We obtained these comparison results in TCO₂eq. between BEVs Europe, BEVs externalities, ICEV petrol and ICEV diesel for each LC phase:

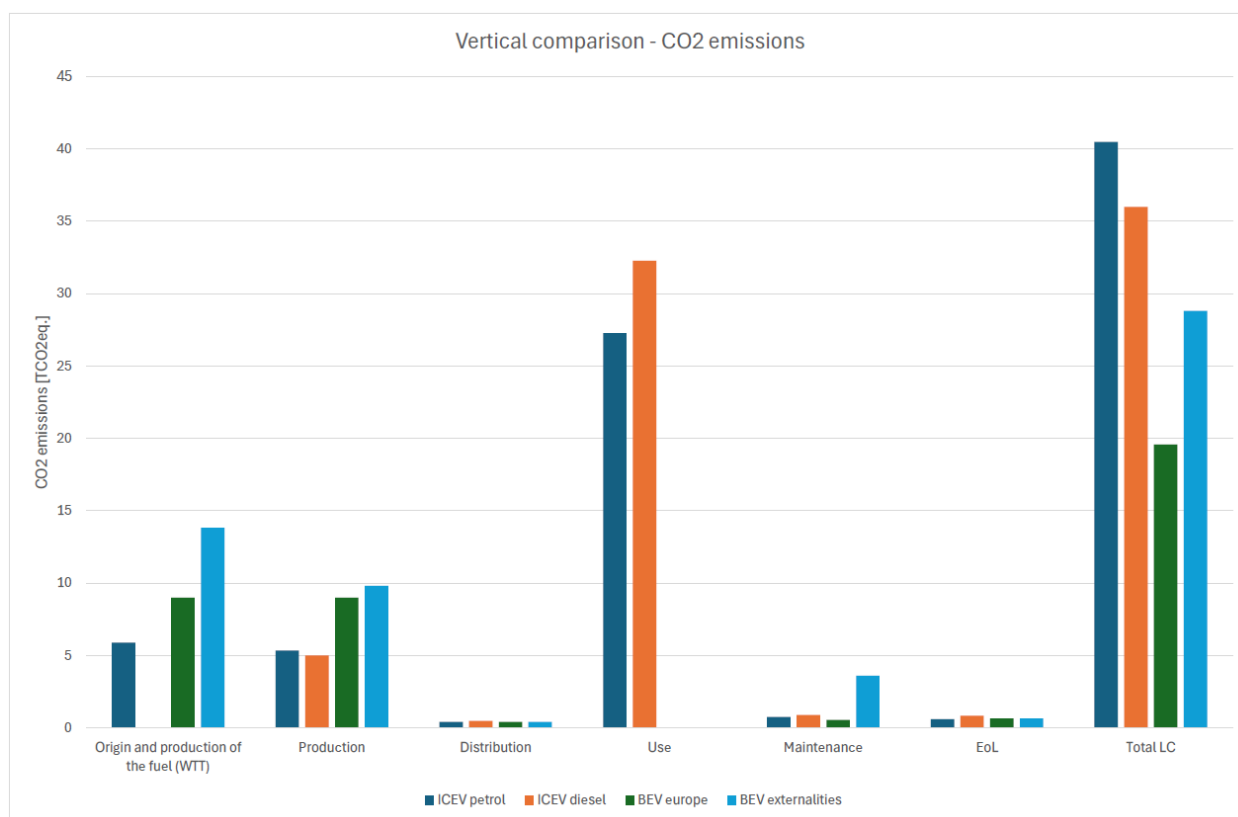


Figure 24: Histogram of the vertical comparison between BEV Europe, BEV externalities, ICEV petrol and ICEV diesel

Here is a recapitulative table, to have a clearer overview of the comparison results:

Origin and production of the fuel	BEV externalities	>	BEV europe	>	ICEV petrol		
Production	BEV externalities	>	BEV europe	>	ICEV petrol	>	ICEV diesel
Distribution	BEV externalities	≈	BEV europe	≈	ICEV petrol	≈	ICEV diesel
Use	ICEV diesel	>	ICEV petrol	>	BEV europe	=	BEV externalities
Maintenance	BEV externalities	>	ICEV diesel	≈	ICEV petrol	>	BEV europe
EoL	ICEV diesel	>	BEV europe	≈	BEV externalities	>	ICEV petrol
Total LC	ICEV petrol	>	ICEV diesel	>	BEV externalities	>	BEV europe

Figure 25: Recapitulative figure of the vertical comparison

6.2 Horizontal comparison : the most impacting LC phases

It's also possible now to rank the different phases in ascending order of importance based on the aggregated CO₂eq. emissions we found for ICEVs and BEVs separately.

The purpose of this section is to highlight one final specificity: which phases emit the most CO₂eq. within each type of vehicle.

BEVs Europe:

When we compare all the LC phases in ascending order, we obtain this histogram:

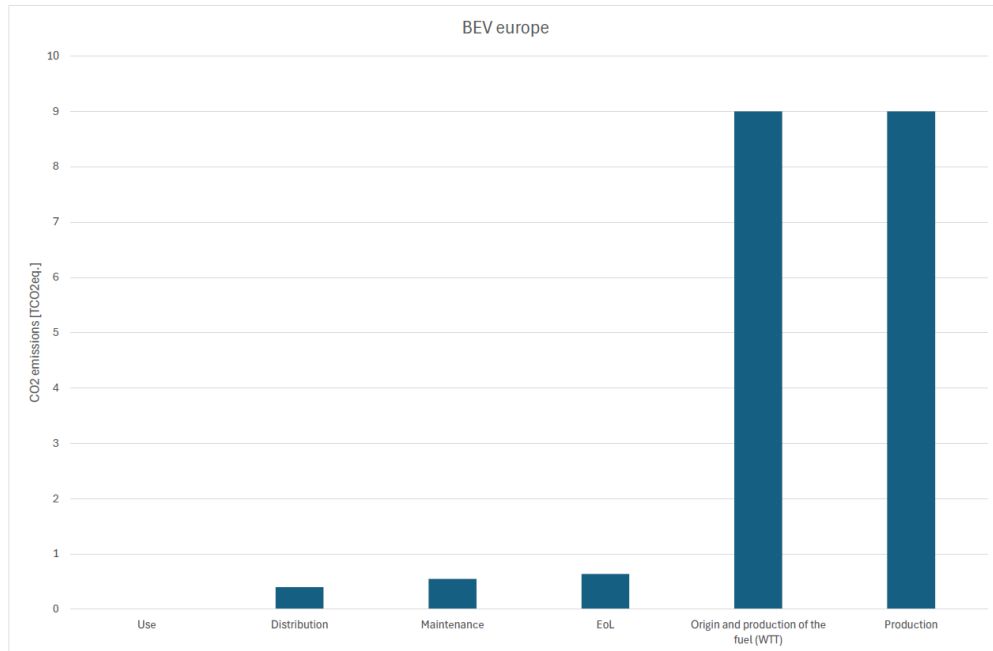


Figure 26: Histogram of the horizontal comparison for BEV europe

The most CO₂eq.-consuming stages for a BEV europe are therefore:

BEV Europe: **Production = WTT > EoL > Maintenance > Distribution > Use**

BEVs externalities:

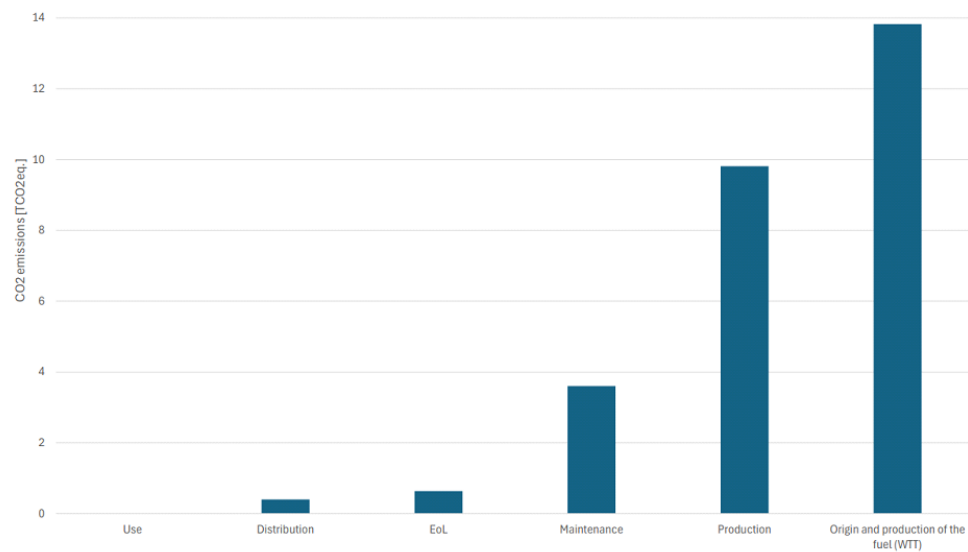


Figure 27: Histogram of the horizontal comparison for BEV externalities

The most CO₂eq. -consuming stages for a BEV externalities are therefore:

BEV externalities : **Production** > **WTT** > **EoL** > **Maintenance** > **Distribution** > **Use**

The ascending order is different from the BEV europe's one, the WTT phase is bigger than the production and the maintenance is bigger than the EoL phase.

ICEVs petrol:

When we compare all the LC phases in ascending order, we obtain this histogram:

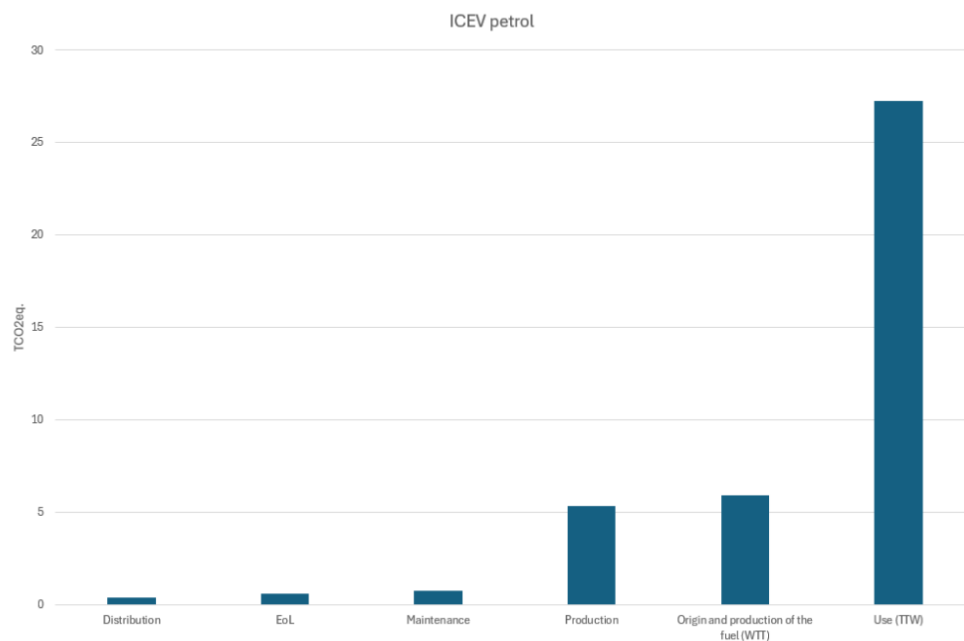


Figure 28: Histogram of the horizontal comparison for ICEV petrol

So, the most CO₂eq.-consuming stages for ICEV petrol are therefore:

ICEV petrol: **Use** > **WTT** > **Production** > **Maintenance** > **EoL** > **Distribution**

ICEVs diesel:

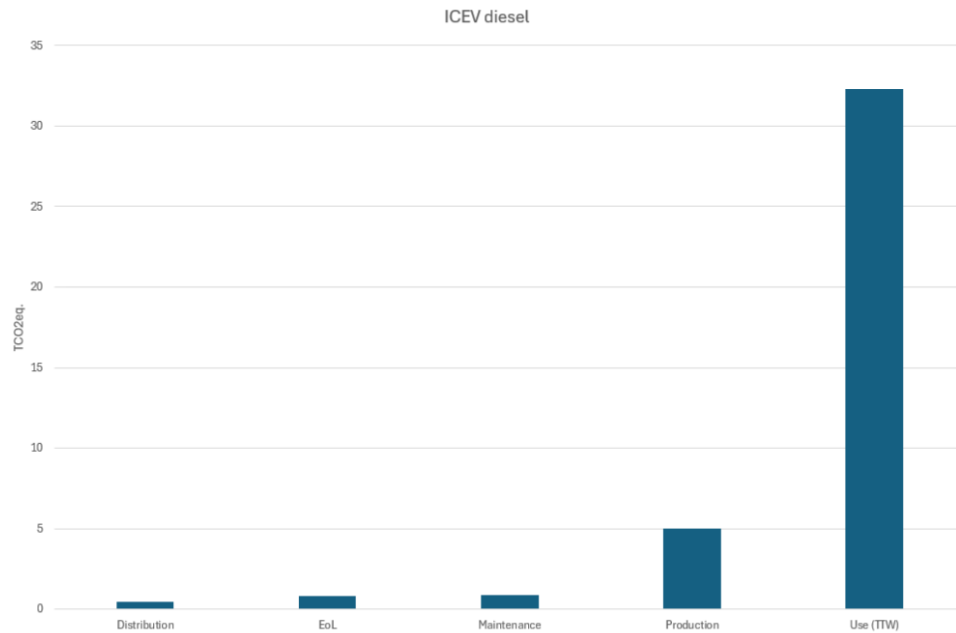


Figure 29: Histogram of the horizontal comparison for diesel

So, the most CO₂eq.-consuming stages for ICEV diesel are therefore:

ICEV diesel: **Use** > **Production** > **Maintenance** > **EoL** > **Distribution**

In the end, the ICEV petrol and ICEV diesel have the same ascending order of importance of the LC phases in terms of CO₂eq. emissions.

