INSTITUTO SUPERIOR TÉCNICO
Universidade Técnica de Lisboa

Environmental and Economical Competitiveness of Battery Electric Vehicles in the Portuguese Market: exploring the potential economical advantages of "Vehicle-to-Grid" systems

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Dissertação para a obtenção do Grau de Mestre em

Engenharia do Ambiente

Júri

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Abril 2012

Acknowledgments

I would like to thank Professor Filipe Moura whose guidance and precious contributions eased the difficulty of this work.

A particular thanks to family and friends, without their support, friendship and love this work would not have been possible, but more importantly I would not be the person that I am today.

Abstract

The objective of the thesis is to characterize and compare the lifecycle total costs of ownership and lifecycle environmental impacts of two different types of powertrain: a battery electric vehicle (BEV) and a gasoline internal combustion engine (ICEV) in the Portuguese car market. In addition, an analysis on the capacity of BEV providing 'Vehicle-to-grid' (V2G) electricity services by returning power back to the grid when plugged to the energy grid, besides charging. This study concludes that BEV's economical and environmental performance is higher than its ICEV counterpart. From the two V2G services assessed, this study concludes that regulation down has some economic interest, while regulation up with current market conditions does not provide an interesting perspective from a vehicle owner economic point of view. The LCA suggests, according to the results obtained that BEV lifecycle impact corresponds to about 71% of the total lifecycle impact of a gasoline ICEV; this conclusion however is conditioned by a set of assumptions, particularly: the electricity mix, other fuels could reduce ICEV environmental impact, battery-recycling stage and mileage and service time.

This study was developed as part of a broader study that aims to identify the problems and opportunities in the sustainability and economics of electric drive vehicles in the Portuguese market.

Resumo

O objectivo desta tese é caracterizar e comparar o custo económico e o impacto ambiental do ciclo de vida de dois tipos de veículos no mercado e realidade portuguesa: o veículo eléctrico a bateria (BEV) e o tradicional motor de combustão interna a gasolina (ICEV). Além desta análise é estudada a possível capacidade dos veículos eléctricos de fazerem serviços de regulação da rede eléctrica nacional ao injetarem electricidade nesta, em alturas de necessidade ou pela absorção de picos (V2G). Este estudo conclui na vantagem económica e ambiental dos BEV em relação aos ICEV a gasolina. Em relação aos dois serviços de regulação analisados, regulação para cima (ie, injetar electricidade na rede) e para baixo (ie, receber electricidade da rede), esta tese conclui que regulação para baixo tem interesse económico. Já a regulação para cima gera mais custos do que benefícios financeiros para o dono do veículo eléctrico.

Este estudo foi desenvolvido como parte de um estudo mais abrangente que pretende identificar oportunidades e problemas na sustentabilidade e economia de veículos de tracção eléctrica na sociedade Portuguesa.

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List of Acronyms

A	Rated maximum circuit (Amperes)
BEV	Battery Electric Vehicle
$c_{annualized}$	Annualized cost (€)
C_{life}	Total amount of cycles from the battery (dimensionless)
$c_{lifecycle}$	Total lifecycle cost (€)
CO	Carbon Monoxide
CO2eq	Carbon Dioxide equivelant
d	Interest rate (%)
DALY	Disability Adjusted Life Years
d_d	Distance driven (km)
DGEG	Direcção Geral de Energia e Geologia
DoD	Depth-of-Discharge (%)
d_{rb}	Range buffer (km)
EC	European Comission
E_{disp}	Energy dispatched for regulation (kWh)
ENE2020	Estratégia Nacional para a Energia 2020
ENTSO-E	European Network of Transmission System Operators for Electricity
$E_{recharge}$	Amount of kWh recharged since plugged in (kWh
E_s	energy storage capacity in the battery (kWh)
EU	European Union
EV	Electric Vehicle
GHG	Green House Gases
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
ISO	International Organization for Standardization
LCA	Lifecycle Assessment
LCC	Lifecycle Cost
LCI	Lifecycle Inventory
L_{ET}	Total energy delivery rate of the battery (kWh)
$LiFePO_4$	Lithium Iron Phosphate
n	Lifespan of the vehicle (years)
η_{inv}	Efficiency of invernter from DC to line AC
NOX	Nitrogen Oxides
η_{veh}	Vehicle efficiency (kWh/km)
PAF	Potentially Affected Fraction
p_{cap}	Price paid for capacity (€/kW-h)
P_{contr}	Contracted power capacity
PDF	Potentially Disappeared Fraction or Probability Distribution Function
P_{down}	Power limited by the vehicle for regulation down (kW)
PE	Polyethylene
p_{el}	Price paid for energy (€/kWh)
P_{line}	Line power capacity (KW)
PP	Polypropilene
Pt	ECOPOINTS
P_{up}	Power limited by the vehicle for regulation up (kW)

P_{V2G}	Power available for vehicle to grid (kW)
PVC	Polyvinyl chloride
PVDF	Polyvinylidene fluoride
r_{cap}	Revenue from capacity payment (€)
R_{d_c}	Dispatch to contract ratio
reg down	Regulation down
reg up	Regulation up
r_{el}	Revenue from energy payment (€)
$r_{el\ down}$	Revenue from energy payment in regulation down (€)
$r_{el\ up}$	Revenue from energy payment in regulation up (€)
REN	Redes Energéticas Nacionais
RSC	Road Service Contribution
SCT	Single Circulation Tax
SO	System Operator
TCO	Total Cost of Ownership
t_{contr}	time duration of regulation contract
$t_{plug\ day}$	Number of hours vehicle is pugged per day (h)
$t_{plug\ year}$	Number of hours vehicle is pugged per year (h)
TPP	Tax on Petroleum Products
TSI	Twin-charger, Stratified Injection
V	Line Voltage (Volts)
V2G	Vehicle-to-Grid
VAT	Value Added Tax
VT	Vehicle Tax
VW	Volkswagen
WHO	World Health Organization

1. Introduction

The present chapter introduces the topic, defines the background and motivation before presenting the research question. The methodology and outline of the research follow. Importantly, there is a brief description and discussion on the issues of energy security and dependency related with the Portuguese energy market structure and, more specifically, the case of the transportation primary energy consumption. The chapter ends with a description of the characteristics of a standard electric vehicle that is the focus of the present research and constitutes an opportunity for reducing the energy and environmental burdens related to the use of fossil-fuelled private cars.

1.1. Background and Motivation

Over the last years the awareness of society over the environment, sustainability and energy consumption has brought to light concerns on the impact of human activities. The development of modern societies is profoundly dependent on energy. This essential resource can be obtained from a variety of sources, each source having advantages and disadvantages, and particular concerns are related with their environmental performance.

The Portuguese energy profile is strongly dependent on fossil fuels, accounting for 80% of total primary energy consumption. The weight of fossil fuels in the Portuguese energy market is particularly worsened by the lack of endogenous resources leading to a foreign energy dependency in Portugal of almost 80% (Eurostat 2011a) giving rise to energy security issues also.

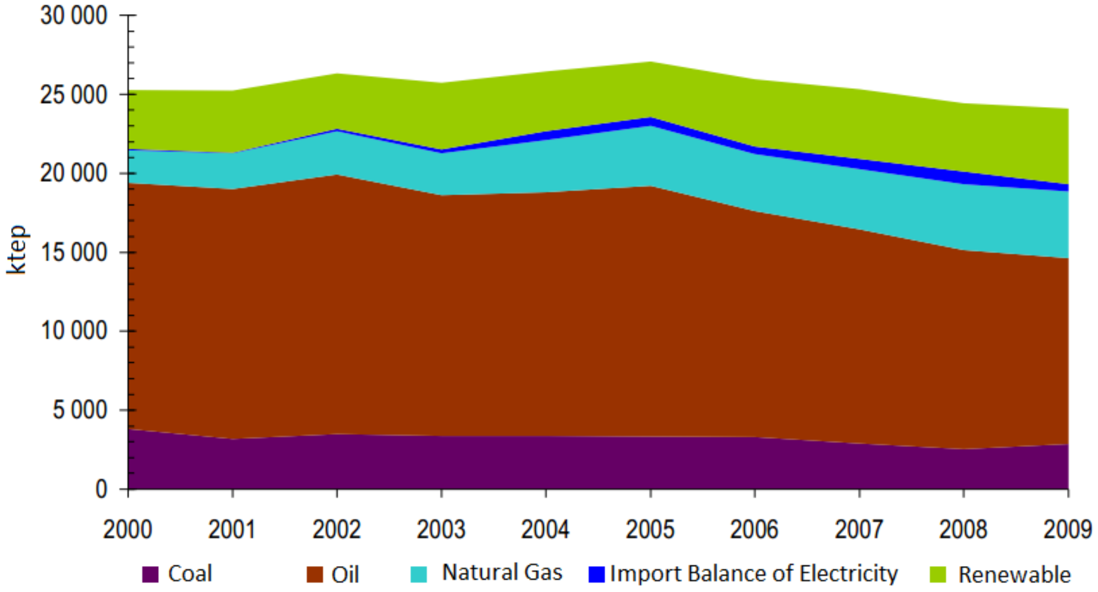

Figure 1 – Primary energy consumption in Portugal (source: DGEG, 2010).

According to DGEG[1] electricity accounts for about a fifth of final energy consumption, as it can be seen in Figure 2.

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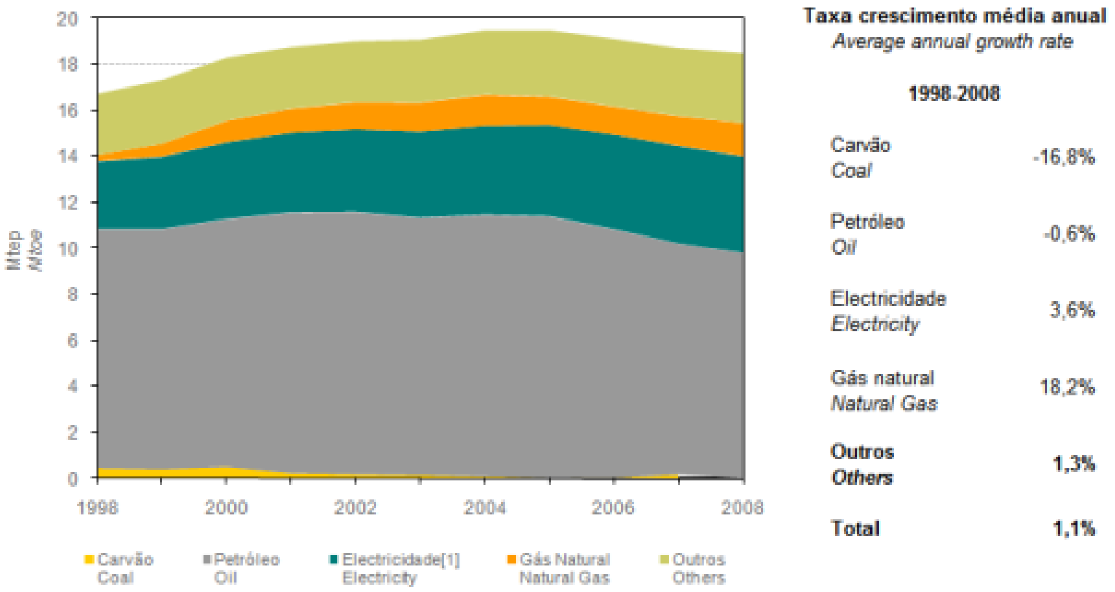
[1] Direcção Geral de Energia e Geologia (*Directorate-General of Energy and Geology*)



Taxa crescimento média anual
Average annual growth rate

1998-2008

Carvão *Coal*	-16,8%
Petróleo *Oil*	-0,6%
Electricidade *Electricity*	3,6%
Gás natural *Natural Gas*	18,2%
Outros ***Others***	**1,3%**
Total	**1,1%**

Figure 2 – Final energy consumption in Portugal by source (source: DGEG).

In recent years a strong investment in alternative/renewable electricity production processes has been made in Portugal, and the country dependency has decreased. Consequently, the electricity mix has become more sustainable, including environmental performance.

Several activity sectors, such as the transportation, are directly dependent on fossil fuels. As such, the effort to produce electricity in a more sustainable way cannot truly reduce the weight of fossil fuels in Portugal if these sectors aren't addressed. The consumption of fossil fuels is not only problematic for economic or security/dependency on third parts reasons, they are the main cause for the rising concentration of greenhouse gases (GHG) in the atmosphere.

In the European Union (EU), the emission of GHG *per capita* varies from 5.27 tons of CO_{2eq} in Latvia to 26.00 tons of CO_{2eq} in Luxemburg. Portugal, with an emission of 7.34 tons of CO_{2eq} per capita, is bellow the EU average, being the eighth country in the union with lower emissions (United Nations Statistics Division 2010).

According to the Kyoto Protocol, by 2012 Portugal could increase its emissions to a maximum of 27% based on the 1990 values. This maximum value was surpassed for the first time in 1999, and was above the limit for the following decade. 2009 was the first year when GHG emissions were reduced bellow the protocol cap with an increase of 24% relatively to 1990 (Eurostat 2011b).

The EU has been one of the main world players in the effort against climate change, putting pressure on several countries to define strict GHG emission goals and assuming more ambitious efforts. In January 2007, the European Commission (EC) adopted a communication proposing an energy policy for Europe, with the goal to combat climate change and boost the

EU’s energy security and competitiveness. This set out the need for the EU to draw up a new energy path towards a more secure, sustainable and low-carbon economy, for the benefit of all users, today and future generations. One aim is to give energy users greater choice besides spurring investment in energy infrastructure. Based on the European Commission’s proposal, in March 2007 the Council endorsed the following targets(European Comission 2011a):

- Reducing greenhouse gas emissions by at least 20 % (compared with 1990 levels) by 2020;
- Improving energy efficiency by 20 % by 2020;
- Raising the share of renewable energy to 20 % by 2020;
- Increasing the level of biofuels in transport fuel to 10 % by 2020.

The Kyoto Protocol had above all else a symbolic meaning – to inform and create awareness on populations and nations on climate change subjects. Nearing the end of this treaty, a debate to define new goals is being discussed in the international level. Though the latest international negotiations haven’t been successful it is expected that sooner or later new and stricter emission goals be created.

The transport sector has a large contribution in energetic and environmental problems. It corresponds to about 1/3 of the final energy consumed in Portugal and is responsible for 2/3 of petroleum products consumption (Direcção Geral de Energia e Geologia 2010). Road transports are the principal responsible for the deterioration of air quality in urban areas. In the Lisbon metropolitan area, road transportation is responsible for over 40% of CO and NOx emissions (Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa & Comissão de Coordenação e Desenvolvimento Regional de Lisboa e Vale do Tejo 2006).

The transport system is a sector with large inertia, innovations are difficult to implement and results take a large amount of time to be seen. The problems in this system are highly complex, therefore so are their solutions. To achieve higher system efficiency, that in turn promotes a sustainable mobility, there are multiple solutions and different problem approaches (David & Banister 2008; Vieira et al. 2007):

- Structural change – include construction of new routes, new transport modes and urban planning reorganization, this last, proposing the organization of activities in a proximity paradigm. Proximity mobility is by far the solution with the largest impact and results in mobility transfers (motorized to soft modes). These however are the solutions that require larger investments and are hard to apply because they interfere with everyday decision of citizens and companies;
- Reducing the number of trips – can be obtained by performing everyday activities online (shopping or even working). Though this processes are rather simple and inexpensive, their impact is strict and debatable, time saving in mobility could originate other voyages motivated by other activities.

- Modal shift – consists in the substitution of current transports for more efficient ones; for example substituting the individual transport for public transport, which with high occupation rates have higher efficiencies than individual transport. In urban environment an automobile with two passengers, is has efficient has a urban bus with an occupation rate of 15% (Alves 2005).
- Technological shift – has the objective of delivering the exact same service but more efficiently. Change can be evolutionary or disruptive; an evolutionary change occurs within the current system (the evolution of the internal combustion engine over the years); a disruptive change consists in a system substitution, where for example the electric vehicle is included has a solution to part of the transport system problems, substituting the internal combustion vehicles.

An electric vehicle is a vehicle that utilizes electric energy for propulsion; it has an electric motor that utilizes this type of energy, transforming it into kinetic energy. There are multiple ways a vehicle can store its electricity, the two main ways are through a fuel cell or a battery; the latter will be the focus of this study.

According to electric vehicle supporters, an EV has some advantages when compared to its ICE counterpart(United States Department of Energy et al. 2012):

- Engine efficiency – the electric motor is more efficient than the internal combustion engine, contributing to a local lower energy consumption;
- Electricity is cheaper than petrol or diesel and can be produced from variable sources, which in dependent countries like Portugal is a positive characteristic; it can use renewable energy sources, reducing the dependency on fossil fuels in the transport sector and therefore contributing to the decarbonizing of this sector;
- No local emission – this is a positive characteristic on the utilization of this type of powertrain for they can improve the air quality in urban areas;
- Silent – this is a characteristic that is both positive and negative; the positive is that the vehicle is more silent and therefore there is less noise pollution (particularly important in urban environments); the negative is a pedestrian security issue, where due to a more silent vehicle a pedestrian is not aware of the vehicle, this issue however could be resolved rather simply either by a noise emitted by the vehicle in urban areas, and the eventual habituation of pedestrians to this new reality.

Some of these EV assumptions will be proven throughout this work, in particular the lower cost of the EV and its lifecycle impact.

Though the EV advantages, there are many limitations to their use, of which the author would highlight:

- Energy supply network – a big investment is required nationally to be able have an energy supply availability at least has convenient has the ICEV fuel network;

- Limited energy storage – current BEVs have a limited autonomy (100 to 200 km);
- High charging time – between 6 to 8 hours on a normal supply charger, or 30 minutes for (80% charge) in a fast charger.
- High acquisition costs – particularly associated with high battery costs, according to(Delucchi & Lipman 2001) these could vary (for lithium ion batteries) from 30 to 50% of the total vehicle cost.

In light of these limitations some consumers could see them as sufficiently strict to not make the EV a viable option.

In spite of these limitations, the Portuguese government considered the EV a good opportunity and has been making considerable investments in this sector. The EV has some incentives in purchase (reduction in the acquisition tax) and use (electricity VAT reduction), and is currently building a pilot charging network with 1300 normal chargers and 50 fast chargers that should have been operational by the end of 2011 (INTELI Inteligência em Inovação 2010).

In the White Book on Transports by the EC (European Comission 2011b), is presented a roadmap for the EU that comprises 40 concrete initiatives for the next decade to build a competitive transport system that will increase mobility, remove major barriers in key areas and fuel growth and employment. At the same time, the proposals will dramatically reduce Europe's dependence on imported oil and cut carbon emissions in transport by 60% by 2050. The key goals will include:

- No more conventionally-fuelled cars in cities;
- 40% use of sustainable low carbon fuels in aviation; at least 40% cut in shipping emissions.
- A 50% shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport.
- All of which will contribute to a 60% cut in transport emissions by the middle of the century.

The strategies defined in this report ensure that the goals for GHG emission reductions should be achieved by an increase in system efficiency and not through mobility restrictions. New vehicle technologies and traffic management are considered essential elements for this strategy. EVs present a system advantage of being very silent, which would permit transferring into nocturnal periods the distribution of goods, removing this service from times of the day with higher congestion.

1.2. Research Question

The present work is developed to answer two main questions:

1. Is the BEV truly more economical than an ICEV, and does in fact V2G add any monetary value to the BEV economics in the Portuguese market?

2. Is the BEV an environmentally friendlier choice than its ICEV counterpart, considering the entire lifecycle of each powertrain in the Portuguese society?

Beside what has been described in the previous section in terms of the general advantages of the BEV, there is currently no study that answers these questions, to our knowledge, and more specifically, to the Portuguese case. Before any decision on whether or not electric vehicles should be supported (either by governments and populations) as a more advantageous technological solution, these questions should be answered. They will present decision makers and the general public with the economic and environmental advantages and disadvantages of each powertrain. It should be emphasized that this study only focus on BEVs and gasoline ICEVs and therefore the decision is only between these two alternatives, although the methodology used here is applicable to other technological alternatives.

In economic terms, the objective of this dissertation is to produce a model that can characterize the total costs of car ownership of a BEV and an ICEV, meaning that every cost from purchase, energy, maintenance and others are considered, summed and compared in order to conclude which is the option with greater economic interest for the car owner. The possibility of the BEV providing V2G services is also addressed in this part of the work.

Environmentally, the objective is the same, to account all lifecycle environmental impacts of each powertrain and determine which one has the lowest impact.

This dissertation does not aim to answering these questions to all type of EVs and ICEVs. It only addresses the current available technologies for both powertrains. Therefore, any technological developments in either option should be added to the model and the results should be analyzed again.

1.3. Methodology and Dissertation Outline

In broader terms, the author follows a typical methodology of a lifecycle costing and a lifecycle assessment of a currently available and comparable BEV and ICEV alternatives.

Despite the similarity of their names, lifecycle cost analysis (LCC) and lifecycle assessment (LCA) have major methodological differences. These differences stem from the fact that LCC and LCA are each designed to provide answers to very different questions. Lifecycle assessment evaluates the relative environmental performance of alternative product systems for providing the same function. This environmental performance is assessed as holistically as possible, aiming to consider all important causally-connected processes, all important resource and consumption flows, regardless of whether or not they eventually impact anyone. Lifecycle cost compares the cost-effectiveness of alternative investments or business decisions from the perspective of an economic decision maker such as a manufacturing firm or a consumer. These differences in their purpose have properly resulted in differences in their scope and method. (Norris 2001)

This dissertation is organized in 7 chapters though there is a division in two main parts, the lifecycle costing and lifecycle assessment. The reason for this division is mainly for the benefit of the reader when reading the dissertation.

In the first chapter, background and motivation, research question, methodology and outline are presented. The energy and transport main challenges are presented with a specific emphasis in Portuguese foreign dependency. The chapter ends with a description of the characteristics of an electric vehicle.

The second chapter gives a basic description of the electric vehicle, beginning with a small historical note, a definition of the commercially available types of electric vehicles and ending with a description of the major drawbacks of BEVs and the definition of V2G.

The third chapter presents the lifecycle costing of the two studied alternatives; the concept of LCC is presented, followed by the methodology for cost calculations, a characterization of the Portuguese electricity market, and the method for calculating V2G revenues and costs, the results of this chapter, go through a sensitivity analysis and are presented and discussed.

The forth chapter in terms of structure is very similar to the third chapter but for the environmental aspect of this work, that is the lifecycle assessment (LCA). A typical LCA outline is followed: first the concept of LCA is described, then the objective and scope of the analysis, followed by data collection for production of the lifecycle inventories, the results of the analysis and their respective discussion.

The fifth chapter presents the main conclusions of this dissertation with a summary of the main findings, the consequences these results have in policy making, followed by the main limitations of this study and ends with leads for future work.

After listing the references used here, annexes include additional information used in the development of chapter 3 and 4.

2. The Electric Vehicle

This chapter gives a basic description of the electric vehicle, beginning with a small historical note, a definition of the commercially available types of electric vehicles and ending with a description of limitations of the BEV and the definition of V2G.

2.1. Short review of the long history of the electric vehicle

The idea of an electric vehicle isn't new: the first electric vehicles appeared in the late XIX century and during the first decades of the XX century they were serious competitors of the ICEV. Difficulties in energy storage and charging led to the abandonment of this system.

Throughout the XX century electric vehicle prototypes were presented (particularly during oil crisis) but their massification was never possible. Only recently with developments in battery technology, influenced by the utilization of cell phones, computers and other mobile devices (Bloomfield 2001a), the conditions for development and scale of electric vehicles is possible. Society increasing awareness in pollution, climate change and GHG subjects, produce a pressure in producers to deliver safer and cleaner technologies and energy sources. Above all the shrinking of oil reserves, the instability of oil producing countries and therefore oil prices create conditions so that research and development in new technologies not dependent on fossil fuels/oil become of economic interest.

2.2. Different types of electric vehicle and electric mobility in Portugal

An electric vehicle utilizes electric power to run an electric motor that transforms this power into kinetic energy that then moves the automobile. Currently in the market there are three types of electric vehicles:

- Hybrid – is a vehicle that uses two or more distinct power sources to move the vehicle, commonly these combine an internal combustion engine with one or more electric motors. This system permits more efficient fuel consumption than the same vehicle without the electric motors and battery. The battery is charged by the internal combustion engine and from breaking regeneration, therefore the vehicle is only charged with fuel.
- Plug-in Hybrid – has in the hybrid these vehicles possess an internal combustion engine and an electric motor (or more), which combined used, increase the vehicle efficiency. The electric motor is used for low speeds and is mainly indicated for urban use. The batteries in these vehicles are larger than in most hybrids and can be charged through the internal combustion engine, regenerative breaking and also by plugging the vehicle to the electric grid.
- Battery Electric – this type of vehicle only has an electric motor, powered by a battery. This battery is recharged when connected to the power grid and also through regenerative breaking. There are other types of electric vehicle that utilize fuel cells instead of batteries, but these are not yet commercially available.

In this dissertation the focus will be only on pure battery powered electric vehicles.

The National Energy Strategy, which has a timeline to 2020 (ENE 2020) (XVIII Governo Constitucional 2010), has been presented in March of 2010 and in its objectives is mentioned the reduction of Portuguese energy dependency, achieving the EU goals in terms of climate change for 2020 and promote the competitiveness and growth of the Portuguese energy sector. The program includes an investment plan of 31 billion Euros throughout the next decade, being the core areas of investment, energy efficiency and renewable energy sources.

The transport sector as previously mentioned is responsible for a third of final energy consumption, and about 52% of the imported petroleum is destined to this sector. EVs are not only more energy efficient, but also permit a diversification on utilized energy sources, this fact means that through electric mobility a reduction of the consumption of fossil fuels could be obtained. This is why EVs are a key element in the ENE 2020.

The strategy intends to substitute 10% of consumed fuel in the road transport sector for electricity. If the increase in electricity demand would be produced from renewable sources this would represent an import reduction of 5 million oil barrels. According to the national authorities that defined this strategy the substitution of ICEVs for BEVs would also decrease the sectorial final energy consumption by 2% due to increased efficiencies.

Portugal has also been very involved in promoting electric mobility, in particularly by offering benefits when buying and using an electric vehicle and especially through the MOBI.E project.

In order to promote the rapid diffusion of electric vehicles the following incentives were created:

- Buying incentive – the first 5000 electric vehicles sold from 2010 onwards will have an incentive of 5000€, but the EV must be in the list of eligible vehicles;
- Disposal incentive – in case of vehicle substitution of an end-life-vehicle for an electric vehicle, the incentive can reach 1500€.
- Fiscal deduction for companies – the acquisition of EV permits deductions in corporate tax.
- Electricity consumption incentives – electricity consumed in charging EVs will have taxes at the lower VAT rate of 6%.

In perspective and due to the current economic climate being lived in Portugal and the world, and particularly from June 2011 with the entrance of financial external help from the International Monetary Fund, European Central Bank and the European Commission, some of the aspects are now somewhat in doubt due to stricter austerity measures.

The MOBI.E is the responsible agency for electric mobility in Portugal, one of its functions consists on building a network of recharging spots across the country wich is the most significant step, on a national level, to support electric mobility. It will be available for all users and all electric car brands offering a range of services including fast and normal recharging options, prepaid recharging cards and up-to-date information on charging status, charging spots and all-round support through internet access.

The pilot stage of the project contemplates 1300 normal charging spots and 50 fast charging spots, spread across 25 counties, for public access. Aside from these, the full grid comprises car parks, shopping malls, hotels, airports and highway rest stops, and should have been fully operational by December 2011.(INTELI Inteligência em Inovação 2010)

This award winning project is the most ambitious step towards electric mobility in Portugal and aims to be an international reference in renewable technology implementation and leadership in innovation.

2.3. The potential and limitations of the BEV and V2G

One of the currently available technologies is the battery electric vehicle (BEV), which is supported by several car manufactures has the next powertrain for the automotive industry. Some manufacturers are already producing some models that offer this type of powertrain claiming that these are not only more economical but also more environmentally friendly.

Though BEVs have many of the advantages already described there are some limitations to their use. These limitations are caused mainly by the use of batteries as an energy carrier:

- *Price* - it is estimated the price of a battery to be around 750€/kWh (The Boston Consulting Group 2010) nowadays, but with technological development and economies of scale it is estimated that batteries in 2020 would be around 220€/kWh(Dallinger et al. 2011);
- *Weight and volume* - currently the Nissan Leaf battery pack has a 24 kWh in a 300 kg battery, this averages about 0.08 kWh/kg of battery(Nissan 2011), this is also the case given in (Zackrisson et al. 2010) with 0.09 kWh/kg. This means that to carry the amount of energy necessary the vehicle must transport a big volume and weight;
- *Autonomy* - associated with the weight and volume parameter is the vehicle autonomy, currently a BEVs is only capable of doing between 100 and 200 km, when compared to some diesel ICEVs that can do almost 1000 km, this might be the largest responsible for consumers not considering a BEV as a possible vehicle option;
- *Charging time* – there are two types of charging, normal charging that can take 6 to 8 hours to obtain a 100% charge and a quick charge that takes about 30 min to have an 80% charge. When compared to an ICEV that has nearly instant charging time, this is a negative characteristic that can influence consumer decision;
- *Battery wear* – batteries, has explained later on, have a limited capacity or number of cycles (for a constant depth-of-discharge) and loose storage capacity along their life use and therefore require substitution.

Beside these intrinsic limitations to the BEV, there is the problem of availability of charging infrastructures. Given the early stage of this system, the number and geographic distribution of charging points is still very limited.

The massification of electric mobility could contribute to increase the efficiency and safety of the electric grid. Charging the batteries should be done preferably during the night when energy consumption is lower, this way avoiding overload during peak hours. In Japan, the electric vehicle chargers are equipped with a battery so to ensure that the energy transferred to the vehicle is from off peak production.(Kempton 2000) (Camus et al. 2011)

The focus of this study is on this BEV type and particularly on a second generation BEV that support Vehicle-to-Grid (V2G) technology and tries to answer the question if this new type of technology truly is more sustainable than conventional internal combustion engines by characterizing the economic and environmental performance of each vehicle.

According to Kempton(Kempton & Tomić 2005), the concept of V2G is that BEVs can provide power to the electric grid while parked and plugged, on times that the grid requires extra power, and taking advantage of excess production to charge at lower rates. This concept is then expanded in order to apply to different power markets, particularly on the ones that have been identified has adequate for a V2G system – in Portugal the regulation market.

The automotive and electrical industries are especially well matched. The electrical power sector has no or very little storage capacity and therefore the energy required is usually being produced at the moment of consumption, this situation is extremely complicated when a big part of the energy comes from intermittent sources like solar or wind power plants, requiring the electric system to build secondary redundant systems to deal with sudden increases or decreases in energy demand. This secondary systems in Portugal are usually based on hydroelectric dams that produce bellow their maximum and according to the System Operator (SO) requirements increase or decrease power output (in fact some dams in Portugal also support pumping to store excess energy).

An automobile by definition has to have energy storage, and is designed to have large and frequent power fluctuations, because that is a requirement for roadway driving. Besides this cars are in use 4% of their estimated lifetime, being available for V2G the remaining 96%(Kempton & Tomić 2005). These characteristics allow us to say that these two sectors can be very complementary of each other and there is an opportunity here to implement a complementary energy market.

The main attractiveness of V2G is that it can produce income to the vehicle owner, when the car isn’t needed, maximizing car use, by substituting these very expensive auxiliary power systems and therefore bringing positive implications for both the SO and the vehicle owner. This however from the owner point of view has to be done to the extent were the income associated with V2G is higher than it costs. From the System Operator point of view there is the advantage of substituting the secondary systems with a cheaper alternative, reducing costs associated with the electrical grid operation, though there has to be an assurance to the SO that a minimum number of cars are plugged in at all times in order to assure the stability of the grid.

The possibility of having a V2G system assembled in Portugal is of great interest because there have been big investments on solar and particularly on wind power generation in the past decade which influenced significantly the electric grid due to intermittent production associated with these energy sources. In fact this variability has promoted a new plan to build more hydroelectric dams with pumping capabilities in order to try and control this intermittence. The installation of a V2G system could substitute (the expensive) dams or be an important and cheaper complement to these power plants, has indicated in (Turton & F Moura 2008).

3. Lifecycle Costing

In this chapter it is presented the lifecycle costing of the two studied vehicle alternatives; the concept of LCC is presented, followed by the methodology for cost calculations, a characterization of the Portuguese electricity market, and the method for calculating V2G revenues and costs, the results of this chapter then go through a sensitivity analysis and are presented and discussed.

3.1. Lifecycle costing concept

In this section a short definition of lifecycle costing will be given, for more detailed information the reader is remitted to the bibliography on this subject.

LCC refers to the total cost of ownership over the life of an asset. The purpose of an LCC is to determine cost-effectiveness of alternative investments and business decisions, from the perspective of an economic decision maker such as a manufacturing firm or a consumer. The activities of the lifecycle that are of interest in an LCC are the ones causing direct costs or benefits to the decision maker during the economic life of the investment, as a result of the investment, so the object in study in an LCC are the cost and benefit monetary flows that directly impact the decision maker (in this case a consumer).(Norris 2001)(Ferrão 2009)

The timing of an LCC is critical, in this type of analysis a specific time horizon is defined and any cost or benefit occurring outside that scope is ignored; an example is when a computer is bought and sold three years later at a “salvage value” from then on, any cost or benefit that the computer might produce is outside the scope of the analysis because it no longer is in the possession of the consumer.(Norris 2001)

3.2. Methodology and assumptions

The goal of this study is to calculate and compare the lifecycle costs, profits (when applicable) and environmental burdens of various automobile powertrains, these being the traditional gasoline internal combustion engine and battery electric vehicles subdivided into two groups whether they do or not V2G.

For the economic part of this research, calculations for all the identified as pertinent lifecycle costs of the assessed powertrains are done and then annualize those costs to have an idea of the per year costs of having one type of powertrain, the same goes for V2G revenues, where the model used give us the annual revenue and cost of V2G, all in an attempt to characterize the entire costs associated with a particular powertrain. Some of the assumptions are prone to debate; therefore, a sensitivity analysis is performed to key variables, in order to assess how the total costs vary with different inputs. The variation on inputs is given through probabilistic distribution allocated to each variable.

In order to have a comparable analysis it is necessary to identify vehicle-use characteristics that are common to all powertrains. These are mileage over lifetime, service time and type of car. If these parameters were not common to all powertrains then the results would not be comparable to one another.

The values considered were 300,000 km, in a lifetime service of 15 years (20,000 km per year average) and a 5 seat hatchback car type.

Over this study, references of real vehicles were used, that are considered to be in the same range, for example for gasoline powertrains parameters and characteristics of the VW Golf (1.2

TSI Blue motion) are used and its electric counterpart the Nissan Leaf (Nissan 2011; Volkswagon 2011). Specific methods for calculation of intermediary elements are shown in the next chapters.

3.3. The Portuguese Energy Market

For the calculations to assess the costs and revenues of the BEV doing V2G it is required to have a characterization of the electrical power market in Portugal. As referred earlier Portugal has been strongly supporting the construction of alternative energy power plants, as illustrated in the figure bellow and where it is shown the evolution of electricity production in the country over the past years, with a sharp increase on the wind power generation capacity.

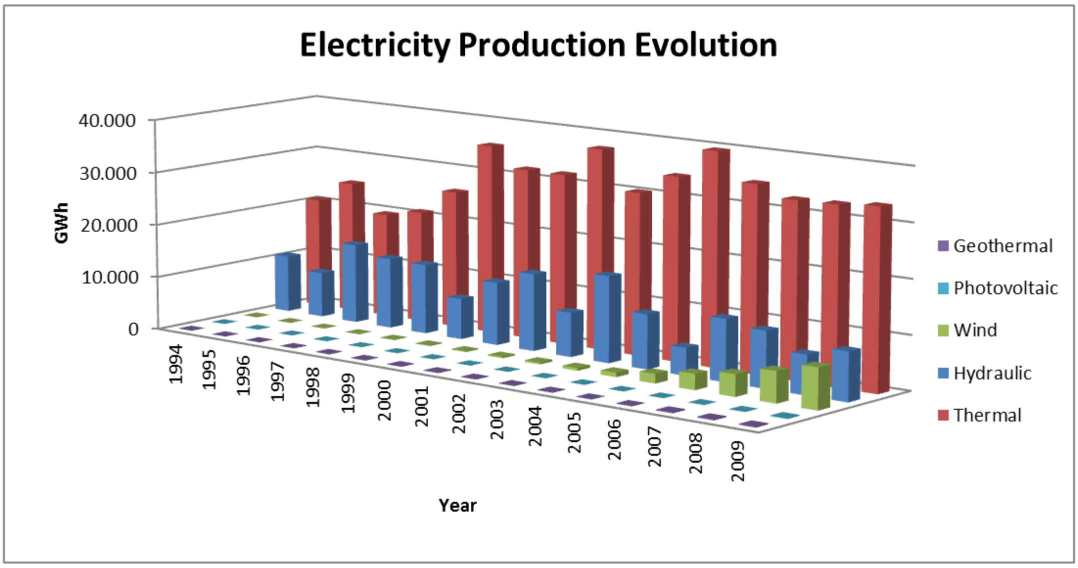


Figure 3 - Electricity production evolution in Portugal (source: author, data from DGEG).

It is also observable that hydraulic power generation is subjected to variability of pluviosity variation, yearly. The increase of renewable electric sources brings a problem of intermittence to the electric grid, where changes in wind intensity can cause an unexpected drop/increase in electricity production.

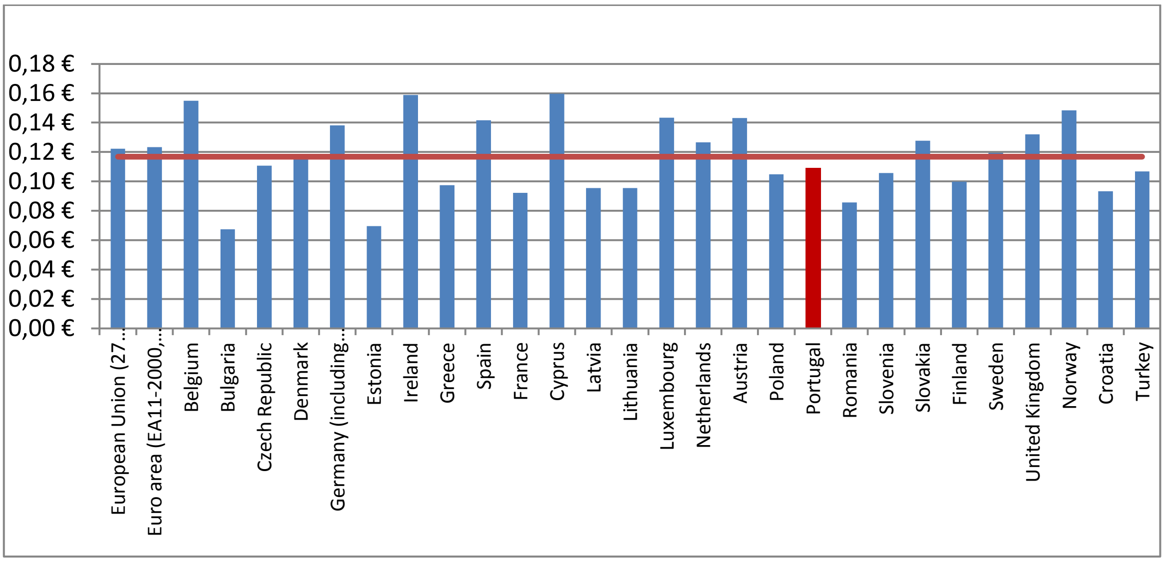


Figure 4 – Electricity prices for household consumers in 2010 (data: Eurostat)

In terms of electricity cost, Figure 4 shows the electricity prices practiced in 2010 for household consumers in a collection of prices made by Eurostat. The average between these countries is shown across the graph, it can be seen that of the countries involved, Portugal has a electricity prices for household consumers below average.

The electric grid operator (SO) has implemented a certain amount of backup systems or ancillary services to face these intermittent production adversities, which can be divided in mandatory system services that all production units need to have or contract others to do for them. These include: voltage regulation, stability maintenance and primary frequency regulation. These are not charged for.

Conversely, complementary services are part of the electric system and are charged for. They include secondary frequency regulation, regulation reserve, synchronous compensation, autonomous start and uninterruptibility. For V2G, Kempton identifies (Kempton & Tomić 2005) two power markets where V2G should be more economically viable; regulation and spinning reserve power markets. In Portugal only the regulation market is noticeable and therefore the only one to be assessed.

Regulation is a complementary service aiming to compensate instant disequilibrium's between energy production and consumption, fine-tuning frequency and voltage, either increasing the amount of energy production (regulation up) or decreasing/using the excess energy (regulation down). In Portugal, this frequency control follows the criteria from ENTSO-E (European Network of Transmission System Operators for Electricity) and acts with three separate systems. Primary frequency regulation starts only a few seconds after a change in the frequency of the grid was detected and is supplied by all power producers directly connected to the National Transport Grid. This service has to be deployed in 30 seconds and be provided for a maximum of 15 minutes. The secondary frequency regulation is deployed to replace primary systems and restore frequency to the normal value; this service needs to be in place in a matter of a few seconds to the maximum of 15 minutes, and is controlled by the SO (in Portugal the operator is REN - Redes Energéticas Nacionais). Tertiary control is applied with the purpose of restitution of the secondary regulation that has been used in the balancing of production and consumption freeing this service and works has a supplement to other reserves in case of a major incident. It starts after 15 minutes, maximum, and can last for a total of 2 consecutive hours (Entidade Reguladora dos Serviços Energéticos 2009; Entidade Reguladora dos Serviços Energéticos 2008; Entidade Reguladora dos Serviços Energéticos 2010; Dallinger et al. 2011)

Here, only secondary regulation is considered because it is more suitable for EV's When compared to tertiary regulation. Energy dispatching requirements are relatively small and fast in secondary while on tertiary they are longer and rarer. Evaluation of the profits made from tertiary market is delayed for future work.

For the calculations of the V2G model parameters, the database of the SO (REN) was used were a year worth of data on electricity prices for both regulation up and down were obtained, as well as capacity price paid, which is equal for both the regulation down and up markets. Beside these parameters the data of actual service use was obtained, permitting the calculation of the dispatch to contract ratio (definition in next section). Data was retrieved (from 01/07/2010 to 01/07/2011) (REN 2011), and average values for each of the following parameters were obtained (refer to the following table):

Table 1 – Grid parameters calculated for V2G calculation (source of data: (REN 2011)**).**

Description of item	Value
Capacity price for both reg up and down (€/kW)	0.0231
Electricity price for reg up (€/kWh)	0.0556
Electricity price for reg down (€/kWh)	0.0242
Dispatch to contract ratio for reg up (dimensionless)	0.28
Dispatch to contract ratio for reg down (dimensionless)	0.13

3.4. Costs and Revenues of V2G

In order to model the costs and revenues of V2G, the author used the base developed by Kempton(Kempton & Tomić 2005) with the updates suggested by Dallinger (Dallinger et al. 2011).

The dispatch to contract ratio, which is the fraction of the total power made available and contracted for, is calculated twice: once for regulation up and another for regulation down, as presented in Equation (1).

$$R_{d_c} = \frac{E_{disp}}{P_{contr} * t_{contr}} \quad \textbf{(1)}$$

Where E_{disp} is the energy dispatched for regulation, P_{contr} is the contracted power capacity and t_{contr} is the duration of the contract.

3.4.1.Limitations

The V2G power is limited by two factors:

1. the total amount of energy batteries can receive and deliver from the grid, and
2. the power the electrical line can supply.

To calculate the line capacity the following the formula $P_{line} = V * A$, was used. Throughout this study, the author considered the characteristics of new installations in Portugal, i.e. 400 V and 63 A, this approach also has a limitation of the actual power available, this considers that the entire power is available for V2G, this might not be true for other electrical appliances might also be in use. To calculate the amount of power limited by the vehicle Equation 2 was used, for regulation up:

$$\boldsymbol{P_{up}} = \frac{(\boldsymbol{E_s} * \boldsymbol{DoD} - (\boldsymbol{d_d} + \boldsymbol{d_{rb}}) * \boldsymbol{\eta_{veh}}) * \boldsymbol{\eta_{inv}}}{\boldsymbol{t_{plug\ day}} * \boldsymbol{R_{d_c}}} \quad \textbf{(2)}$$

And Equation 3 for regulation down:

$$\boldsymbol{P_{down}} = \frac{(\boldsymbol{d_d} * \boldsymbol{\eta_{veh}}) - \boldsymbol{E_{recharge}}}{\boldsymbol{\eta_{inv}} * \boldsymbol{t_{plug\ day}} * \boldsymbol{R_{d_c}}} \quad \textbf{(3)}$$

Where E_s is the battery capacity, DoD the maximum depth of discharge, d_d the kilometers driven, d_{rb} the range buffer the car must always provide, η_{veh} is the vehicle efficiency, η_{inv} is the charging/discharging efficiency, $t_{plug\,day}$ the hours the vehicle is plugged in a day and $E_{recharge}$ the amount of kWh recharged since plugged in (for the first calculation $E_{recharge} = 0$ and in the sensitivity analysis different values are used).

From these limitations of power availability the lower value is chosen (either the car or the line) for that will be the limiting factor for V2G - therefore having found P_{V2G}.

3.4.2.Calculating annual revenue

To calculate the annual revenue from V2G, first the amount of energy actually dispatched for regulation (either up or down) is calculated using Equation (4) bellow:

$$\boldsymbol{E_{disp}} = \boldsymbol{P_{V2G}} * \boldsymbol{R_{d_c}} * \boldsymbol{t_{plug\ year}} \quad \textbf{(4)}$$

Where $t_{plug\,year}$ is $t_{plug\,day}$ multiplied by 250 days in a year, which is an average of the working days in Portugal; and $t_{plug\,day}$ is the time the vehicle is plugged in for a reference value of 15.9 hours was used, i.e. approximately 65% of the day (Dallinger et al. 2011).

Revenue for either regulation up or down is constituted by two parts: capacity made available /whether used or not) and energy dispatched. The capacity payment is calculated using Equation (5),

$$\boldsymbol{r_{cap} = p_{cap} * P_{V2G} * t_{plug\,year}} \quad \textbf{(5)}$$

The revenue from energy changes for either regulation up or down is calculated through using Equation 6:

$$\boldsymbol{r_{el} = p_{el} * E_{disp}} \quad \textbf{(6)}$$

Where p_{el} is the €/kWh price of energy for regulation, accounted for in Table 1. The total revenue is calculated by the sum of the capacity and energy payments.