6.3 Break-even analysis

We will now conduct a break-even analysis to illustrate how CO₂eq. emissions vary with LC mileage for the entire car LC. We will therefore be able to see where the functions of the different types of car intersect in the driving mileage.

On the left of the graph (before the km 0) we've presented the mileage independent LC stages (production, distribution and EoL), and on the graph, the mileage dependent LC stages (use, maintenance and origin and production of the fuel (WTT)). So, the intercept of each function represents the independent phases, and the slope represents the relation between the dependent phases and the CO₂eq. emissions for each type of car/scenario.

We choose to represent 5 different scenarios, with their respective function:

ICEV petrol: $y = 0.2262x + 6.34$

ICEV diesel: $y = 0.2604x + 6.31$

BEV in europe: $y = 0.0988x + 10.0375$

BEV with externalities (the worst scenario in terms of electricity mix in europe, production, weather and driving behavior): $y = 0.1161x + 10.8475$

BEV in china : $y = 0.1994x + 11.4525$

These functions have been found thanks to our results from the median calculations.

The red line represents the FU we have selected in this master's thesis (150,000 km).

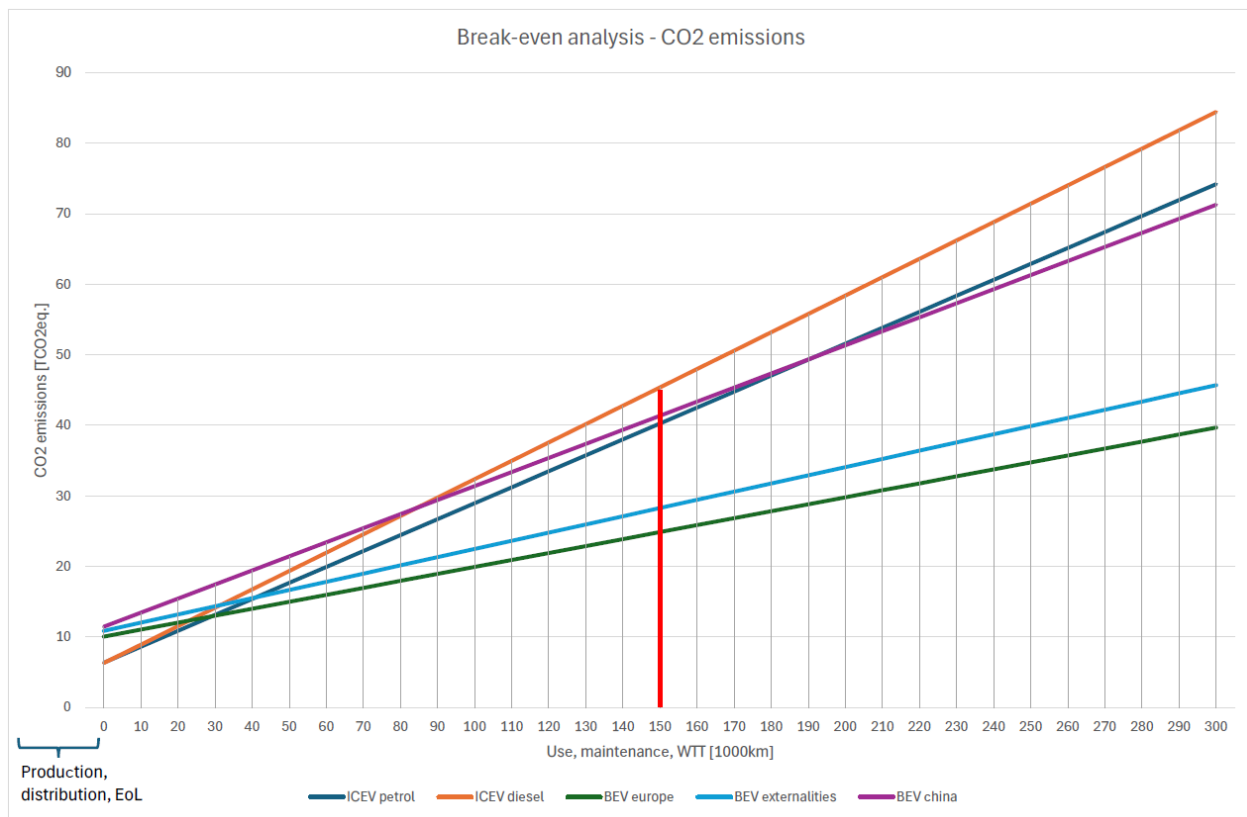


Figure 30: Break-even analysis of CO₂eq. emissions and driving mileage

The break-even point of ICEV petrol with BEV Europe: 29,023 km

The break-even point of ICEV diesel with BEV Europe: 23,066 km

The break-even point of ICEV petrol with BEV externalities: 40,962 km

The break-even point of ICEV diesel with BEV externalities: 31,458 km

The break-even point of ICEV petrol with BEV China: 190,765 km

The break-even point of ICEV diesel with BEV China: 84,303 km

So BEV europe is the best scenario from 29,023 km and ICEV diesel is the worst one from 84,303 km.

At the FU point, BEV europe emits the least, followed by BEV externalities, then ICEV petrol, BEV china and finally ICEV diesel.

7 Discussion

During our research and discoveries concerning the two main types of vehicles available on the market, some points are specific to one category while others are mixed between the two. This section, called the discussion, helps to better understand these hybrid concepts where the problem raised by each sub-category is common to both.

Furthermore, it provides an opportunity for the different externalities affecting the two categories to be taken into consideration, while emphasizing their inherent but independent nature to both solutions (electric or thermal).

This part is also defined as the section where debate about the figures presented throughout the work takes place (BEV against ICEV). The first step was to find them; now it's time to challenge them and, most importantly, to place them in their context.

7.1 Limitations of LCA

It is true that there are differences between LCAs about the same topic, because if it is taken alone, it is just a synthetic model where variances can be created without necessarily being incorrect. Indeed, as previously mentioned in the methodology section, these divergences can arise from various reasons:

- Variation in scope delimitation
- Differences between electricity mixes (especially for our case)
- Use of different quantitative tools
- Assumptions about different arbitrarily chosen values: lifespan or type of battery production, etc. (Nordelöf et al., 2014; Horne, 2009).

Nevertheless, this tool remains relevant and extremely useful to compare processes.

7.2 Weight of the vehicles

In the past 30 years, the average weight of passenger cars has increased by an average of 30%, leading to a greater need for energy to move them. As a simple example, a classic passenger car produces half as much as its SUV version (Baranna & Hache-Vinceno, 2023). This means that consumers also have a role to play in balancing the carbon footprint: through their purchases and

interests, they can limit the production of such items by shifting their choices to something less ecologically demanding.

For information purposes, in figure 7.2, the weight of the different types of Volkswagen Golf over the last 30 years (Danilecki et al., 2017). This shows how the end consumer is increasingly interested in larger, more spacious cars, and despite the daily environmental challenges, it is ultimately up to them to decide which vehicle they will drive:

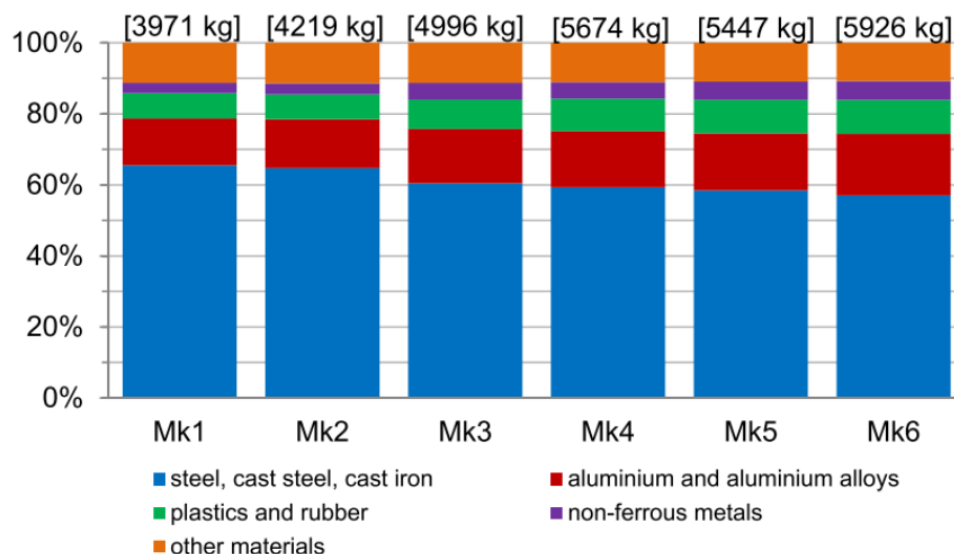


Figure 31: Emissions of CO2 eq related to the production of materials used in the VW Golf (Danilecki et al., 2017)

In Figure O.1 ¹, created by J. Bertaux in 2023, there is a table with examples from other major brands and the respective weights of their products, which further supports the stance explained earlier.

7.3 Geo-political tensions in the supply chain

Currently, lithium supply mainly comes from two sources: the Andes region (Bolivia, Chile, Argentina), which contributes around 70%, and Tibet, accounting for about 30%. The extraction processes in the Andes have led to geopolitical tensions and significant deforestation. Meanwhile, Tibet is under pressure from China over its possession of metal. This therefore raises questions about the true ecological and ethical nature of the electric car (Courbe, 2019).

¹In appendix O: Discussion, figure O.1: Life cycle Greenhouse Gas (GHG) Emissions and impact on Mass (Bertaux, 2023)

This example focuses solely on lithium but can be adapted for any type of precious metal.

7.4 Vehicle usage/type of journey

Another significant point is the impact of driving on CO₂eq. emissions. It deals with how the driver behaves behind the wheel: aggressive driving increases these by up to 20% (Schneider et al., 2023).

Furthermore, if this behavior is coupled with very short journeys requiring frequent stops, wear due to friction of the various parts of the vehicle is also accentuated. Leading to higher maintenance costs and a lesser lifespan for the spare parts. Indeed, as explained by Nordelöf et al. (2014), where and how the consumers drive influence greatly how they consume (figure O.2¹). For ICEVs, city driving emits more than suburban driving and highway driving emits the least. It's the same for PHEV electricity part.

7.5 Other environmental indicators

As shown in Figure O.3², the impact of a car production is beyond CO₂eq. emissions only. It includes the effects the industry has on the surrounding areas where it operates:

- Human health
- Water eutrophication
- Water consumption
- Ozone formation
- ...

All these factors must be taken into account to conduct a comprehensive analysis of a vehicle's ecological impact. However, this work focuses solely on one variable, CO₂eq. emissions. It is crucial to understand that this is just one among many factors and that their exclusion from the focus of this analysis does not diminish their global importance.

¹In appendix O: Discussion, figure O.2: Effect of the type of vehicle and the type of driving on the CO₂ emissions (Nordelöf et al., 2014)

²In appendix O: Discussion, figure O.3: Relatives changes in the environmental impacts of the base case with a battery manufactured with the electricity mix of different countries (Philippot et al., 2023)

8 Conclusion

It's now time to conclude this analysis with a focus on the crucial steps of our work and the insights we can draw from it.