3.4.3. Calculating costs

The costs regarding V2G are calculated by adding the extra wear from performing this service, which on regulation up is the extra degradation (cycling) on the batteries and energy required. The degradation of the charging infrastructure should also be accounted for in the fixed costs.

On regulation down these do not apply because no extra degradation or energy happens.

3.5. Total cost of ownership

Total cost of ownership (TCO) is a support tool for investment decision-making that quantifies systematically all costs generated over the lifetime of a product or service, including all direct and indirect costs. In essence TCO determines a figure that reflects the total cost of investment by the individual or organization, including one-time purchases and recurring costs (costs occurring on a periodic basis and originated from the use, maintenance, upgrades, annual licensing fees, insurance, taxes, depreciation, opportunity costs, as well as support of the application or investment – finance costs), including all costs and not just the initial start-up cost (Filipe Moura 2009).

The costs selected for this study obeyed to 2 criteria: relative importance in the overall lifecycle cost of the vehicle and if the costs are accounted for differently among powertrains analyzed. That is, costs that are equal whatever the powertrain considered are not included here, since this is a comparative analysis. The fixed costs identified, which are those that occur whether the vehicle is used or not were charging infrastructure cost, depreciation, financing cost, fees and taxes. The variable costs (expenses that change in proportion to the use of the vehicle) included were fuel/energy costs, degradation/battery substitution and maintenance costs.

3.5.1. Description of selected costs

After the calculation of the total lifecycle costs the value is annualized according to Equation (7).

$$\boldsymbol{c_{annualized} = c_{lifecycle} * \frac{d}{1-(1+d)^{-n}}} \quad \textbf{(7)}$$

Where $c_{annualized}$is the annualized cost; $c_{lifecycle}$is the total lifecycle cost; d is the interest rate (3% is used throughout this text) and n is the lifespan of the vehicle (15 years).

3.5.2.Charging Infrastructure Costs

A method was developed to calculate an average cost for the traditional gasoline/diesel charging infrastructure as well for the electric charging facilities, based on the amount of fuel/energy the vehicle will require over its life and information about fueling stations given by the largest fuel reseller in Portugal (GALP) and Siemens who is currently producing electric vehicle chargers. The objective was to find a way to calculate how much does the fueling/charging infrastructure costs in the lifecycle of one vehicle. The procedure is shown later on for each type of powertrain.

This parameter is of particular importance in the BEV, because the home charging infrastructure is a cost that the vehicle owner will have to pay for, while on the ICEV, the price of the fueling infrastructure is passed on to the fuel price (and therefore is accounted for in retailers' fuel price. This also could happen in the BEVs on the public charging infrastructure, however no information still exists on the price of electricity that will be charged on this service. The values found are somewhat in line with what is presented in (Graham 2001).

3.5.3.Depreciation

Loss of vehicle value due to depreciation in the first few years of a vehicle's life is a critical factor in overall ownership costs. Depreciation is the amount by which the value of a vehicle declines from its purchase price and can be calculated by deducting its residual value to the initial purchasing price. There are many factors that affect the residual value of the vehicle, varying from age, cumulative mileage and wear of the car, but also the rate of depreciation is strongly dependent on other factors like brand image, mileage range, trim line and vehicle class or external factors such as new model pricing and purchase power of households (Filipe Moura 2009).

There are several methods to estimate the depreciation of used vehicles. In this study the simplest "one-hoss shay" method is used for all types of powertrains. In this method it is assumed that the asset delivers the same services for each vintage, the discount rate is set to zero and the annual depreciation is constant over time (for the objective of this study this simplification seems to be adequate) and the one-hoss shay method becomes a straight line (calculated by taking the purchase price of an asset subtracted by the salvage value divided by the expected service life years)(Filipe Moura 2009).

3.5.4.Financing Costs

Financing costs are the interest expense on a loan or a lease in the amount of the purchasing price including the applicable initial charges and fees, assuming a down payment (typically the 20% used on this work) and a loan or lease term of 3 to 4 years. The interest rates considered are the prevailing rate that banks and other direct automotive lenders charge consumers. Even if the car would be bought without loans, the inclusion of financing costs in the determination of the TCO of vehicles is appropriate because it would reflect the opportunity cost of the return that could have been made if the purchase price were invested elsewhere (though the interest rates could be different depending on the investment made)(Filipe Moura 2009).

3.5.5.Fees and taxes

Taxes and fees vary greatly from country to country, in this study the Portuguese taxes and fees were used in the calculation. The taxes in Portugal can be divided in two categories: acquisition taxes and use/owner taxes.

The acquisition taxes in the automobile sector are the VAT (Value Added Tax) and the VT (Vehicle Tax, *Imposto sobre Veículos* - ISV in Portuguese). These are paid upon purchase, and therefore are already included in the car value and so are accounted for.

Use taxes are those that depend exclusively on the amount of use given to the vehicle:

- Tax on Petroleum Products (TPP) that concerns petroleum derivatives;
- Road Service Contribution (RSC) which objective is to finance the road networks.

Both these taxes are assigned to the fuel seller (and therefore are transmitted to the consumer in the price of fuel, which is why these are not considered in the present analysis). Tolls are not considered in this study for they would be equal among the different powertrains.

Owner taxes are are usually paid annually and include the SCT (Single Circulation Tax) paid during the month of the driving plate and is constituted by two components an environmental and an engine size component. Finally there is the National Medical Emergency Institute Tax that is paid by the vehicle insurance company. The latter and insurance costs are not considered because in principle there exists no difference between different powertrains.

Ultimately, the only tax that is required to study is the SCT, because all other either are accounted in some other part of the cost model or the value of the tax is equal among all powertrains and hence they are not considered.

3.5.6.Fuel/Energy

Fuel or energy costs are estimated by calculating the consumption of fuel/energy over the life of the vehicle multiplied by the fuel/energy price. The price of gasoline used was the current price in Portugal. The price of electricity was taken from a 2010 domestic bill.

When doing regulation up, the energy discharged from the batteries to the electric grid needs to be accounted as an extra energy cost added to the energy costs required for vehicle motion:

$$Reg\ up\ energy\ costs = [Energy\ for\ motion\ (kWh) + Energy\ for\ reg\ up\ (kWh)] \ * \\ * \ Price\ of\ energy\ (€/kWh)$$

When doing regulation down, meaning that there is ‘regulation energy’ being charged from the electric grid to the batteries, the vehicle will require less charging from ‘normal energy’ for vehicle motion; because these types of energy are charged at different rates they need to be accounted separately:

$$\begin{aligned} Reg\ down\ energy\ costs = \{[&Energy\ for\ motion\ (kWh) - Energy\ for\ reg\ down\ (kWh)\ ] * \\ &* Price\ of\ energy\ (€/kWh)\ \} + \{Energy\ for\ reg\ down\ (kWh) * \\ &* Price\ of\ reg\ down\ energy\ (€/kWh)\} \end{aligned}$$

3.5.7.Degradation/battery substitution

This factor applies essentially to the BEV, where the batteries along the vehicle service time have to be substituted due to wear. The method presented by Dallinger (Dallinger et al. 2011) and Kempton (Kempton & Tomić 2005) is used to estimate the amount of batteries required over the vehicle service time. First the amount of energy required from the batteries is calculated for the vehicle’s service time. This is calculated using the average Depth of Discharge, the number of cycles the battery can do and the amount of energy required over the lifecycle of the vehicle, finding the amount of batteries the vehicle will require. The price of batteries used is obtained by multiplying the battery capacity (kWh) and reference value found in the literature (refer to (Graham 2001) and (Arthur D. Little 2002)) of about 300US$/kWh (Delucchi et al. 2000) converted into Euros. In (Hill et al. 2012) it was determined that battery cycle life during V2G duty is a critical parameter, which can determine whether or not the business model is viable.

3.5.8.Maintenance

For the maintenance costs a great deal of approaches can be chosen. There is here an obstacle not easy to overcome since there is no real information on how maintenance on battery electric vehicles is going to be. Still, it is commonly accepted that since BEVs have less moving parts then their equivalent ICEVs, they would require less maintenance, reducing the corresponding costs. A member of Nissan, in Portugal confirmed this and they estimated the maintenance costs of the Nissan Leaf would be 25% less than that of an ICEV.

This was the approach to this problem, using the data in (Filipe Moura 2009) which gives the average maintenance costs of an ICEV. As such, a approximate value for the BEV maintenance costs is obtained by subtracting 25% of the costs that do not include battery degradation. The values obtained are in line with what is presented in (Graham 2001).

3.6. The Gasoline Internal Combustion Engine

This section presents the life cost characterization of a gasoline internal combustion engine vehicle. As a base for comparison with the Nissan Leaf, the 1.2L TSI Bluemotion VW Golf was chosen; the reasoning behind the utilization of this model is to use a vehicle in the same segment has the Leaf (5 door hatchback), that therefore have similar characteristics and compete for the same final consumers; the 1.2L TSI Bluemotion powertrain was chosen because it is one of the most efficient gasoline powertrains available, and provides a power similar to the Leaf (around 100 hp).

3.6.1.Charging infrastructure

The following scheme shows how the costs for the charging infrastructure were calculated:

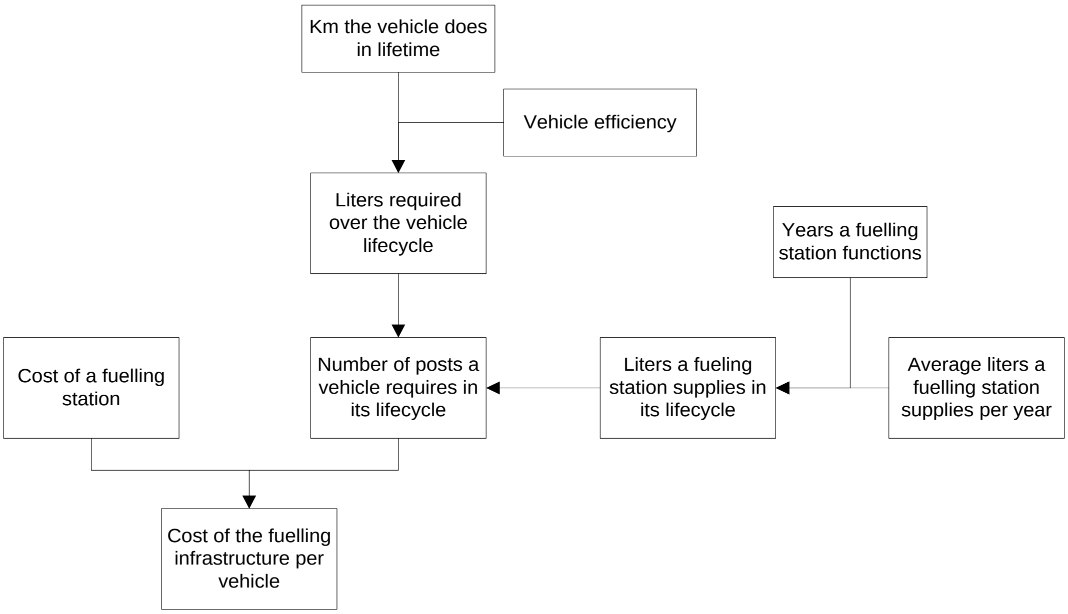


Figure 5 - Methodology for Fueling Infrastructure Calculations (source: author).

Has said the VW Golf is the base model used for the calculations and the information given by GALP about the fuel infrastructure. The following table shows the values used and the cost of fueling infrastructure calculated for an ICEV.

Table 2 - Gasoline infrastructure costs parameters considered (source: author).

Description of item	Value
Km in vehicle life time (km)	300,000 km
Fuel consumption (L/km)	0.06 L/km
Years a fuel station works	20 years
Average liters a fuel station supplies (m^3)	2500 m^3
Cost of a fueling station (€)	1,000,000 €
Cost of the fueling infrastructure per vehicle in lifecycle (€)	360 €

Though these calculations give us an important parameter of cost, they are not included in the cost evaluation because this value is passed on from the fuel reseller to the consumer, being internalized in the fuel price.

3.6.2.Depreciation

The reference cost of a new 2011 VW Golf was used. The residual value was assumed to be the same as the current price of a 15-year old Golf. The values were 22.000€ for a new VW Golf and 2.500€ for a 15-year old model.

3.6.3. Financing costs

As mentioned above the financing costs used on this work are based on a 20% down payment and a (conservative) interest rate of 3%. Therefore the required loan would be 80% of the 22,000€ giving the necessary loan of 17,600€, which with an interest rate of 3% gives a financing cost of 528€.

3.6.4. Fees and Taxes

Again the VW Golf is used to estimate the SCT, using the Portuguese law. The results are summarized below.

Table 3 - Single Circulation Tax for the VW Golf used (source: author).

Description of item	Value
SCT for an engine capacity of 1.2L (per year)	26.30€
SCT emissions for 121 gCO_2/km (per year)	79.10€
Total SCT (over 15 year service time)	1,581.00€

3.6.5. Fuel/Energy

Considering the cumulative service time mileage (15 years and 300,000 km) and an average fuel consumption of 6L/100km, the author estimates that the lifetime fuel costs as 27.000€,, giving an average gasoline price of about 1.5 €/L.

3.6.6. Degradation

The degradation on ICEVs is not considered, for this cost is accounted for, on depreciation and maintenance costs.

3.6.7. Maintenance

Only the scheduled maintenance part is considered in this study due to the difficulty to assess how the BEV will behave and therefore how much the non-scheduled (e.g., accidents repair costs) maintenance will cost to the vehicle owner. The values associated with maintenance are taken from (Filipe Moura 2009), and are summarized in the following table:

Table 4 - Scheduled maintenance frequency and costs (source: (Filipe Moura 2009)**)**

Description of item	Cost	Periodicity ('000 km)	Frequency (over 300,000km)	Price
Recurrent Scheduled Maintenance Group I	20,00 €	5	60	1.200,00 €
Recurrent Scheduled Maintenance Group II	25,00 €	20	15	375,00 €
Recurrent Scheduled Maintenance Group III	130,00 €	20	15	1.950,00 €
Recurrent Scheduled Maintenance Group IV	230,00 €	45	6	1.380,00 €
Spark plugs, inspect wires	55,00 €	45	6	330,00 €
Windshield wiper blade inserts	20,00 €	20	15	300,00 €
Transmission/Transaxle service	70,00 €	50	6	420,00 €
Power cooling system flush	70,00 €	60	5	350,00 €
Front disc brakes	160,00 €	90	3	480,00 €
Rear brake pads/shoes	130,00 €	90	3	390,00 €
Tires (set of four)	355,00 €	60	5	1.775,00 €
Muffler, exhaust pipe	245,00 €	100	3	735,00 €
Battery	75,00 €	100	3	225,00 €
Struts/shocks	530,00 €	130	2	1.060,00 €
			TOTAL	10.970,00 €

Notes: Group I includes: lubricate and inspection of front suspension, oil change, oil filter change and refill windshield wiper fluid;

Group II includes: all of Group I, safety inspection and rotate tires;

Group III includes: all of Group I, tire rotation and wheel balancing, clean, inspect and adjust brake system, inspect cooling system, tighten hoses, inspect exhaust system and heat shields;

Group IV includes: All of Group I and replace air filter, replace fuel filter, check engine timing, inspect cooling system, tighten hoses, inspect fuel tank cap and lines, tire rotation and wheel balancing, clean, inspect and adjust brake system, inspect exhaust system and heat shields.[9]

3.7. The Battery Electric Vehicle

This section presents the cost characterization for a BEV for which the chosen reference vehicle was the Nissan Leaf.

3.7.1. Charging Infrastructure

Following the same method has for the ICEV, a model for calculation of the charging infrastructure was developed which is schematized in the next figure:

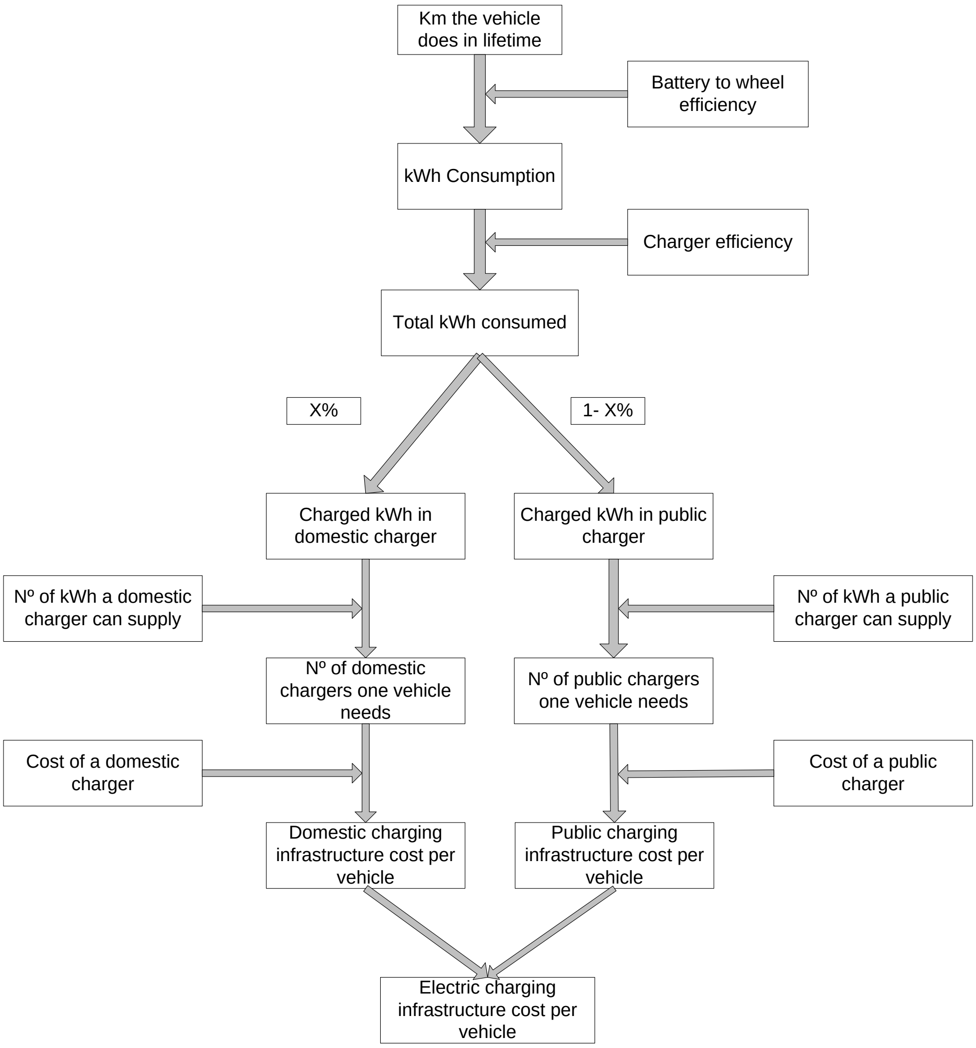


Figure 6 - Model for electric infrastructure calculation (source: author).

For reference values, the author contacted Siemens that is currently producing electric chargers. It should be mentioned that the chargers referred to in this study are always capable of not only charging the vehicle but also receiving energy (V2G capable). However, Siemens could not specify the amount of kWh a charger (either domestic or public) could supply over its lifetime. With this in mind an approximation was done with the power of each type of charger and an attributed time of continuous work. It was considered that a home charger (with a 6/8 hour recharging time and 4.6 kW) would be able to provide electricity over 15 continuous years and a public charger (0.5/1h recharging and 22 kW) 10 continuous years. With these parameters the total amount of kWh each charger would supply was calculated (refer to Table 5).

Table 5 – Main inputs and assumptions of the electric charging infrastructure costing model (source: author).

Description of item	Value
Km in vehicle life time (km)	300,000
Vehicle efficiency (kWh/km)	0.14
Charger efficiency (%)	80%
Charged in domestic charger (%)	80%
Charged in public charger (%)	20%
Nº of kWh a domestic charger can supply (kWh)	604,440
Nº of kWh a public charger can supply (kWh)	1,927,200
Cost of a domestic charger (€)	5,000
Cost of a public charger (€)	7,000
Electric charging infrastructure cost per vehicle (€)	**370**

While on the ICEV the infrastructural costs were not considered (for they are accounted in fuel price), BEV lifecosts must include them. In the case of the domestic charging, these costs are an investment that the vehicle owner must do. In the case of the public network, though it could be said that like in the ICEV the infrastructure costs could be passed down to electricity prices, there is no information at this time on those rates might be.

3.7.2.Depreciation

The same "one-hoss shay" method was used to calculate the depreciation of the Nissan Leaf, with a purchasing price of about 35,000€, considering a salvage price of 2.000€ over the 15 years of use. The battery depreciation or wear is considered in a different parameter. Therefore, subtracting the cost of a new battery (5,500€) to the vehicle price (35,000€), meaning that 2,000€ is the BEV salvage price without the battery.

3.7.3.Financing costs

Using the same method as previously, the financing costs were calculated with a 20% down payment and an interest rate of 3%. Therefore, the required loan would be 80% of the 35,000€, i.e.28,000€. Considering an interest rate of 3% gives, the financing cost amounts to 840€.

3.7.4.Taxes and fees

According to the current Portuguese law, BEV are free from paying the VT, SCT, TPP and the RSC, and therefore because all other taxes are equal to the ICEV (insurance, polls, and the National Medical Emergency Tax etc.), no taxes are considered in the BEV though they are considered later on for sensitivity analysis to our assumptions.

3.7.5.Fuel/Energy

Considering a cumulative lifetime mileage of 300,000km and an average of 0.14 kWh/km, total lifetime energy consumption amounts to 50,400 kWh (including an additional consumption of 20% to account for the vehicle charger and battery efficiency losses). Assuming an average constant electricity price of 0.13 €/kWh, the cost for the energy part on the vehicle lifecycle is 6,552€.

3.7.6.Degradation/battery substitution

To estimate the costs associated with the use of batteries, the approach used was to first define an average Depth of Discharge (DoD) for the battery. Here, the author used a DoD of 80%(Kempton & Tomić 2005). Then calculation of the amount of cycles (C_{life}) the battery can do with the given DoD is given by the following expression (8) in (Dallinger et al. 2011):

$$C_{life} = 1331 * DoD^{-1.8248} \quad \textbf{(8)}$$

Following the calculation of the energy delivery rate of the battery (L_{ET}) in kWh according to Dallinger:

$$L_{ET} = C_{life} * DoD * E_s \quad \textbf{(9)}$$

were E_s is the energy storage in the battery (24 kWh for Nissan Leaf).

The calculation of the number of batteries the car needs over its lifetime is based on the estimate of L_{ET} and the total kWh required to perform 300,000 km.. Using a price for a single battery of 220€/kWh times the 24 kWh capacity of the Leaf battery, confirmed by the values used by Dallinger (Dallinger et al. 2011), the total cost associated with battery degradation and substitution is 6,930 €.

3.7.7.Maintenance

As said previously no actual maintenance cost estimations for real use of electric vehicles has been made. As communicated by Nissan in Portugal, a subtraction of 25% to the costs estimated for the ICEV, yielding a maintenance costs for a BEV of 8,228€.

3.8. The Battery Electric Vehicle with V2G Technology

As discussed previously V2G was evaluated for the secondary reserve power market for both regulation up and down.

3.8.1. Calculation of revenues from Regulation Up services

Table 6 presents the parameters and estimated annual revenues from regulation up with V2G, using the equations presented in section 3.4.2 (page 56).

Table 6 - Regulation up revenue parameters and results (source: author)

Description of item	Value
P_{V2G} (kW)	1.740
$t_{plug\ year}$ (h)	3,975.000
$R_{d_{c}\_up}$	0.280
E_{disp}(kWh)	1,922.000
p_{cap} (€/kW-h)	0.023
p_{el} (€/kWh)	0,056
r_{cap} (€)	159.520
$r_{el\ up}$(€)	106.82 0
Revenue from Reg up (€)	**266.350**

3.8.2.Calculation of costs for Regulation Up

Some terms of the cost calculations are the same as for the BEV with no V2G and so they will not be presented. Depreciation, financing, taxes and vehicle maintenance are considered to be equal either the car does V2G or not. It is necessary to remember that these costs are lifecycle costs that are to be annualized.

Charging infrastructure

The same method was used, with the only exception that to the total kWh consumption is added the extra energy required for V2G, while all other parameters remain the same. The total infrastructural costs of a BEV doing V2G regulation up is of 582€, considering that the energy dispatched was 1,922kWh (refer to Table 6, in previous page).

Fuel/Energy

As before, the total amount of energy is obtained, by calculating the total amount of kWh necessary for the vehicle's mobility plus the kWh required for V2G systems, accounting for the charger and battery efficiency also.

Table 7 - Energy life costs of BEV with regulation up V2G (source: author).

Description of item	Value
kWh charged due to V2G	28,834.00
kWh charged due to vehicle use	50,400.00
Charger and battery Efficiency	0.80
Total kWh charged (use+V2G)	79,234.00
Electricity cost for private consumer (€)	0.13
Total Cost (€)	10,300.00

Degradation/Battery substitution

To obtain the value for battery degradation costs, the same method is used. Adding to the total amount of kWh, the energy required for regulation up and applying the same equations already presented. Thereafter, a division of the total kWh required (driving + V2G reg up) by the total amount of kWh a battery can supply over its lifetime, and estimate the total amount of batteries the car will need, for a 15 year and 300,000km service period.

Table 8 - V2G regulation up battery degradation/substitution cost (source: author).

Description of item	Value
DoD (dimensionless)	80%
C_{life} (number of cycle)	2,000
L_{ET} (kWh)	39,999
Price/battery **[7]** (€)	5,500
Consumption + V2G (kWh)	79,234
Number of batteries	~2
Battery cost	**10,895**

3.8.3.Calculation of revenues from Regulation Down services

Table 9. presents the parameters and estimated annual revenues from regulation up with V2G, using the equations presented in section 3.4.2 (page 56).

Table 9 - Regulation down revenue parameters and results (source: author).

Description of item	Value
P_{V2G} (kW)	2.420
$t_{plug\ year}$ (h)	3,975
$R_{d_c\_down}$	0.130
E_{disp}(kWh)	1,289
p_{cap} (€/kW-h)	0.023
p_{el} (€/kWh)	0.024
r_{cap} (€)	222
$r_{el\ down}$(€)	31.220
Revenue from Reg down (€)	**253**

3.8.4.Calculation of costs for Regulation Down

Due to the nature of regulation down services and considering the applied methodology the only cost calculation that is different from the cost of the BEV with no V2G is the decrease in energy consumption. This means that part of the electricity charged will be paid at a lower rate which is the regulation down tariff owed to the vehicle owner.

Table 10 - Energy life costs of BEV with regulation down V2G (source: author).

Description of item	Value
kWh charged due to V2G	19,343
kWh charged due to vehicle use	50,400
Total kWh charged (use - V2G)	31,057
Electricity cost for private consumer (€)	0.13
Total Cost (€)	**4,037**

3.9. Discussion of results

In this section the main results of the LCC study are presented, followed by a sensitivity analysis and a discussion of the obtained outcome.

Table 11 presents the costs and corresponding decomposition for each of the evaluated vehicles in order to have an idea of how each factor influences the final cost. Alongside, it is shown the revenues of V2G estimated for both power markets analyzed.

Table 11 - Cost comparison of the ICEV, BEV, BEV reg up and BEV reg down (source: author)

Description	ICEV	BEV	V2G – Reg up	V2G – Reg down
Charging infrastructure	0%	1%	1%	1%
Depreciation	33%	55%	47%	57%
Financing	1%	2%	1%	2%
Taxes	3%	0%	0%	0%
Energy/Fuel	45%	13%	18%	8%
Degradation/battery substitution	0%	14%	19%	14%
Maintenance	18%	16%	14%	17%
Cost (€/per year)	- 4,991 €	- 4,224 €	- 4,887 €	- 4,013 €
Revenue (€/per year)	-	-	266 €	253 €
Total (€/per year)	- 4,991 €	- 4,224 €	- 4,621 €	- 3,760 €
Percent variation compared to the ICEV	-	*(-15.0%)*	*(-7.4%)*	*(-24.7%)*

The present sensitivity analysis is motivated by some of the limitations and assumptions of the analysis presented in the previous sections. These include, for example, the fact that some input variables and parameters of the model were determined based on other studies, for instance, the unit price of the BEV batteries per kWh (€/kWh), maintenance costs of BEV. And other inputs that change over time - e.g., gasoline prices or electricity prices. For this analysis the software @Risk (www.palisade.com) is used to add some variability to all inputs by attributing a probability density to each one. The program was then left to do 1,000 iterations for each of the configurations analyzed.

The output to be analyzed is the total final profits (revenues – costs) for each powertrain, and for either V2G regulation up or down. In annex the type of distribution and their parameters are presented for each input. Next the regression coefficient graphs are shown for each case representing the more important variables and in the end of this section the final distribution function for each powertrain is presented.

Figure 7 presents the main parameters and corresponding weight in the total costs of an ICEV. It is observable that the main parameters that influence the total ICEV cost are the amount of km done in lifecycle, service time, car price and price of gasoline. The lifecycle km and the price of gasoline are very important because these are directly involved in the calculation of energy costs, which account for 45% of total cost. The number of years the device will last is important because it is directly connected to the equation of annualized cost: more years implies more time to amortize the investment. Finally, car price is a natural important factor for it is used to find depreciation costs (accounting for 33% of total costs).

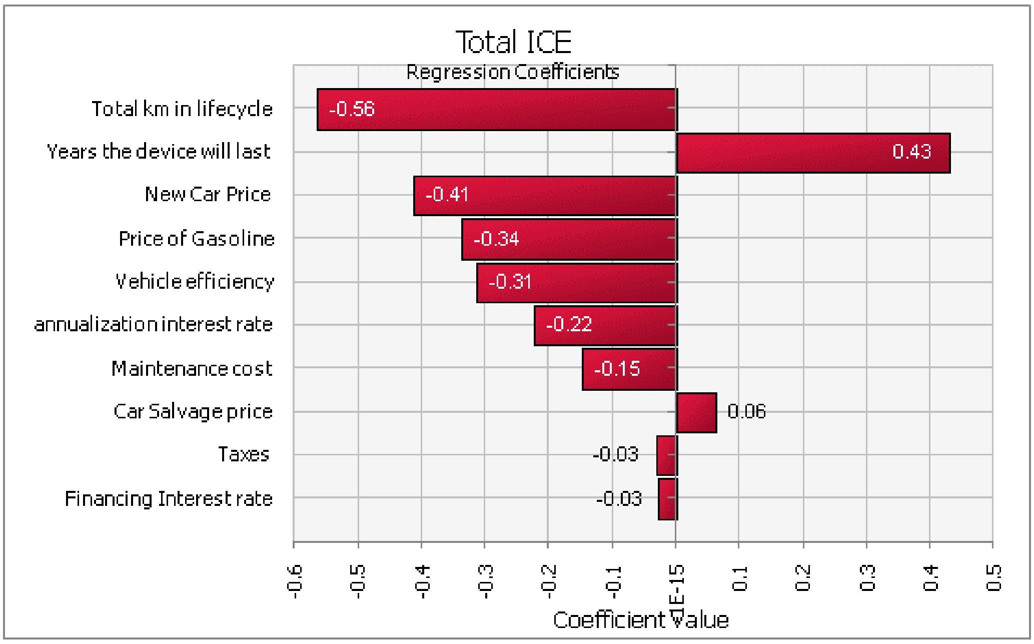


Figure 7 - Internal Combustion Engine sensitivity analysis regression coefficients (source: author).

In contrast with the ICEV, the weight of new car price on total cost of the BEV has the largest influence, and not energy as in the conventional engine (refer to Figure 8). This factor is common to the BEV either it does or not V2G. Naturally, as the car price increases, the importance of depreciation increases as well. Depreciation accounts for more than half of lifecycle costs in BEV.

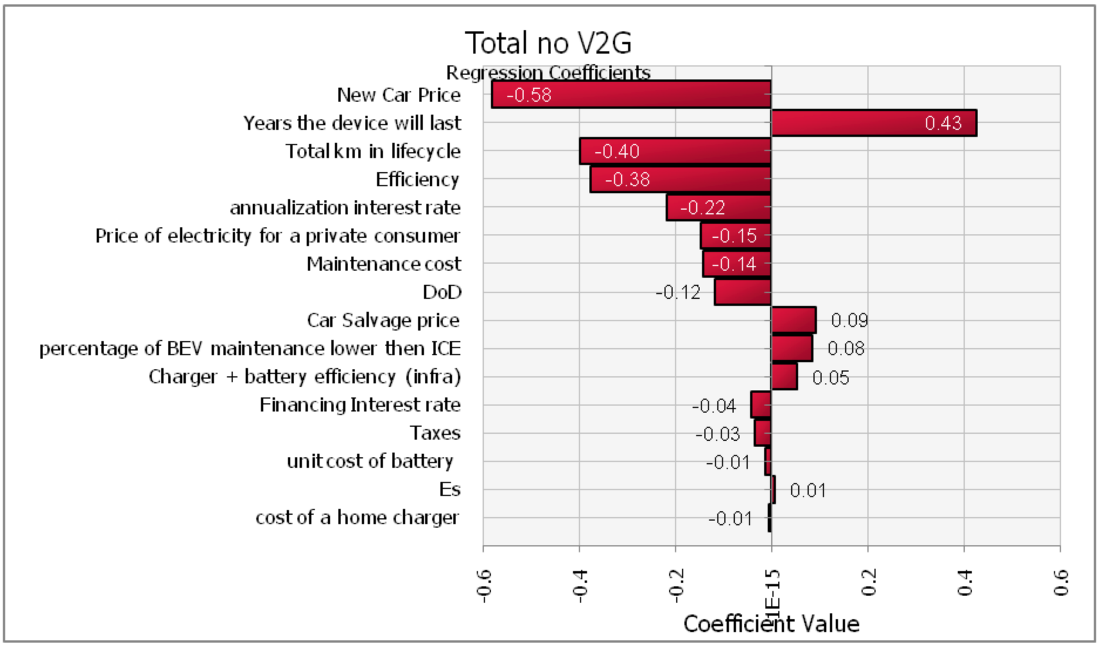


Figure 8 - Battery Electric Vehicle sensitivity analysis regression coefficients (source: author).

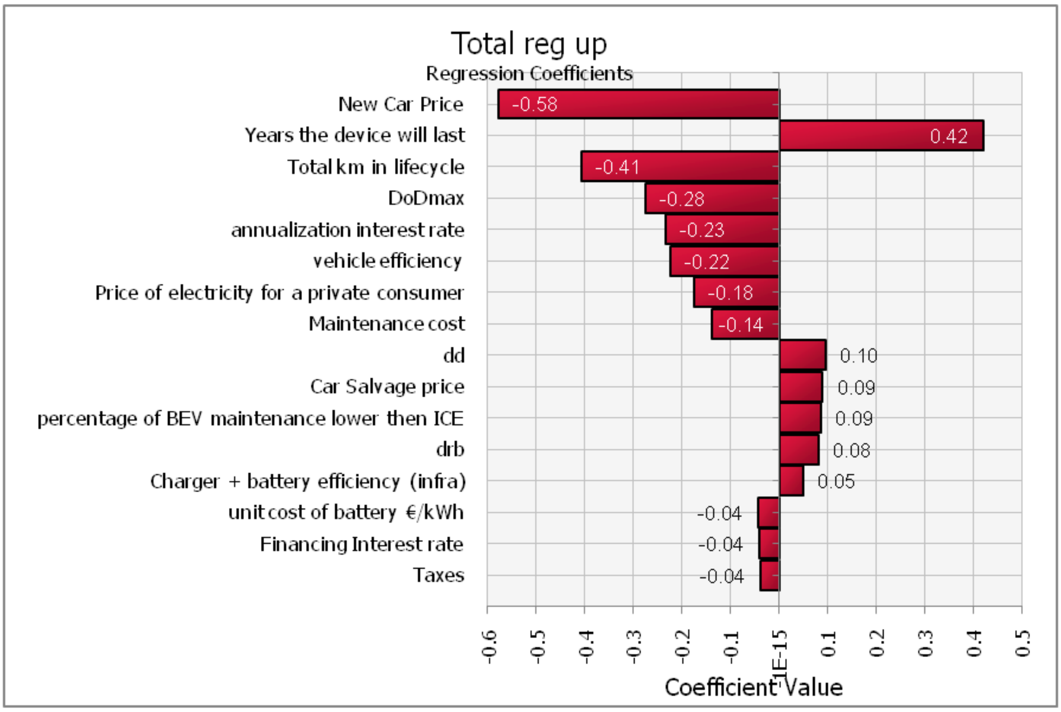


Figure 9 - V2G regulation up sensitivity analysis regression coefficients (source: author).

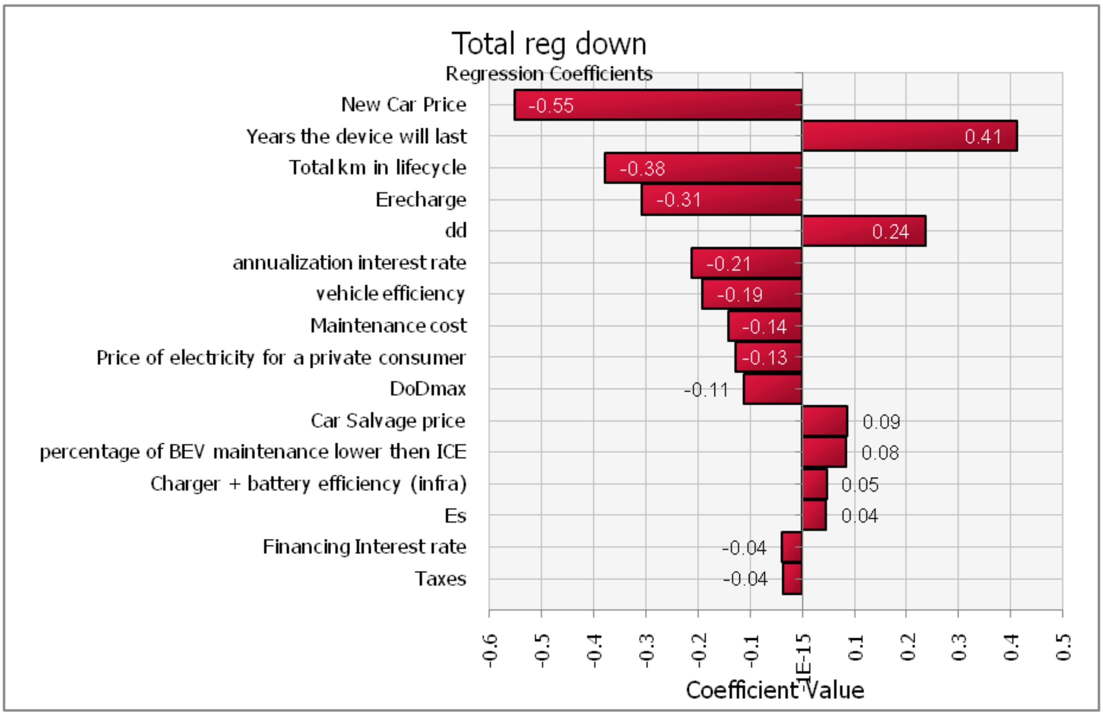


Figure 10 - V2G regulation down sensitivity analysis regression coefficients (source: author).

On V2G regulation up and down, the same prime parameters appear in first place. The difference comes on the DoD for regulation up and $E_{recharge}$ for regulation down. These two parameters are in fact very alike for they both limit the “capacity” of the battery; either because it cannot discharge anymore (DoD_{max} in regulation up) or because it has already charged a great deal and therefore there is little left for regulation down ($E_{recharge}$).

Table 12 (below) presents the probability density functions (PDF) parameters of all lifecycle cost estimates. From the 1,000 iterations of the sensitivity analysis (nº observations=1,000), considering the central limit theorem, normal distributions are good PDF for the results obtained. The table below also presents the 2-tailed t-test to assess whether the means of each two configurations (always compared to the reference ICEV) are statistically different from each other. Figure 11 (next page) is an illustration of the PDF that each case follows on the sensitivity analysis.

Table 12 – Probability Density Functions of the final lifecycle costs (source: author)

	ICEV	BEV	V2G – Reg up	V2G – Reg down
Mean	5,612 €	4,214 €	4,378 €	4,096 €
Standard Deviation	1,448 €	1,098 €	1,099 €	1,145 €
t-test *(p-value)*	-	*-24.33* *1E-113*	*-21.47* *3E-91*	*-25.97* *2E-127*
Dif. Regarding ICEV	-	-1,398 €	-1,234 €	-1,516 €

* Two tailed t-test for equality of means with equal variance.

Firstly, the author concludes that the means are statistically different, considering the very low *p-values* (i.e., there is very low probability that means are equal to each other, on a pairwise analysis with ICEV values). Secondly, the figures show that, on average, BEVs are more economical then ICEVs. Still, the variance of the results is wide and therefore it should be estimated the probability of this occurring, since the difference between the results is that wide. When considering V2G services from BEV, the author concludes that doing regulation up is less advantageous than BEV (no V2G). Conversely, doing Regulation Down is more beneficial than no doing any V2G. Again, differences of the means are low, and therefore estimations of the probabilities of each configuration being higher than the others should be done.

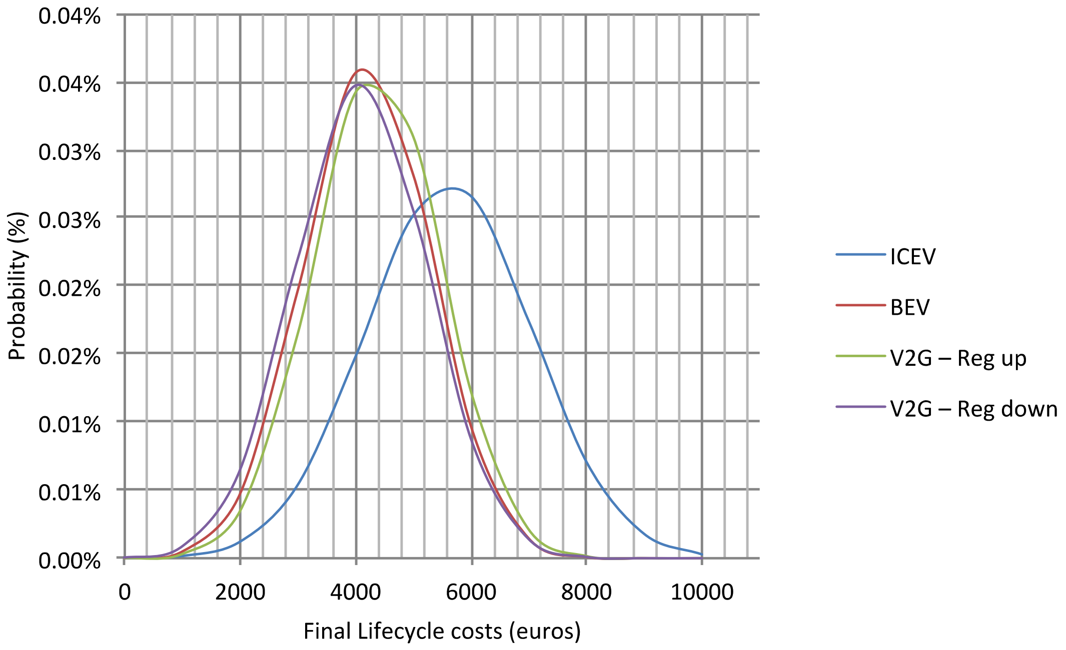


Figure 11 - PDF comparison of the analyzed cases (source: author).

Let us define the following continuous variables:

- X are the variables in the rows from the table below and $X\sim Normal(X_X,\ s^2_X)$;
- Y are the variables in the columns form the same table and $Y\sim Normal(X_Y,\ s^2_Y)$

Testing whether Y is lower than X is equivalent to testing if a variable $Z=X-Y$ is negative or equal to zero, where $Z\sim Normal\ (X_Y-X_X\ ,\ s^2_Y+s^2_X)$. The matrix in Table 13 presents the probability of variables in each row being lower or equal to variables in every column.

Table 13 – Probability of LCC in column being lower than LCC in row (source: author)

	ICEV	BEV	V2G – Reg up	V2G – Reg down
ICEV	-	78%	75%	79%
BEV	-	-	46%	53%
V2G – Reg up	-	-	-	57%

These results conclude that BEV's LCC have a 78% probability of being lower than ICEV's LCC. Interestingly, there is a 46% cumulative probability of 'Regulation up' LCC being lower than BEV. This is certainly explained by the fact that although statistically different, the means are very close such as the corresponding variances. As such, there is a significant overlap of both PDFs. Clearly, 'Regulation down' mean LCC are lower than BEV and 'Regulation up'. Still, there is still 40% to 50% cumulative probability of LCC of 'Regulation down' being higher than 'regulation up' and BEV, respectively. The author concludes then that providing V2G services might bring marginal benefits for BEV owners.

3.10. Conclusions

As for V2G the results are coincident with the ones presented by Dallinger (Dallinger et al. 2011), (Dallinger et al. 2011), which concludes that regulation up is not economically feasible since the costs associated with this market are larger than the gains (due to energy consumption that is paid bellow buying price and battery wear), this situation is confirmed in (Filipe Moura 2006). Regulation down is confirmed has economically interesting because there is no extra cycling on the batteries and the energy comes at a lower rate, confirming both conclusions of Kempton (Kempton & Tomić 2005) and Dallinger (Dallinger et al. 2011). That said the gains are small, which could discourage BEV users of adhering to this system. This conclusion could imply that currently V2G could be more interesting from the SO point of view than to the consumer, for it could reduce the need for grid stability infrastructures. This situation could lead to an increase of V2G services value in the future, if this system is applied or if its opportunity costs would be higher (for example, building additional dams for hydroelectric electricity storage during off-peak periods).

The author would like to add that if the SO would not be permit the BEV owner to do just regulation down, but demand both up and down, the life cycle costs of doing both regulation services would be around 4,158 €, meaning that even with the obligation of doing regulation up, the profits of regulation down would be sufficient to compensate the costs of regulation up. That said, this obligation further decreases the positive implications in doing regulation services (reducing to 56 € the annual benefit of doing regulation services). The representation of the PDF in the sensitivity analysis is not done, for the simple reason that it would not add any new information to the study.

It needs to be referenced that any of the results of this study must take into account the limitations that are implied to the model: the type of vehicles analyzed, the parameters used for the Portuguese energy market, or other parameters where an alteration could present a different balance between technologies, this is particularly true in this case because the cost disparity is not that large. One should not forget that tough the use of Monte-Carlo simulation is used in this work for the sensitivity analysis, there are limitations with the use of this method, particularly the assumption that all parameters are completely independent between each other, which is not always true.