First and foremost, the values derived from our research provided data that needed to be transformed into information to derive knowledge. This knowledge, the amount of CO₂eq. per LC stage and for the total LC, proved crucial to answering the research question: "Which type of car (ICEVs diesel/petrol and BEVs) emits the most CO₂eq. over its entire LC and which LC phases are the most impactful"? To achieve this, it was necessary to divide the LCA into key moments, group some by similarity and define with precision these moments in order to assign for each of them a TCO₂eq. emissions result thanks to the analysis of our data sources.

For this conclusion, we will focus mainly on BEVs europe and ICEVs petrol and diesel.

Origin and production of the fuel (WTT)

The first major differentiation between ICEVs and BEVs lies in the origin and production of the fuel: electricity, gasoline, or diesel. For the latter two, it was quite complicated to find CO₂eq. emission results for their production, as many authors struggle to find reliable sources and clear results, especially for crude oil feedstock extraction. Many authors also group together the WTT and TTW phases, so we didn't have access to precise results for the WTT phase alone. Nevertheless, we obtained a result of 5.9 T CO₂eq. for petrol and for diesel, an extreme value not taken into account in our analysis. For electricity, depending on the country that produces it, the values fluctuate enormously with results ranging from 27.94 to 270.3 gCO₂eq./kWh just within our European sample. This becomes one of the primary causes of CO₂eq. emission fluctuations within the same category. For the electricity mix of Europe our median is 9 TCO₂eq. for 150,000 km of driving. This result could be greatly improved if the European electricity mix becomes greener. So, for this phase a BEV emits more than an ICEV.

Production

As for the previous section, production is a stage where electric vehicles still have much progress to make. Nevertheless, it must be clear that this technology is much more recent than its thermal counterpart and we can expect technical advances almost yearly.

However, the reality is that the CO₂eq. emissions from the production of an electric vehicle (9 TCO₂eq.) are larger than those of the thermal vehicle (5.34 and 5 TCO₂eq.). Therefore, there is

indeed a significant advantage for thermal vehicles in this stage of the LCA.

Distribution

Although deliberately little discussed during the analysis because of its low contribution on CO₂eq., distribution remains a stage on its own in the product's LC. With a generally higher weight by a factor of 1.3/1.4, the logistics of an electric car are more CO₂eq.-intensive than its thermal counterpart but this has such a low impact that it has not been taken into account in our analysis. So we obtained the same value for BEVs and ICEVs for the distribution phase: approximately 0.4 TCO₂eq.

Use (TTW)

Use is the part most subject to externalities (even if the consequences do not apply to the phase itself for BEVs, but rather to the WTT phase, nevertheless this is during this phase that these externalities can happen):

- Driving behavior
- Type of driving (urban area, agglomeration, etc.)
- Vehicle weight

It thus becomes necessary to refocus not only on the vehicle but on the person driving it. Indeed, the three examples cited above are all, in reality, everyday choices made by the consumer: aggressive driving increases fuel consumption of a BEV by 20%, the area where the vehicle operates massively influences its lifespan and maintenance needs, and finally, it is up to the consumer to choose a product suited to their actual needs (the latest SUV in the city is not the best solution for everyone, just as an electric vehicle in an area with few charging stations is not either).

In terms of results, the median for BEV is 0, the consumption of electricity during the driving of the vehicle emits 0 CO₂eq. and for ICEVs, this is the most contributing phase with 27.28 TCO₂eq. for an ICEV petrol and 32.29 TCO₂eq. for an ICEV diesel.

Maintenance

In terms of maintenance, CO₂eq. emissions are higher for ICEVs (0.75 TCO₂eq. for petrol and 0.88 TCO₂eq. for diesel) than for BEVs (0.55 TCO₂eq.), since ICEVs are made up of more components to be replaced, fluid to be refilled, and so on.

End-of-Life

For an electric vehicle, this is still far below the expectations left by the industry. With a battery lifespan of 5 to 15 years, this interval is far too wide and does not provide a tangible basis for the market. However, to address this problem, numerous solutions exist to limit the impact during the EoL: first recycling (Remanufacture and repurposing used batteries) and second recycling (allows saving up to 61% of steel, 13% of aluminum, and 20% of cathode materials)

Unfortunately, despite promising figures for recovery rates reaching up to 85/90% in the coming years, currently, we are closer to 50% but due to the youth of the network, constantly changing external policies, only 5% of batteries are actually recycled.

And for ICEVs, the EoL phase is an already mature process, well established and developed for many years, so we obtained the following figures: 0.6 TCO₂eq. for petrol and 0.84 TCO₂eq. for diesel.

Total LC

We have two different results for each vehicle type: the addition of the results from all LC phases (previous sections) and a result based on the median of the "Total LC results" from our data sources. For BEVs europe, the first is equal to 19.587 TCO₂eq. and the second is equal to 36.269 TCO₂eq. For ICEVs petrol, 40.27 TCO₂eq. and 40.5 TCO₂eq. and finally for ICEVs diesel, 45.38 TCO₂eq. and 36 TCO₂eq. So, for both cases, the BEV emits fewer CO₂eq. emissions during its LC (except with diesel where it is approximately equal $36.269 \approx 36$).

Other Environmental Impacts

Finally, although this does not entirely fall within the initial scope of the work, it would be dishonest not to highlight impacts other than CO₂eq. emissions, such as:

- Eutrophication and water ionization
- Human health
- Resource scarcity
- ...

All these externalities are only briefly mentioned in this work, but their ecological impacts are indeed present in our daily lives. The fact that they are not explored in depth does not mean they are negligible; on the contrary.

The final message is that there is no perfect solution even if the total LC of BEVs is lower than the one of ICEVs after 150,000 km of driving. So many variable external factors need to be taken into account (the electricity mix, the driving behavior, the processes of production and recycling etc.). The often-cited example of an electric car manufactured in Norway and driven there is quickly debunked when we learn that it is sensitive to cold temperatures.

Nevertheless, it is possible to find the appropriate solution for each driver based on their situations and expectations. To achieve this, it becomes crucial to educate future buyers so that they understand what they are purchasing and under what conditions. It becomes clear that humans remain the pivotal factor that tips the scales:

- Through their driving habits
- Through their choice of transportation mode
- Through their choices as consumers

Therefore, the focus is no longer solely on determining whether electric or combustion vehicles consume more, but rather on understanding that each end user responds to a set of constraints and needs. These factors, although external to the LCA process, must be taken into account as they are what ultimately influence the decision in one direction or another. Once internalized, it would be possible to offer a genuine analysis per individual of which type of vehicle would emit the least for that consumer.

To improve even more the score of BEVs, we must encourage policymakers to implement greener electricity mixes based on renewable energy sources, to invest in research and the implementation of more eco-friendly manufacturing and recycling processes for batteries and ultimately to encourage end consumers to be responsible in their purchasing choices in relation to their own conditions and situation.

Nevertheless, to strictly stick to the initial scope, a BEV in Europe emits less CO₂eq. than an ICEV after 29,023 with European electricity mix.

And the most emitting steps are:

BEV: WTT > Production > EoL > Maintenance > Distribution > Use

ICEV (petrol or diesel): Use > WTT > Production > Maintenance > EoL > Distribution

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10 Appendices

Appendix A: Euro V and VI

	Euro V Heavy-Duty		Euro VI Heavy-Duty	
	Euro V SS ^a	Euro V T ^b	Euro VI SS ^a	Euro VI T ^b
Emission limits (g/km)				
CO	1.5	4.0	1.5	4.0
HC	0.46	0.55	0.13	0.16 ^d
CH ₄ ^c		1.1		0.5
NO _x	2.0	2.0	0.4	0.46
PM	0.02	0.03	0.01	0.01
PN (#/km)			8.0 × 10 ¹¹	6.0 × 10 ¹¹
Smoke (1/m)	0.5			
Ammonia (ppm) ¹²			0.01	0.01
Fuel Sulfur Limit (ppm)	10	10	10	10
Test Cycle	ESC & ELR	ETC	WHSC	WHTC

^a Steady-state testing; ^b Transient testing; ^c For Euro V for Natural Gas only, for Euro VI, NG and LPG; ^d Total HC for diesel engines, non-methane HC for others

Figure A.1: Maximum emissions allowed by Euro 5 and 6 (Tran, 2023)

Appendix B: ISO standards 14040 - 14045

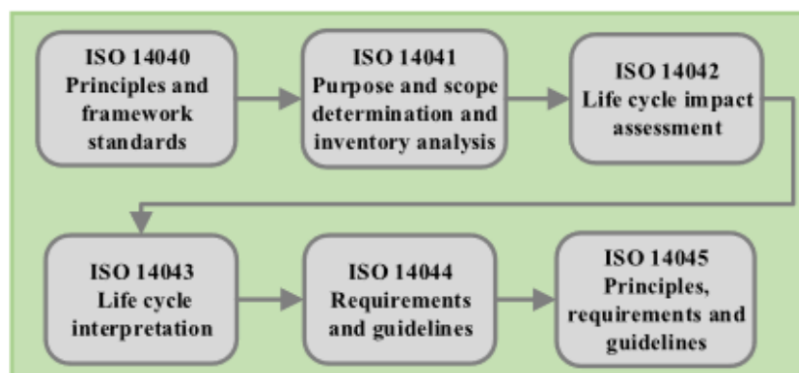


Figure B.1: ISO series standards about LCA (Lai et al., 2022)

Appendix C: Types of cars produced in Europe in 2019

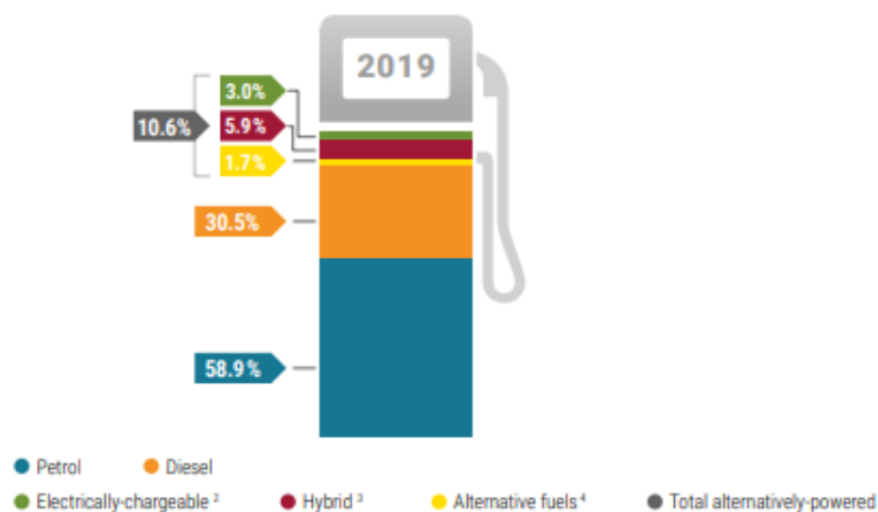


Figure C.1: Types of new cars produced in Europe in 2019 (European Automobile Manufacturers' Association, 2021)

Appendix D: LC structures and boundaries references

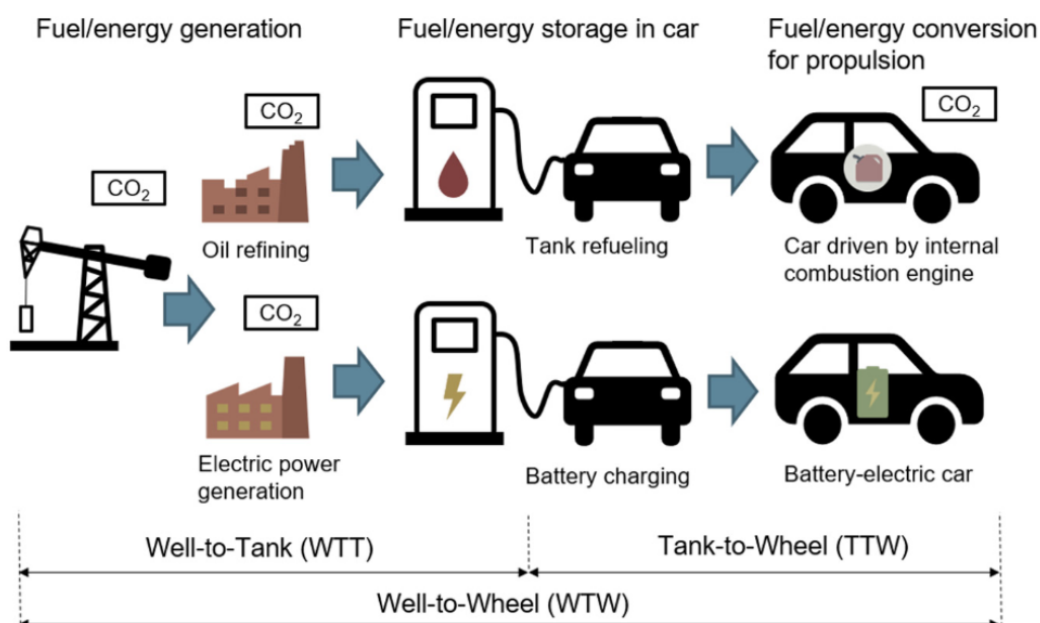


Figure D.1: Sequences of energy provision and conversion for vehicle propulsion (Hirz & Nguyen, 2022)