4. Lifecycle Analysis

In this chapter, the author follows a typical Lifecycle Analysis (LCA) outline. Beginning with a brief description of the concept of LCA, then the objective and scope of the analysis follows. Thereafter, the author builds the lifecycle inventories based on data collection and finish with the presentation and discussion of the results obtained.

4.1. Lifecycle assessment concept

A lifecycle assessment is a technique aiming to compare relative environmental performance of alternative product systems for meeting the same end-use function, from a broad, societal perspective along their entire lifecycle. (Ferrão 2009)

The principles associated with LCA are defined in the ISO 14040 to 14049 norms, that define LCA has "*the compilation of entering and exiting flows and the environmental impact assessment associated with a product through its lifecycle"*; and lifecycle defined has "*the consecutive and connected states of a product, since material extraction or natural resource transformation, until final deposition of the product in nature"*.(Ferrão 2009)

As such, all processes causally connected to the physical lifecycle of the product, are activities that should be included when performing an LCA. These include the following stages: entire pre-usage supply chain, use with corresponding supply processes, and end-of-life with corresponding supply processes. The flows considered are mainly physical measurements, for example pollutants, mass and energy.(Norris 2001)

A typical methodology for a LCA is followed in this research: Firstly the objective and scope, where it is defined the functional unit, the system boundaries and main limitations and assumptions; Lifecycle Inventory, is the core of a LCA study, it is the collection of all inputs and outputs across the entire lifecycle of each powertrain; Impact Assessment, is the phase that analysis the ecologic and human impacts of the emissions identified during the inventory phase, it comprises the characterization/classification of the emissions in intermediary indicators, these indicators are then normalized, and finally aggregated into larger indicators; Interpretation is the final step where the obtained results are interpreted and a critical review of each step is done.(Institute for Environment and Sustainability 2010)

4.2. Objective, scope and methodology

The objective of this analysis is to produce a comparison between the lifecycle of a conventional Internal Combustion Engine Vehicle (ICEV) and a Battery Electric Vehicle (BEV) through all the lifecycle stages of the product (production, use and disposal). V2G is not a part of this study, because by definition a LCA compares two products or services that provide exactly the same utility and use the same functional unit. Therefore the comparison between an ICEV and a V2G BEV is not an acceptable approach because an ICEV cannot provide V2G. Such comparison should be made between V2G services provided by a BEV (or a group of BEV's) and "conventional" power services provided by, for example, a hydroelectric dam with pumping capability or a power plant. And this would go beyond the scope of this master thesis and so it is proposed as future work.

The author used SimaPro 7.3.2 software from PRé Consultants to perform the LCA of both powertrains and their comparison. This software has multiple databases built in. Here, the author adopted the Ecoinvent database because it is a very complete and available for the

European context. The Ecoinvent database provides a vast list of products and processes that occur since the extraction of the necessary raw materials to the production and use of the product, and finally its disposal.(Ferrão 2009)

For the evaluation of the environmental impacts associated with the production, use and disposal of the vehicle the Eco-indicator 99 was used, with a cut-off of 5%, meaning that all processes with an impact bellow 5% are not shown in the network trees. The eco-indicator 99 method was chosen because it is largely used in this sort of analysis and matches well the European context.

The eco-indicator 99 is a damage-oriented method for lifecycle impact assessment. Furthermore, it is both a science-based impact assessment method for LCA and a pragmatic ecodesign method. It offers a way to measure various environmental impacts, and shows the final result in a single score (PRé Consultants 2011). In this method, damage models were developed that link inventory results into three damage categories (endpoints in ISO terminology) (PRé Consultants 2011):

1. Damages to Human Health that are expressed in Disability Adjusted Life Years or DALY's. This method, developed by Murray, is used by the WHO and the World Bank. An important element is a scale that rates the different disability levels. Damage models have been developed for respiratory and carcinogenic effects, the effects of climate change, ozone layer depletion and ionizing radiation. In this model, four steps are used:
    i. Fate analysis, linking an emission (expressed as mass) to a temporary change in concentration;
    ii. Exposure analysis, linking this temporary concentration change to a dose;
    iii. Effect analysis, linking the dose to a number of health effects, such as occurrence and type of cancers; and
    iv. Damage analysis, links health effects to DALYs, using estimates of the number of Years Lived Disabled (YLD) and Years of Life Lost (YLL).
2. Damages to Ecosystem Quality that are expressed as the percentage of species disappeared in a certain area, due to the environmental load (Potentially Disappeared Fraction or PDF). The PDF is then multiplied by the area size and the time period to obtain the damage. Three indicators are part of this model:
    i. Ecotoxicity is expressed as the percentage of all species present in the environment living under toxic stress (Potentially Affected Fraction or PAF). As this is not an observable damage, a rather crude conversion factor is used to translate toxic stress into real observable damage, i.e. convert PAF into PDF;
    ii. Acidification and Eutrophication are treated as one single impact category. Damage to target species (vascular plants) in natural areas is modeled. Unfortunately the model was only available for the Netherlands, and it is not suitable to model phosphates;

    iii. Land use and land transformation is based on empirical data of occurrence of vascular plants as a function of land use types and area size. Both local damage on occupied or transformed area and regional damage on ecosystems are taken into account.

3. Damages to Resources that focus particularly in minerals and fossil fuels and are expressed as surplus energy for the future mining of resources. For minerals, geostatistical models are used that relate availability of a resource to its concentration. For fossil fuels surplus energy is based on the future use of oil shale and tar sands.

The most fundamental problem in LCA is that when value choices have to be made, a single truth simply does not exist. For example, a substance that is classified as "possible carcinogenic" can be seen as extremely dangerous by one person, whilst another would not be bothered at all. To deal with this problem, three different perspectives were developed(PRé Consultants 2011):

- In the default Hierarchist perspective, contribution of “Human Health” and “Ecosystem Quality” are 40% each. “Respiratory effects” and “Greenhouse effects” dominate “Human Health” damages, “Land use” dominates “Ecosystem Quality” and “Resources” are dominated by “Fossil fuels”. This perspective is the one used in the LCA study of this thesis.
- In the Egalitarian perspective, “Ecosystem Health” contributes 50% to the overall result. The relative contributions within the damage categories are about the same as in the Hierarchist perspective, except for carcinogenic substances. A Hierarchist would consider a substance as carcinogenic if sufficient scientific proof of a probable or possible carcinogenic effect is available;
- In the Individualist perspective, “Human Health” is by far the most important category. Carcinogenic substances however play virtually no role. The individualist would only include those substances for which the carcinogenic effect is fully proven. The Individualists would also not accept (based on experience) that there is danger fossil fuels can be depleted and therefore this category is left out. For this reason Minerals become quite important.

In this evaluation and in order to be able to, on a later time, use these results with other analysis, the full assembly of the vehicle is taken into account. So all raw materials are accounted for, transport of these materials, energy and processes to make, use and dispose of a vehicle are accounted. The following diagram illustrates the generic lifecycle stages applicable to both powertrain lifecycles.

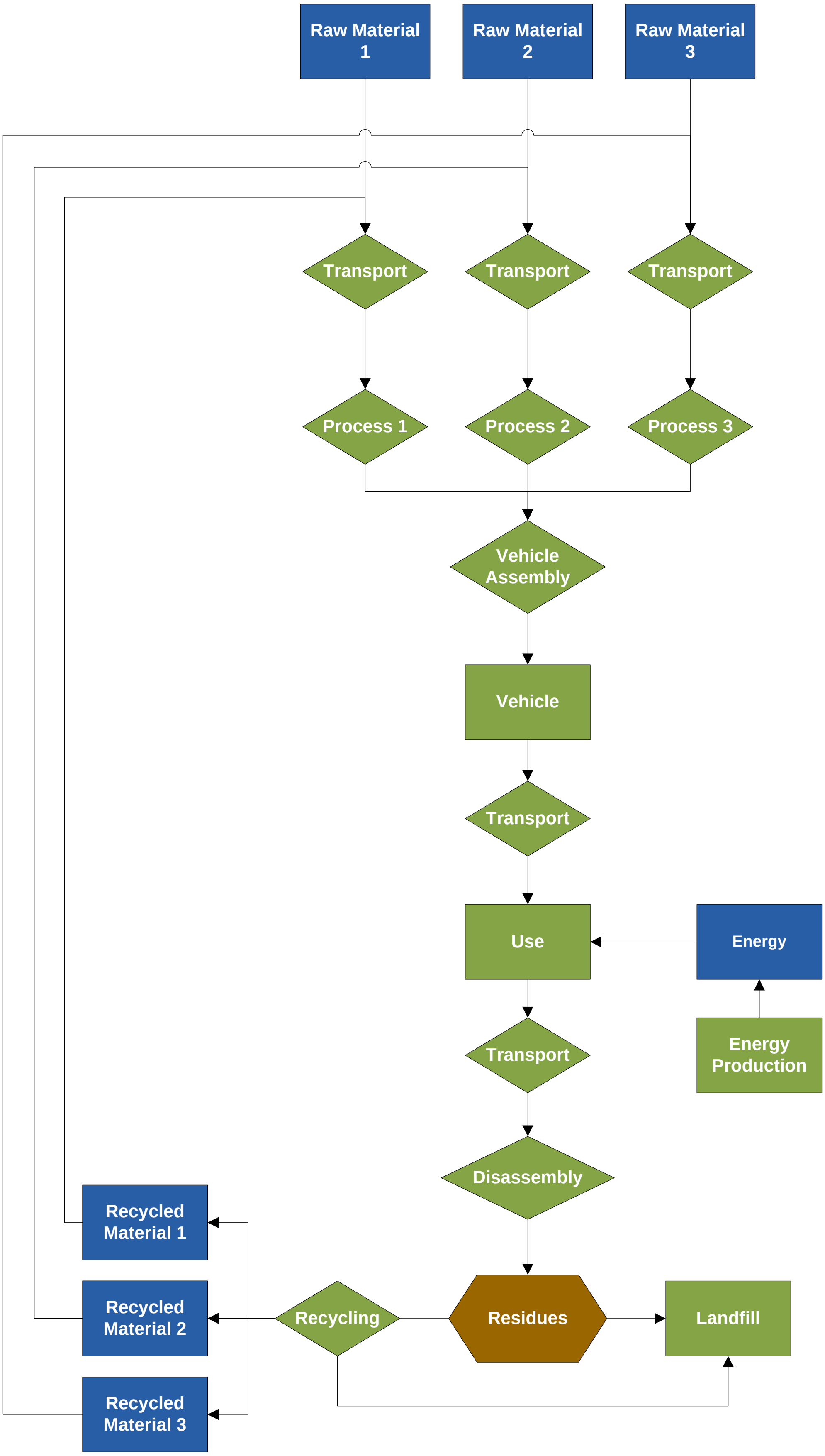


Figure 12 – General lifecycle stages assessed on this research for a vehicle (source: author)

The next step was to collect the data required to build the Lifecycle Inventory for the BEV and the ICEV. In short, collect the material and energy inputs for vehicle and battery production. The objective is to compare the powertrains of two different vehicles: as described in the LCC before, the VW Golf and the Nissan Leaf. As this information is not easily available, contacts with the brands to obtain this information were made. However both companies were reluctant to provide the required data. This required a new approach to the problem.

The Ecoinvent database (Swiss Centre for Life Cycle Inventories 2007) has a process of production of a generic VW Golf (though of an older model), and Volkswagen (VW) published a basic LCA on its TSI engines (Volkswagen Group Research - Environment Affairs Product 2009), that includes the powertrain assessed in the LCC, since these are the most efficient. These sources provided some of the necessary information. The ICEV production used is the process for the production of a VW Golf on the Ecoinvent database. Assuming that BEV are similar to ICEV, except for the internal combustion engine that is replaced by an electric motor and has a larger battery, the author subtracted the material input of the TSI 1.2L engine to the VW Golf on the Ecoinvent database, giving an approximation of the processes and material flows involved in the production of a vehicle excluding the powertrain parts and components. The material flows and processes involved in the production of an electric motor were added to this basis, based on (De Almeida et al. 2008; Bloomfield 2001b). With respect to the overall lifecycle analysis of the BEV, it is considered the use of two batteries over the service time because a BEV would require two batteries for 300.000 km life service (see the LCC analysis for more information).

Acknowledging that this approach implies imprecision when compared to a complete and accurate LCI, this was the information that was available for this work, and it is the author belief that it will give a reliable comparison between the two. The production stage has a smaller contribution in the total LCA than the use stage, as discussed later in this dissertation.

Nissan did not share the information on batteries and so other sources of information had to be used. The data for the batteries was taken from (Zackrisson et al. 2010). Moreover, the battery model assessed here is not currently being produced, since it is still in development. The author modeled the battery based on (Zackrisson et al. 2010) to match the power output of the Nissan Leaf and thus obtaining a lighter battery when compared to the Leaf’s battery pack. This meant that another source of imprecision is added to the analysis.

For the use stage, the author used the same assumptions, values and data from the LCC analysis performed before:

- 300.000 km of service time (our functional unit being km for the use stage) and corresponding energy consumption (the same energy consumption values were used, not accounting for different type of driving styles and situations); and

- No vehicle maintenance is assessed (beside battery substitution in the BEV) since no reliable information is available up to today. Although it was assumed a 25% cost reduction compared to the standard ICEV, in the LCC analysis, here, the author won't follow the same approach because BEV's maintenance may involve other types of materials and processes that cannot be approximated using the same proportion.

The automotive industry has high recycling ratios and therefore the author modeled the recycling processes both the ICEV and BEV disposals, although the batteries of the BEV presented some difficulties in this sense. Currently the technology to recycle lithium-ion batteries is at its early stage, particularly the type of lithium-ion cell used ($LiFePO_4$) that is still in study and far from commercial use (Zackrisson et al. 2010). Automakers that are currently producing BEV's argue that between now and the moment BEVs will require recycling, there is enough time for a scientific breakthrough in battery recycling, even suggesting that, if necessary, they would store the used batteries until the technology would catch up and also building up enough material stock for promoting investments in large recycling facilities. In this study, battery recycling will not be considered. It is the author belief that today's processes are far from characterizing a recycling process in 10 to 20 years time, besides the existing processes are shrouded in non public patents that complicate the characterization of the processes involved. Batteries' lifecycle are treated separately lifecycle from the overall BEV's LCA and, therefore, when data for recycling will become publicly available and tested, the battery LCA can be easily updated. It is also the author opinion that it is preferable to have an over estimation of the BEV's LCA than to have an artificially estimation with potentially high bias from true values.

4.3. Lifecycle Inventory

In this section, a description of the collected and compiled information for the lifecycle inventories, separately for the ICEV and for the BEV.

4.3.1. Internal Combustion Engine Vehicle Lifecycle Inventory

As discussed previously, the lifecycle of an ICEV (and most products) can be divided into three main stages: production, use and disposal.

Production stage

In terms of production of an ICEV vehicle, a contact with VW to obtain the necessary information on the materials and energy required for the production of a 1.2 TSI VW Golf vehicle was made. However, it is VW policy not to share this information even under a possible confidentiality agreement. Alternatively, the author used Ecoinvent database in SimaPro that has a process "Passenger car /RER/I" that characterizes the production of a VW Golf MK4 (1999), acknowledging that this is an older model of the VW Golf and, as such, accepting some bias to current VW Golf 1.2 TSI.

The “Passenger car /RER/I” process includes material, energy and water use in vehicle manufacturing. Rail and road transport of materials is also accounted for and finally plant infrastructure is also used, namely issues related to land use, building, road and parking construction. This data reflects the production in the European context (Swiss Centre for Life Cycle Inventories 2007). The following table shows the inputs for the production of ICEV.

Table 14 - Energy and material inputs for ICEV vehicle production (source:(Swiss Centre for Life Cycle Inventories 2007)**).**

Material	Quantity	Unit
Aluminum, production mix, at plant/RER U	51.8	kg
Flat glass, uncoated, at plant/RER U	30.1	kg
Alkyd paint, white, 60% in solvent, at plant/RER U	4.2	kg
Heat, natural gas, at industrial furnace >100kW/RER U	2220.0	MJ
Electricity, medium voltage, production UCTE, at grid/UCTE U	2140.0	kWh
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER U	63.0	MJ
Tap water, at user/RER U	3220.0	kg
Transport, lorry >16t, fleet average/RER U	53.0	tkm
Transport, freight, rail/RER U	530.0	tkm
Road vehicle plant/RER/I U	2.91E-07	p
Wire drawing, copper/RER U	10.1	kg
Copper, at regional storage/RER U	10.1	kg
Chromium, at regional storage/RER U	2.4	kg
Nickel, 99.5%, at plant/GLO U	1.4	kg
Platinum, at regional storage/RER U	0.0	kg
Palladium, at regional storage/RER U	0.0	kg
Zinc, primary, at regional storage/RER U	5.9	kg
Lead, at regional storage/RER U	13.0	kg
Ethylene glycol, at plant/RER U	4.8	kg
Ethylene, average, at plant/RER U	18.5	kg
Sulphuric acid, liquid, at plant/RER U	0.8	kg
Polyethylene, HDPE, granulate, at plant/RER U	102.0	kg
Polypropylene, granulate, at plant/RER U	49.0	kg
Polyvinylchloride, at regional storage/RER U	16.0	kg
Synthetic rubber, at plant/RER U	44.1	kg
Steel, low-alloyed, at plant/RER U	99.0	kg
Reinforcing steel, at plant/RER U	891.0	kg
Sheet rolling, steel/RER U	541.0	kg
Section bar rolling, steel/RER U	203.0	kg

Emissions involved in the vehicle’s production stages were estimated using the following factors from the Ecoinvent database (Swiss Centre for Life Cycle Inventories 2007):

Table 15 – Emission outputs for ICEV vehicle production (source: (Swiss Centre for Life Cycle Inventories 2007)**).**

Emissions	Quantity	Unit
Emissions to Air		
NMVOC, non-methane volatile organic compounds, unspecified origin	4.8	kg
Heat, waste	7700	MJ
Emissions to water – river sub-compartment		
COD, Chemical Oxygen Demand	0.193	kg
BOD5, Biological Oxygen Demand	0.026	kg
Phosphate	0.001	kg

The production stage is ended with the transport of the vehicle from Germany (production location) to Portugal, considering the corresponding Ecoinvent process “Transport, lorry 16-32t, EURO5/RER U” for 5400 tkm of materials that correspond to 2 tonnes of vehicle weight transported over 2700 km, approximately.

Use Stage

This part of the vehicle lifecycle is considered to be the most important because it is when the main differences in environmental impacts occur. As mentioned, only the energy necessary for vehicle motion is accounted for on both ICEV and BEV analysis because the BEV maintenance is still unknown to a large extent. Therefore, the author judged preferable not to assess the vehicle’s maintenance here, considering also that, this stage would have only a marginal impact in the overall LCA..

The calculation for energy/fuel requirements to produce the functional unit of 300.000 km in its lifecycle is calculated using the process “Operation, passenger car, petrol, EURO5/CH U”. This process includes fuel consumption, direct airborne emissions of gaseous substances, particulate matters and heavy metals and also heavy metal emissions to soil and water caused by tire abrasion. This process characterizes the operation of a Euro 5 vehicle (Euro 5 is the level in the European Emission Standard, 5 being the best rank a vehicle can have), where the 1.2 TSI Golf is included. The data on this process refers to conditions in Switzerland (Swiss Centre for Life Cycle Inventories 2007).

Disposal stage

The disposal stage comprises the processes that products go through after their use is completed and are not providing the service for which they were devised. Whether due to malfunctioning or substitution, every product comes to a point when it has to be disposed of. A description hereafter some possible ways to dispose of an end-life-vehicle (Tchobanoglous et al. 1993):

- The simplest way is to waste the entire vehicle by sending it to landfill. This possibility is prohibited by law, not only for residue/environmental reasons, but also safety (airbag explosion, for example);

- Valorization is the process of attributing value to the residues, in particular three should be highlighted:
    - *Reutilization* is a process that enables the end-life-vehicle or its parts to recover its original use. In this case, it corresponds to fixing the vehicle in a way that it is reusable on the road again, or by reutilization of vehicle parts and components in other vehicles.
    - *Recycling* corresponds to processing the vehicle materials in order to obtain like-new materials and manufacture new products, avoiding the consumption of raw materials, which might reduce the amount of energy consumption and pollution required (depending on the material and recycling processes).
    - *Energetic valorization* corresponds to producing energy, usually electricity, by burning the inflammable residues of the vehicle, and using the corresponding thermal energy for industrial purposes.

Here, it is only considered recycling and/or subsequent landfill disposal (i.e., those materials not prone to recycling anymore). Recyclable materials addressed are:

- Steel and iron materials;
- Aluminum;
- PE (polyethylene);
- PP (polypropylene);
- PVC (polyvinylchloride);
- Glass.

The energy and/or material input in the recycling processes are based on SimaPro project BUWAL250 database. This process characterizes the recycling for each material group assessed. The Ecoinvent database was not used because the corresponding recycling processes are not available. Alternatively, the processes in BUWAL250 were adapted for application to the present analysis. Other materials and products are considered t be disposed in landfill (engine oil, and other fluids and parts are not considered).

The percentage of recycled materials is based on the Portuguese regulation, specifically in Decreto-Lei n. º 196/2003 (Assembleia da República 2003), updated in the Decreto-Lei n. º 64/2008 (Assembleia da República 2008). This regulation dictates that by January 1st of 2015, recycling of an end-life-vehicle must average 85% of the vehicle's weight every year. Instead of using default recycling percentages of BUWAL250, an 85% recycling ratio on all recyclable materials was used, assuming that the vehicle will last 15 years. All the remaining 15% materials are considered to be disposed in landfill. (Ferrão & Figueiredo 2000)

4.3.2. Battery Electric Vehicle Lifecycle Inventory

BEV is assessed for the same main lifecycle stages and the, corresponding Lifecycle Inventory is produced accordingly. The author assumes the same values for the disposal stage as in

ICEV, except for the batteries, which are analyzed in the use stage. Electric engine components are recycled in the same categories has in the ICEV, as being a part of the vehicle.

Production stage

In order to describe the production stage of the BEV (and due to the reluctance of Nissan to share the information required) a different approach was necessary. Instead of building the inventory from scratch, the author considered that a BEV is the same as an ICEV, but instead of an internal combustion engine, it has an electric engine (and adding a battery, that is considered in the use stage). The approach was to subtract the lifecycle inventory of materials for the 1.2 TSI engine (Volkswagen Group Research - Environment Affairs Product 2009) to the process used for the ICEV ("Passenger car /RER/I"). The referred project does not provide the detailed materials information but rather aggregates them in material groups. Since the author does not consider the energy for the production of the engine, it is assumed that the amount of energy for internal combustion engine production is equal to the energy needed for electric engine production. The following graphic shows the composition of the engines assessed on the lifecycle study produced by VW on their TSI engines(Volkswagen Group Research - Environment Affairs Product 2009):

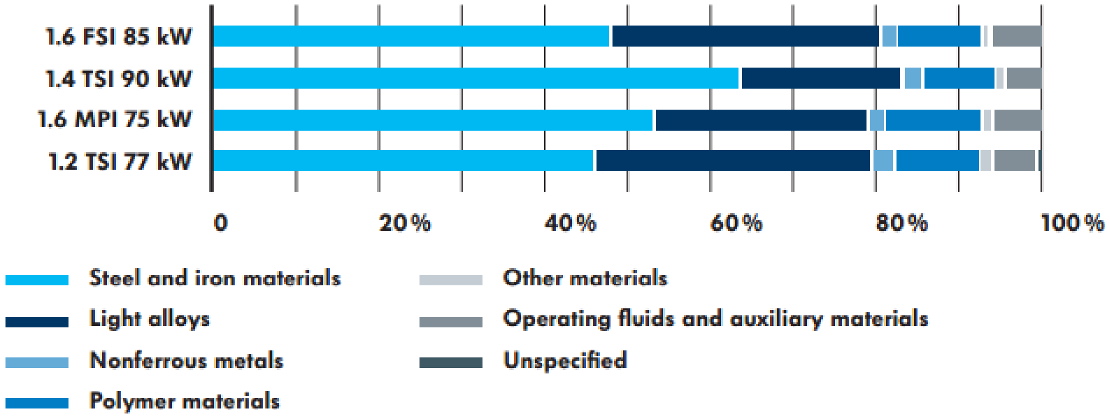


Figure 13 - Material composition of VW internal combustion engines (source:(Volkswagen Group Research - Environment Affairs Product 2009)**).**

Estimating the inventory for the vehicle's production stage without the engine by assuming that the engine has the same material percent-distribution has the entire vehicle. Thereafter, it is added the assembly stage of the electric engine to the lifecycle inventory of the "vehicle without powertrain".

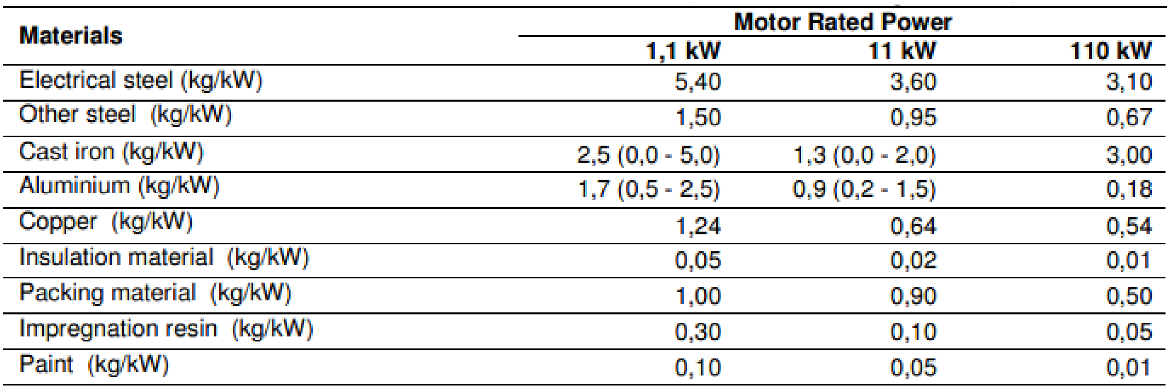
Table 16 - Energy and material inputs for "vehicle with no powertrain" production (source: author).

Material	Quantity	Unit
Aluminium, production mix, at plant/RER U	21.1	kg
Flat glass, uncoated, at plant/RER U	30.1	kg
Alkyd paint, white, 60% in solvent, at plant/RER U	4.2	kg
Heat, natural gas, at industrial furnace >100kW/RER U	2220.0	MJ
Electricity, medium voltage, production UCTE, at grid/UCTE U	2140.0	kWh
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER U	63.0	MJ
Tap water, at user/RER U	3220.0	kg
Transport, lorry >16t, fleet average/RER U	53.0	tkm
Transport, freight, rail/RER U	530.0	tkm
Road vehicle plant/RER/I U	0.0	p
Wire drawing, copper/RER U	9.4	kg
Copper, at regional storage/RER U	9.4	kg
Chromium, at regional storage/RER U	2.2	kg
Nickel, 99.5%, at plant/GLO U	1.3	kg
Platinum, at regional storage/RER U	0.0	kg
Palladium, at regional storage/RER U	0.0	kg
Zinc, primary, at regional storage/RER U	5.5	kg
Lead, at regional storage/RER U	12.2	kg
Ethylene glycol, at plant/RER U	0.0	kg
Ethylene, average, at plant/RER U	16.7	kg
Sulphuric acid, liquid, at plant/RER U	0.7	kg
Polyethylene, HDPE, granulate, at plant/RER U	97.5	kg
Polypropylene, granulate, at plant/RER U	46.8	kg
Polyvinylchloride, at regional storage/RER U	15.3	kg
Synthetic rubber, at plant/RER U	42.2	kg
Steel, low-alloyed, at plant/RER U	96.6	kg
Reinforcing steel, at plant/RER U	869.0	kg
Sheet rolling, steel/RER U	527.7	kg
Section bar rolling, steel/RER U	198.0	kg

Regarding the production stage, it is considered the same emissions estimated for the ICEV.

In order to obtain data on the material inputs necessary for the electric engine production, the following table was used (De Almeida et al. 2008):

Table 17 - Data for material input in electric motor production (source: (De Almeida et al. 2008)**)**



Materials	Motor Rated Power		
	1,1 kW	**11 kW**	**110 kW**
Electrical steel (kg/kW)	5,40	3,60	3,10
Other steel (kg/kW)	1,50	0,95	0,67
Cast iron (kg/kW)	2,5 (0,0 - 5,0)	1,3 (0,0 - 2,0)	3,00
Aluminium (kg/kW)	1,7 (0,5 - 2,5)	0,9 (0,2 - 1,5)	0,18
Copper (kg/kW)	1,24	0,64	0,54
Insulation material (kg/kW)	0,05	0,02	0,01
Packing material (kg/kW)	1,00	0,90	0,50
Impregnation resin (kg/kW)	0,30	0,10	0,05
Paint (kg/kW)	0,10	0,05	0,01

Based on this data the materials input for a motor rated power of 80 kW was obtained. Importantly, the author refer that in (De Almeida et al. 2008) the electric motors assessed are industrial type of motors and therefore their construction is based on the deliverance of the motor rated power (in this case 80 kW) continuously, giving a motor total weight of about 650 kg. The main difference between these types of industrial motors and the ones that could be found in an BEV is that a vehicle motor has a highly variable power output, according to the needs of the driver (varying from a few kW to a maximum of 80 kW), while an industrial type of motor is required to have the same power output continuously (continuous 80 kW). So utilizing a 650 kg motor in this analysis is not a reasonable approach. Estimating that the Nissan Leaf's motor weights about 100 kg the amount of materials required for the production of this 100 kg electric motor is obtained.

The author recognizes that this approach adds more uncertainty to the LCI than if it was built from scratch. Still, time and study scope constrains do not allow to do it any other way.

The production stage is ended with the transport of the vehicle from Germany (considered the production location) to Portugal. This is considered through the process "Transport, lorry 16-32t, EURO5/RER U" for 5400 tkm (2 t vehicle transported over 2700 km).

Use Stage

Regarding the use stage of a BEV, this life stage can be divided into two parts – energy input and batteries.

The energy section of the use stage for the BEV, is simply comprised with the electricity consumption of the vehicle, which has already been accounted in the LCC for a total of 50400kWh. The electricity input used in SimaPro is an adapted process from the Ecoinvent database, because the Portuguese electricity mix wasn't up to date. So to give a reliable electricity input (very important due to its impact on the total LCA of the BEV) the author updated the Ecoinvent process "Electricity mix/PT U" to the Portuguese electricity mix for 2009 based on the data from DGEG. This mix is considered to be static along the service time of the vehicle. This electricity mix is then updated through high voltage, medium voltage and low voltage (to account for energy transport to the vehicle and its corresponding energy losses), arriving to a process of production of one kWh in Portugal upgraded to the year 2009 in low voltage at grid “Electricity, low voltage, at grid/PT U Upgrade 2009”.

Now focusing on the required batteries, BEV will require 2 units for a 300.000 km lifetime service mileage (see LCC for more details). Therefore, the impacts of the production and disposal stages of those batteries must be accounted for. Next is it described the production process of one battery.

The production of a single BEV battery is a complex process. Data for cell production is taken from (Zackrisson et al. 2010), where the material input for the production of one cell, using water as solvent is shown in the following table:

Table 18 - Cell configuration (adapted:(Zackrisson et al. 2010)**).**

Part of cell	Material	Weight (g)
Cathode	LiFePO4	422
Cathode	Aluminum foil	19
Cathode	Carbon black	27
Cathode	PVDF	0
Cathode	Styrene acrylate latex	35
Electrolyte	Ethylene glycol dimethyl ether	157
Electrolyte	Lithium salt (Lithium chloride)	28
Separator	Polypropylene	9
Separator	Polyethylene	9
Electronics	Transistor	10
Electronics	Resistor	10
Anode	Graphite	169
Anode	Carbon black	5
Anode	Copper	46
Anode	PVDF	0
Anode	Styrene butadiene latex	6
Packaging	Polypropylene	5
Packaging	Aluminum foil	7
TOTAL (g)		**964**

The Ecoinvent database (nor any other) offered the element $LiFePO_4$ in their input materials, so it had to be created according to the manufacturing process described in (Zackrisson et al. 2010), yielding the necessary materials and energy to produce a gram of $LiFePO_4$.

Table 19 – Material and energy input for production of one gram of $LiFePO_4$ (source:(Zackrisson et al. 2010)**)**

Material	Quantity	Unit
Graphite, at plant/RER U	0.02	g
Ferrite, at plant/GLO U	0.5	g
Diammonium phosphate, as N, at regional storehouse/RER U	0.84	g
Lithium carbonate, at plant/GLO U	0.23	g
Electricity mix/DE U	3	kJ

In (Zackrisson et al. 2010), the battery assessed is composed by 10 cells per module and 10 modules. Hence, a 10 kWh battery requires 100 cells and, altogether, weighs about 107 kg (plus 10 kg for battery packaging and electronics). The Nissan Leaf battery pack has a different type of lithium cell (with less kWh/kg capacity), with 4 cells per module and 48 modules per battery, giving a 24 kWh battery capacity weighting about 300 kg (270 kg of battery plus 30 kg on packaging and electronics)(Nissan 2011). This said, producing the Leaf's 24 kWh battery with the $LiFePO_4$ and assuming the data from (Zackrisson et al. 2010), will require 10 cells per module and 24 modules, (corresponding to 24 kWh capacity) that weigh about 261 kg - 231 kg plus 30 kg of packaging (polypropylene) and electronics (transistors).

Table 20 - Battery characterization (source: author).

	Cells per module	Modules per battery	Number of cells	kg of cells	Packaging + Electronics	Total (kg)	kWh
Leaf battery	4	48	192	270.0	30	300.0	24
Battery (Zackrisson et al. 2010)	10	10	100	96.4	10.7	107.1	10
Theoretical Battery	10	24	240	231.4	30	261.4	24

In terms of energy requirements for the production of a battery, again (Zackrisson et al. 2010) gives an estimate of about 11.7 kWh of electricity (German mix used) and 8.8 kWh of natural gas per kg of lithium-ion battery. All of the assumptions made by Zackrisson were verified by the author in other battery LCA studies (Majeau-Bettez et al. 2011) and the process in the ecoinvent database for obtaining the lithium carbonate ore was confirmed in (Stamp et al. 2012).

In terms of battery final destination, given that recycling technology for $LiFePO_4$ batteries is not yet commercially available, and that the processes of recycling batteries are still in early stages, this work considers a scenario where there is no battery recycling – accounting only for transport of the battery to landfill, which is considered to be a transport by lorry of 300 kg of battery for 20 km, giving a 6 tkm input. This extreme scenario is chosen to give the reader an over estimation of the total LCA of a battery, so that this analysis is not biased in favor of any powertrain.

4.4. Impact Assessment and Interpretation

This subchapter contains the main results of the LCA obtained from SimaPro, regarding the ICEV and BEV, ending with a comparison analysis between both alternatives. This chapter comprises both the impact assessment and interpretation phases of a typical LCA. The reader is reminded that in this LCA, the Eco-indicator 99 with the Hierarchist perspective was used.

The results are shown according to a scheme: First the network tree, where the processes The yellow box illustrates the entire lifecycle process. The blue boxes symbolize assemblies, the grey ones are processes present in the database, the red boxes indicate disposal scenarios and green boxes symbolize reutilization. The connecting red lines correspond to environmental impacts (thicker represents bigger impacts) and the green lines correspond to avoided environmental impacts. The second result corresponds to the characterization step, where the emissions identified in the LCI are gathered in several categories, and this result in a graph giving the contributions of each life stage in the different impact categories (in percentage). The third result shown in this work is the weighing/normalization step, this permit to obtain a relation between different impact categories, the normalization factors utilized correspond the average European contribute to each environmental theme. Fourth and final result gives the impact for each life stage in terms aggregated in the three main impact indicators (human health, ecosystem quality and resources).

4.4.1. Results for the Internal Combustion Engine Vehicle

Figure 14 represents the network tree characterizing the lifecycle of the assessed ICEV, followed by the Classification/Characterization of the LCA in Figure 15, Normalization/Weighing step on Figure 16, and finally the total contribution of each life stage to the total lifecycle aggregated in the main impact categories, Figure 17 and Table 21.

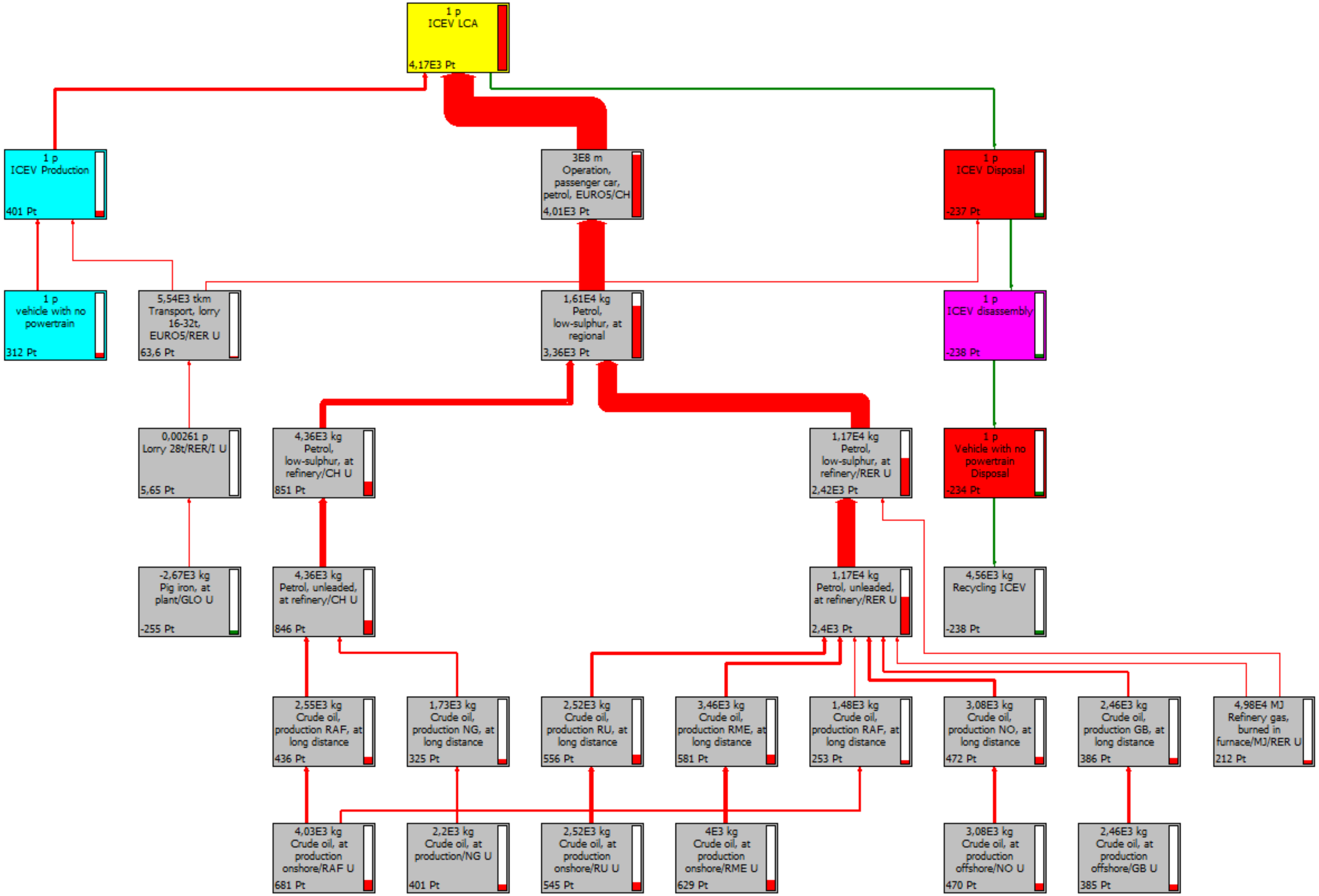


Figure 14 - ICEV LCA network tree with a 5% cut-off (source: author)

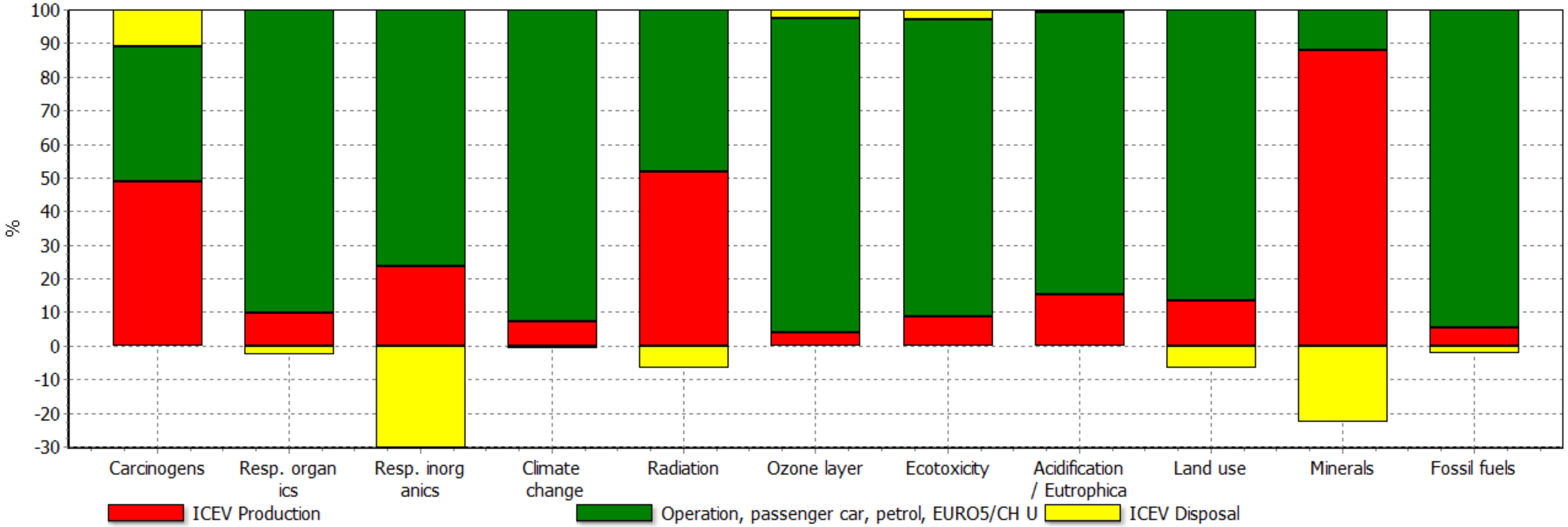


Figure 15 - Lifecycle assessment of the ICEV - Characterization Step (source: author).

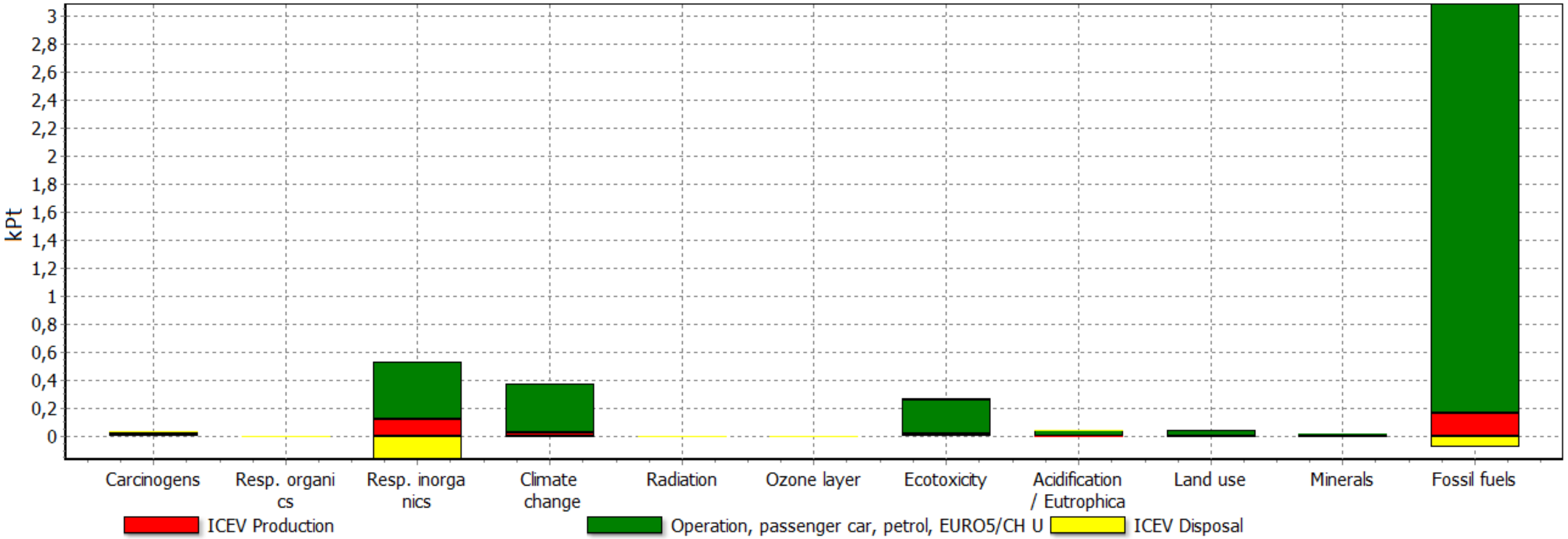


Figure 16 - Lifecycle assessment of the ICEV - Weighing Step (source: author).