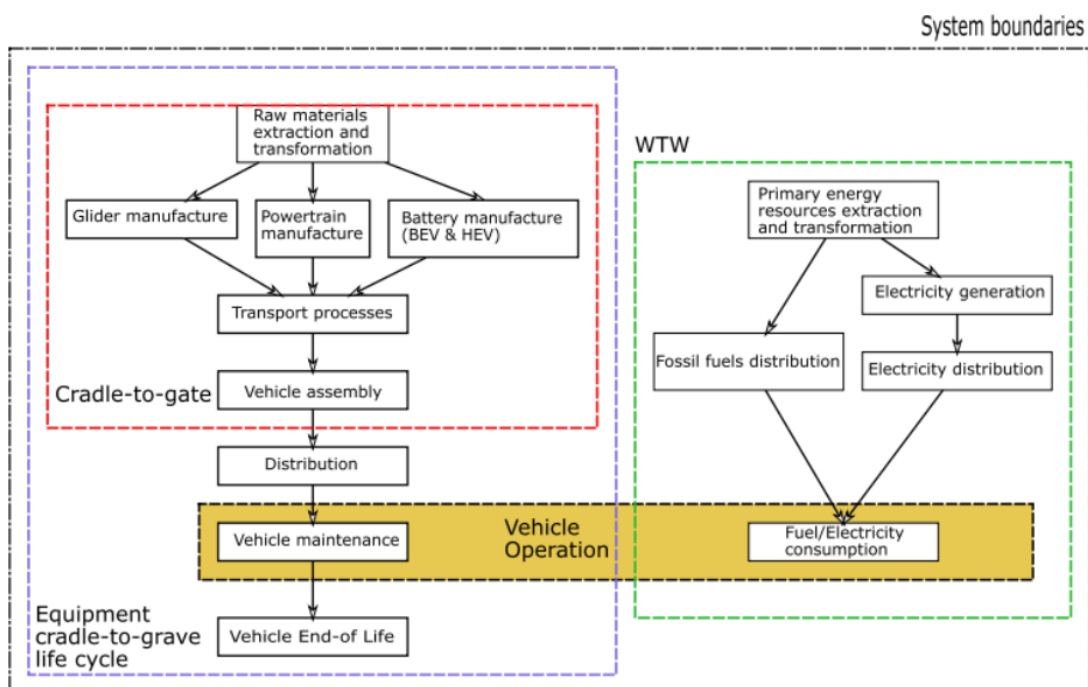


Figure D.2: Life cycle structure and boundaries (Nordelöf et al., 2014)

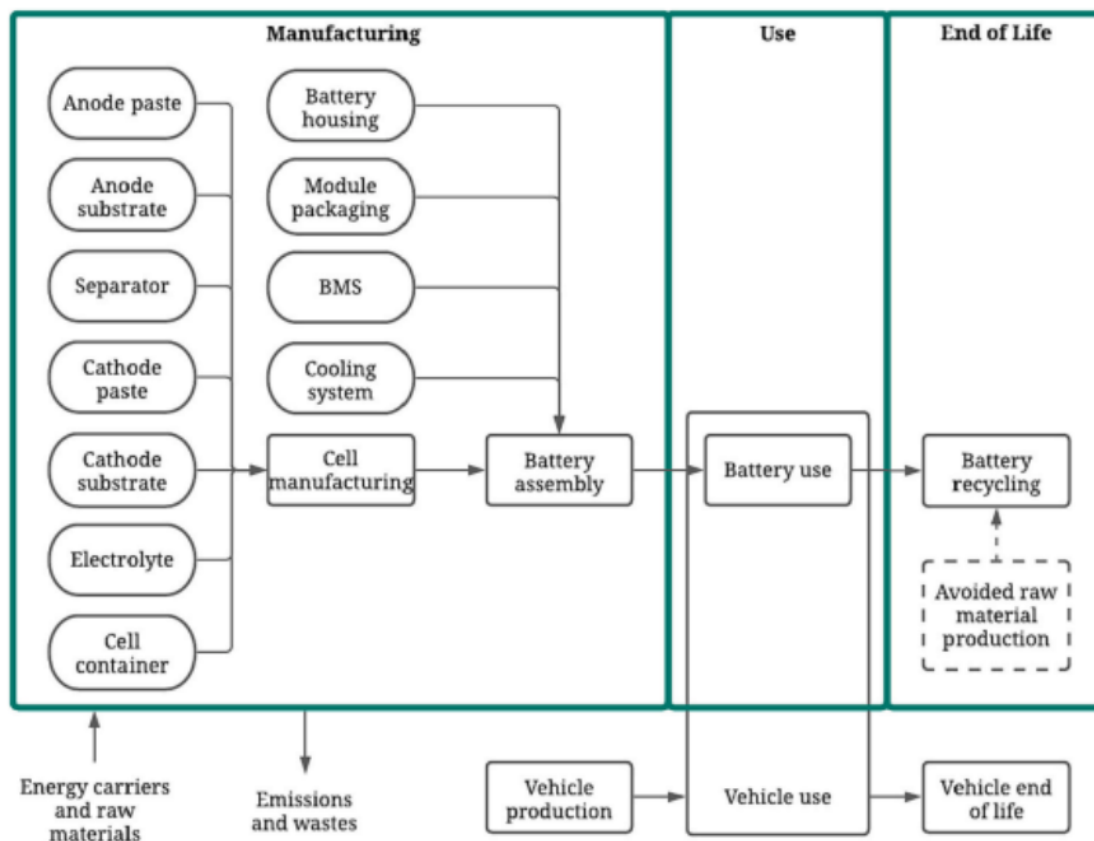


Figure D.3: System boundaries (Philippot et al., 2023)

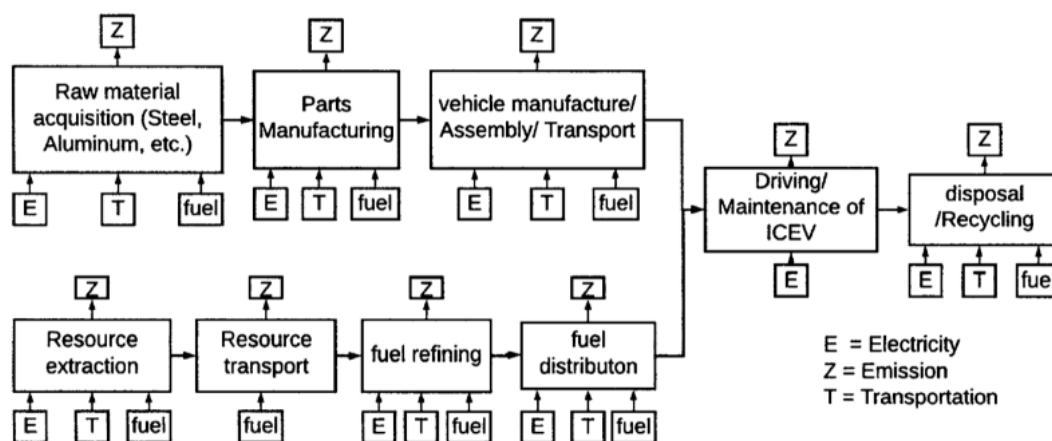


Figure D.4: Life cycle structure and boundaries for ICEVs (ref à retrouver)

Appendix E: How to read a boxplot ?

A boxplot is a standardized way of displaying the distribution of data based on its five-number summary (“minimum”, first quartile [Q1] (25th percentile), median (50th percentile), third quartile [Q3] (75th percentile) and “maximum”). The interquartile range (IQR) represents the range between Q1 and Q3, in other words, 50% of the observations.

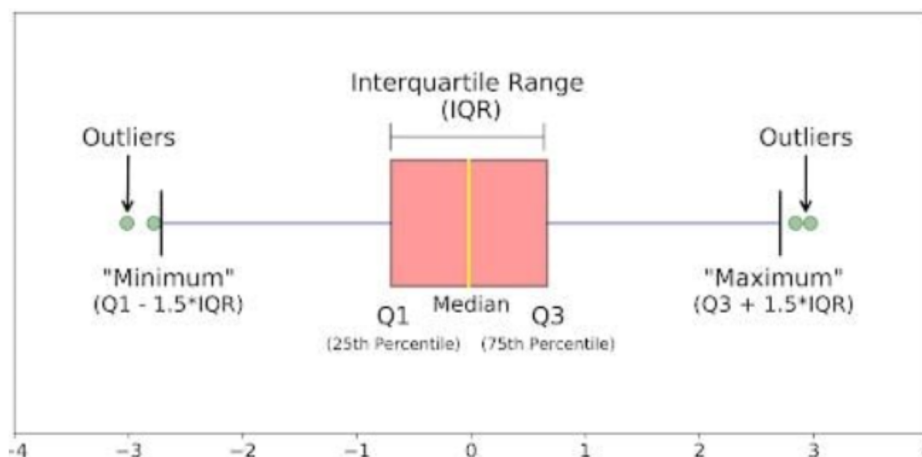


Figure E.1: How to read a boxplot ? (Galarnyk, 2024)

Appendix F: Fractional distillation in oil refining

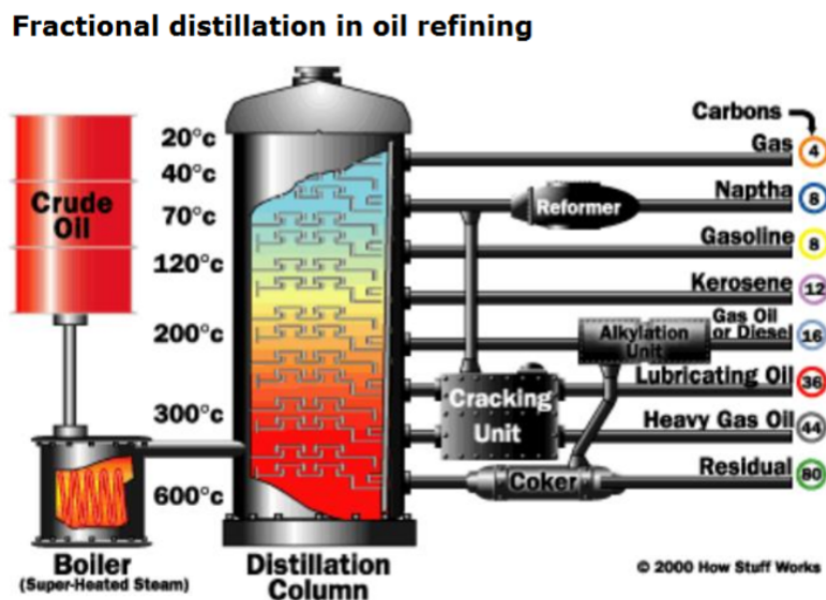


Figure F.1: Fractional distillation in oil refining (European Automobile Manufacturers' Association, 2016)

Appendix G: Emissions of WTW LC of BEVs and ICEVs

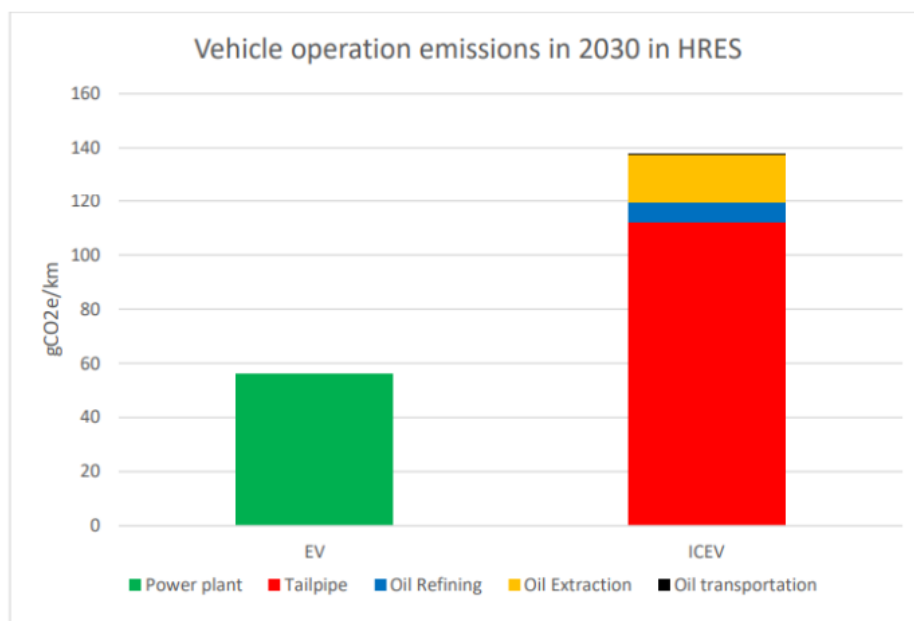


Figure G.1: Emissions per kilometer of operation of vehicles in 2030 in HRES (Gopinathan, 2020)

Appendix H: Mass breakdown analysis

Mass and energy balance of ICEV, EV, and PHEV vehicle production (Argonne National Laboratory, 2019; Electric Vehicle Database, 2019; Ecoinvent, 2020; Electric Vehicle; Rosenfeld et al., 2019).