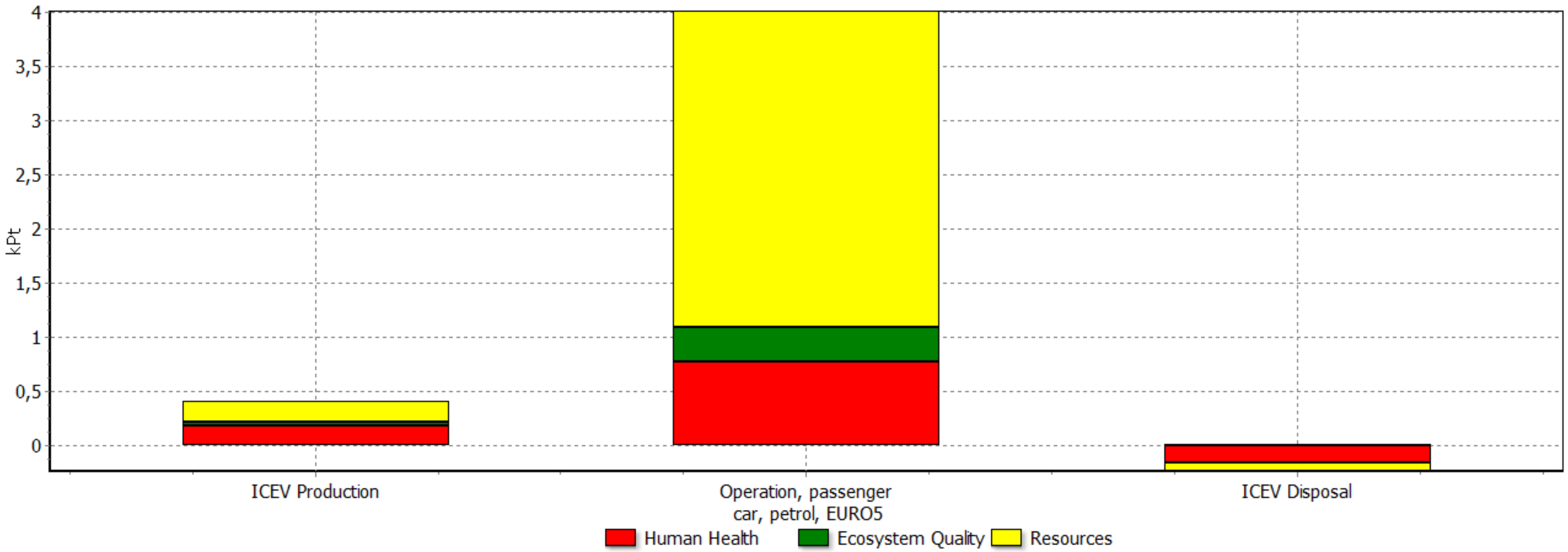


Figure 17 - Contribution of each life stage on the total lifecycle of ICEV (Eco-indicator 99) (source: author).

Table 21- Contribution of each life stage in the total lifecycle of an ICEV (units: Ecopoints; Eco-indicator 99) (source: author).

Category	**ICEV Production**	**Operation, passenger car, petrol, Euro5**	**ICEV Disposal**	**Total**
Human Health	174 *(4.2 %)*	773 *(18.5%)*	-161 *(-3.7%)*	786 *(18.8%)*
Ecosystem Quality	37 *(0.9%)*	317 *(7.6%)*	4.93 *(0.1%)*	359 *(8.6%)*
Resources	189 *(4.5%)*	2920 *(70%)*	-81.1 *(-1.9%)*	3030 *(72.6%)*
Total	401 *(9.6%)*	4010 *(96.1%)*	-237 *(-5.7%)*	4170 *(100%)*

As presented in the above figures and tables, the lifecycle of the ICEV was graded 4170 Pt (ecopoints) of which:

a) The Production stage has 401 Pt, (10% of the total impact);
b) The Disposal stage has -237 Pt (- 6% of the total impact), meaning that it contributes negatively to the overall impact; and
c) The Use stage that includes energy consumption only and is the largest responsible for the overall environmental impact of the vehicle, amounting to 4010 Pt, i.e., 96% of total impact).

During the production and operation stages, Resources extraction and consumption hold the greatest impact followed by impacts on Human Health. The disposal stage is characterized by an impact on Ecosystem Quality, and impact reductions on the remaining categories, due to the high levels of materials recycling of automobiles. Overall, Resources is the impact category with the highest environmental impact (72.6%), followed by Human Health (18.8%) and Ecosystem Quality (8.6%).

In most intermediary indicators, it can be observed that car use (‘Operation’) is the main responsible for environmental impacts. There are however a few exceptions. In Carcinogens and Radiation, Production holds about half of the impacts and in Minerals, the main contributor is the vehicle Production tool, being responsible for about 87% of the total impact in this category. The intermediary indicator with the biggest impact is Fossil fuels, followed by Respiratory Inorganics and Climate Change though these present 8-fold smaller contributions when compared with Fossil Fuels (by a factor of 8). The main responsible for these results is the gasoline production, use and respective emissions.

4.4.2.Results for the Battery Electric Vehicle

The following figures and tables characterize the lifecycle of a BEV, and follow the same scheme for presenting the results as used before.

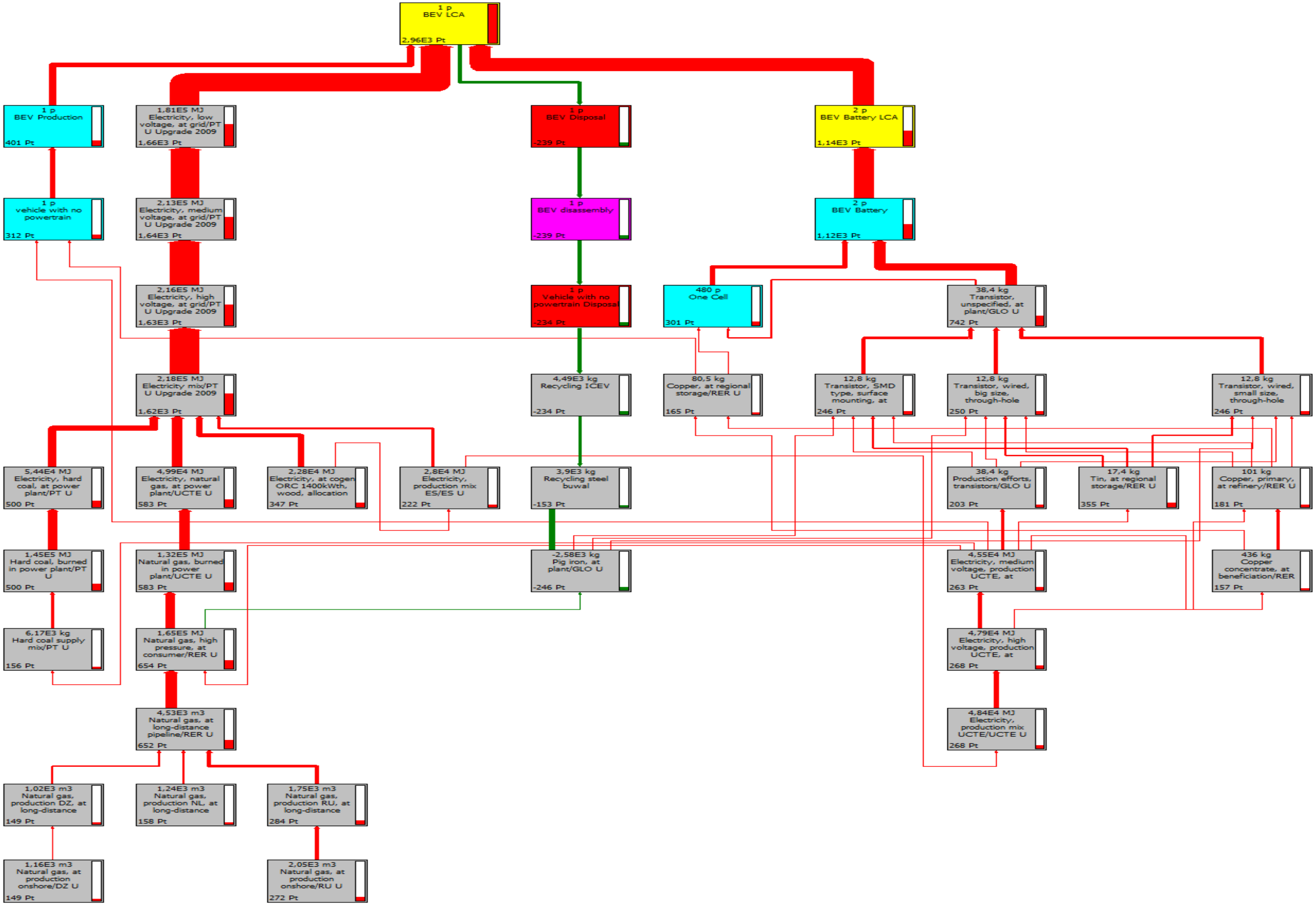


Figure 18 - BEV LCA network tree with a 5% cut-off (source: author).

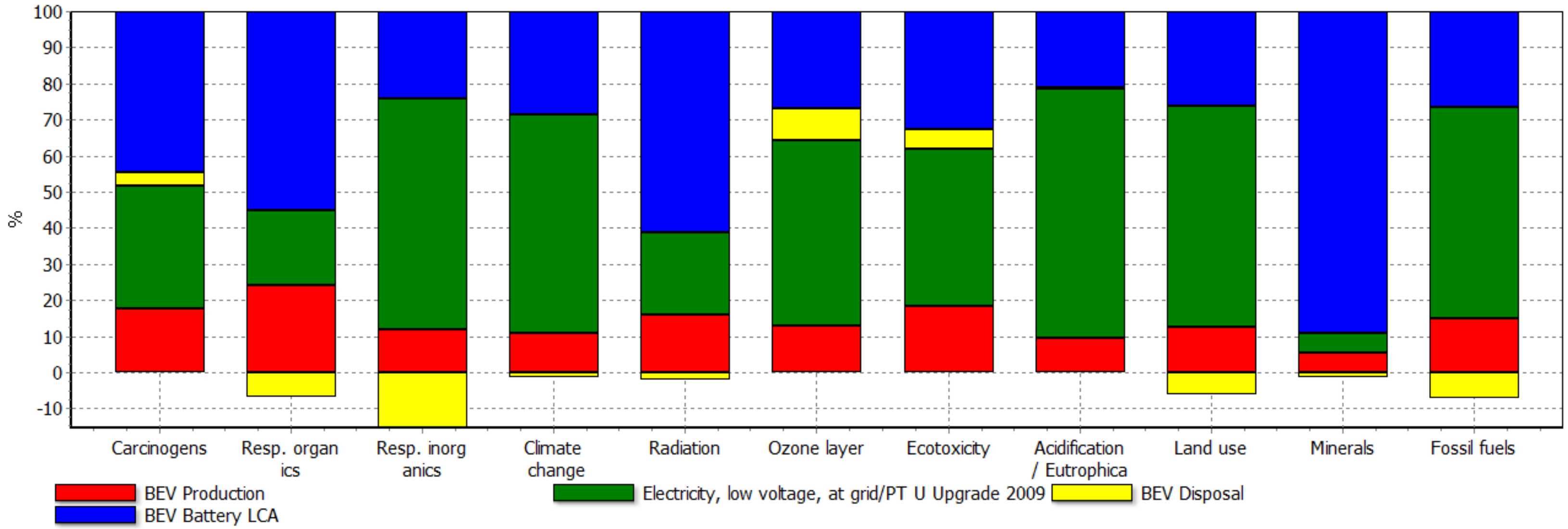


Figure 19 - Lifecycle assessment of the BEV - Characterization Step (source: author).

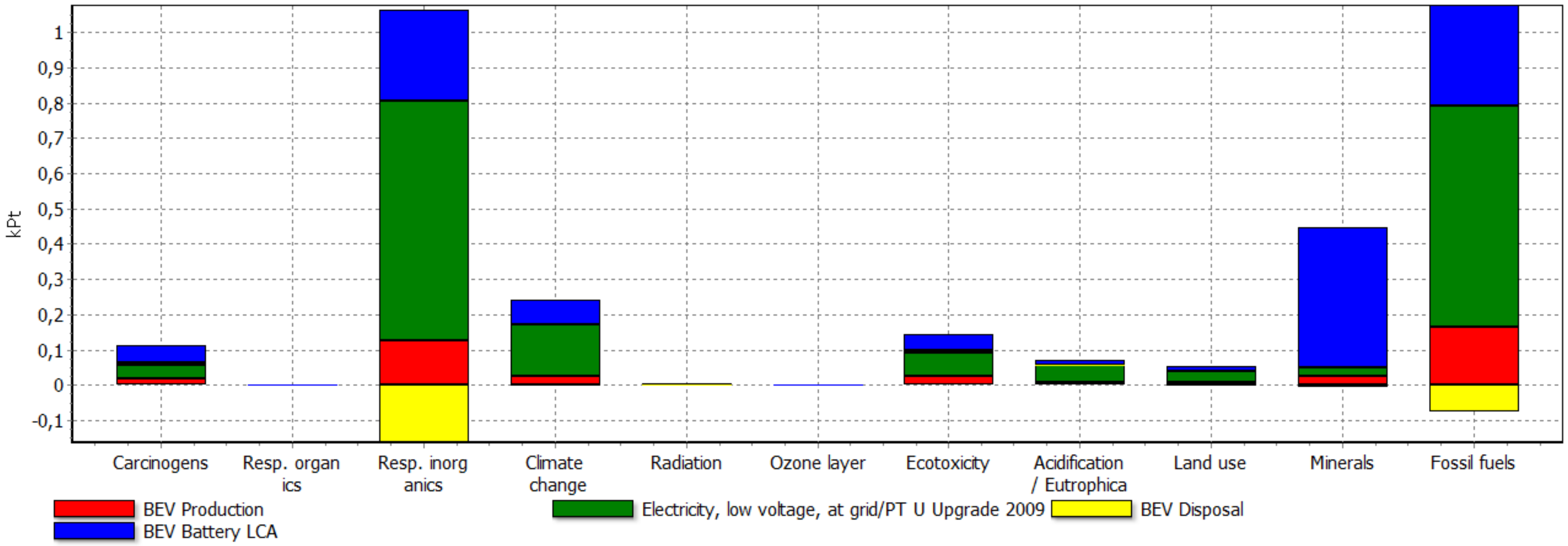


Figure 20- Lifecycle assessment of the BEV - Weighing Step (source: author).

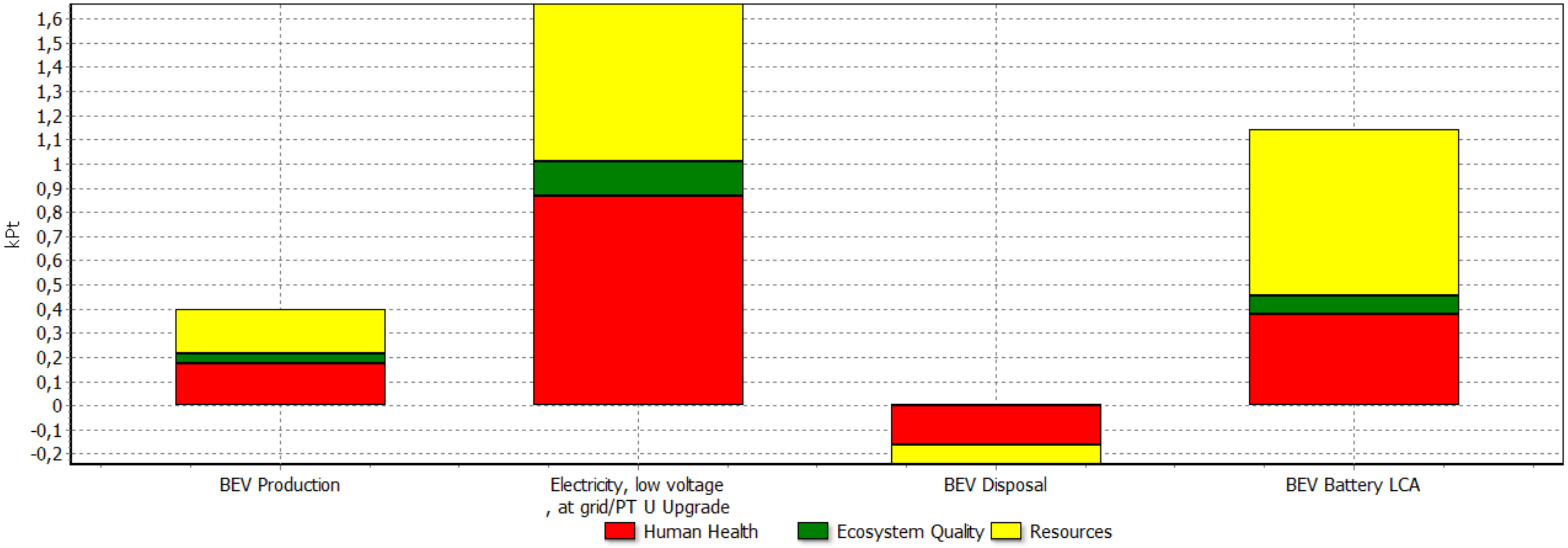


Figure 21 - Contribution of each life stage in the total lifecycle of the BEV (Eco-indicator 99) (source: author).

Table 22 - Values of the contribution of each life stage in the total lifecycle of BEV (units: Ecopoints; Eco-indicator 99) (source: author).

Category	Production	Electricity, low voltage, at grid/PT U Upgrade 2009	Disposal	Battery LCA	Total
Human Health	174 *(5.9%)*	866 *(29.2%)*	-162 *(-5.5%)*	380 *(12.8%)*	1260 *(42.6%)*
Ecosystem Quality	40 *(1.3%)*	144 *(4.9%)*	4.96 *(0.1%)*	75.8 *(2.5%)*	265 *(8.9%)*
Resources	187 *(6.3%)*	653 *(22.0%)*	-81.6 *(-2.7%)*	684 *(23.1%)*	1440 *(48.6%)*
Total	401 *(13.5%)*	1660 *(56.0%)*	-239 *(-8.1%)*	1140 *(38.5%)*	2960 *(100%)*

Figures and table above present the lifecycle ecopoints of a BEV that amount to 2960 Pt where:

a) The Production stage accounts for 401 Pt , i.e. 13.5% of the total impact;
b) The Use stage accounts for 1660 Pt , i.e. 56% of the total impact (again, energy consumption is the largest responsible on the environmental impact of the vehicle);
c) The Disposal stage with -239 Pt , i.e. -8% of total impacts; and
d) The Battery total LCA (which is shown on section 4.4.3) that amounts to 1140 Pt and a 38.5% contribution.

The production stage main impact category is Resources with 6.3% of the total impact, followed by Human Health (5.9%); the operation (energy) stage is the largest contributor, and its main intermediary indicators are Human Health with 29.2% followed by Resources with 22%; in the disposal phase there is a small impact on Ecosystem Quality (0.1%) and impact reductions on the remaining categories; finally the battery LCA main impact category is Resources with 48.6%, then Human Health, 42.6%, and Ecosystem Quality with about 9%.

In the intermediary indicators, it is observed that Operation and/or Battery LCA are the main responsible for the environmental impact. The main responsible for the environmental impact is again Fossil Fuels though almost with the same weight as the Respiratory Inorganics indicator, followed by a mentionable Minerals impact. On Fossil Fuels and Resp. Inorganics categories the main responsible for the impact is electricity production; in detail the Fossil fuel indicator major responsible is energy production from natural gas, and on Respiratory inorganics the emission on electricity production of particulates with less than 2.5 µm. The indicator Minerals the larger accountable impact is from the battery production stage, particularly the production and extraction of Tin and Copper.

If battery-recycling processes were considered in this analysis the total LCA impact of the batteries would be lowered and therefore the BEV total environmental impact would also be reduced.

4.4.3.Battery LCA

The batteries are a crucial element in a BEV, and has seen in the previous section are responsible for a considerable amount of the environmental impact of this type of powertrain, therefore, the author believes that their impact assessment should be also shown. As before the same graphs and tables are shown, this analysis comprises the production and disposal of one battery (has the use phase is accounted in the vehicle LCA).

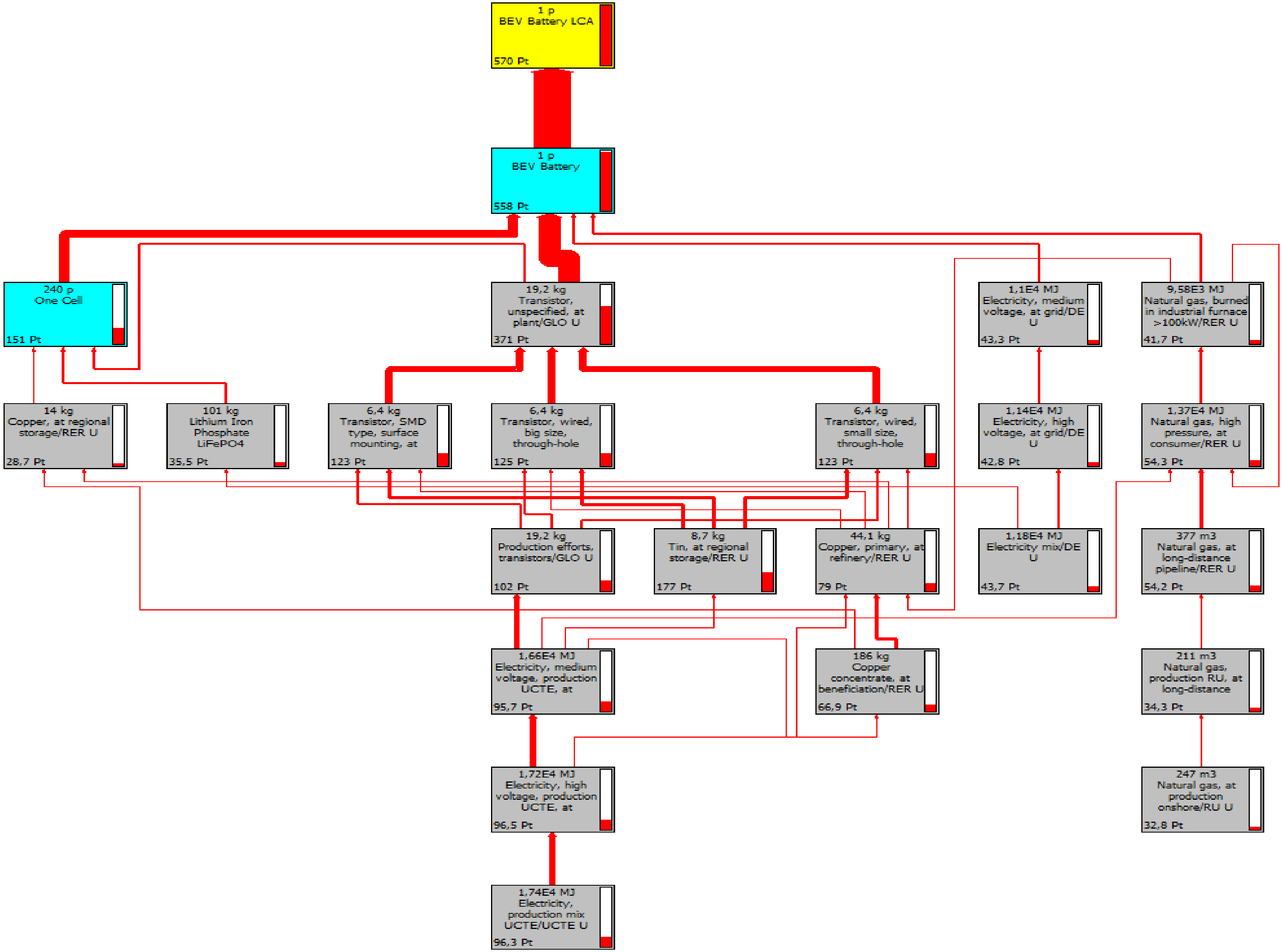


Figure 22 - Battery LCA network tree with a 5% cut-off (source: author).