Materials and Energy	Unit	ICEV	EV	PHEV
Chassis*				
Aluminium casting part [Metal parts]	kg	3.7	4.1	3.9
Cast iron [Metal parts]	kg	22.9	25.3	25.6
Copper wire [Metals]	kg	3.7	4.1	4.6
Plastic part [Plastic parts]	kg	5.9	6.5	7
Steel plate	kg	282	311.3	340.9
Styrene-butadiene-rubber [Plastics]	kg	14.8	16.3	17
Vehicle Body				
Aluminium sheet [Metal parts]	kg	8.9	4	4.2
Copper wire [Metals]	kg	3.4	11.5	11.3
Float flat glass [Minerals]	kg	32.4	38.9	37.9
Plastic part [Plastic parts]	kg	123	110.1	130.7
Steel sheet with zinc plated [Metals]	kg	509.6	416.3	392.2
Styrene-butadiene-rubber [Plastics]	kg	4.9	2.7	3
Powertrain System*				
Aluminium ingot [Metals]	kg	47.1	–	–
Cast iron part [Metal parts]	kg	0.5	–	84.5
Copper wire [Metals]	kg	15.5	12.6	10.4
Plastic part [Plastic parts]	kg	43.5	18.2	31.1
Steel plate	kg	127.9	0.8	186.1
Styrene-butadiene-rubber [Plastics]	kg	0	–	–
Aluminium sheet part [Metal parts]	kg	–	–	50.8
Lead acid battery				
Glass fibers [Minerals]	kg	0.8	0.6	0.6
Lead [Metals]	kg	25.7	20.7	20.7
Polypropylene part [Plastic parts]	kg	2.3	1.8	1.8
Sulphuric acid (98%) [Inorganic intermediate products]	kg	2.9	2.4	2.4
Thermal energy from natural gas	MJ	61.7	49.8	49.8
Water (process water)	kg	423.0	423.0	423.0
Electricity [Medium Voltage]	MJ	37.8	30.5	30.5
Transmission system				
Aluminium casting part [Metal parts]	kg	29.7	14.8	14.7
Cast iron [Metals]	kg	24.4	–	–
Copper wire [Metals]	kg	–	13.9	13.9
Steel plate	kg	28.1	44.4	44.5
Styrene-butadiene-rubber [Plastics]	kg	4.7	–	–
Lithium Hexafluorophosphate (RoW) (PVDF)				
Electricity [Medium Voltage]	MJ	–	2094.4	589.4
Thermal energy from coal	MJ	–	9805.6	2801.6
Generator				
Aluminium casting part	kg	–	–	18.2
Copper wire	kg	–	–	14.0
Steel plate	kg	–	–	18.2
Vehicle assembly				
Electricity [Medium Voltage]	MJ	4338.2	4338.2	4338.2
Thermal energy from natural gas	MJ	5573.9	5573.9	5573.9

Materials and Energy	Unit	ICEV	EV	PHEV
Vehicle Fluids				
Ethylene glycol [Organic intermediate products]	kg	27.2	14.4	20.8
Water (Deionised for operating materials)	kg	75.1	41.4	47.8
Gasoline blendstock (For operation)	kg	168.1	5.2	161.1
Naphtha [For Operation]	kg	112.1	3.5	107.9
Methanol [For Operation]	kg	47.9	27	27
Plastic part [Plastic parts]	kg	–	13.5	13.6
Traction motor				
Aluminium casting part [Metal parts]	kg	–	33.3	18.2
Copper wire [Metals]	kg	–	25.6	14
Steel plate	kg	–	33.3	18.2
Electronic controller				
Aluminium casting part [Metal parts]	kg	–	41.7	13.1
Copper wire [Metals]	kg	–	6.2	2.3
Steel plate	kg	–	3.8	1.4
Styrene-butadiene-rubber [Plastics]	kg	–	2.8	1
Plastic part [Plastic parts]	kg	–	–	6.6
Li-Ion battery*				
Aluminium casting part [Metal parts]	kg	–	120.7	35
Copper wire [Metals]	kg	–	57.9	16.8
Ethylene glycol [Organic intermediate products]	kg	–	11.4	3.3
Glass fibers [Minerals]	kg	–	2.5	0.7
Polyethylene terephthalate compound [Plastics]	kg	–	1	0.3
Polypropylene compound [Plastics]	kg	–	5.4	1.6
Steel Plate	kg	–	3	0.9
Water (Deionised)	kg	–	43.1	12.4
Graphite	kg	–	81.2	23.5
Lithium Hexafluorophosphate (LiPF6)	kg	–	7.9	2.3
Ethylene Carbonate	kg	–	21.9	6.4
Polyethylene high density granulate	kg	–	1.8	0.5
Cobalt (NMC)	kg	–	113.2	32.8
	kg	–	–	3

Source: Data based on GREET 2019; (*) Confidential industry data; Ecoinvent data (Ecoinvent, 2020).

Figure H.1: Mass and energy balance of ICEV and BEV's vehicle production (Shafique et al., 2021)

Assembly	Mass [kg]	
	ICEV	BEV
BiW	292.7	303.6
Closures	176.5	170.0
Suspension/chassis	252.7	252.5
Interiors	173.9	177.1
Drivetrain	222.5	459.8
Electronics	56.7	53.0
Total vehicle	1175.0	1415.7

Figure H.2: Mass breakdown analysis of ICEV and BEV modelled in LCA (Del Pero et al., 2018)

Appendix I: Powertrain system ICEVs petrol and diesel

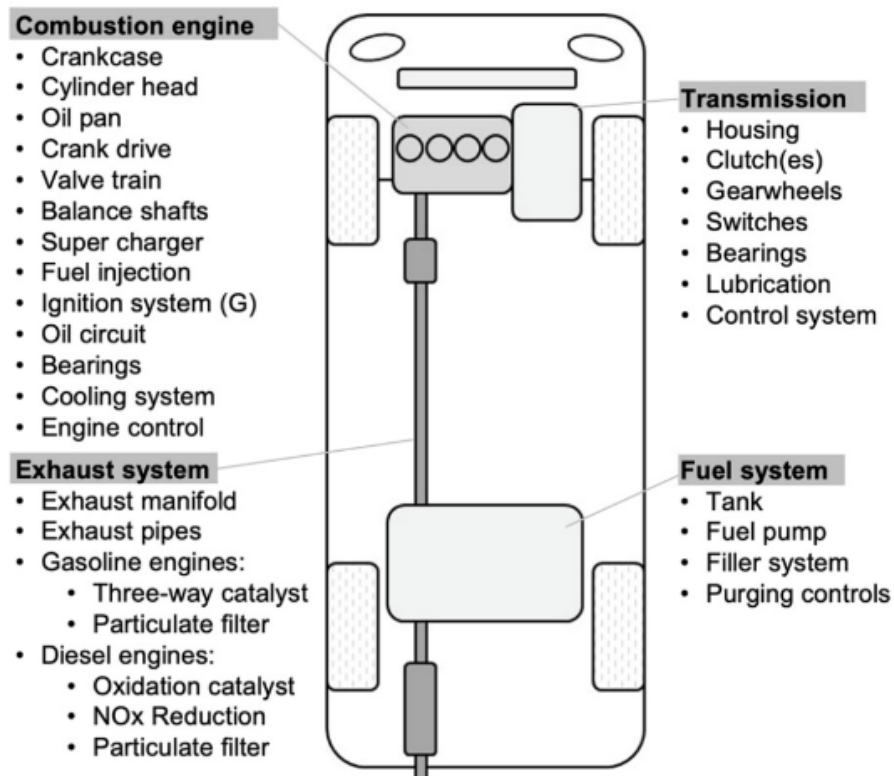


Figure I.1: Powertrain structure of conventionally driven cars diesel and petrol (Hirz & Nguyen, 2022)

Appendix J: CO₂eq. emissions during production phase for ICEVs

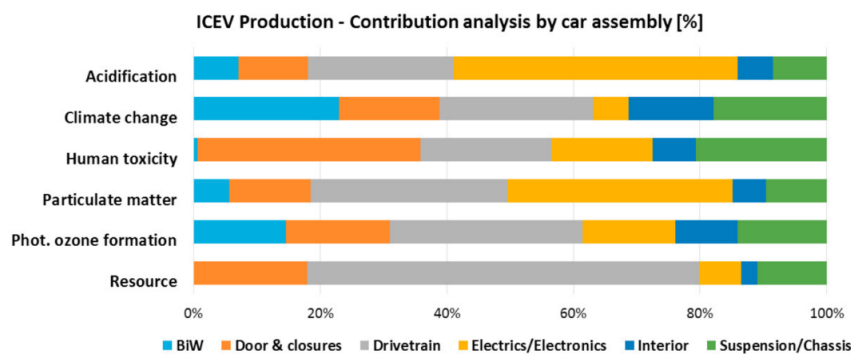


Figure J.1: Contribution analysis by vehicle assembly of production impacts (ICEV), (climate change for CO₂eq. emissions)(Del pero et al., 2018)

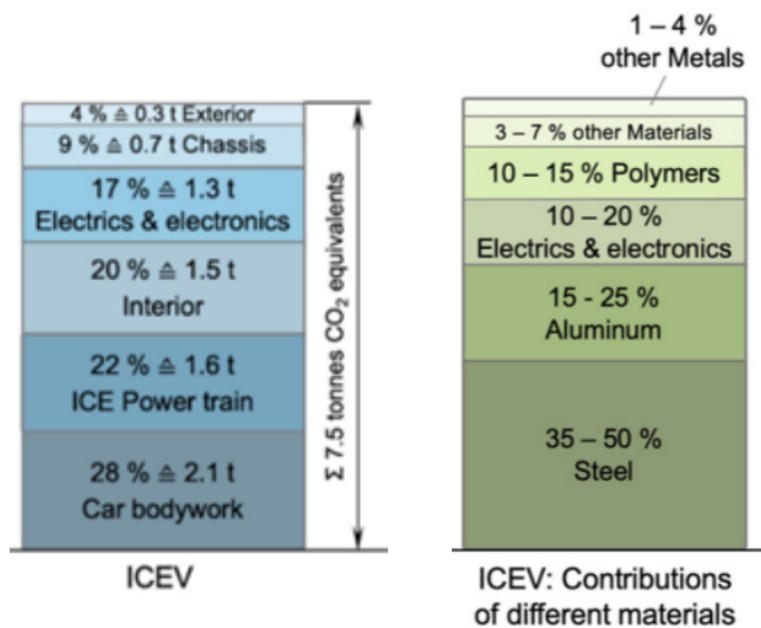


Figure J.2: CO₂eq. emissions of the production of the parts and the materials constituting an ICEV (Hirz & Nguyen, 2022)

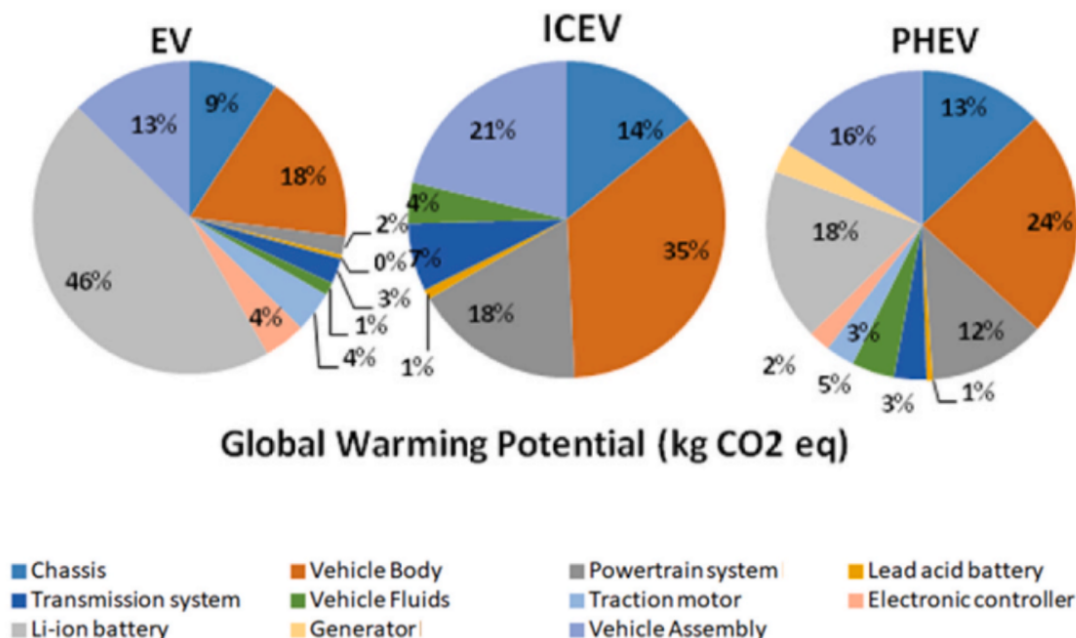


Figure J.3: Contribution of the components of each vehicle during the production phase (Shafique et al., 2022)

Appendix K: EoL phase of ICEVs and BEVs

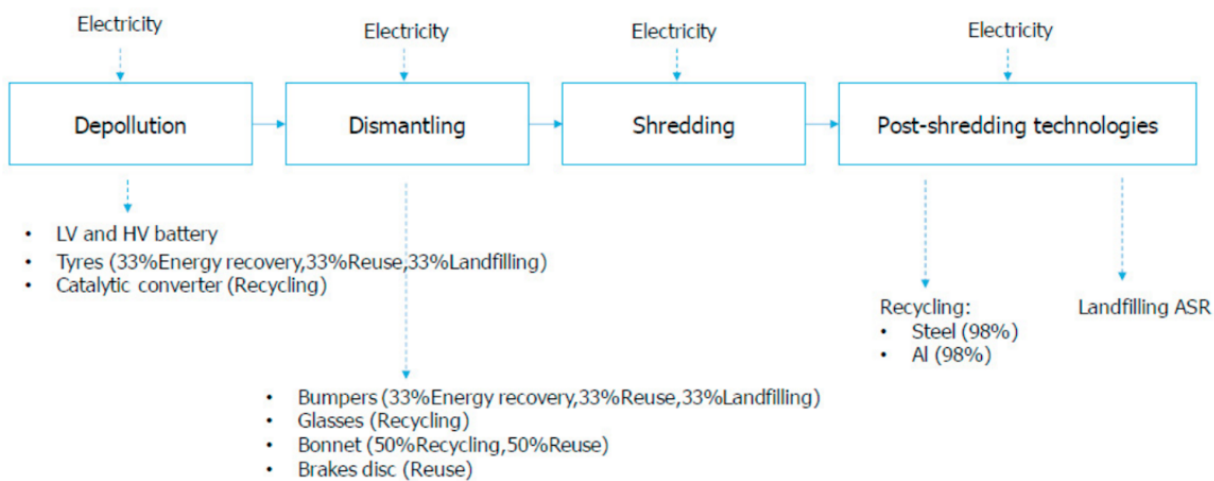


Figure K.1: Allocation of components and materials to EoL processes for ICEVs and BEVs (Del Pero et al., 2018)

Appendix L: Electricity mix per country

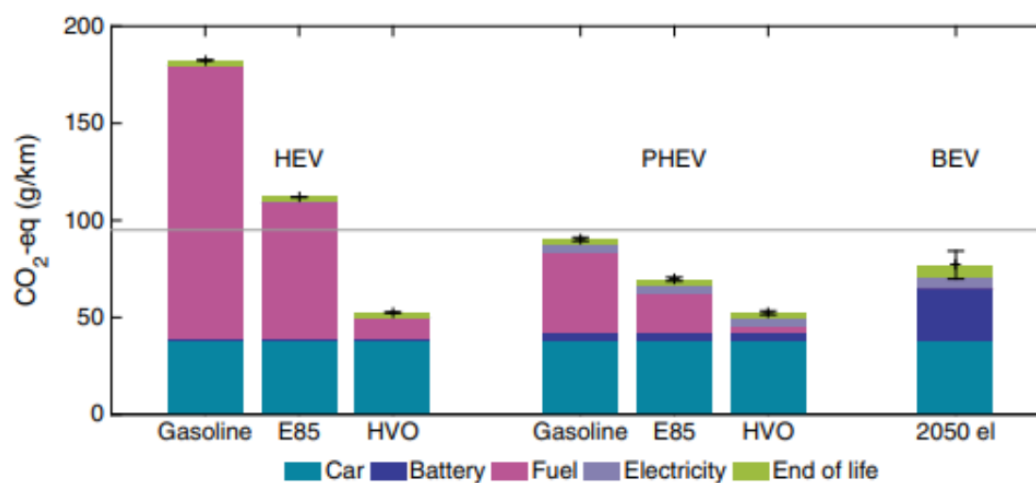


Figure L.1: Life Cycle CO₂eq. emissions from the HEV, PHEV and BEV model when using 2020 and 2050 European electricity (Andersson Borjesson, 2021)

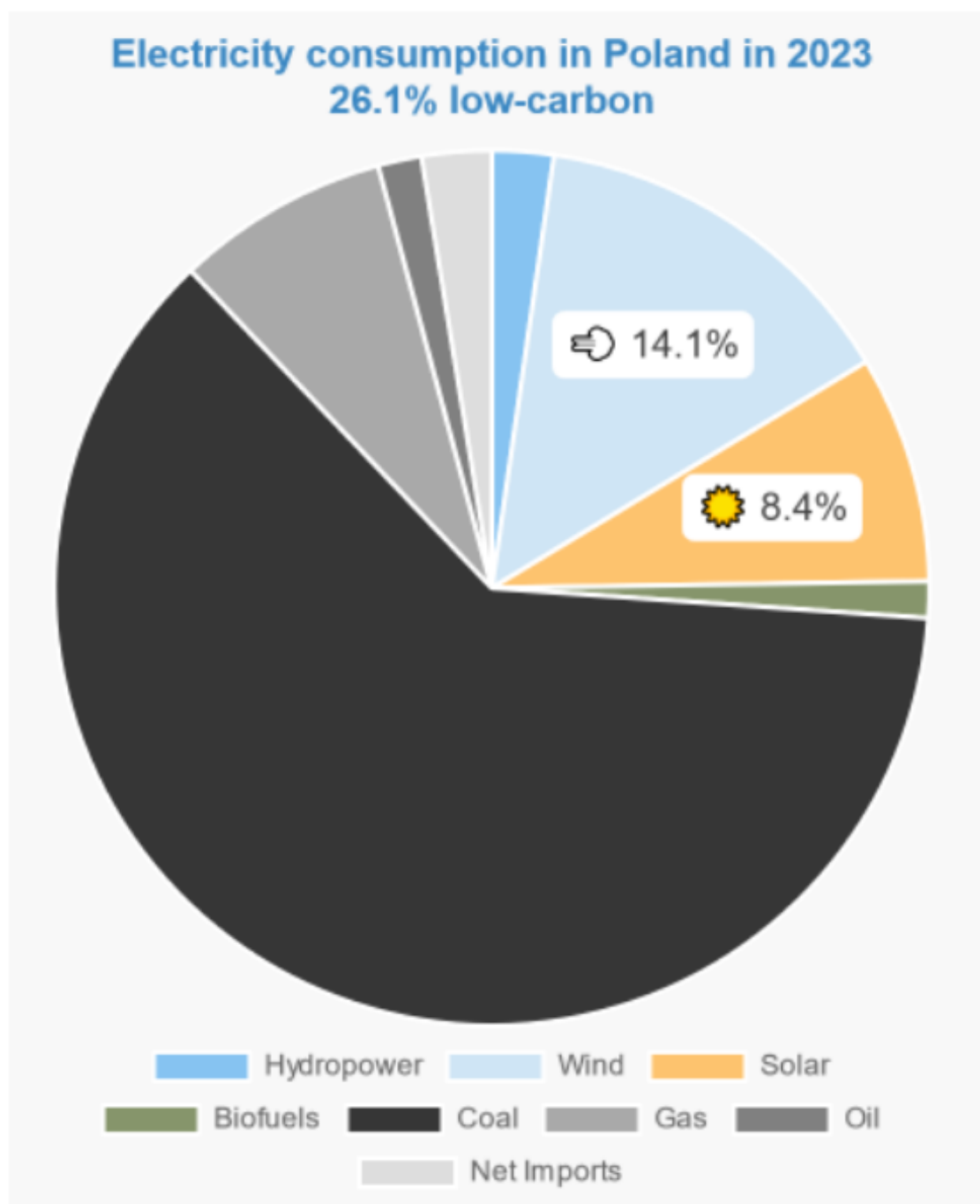


Figure L.2: Electricity consumption in Poland in 2023 (lowcarbonpower, 2023)

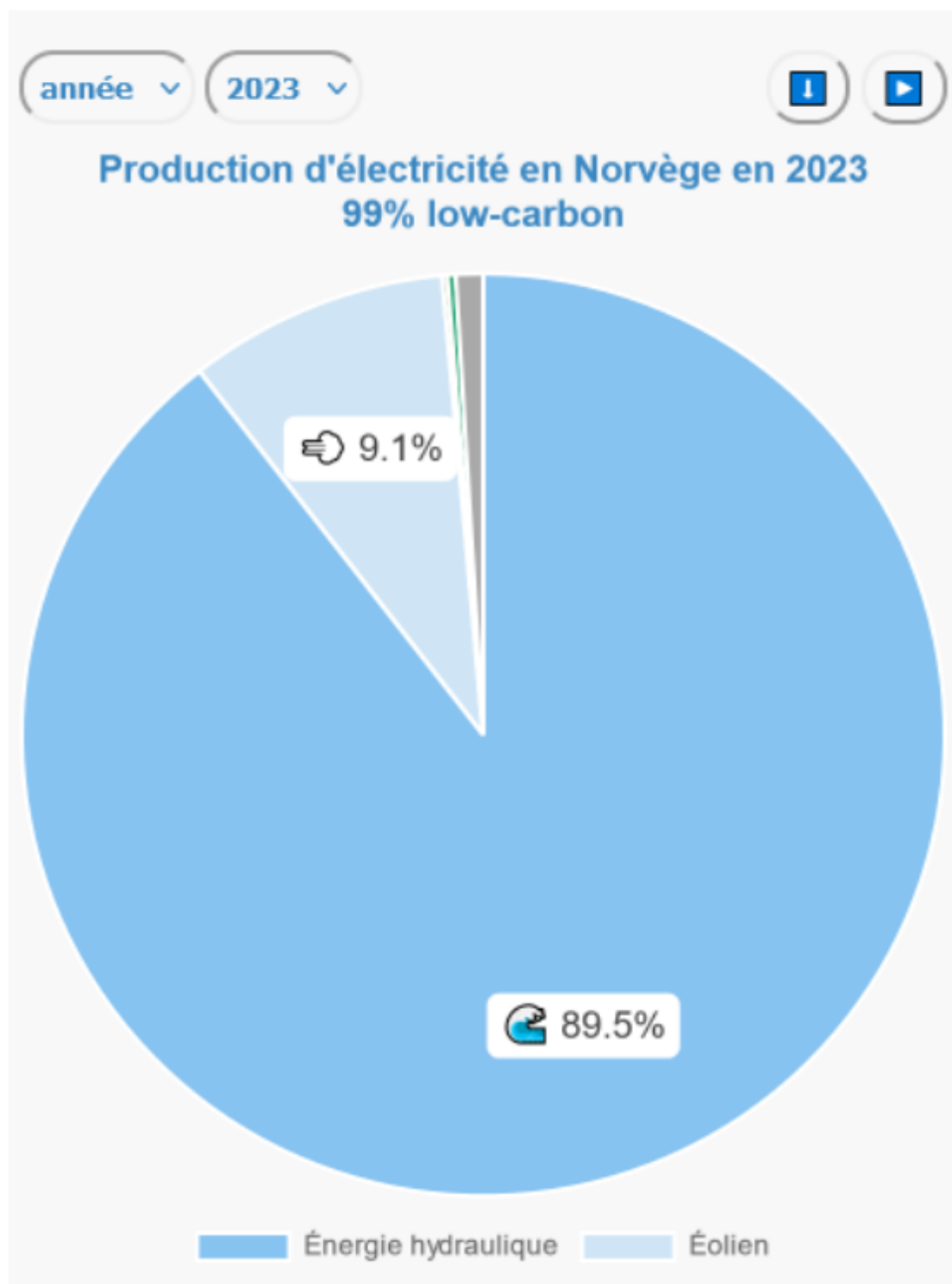


Figure L.3: Electricity consumption in Norway in 2023 (lowcarbonpower, 2023)

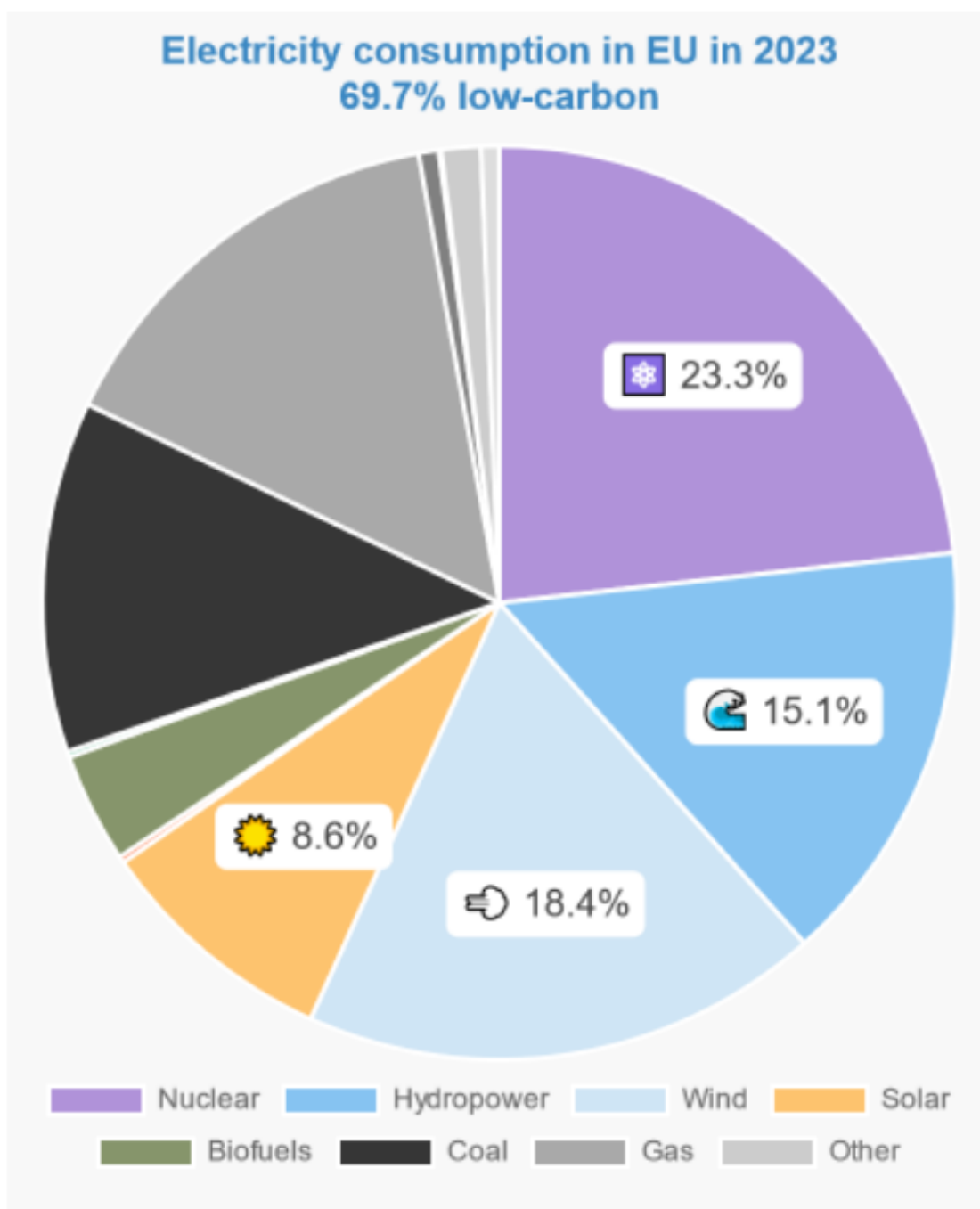


Figure L.4: Electricity consumption in EU in 2023 (lowcarbonpower, 2023)

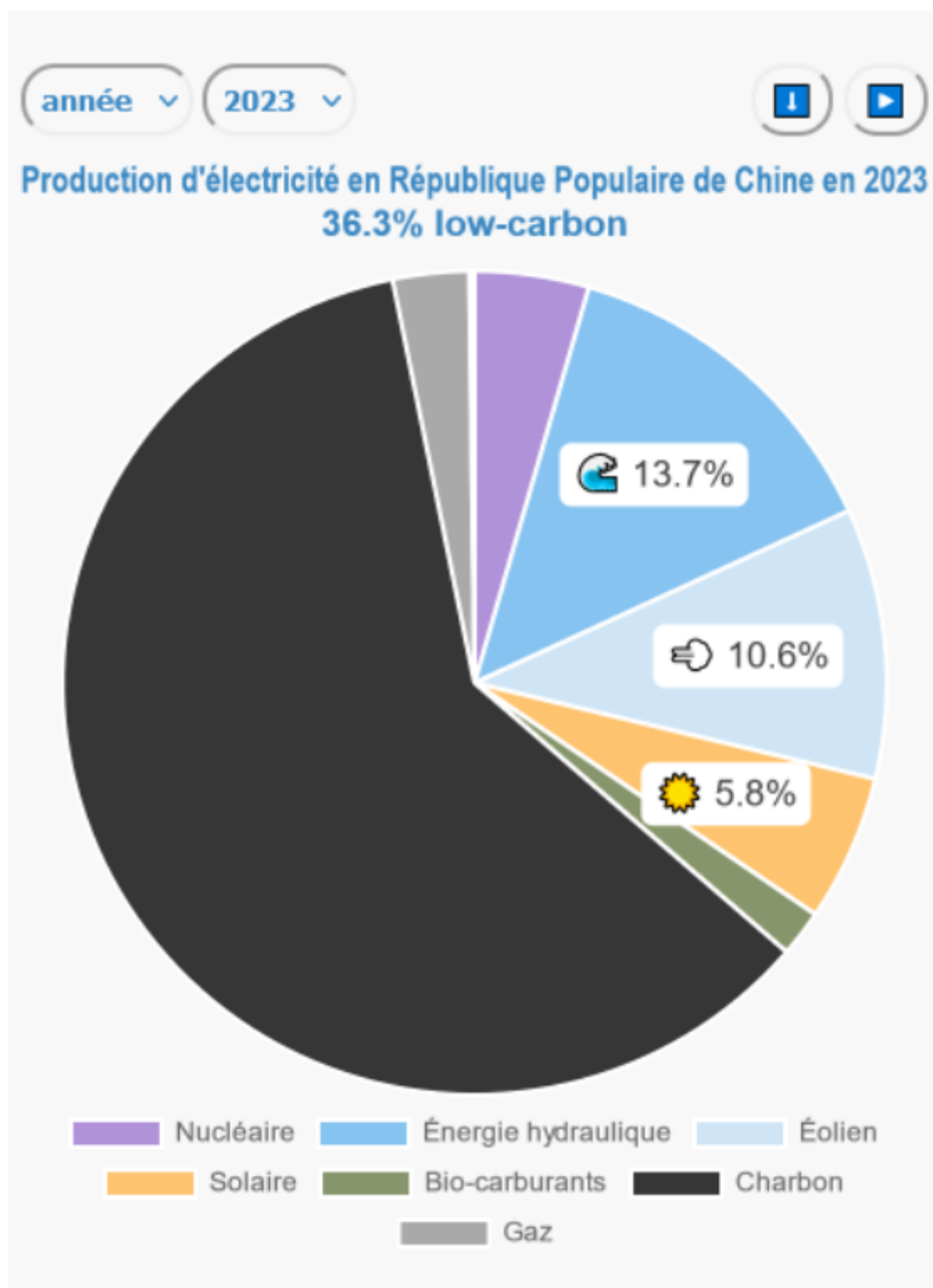


Figure L.5: Electricity consumption of the Democratic Republic of China in 2023
(lowcarbonpower, 2023)

Appendix M: Aging of a battery

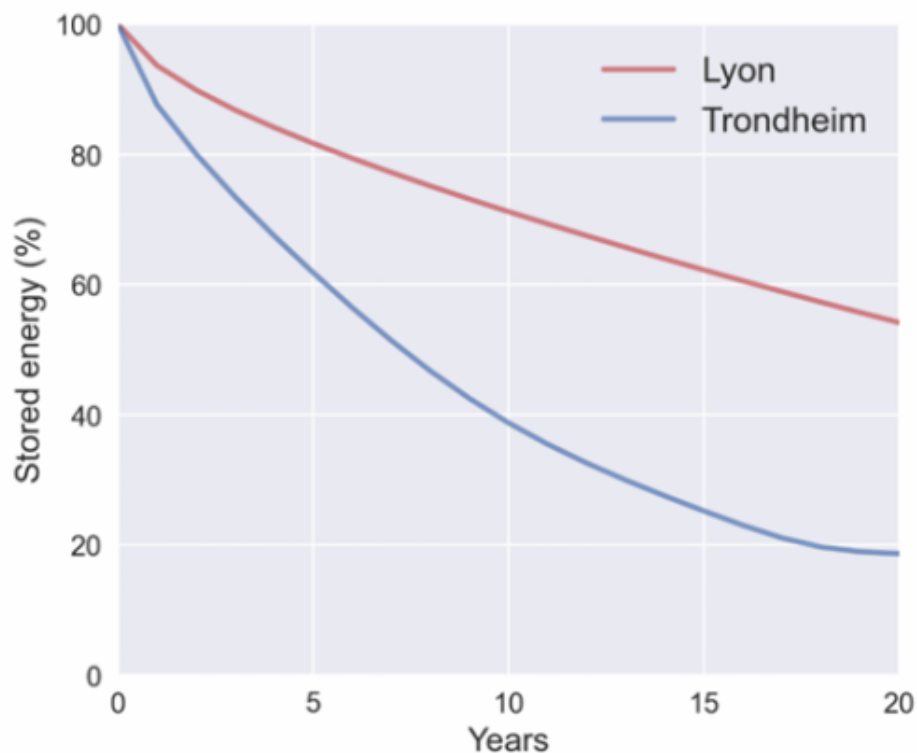


Figure M.1: Capacity loss of a 33.3 kWh (26.6 kWh usable) during 20 years in Lyon and in Trondheim (Lavisse et al., 2023)

Appendix N: Median results and boxplots

N	21
Median	33,75
Range	40,62
Minimum	12,08
Maximum	52,70

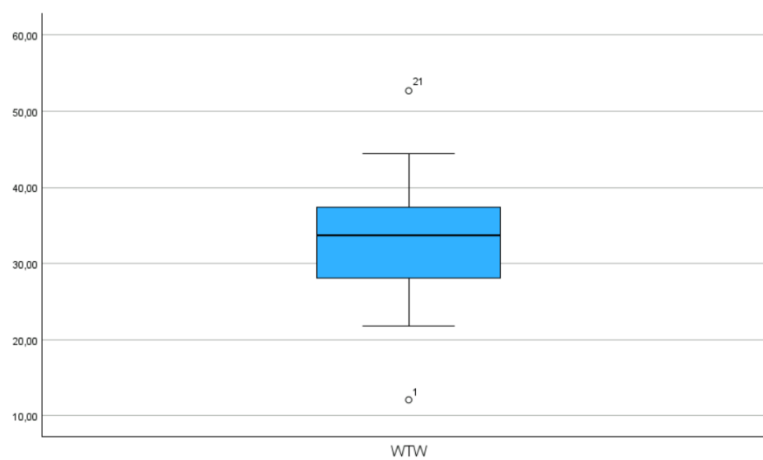


Figure N.1: Median results for the WTW LC of an ICEV petrol in TCO₂eq. and boxplot

N	9
Median	30,00
Range	59,38
Minimum	7,67
Maximum	67,05

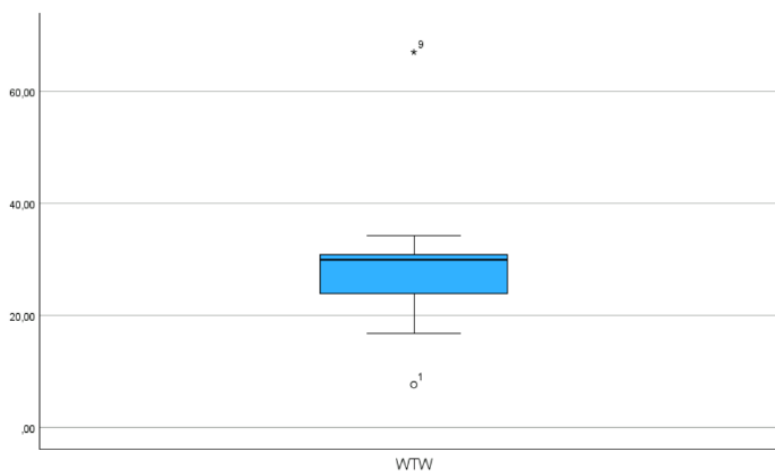


Figure N.2: Median results for the WTW LC of an ICEV diesel in TCO₂eq. and boxplot

N	17
Median	3,0500
Range	8,50
Minimum	1,50
Maximum	10,00

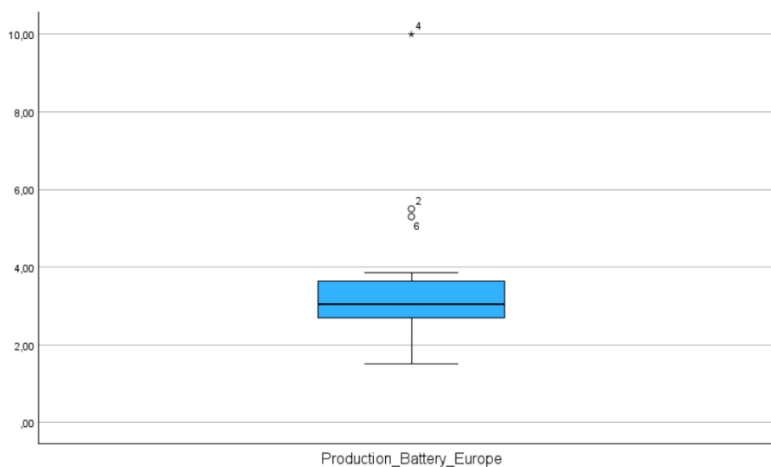


Figure N.3: Median results of production of a battery in Europe in CO₂eq. and boxplot

N	6
Median	3,81050
Range	5,045
Minimum	2,705
Maximum	7,750

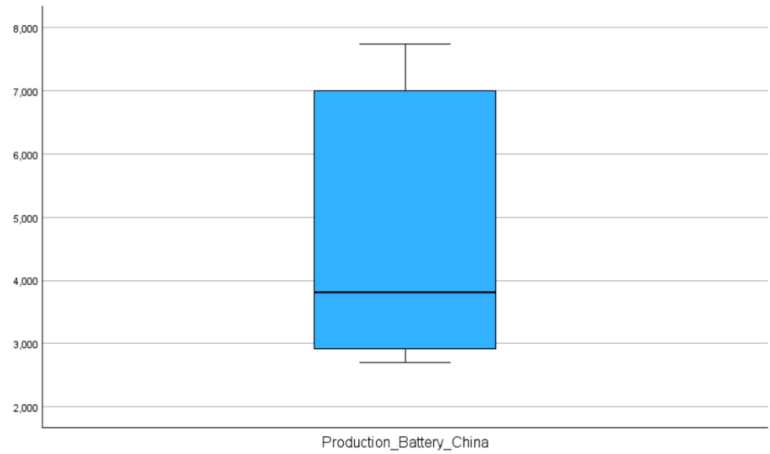


Figure N.4: Median results of production of a battery in China in CO₂eq. and boxplot

N	5
Median	6,0000
Range	5,55
Minimum	3,45
Maximum	9,00

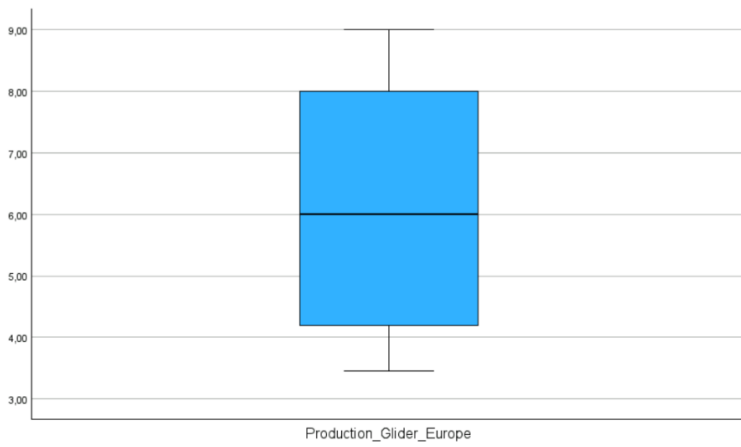


Figure N.5: Median results of production of a glider CO₂eq. and boxplot

Appendix O: Discussion

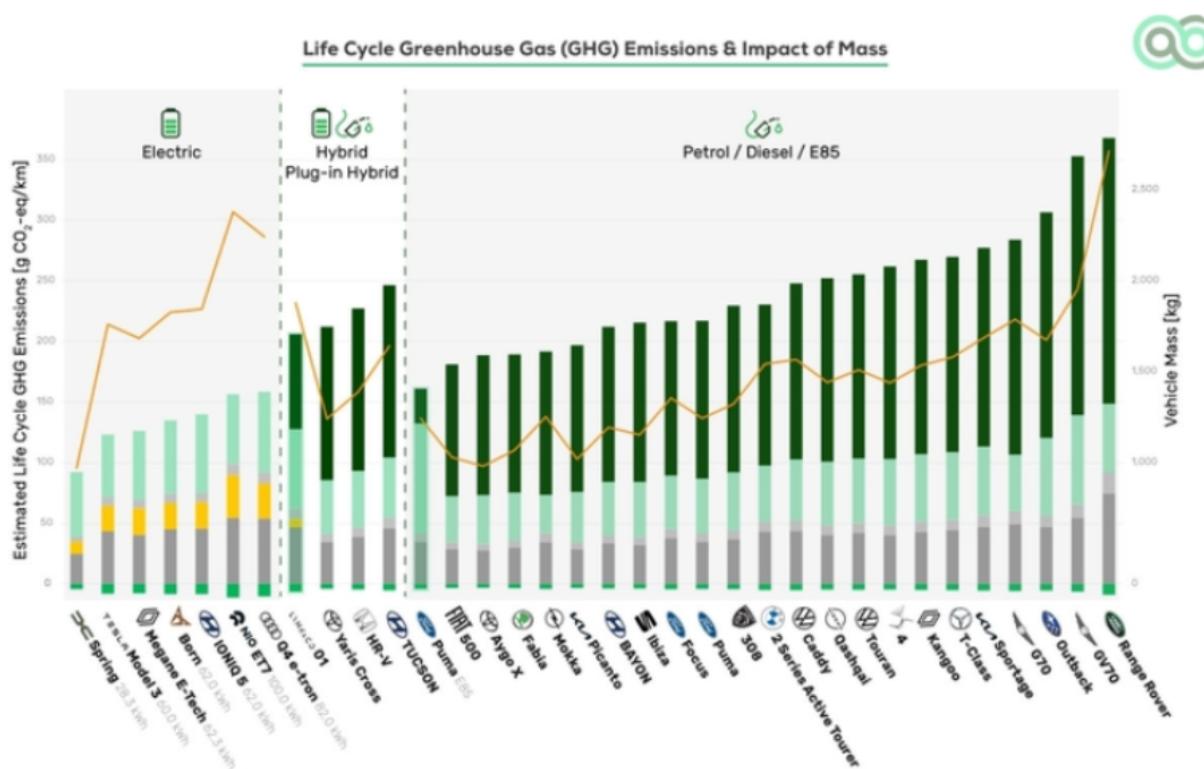


Figure O.1: Life cycle Greenhouse Gas (GHG) Emissions and impact on Mass (Bertaux, 2023)

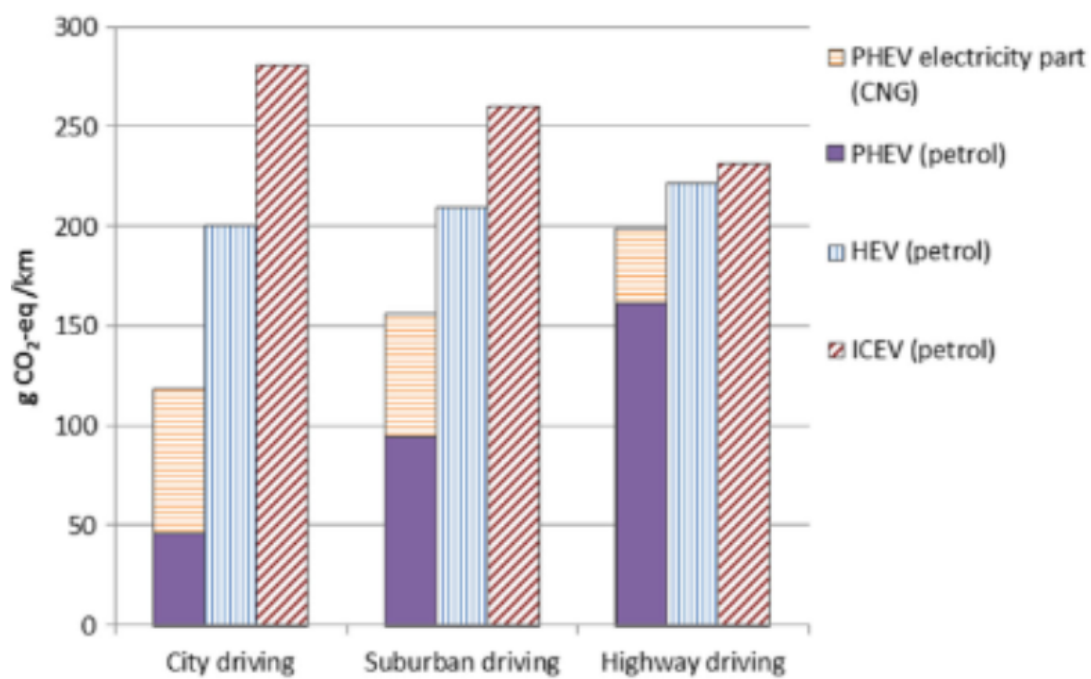


Figure O.2: Effect of the type of vehicle and the type of driving on the CO₂ emissions (Nordelöf et al., 2014)



Figure O.3: Relatives changes in the environmental impacts of the base case with a battery manufactured with the electricity mix of different countries (Philippot et al., 2023)

Abstract :

This master's thesis aims to compare the CO₂equivalents (CO₂eq.) emissions of Battery Electric Vehicles (BEVs) and Internal Combustion Engine Vehicles (ICEVs) fuelled with petrol and diesel over their entire life cycle (LC). The study seeks to identify which phases have the most significant impact on CO₂eq. emissions for each vehicle type. It addresses the question: "Which type of car (ICEVs diesel/petrol and BEVs) emits the most CO₂eq. over its entire LC and which phases are the most impactful"? The underlying aim of this master's thesis is to provide a clear and comprehensive overview of the situation, given the number of divergent conclusions and findings in the literature.

This research employs the Life Cycle Assessment (LCA) methodology, as defined by ISO (International Organization for Standardization) 14040. LCA is chosen for its comprehensive evaluation of environmental impacts from raw material extraction, production, use, to end-of-life processes, providing a cradle-to-grave analysis. A literature review on the subject (LCA of BEVs and ICEVs) was carried out including data from scientific articles, industrial texts, and popular sources to ensure a broad and accurate perspective. The CO₂eq. emissions results of all these data sources are then pooled to obtain a single CO₂eq. emissions value for each phase and total LC for each type of car.

The findings indicate that BEVs have higher CO₂eq. emissions during the production phase, primarily due to battery manufacturing and during the origin and production of the fuel but with potential improvements when loaded with renewable energy. However, BEVs show significantly lower, even null, results during the use phase. ICEVs consistently emit CO₂ throughout their operational life due to fossil fuel combustion. The end-of-life phase reveals potential for emissions reduction through effective recycling, particularly for BEV batteries. The study also highlights regional variations, with different energy mixes and regulatory environments impacting overall CO₂eq. emissions.

The research concludes that BEVs offer a lower total carbon footprint compared to ICEVs, particularly as the electricity-mix becomes greener. This underscores the need for advancements in renewable energy sources, battery production and recycling technologies. Policymakers and industry stakeholders should support these developments and promote the use of renewable energy for charging infrastructure. The study also supports the fact that the end consumer is a key point in this analysis via their driving behavior and their purchasing choices as a consumer. These findings provide valuable insights for making informed decisions towards sustainable automotive practices and highlight the importance of a holistic approach to evaluating vehicle environmental impacts.

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