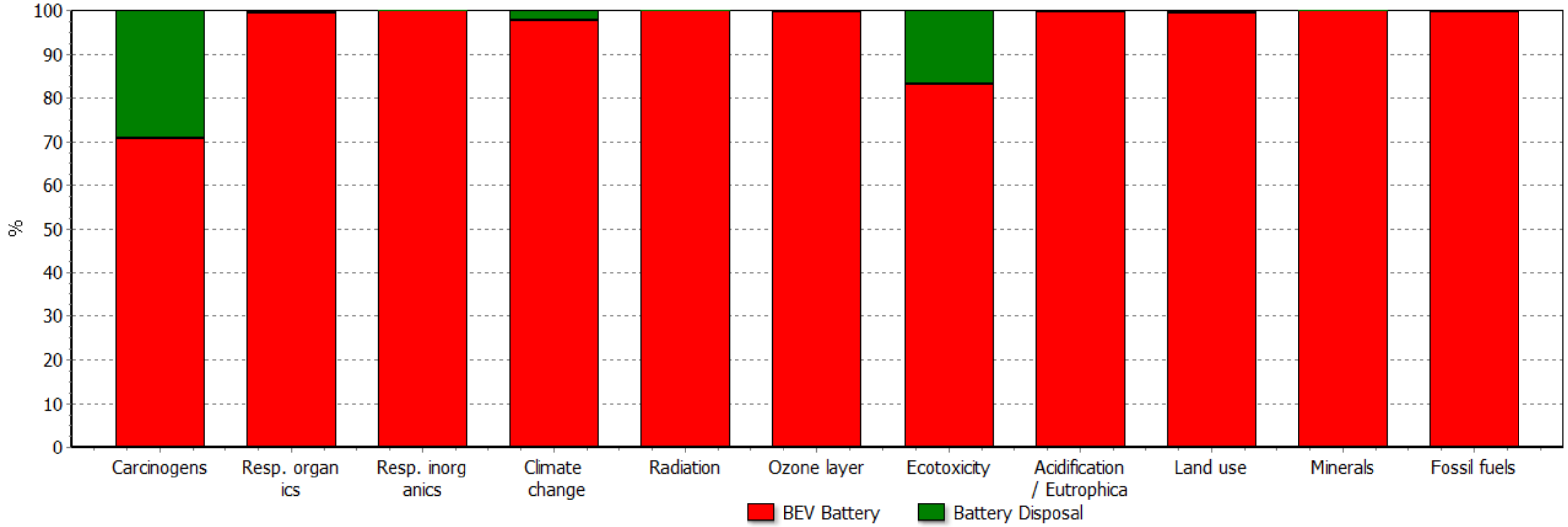


Figure 23 - Lifecycle assessment of a battery - Characterization Stem (source: author).

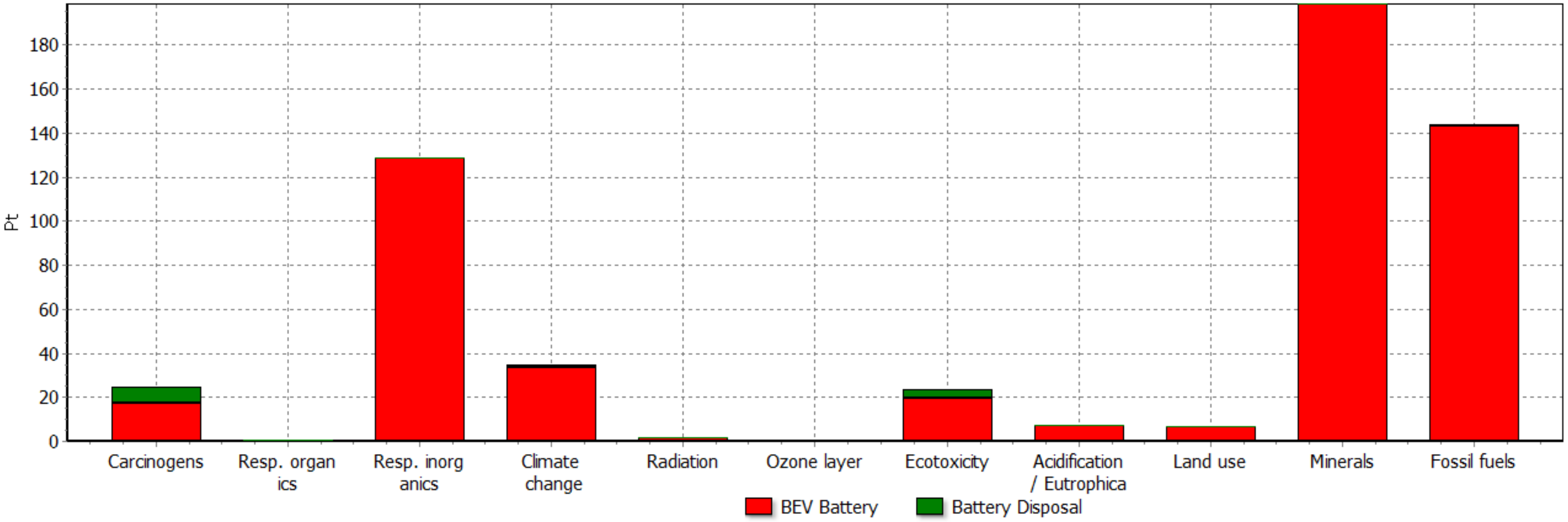


Figure 24 - Lifecycle assessment of a battery - Weighing Step (source: author).

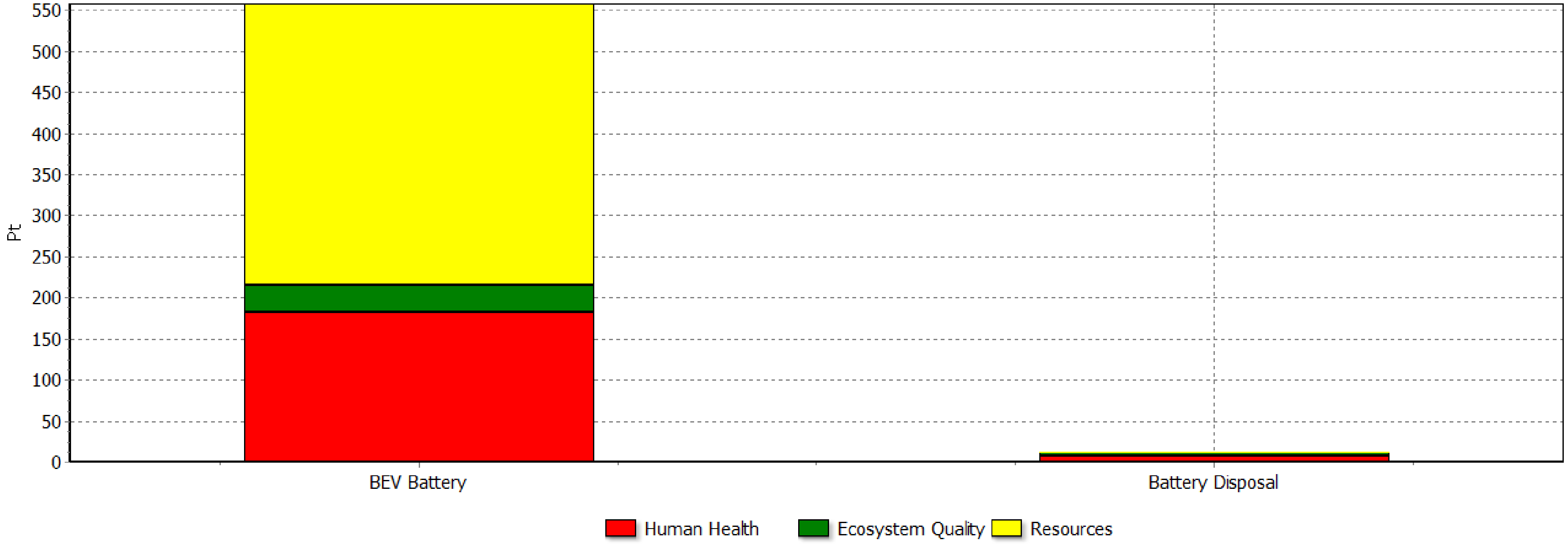


Figure 25 - Contribution of each life stage in the total lifecycle of one battery (Eco-indicator 99) (source: author).

Table 23- Values of the contribution of each life stage in the total lifecycle of one battery (units: Ecopoints; Eco-indicator 99) (source: author).

Category	**Battery Production**	**Battery Disposal**	**Total**
Human Health	182 *(31.9%)*	8.19 *(1.4%)*	190 *(33.3%)*
Ecosystem Quality	33.9 *(5.9%)*	4.05 *(0.7%)*	37.9 *(6.6%)*
Resources	342 *(60.0%)*	0.298 *(0.1%)*	342 *(60.1%)*
Total	558 *(97.9%)*	12.5 *(2.1%)*	570 *(100%)*

The previous figures and tables present the lifecycle ecopoints of the battery which amount to 570 Pt, where:

a) The production accounts for 558 Pt, i.e. 98% of the total impact;
b) The disposal stage is responsible for 12.5 Pt, or 2% of the total environmental impact;

The author reminds that in this LCA the energy in use is not accounted, for it is accounted in the BEV LCA; another point is that this analysis is for one battery and that a BEV requires 2 batteries in its lifecycle.

The categories with the highest contribution for the total lifecycle impact is Resources with a 60% input, followed by Human Health with 33%, Ecosystem Quality has a small contribution of 7%. If battery recycling processes were considered in this analysis, the total LCA impact of the batteries would be lower, as one could expect negative points from the disposal phase, in contrast with the positive points from disposing of the battery in a landfill.

In terms of the intermediary indicators, only Carcinogens and Ecotoxicity have a contribution from disposal worth noting, with a 30% input in Carcinogens and a 17% in Ecotoxicity; all other indicators are dominated with the battery production phase.

Minerals is the most important parameter (production of Tin and Copper), followed by Fossil Fuels (burning of Natural Gas) and Respiratory Inorganics (again from Tin and Copper production). The conclusions of this are consistent with the revealed in

4.4.4.Comparison between an ICEV and a BEV

This sub-section addresses the second main objective of this research, i.e. a comparison between the lifecycle environmental impact of the ICEV and the BEV, after having presented their respective LCA separately.

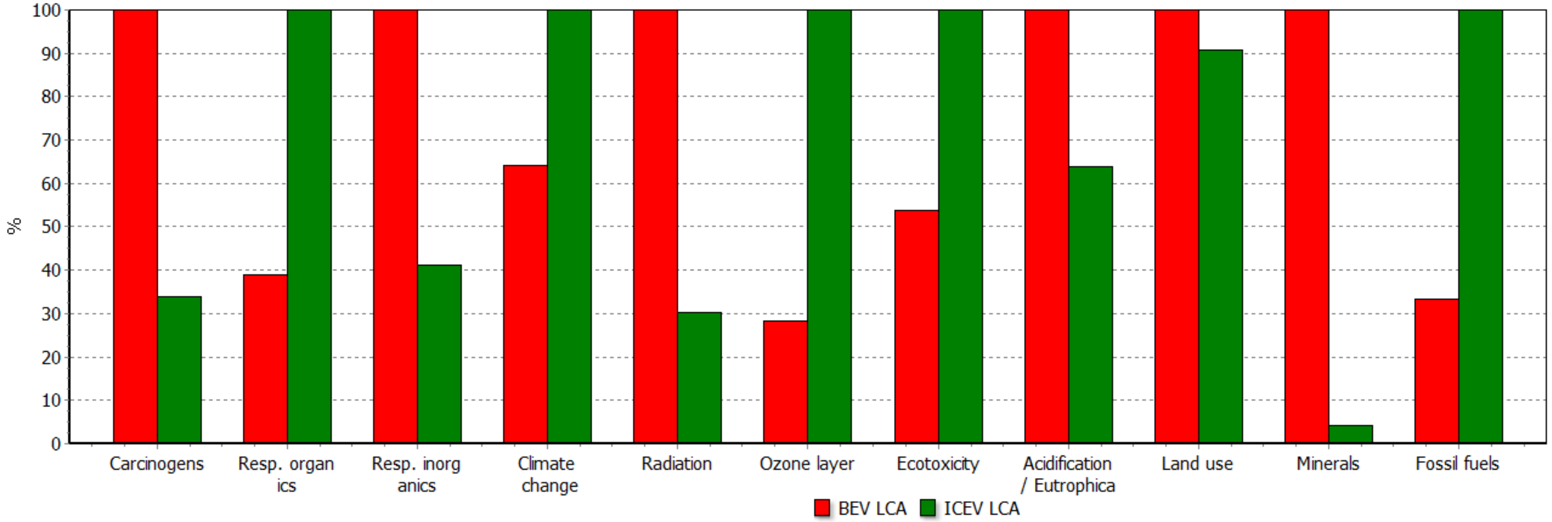


Figure 26 - Lifecycle comparison of ICEV and BEV powertrains - Characterization Step (source: author).

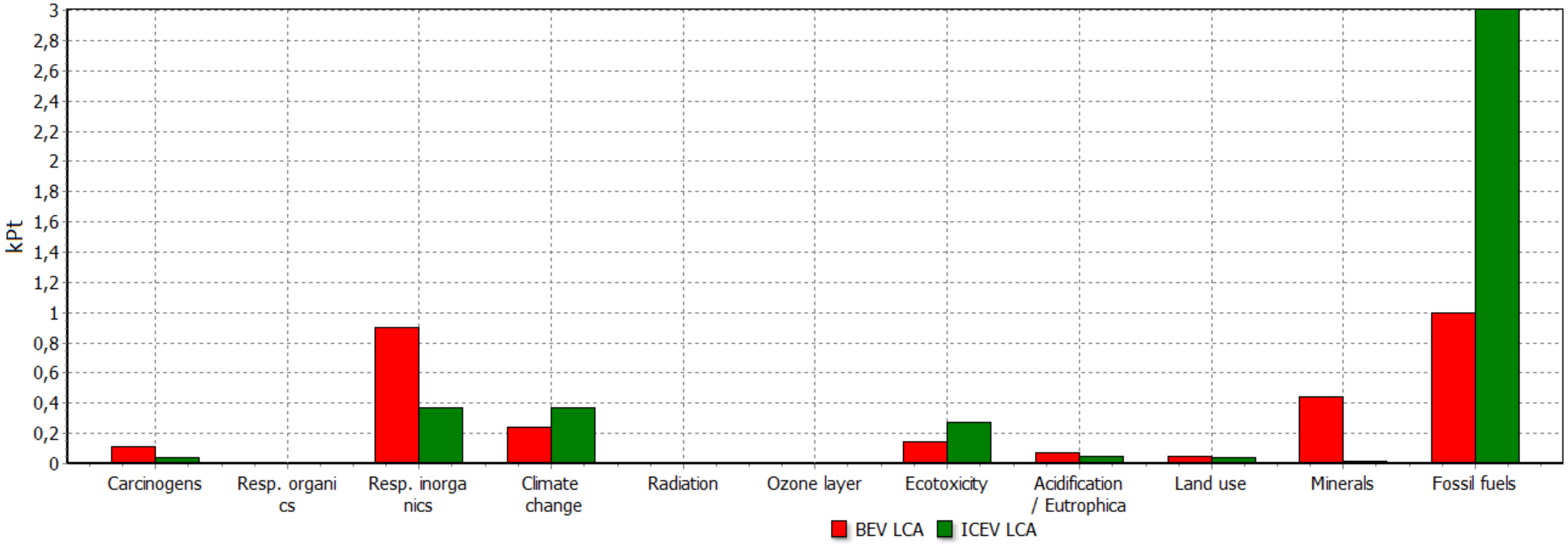


Figure 27 – Lifecycle comparison of the ICEV and BEV powertrains - Weighing Step (source: author).

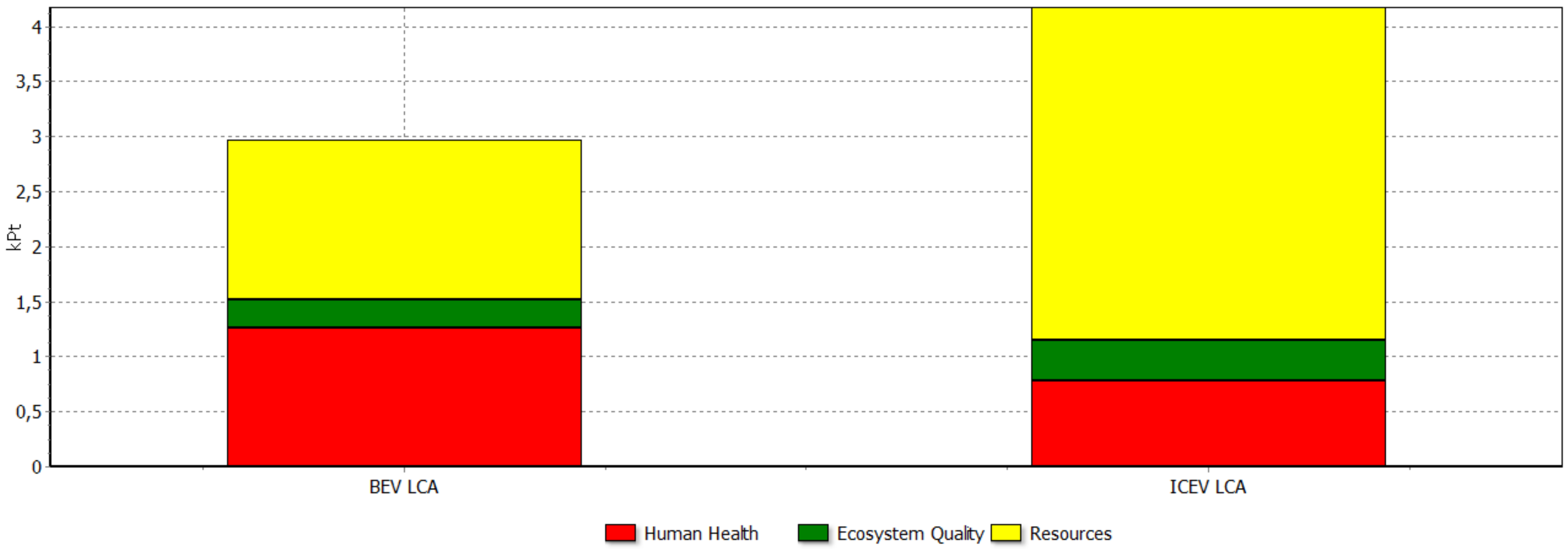


Figure 28 – Final LCA comparison of ICEV and BEV powertrains (source: author).

Table 24 – Values for the contribution of each category in the total LCA of the powertrains (source: author).

Category	**ICEV LCA** Ecopoints (% share)	**BEV LCA** Ecopoints (% share)	**Difference (ICEV-BEV)** Ecopoints (% variation)	**Difference (BEV-ICEV)** Ecopoints (% variation)
Human Health	786 *(19%)*	1260 *(43%)*	-474 *(-38% of BEV)*	474 *(60% of ICEV)*
Ecosystem Quality	359 *(9%)*	265 *(9%)*	94 *(35% of BEV)*	-94 *(-26% of ICEV)*
Resources	3030 *(73%)*	1440 *(49%)*	1590 *(110% of BEV)*	-1590 *(-52% of ICEV)*
Total	4170 *(100%)*	2960 *(100%)*	1210 *(41% of BEV)*	-1210 *(-29% of ICEV)*

As illustrated in the previous figure, the total lifecycle environmental impact of the BEV powertrain is approximately 30% smaller than that of the ICEV, proving to be environmentally more efficient, globally speaking, and according to the assumptions in this study. This is in line with the described in (Frischknecht & Flury 2011)

The intermediary indicators in Figure 26 show that each alternative is balanced, with 6 categories where the BEV has a larger impact (Carcinogens, Respiratory inorganics, Radiation, Acidification, Land use and Minerals) and the remaining 5 categories where ICEV have their larger impacts (Respiratory organics, Climate change, Ozone layer, Ecotoxicity and Fossil Fuels).

As seen in the previous separate analysis, environmental impacts related with Fossil Fuels use present the larger lifecycle environmental burdens.

It should be noted that though in both alternatives the largest responsible for the total impact are the environmental impacts related to Resources category, in the case of the ICEV powertrain, it is twice as big as for BEV. Human health related environmental impacts come second in the ranking of LCA burdens, and, conversely to Resources, BEV has a 60% larger impact than ICEV powertrain. Lastly, Ecosystem Quality environmental problems correspond to 9% of overall LCAs and, again, BEV present 30% lower environmental impacts than ICEV.

4.5. Discussion

The present section aims to examine technologies and noting similarities and/or differences regarding their environmental performances.

Basically, this analysis suggests that according to the results obtained and acknowledging the assumptions of this study, BEV lifecycle impact corresponds to about 71% of the total lifecycle impact of a gasoline ICEV (having the eco-indicator 99 as a basis for analysis and the Hierarchist perspective). Therefore, it is a more environmentally appropriate choice for auto mobility. The following table represents a comparison of both LCA intermediate indicators, where the option with the highest impact on each category is marked in red.

Table 25 - Intermediate Indicators LCA Comparison.

Category	Unit	ICEV LCA	BEV LCA
Carcinogens	DALY	0.00146	0.00429
Resp. Organics	DALY	1.05E-4	4.11E-5
Resp. Inorganics	DALY	0.0142	0.0346
Climate Change	DALY	0.0143	0.00917
Radiation	DALY	5.87E-5	1.94E-4
Ozone Layer	DALY	9.91E-6	2.79E-6
Ecotoxicity	PAF*m2yr	3.46E4	1.86E4
Acidification	PDF*m2yr	581	912
Land Use	PDF*m2yr	567	625
Minerals	MJ surplus	784	1.85E4
Fossil Fuels	MJ surplus	1.26E5	4.21E4

Has can be seen from Table 25 and Figure 26, the sub-categories were the BEV requires improvement to be completely more environmental friendly then the ICEV are: Carcinogens, Resp. Inorganics (connected to electricity production), Radiation, Acidification, Land Use and Minerals.

This said the author emphasizes that this conclusion should not and cannot be generalized to all ICEVs when compared to BEVs, since it is conditioned by a set of assumptions that may change the result of this analysis, including the following:

- The energy mix for electricity production varies from country to country, thus having a significant impact on the environmental burdens;
- Other type of fuels such has diesel and/or biofuels could reduce the significantly ICEV’s environmental impacts (recall that impacts related to fossil fuel consumption have the larger share of LCA results);
- Including the battery-recycling stage in the corresponding LCA could make the difference between the two powertrains bigger; and
- The mileage and service time of the vehicle considered may also change the results of this work (for instance, by increasing the quantity of batteries for the BEV powertrain).

The conclusions of this study support the claims of electric vehicle supporters and manufacturers that in fact this type of powertrain is more environmentally appropriate than their internal combustion engine counterparts, though the difference between them should be addressed cautiously for it might not be sufficiently wide to jump into definite conclusions. These are rather framed by the assumptions adopted in the present research but, overall, they strongly suggest towards that direction, i.e. BEV is potentially more interesting than ICEV from an LCA perspective.

5. Conclusions and policy implications

This chapter presents the main conclusions of this dissertation with a summary of the key findings and possible policy implications, followed by a general listing of the main limitations of this study and ends with leads for future work.

5.1. Key findings

The following table shows the results obtained from the LCC analysis. These show that the BEV has today a higher economic performance than the ICEV.

Table 26 - LCC comparison of BEV and ICEV (source: author).

	ICE	BEV	BEV with V2G Regulation Up services	 Regulation Down services
LCC	-€ 4,991	-€ 4,224	-€ 4,621	-€ 3,760
Variation compared to ICEV	-	€ 767	€ 370	€ 1,231
(% variation)	-	*(-15%)*	*-0.09*	*(-19%)*

After the sensitivity analysis, consisting in adding variability to the model parameters the probabilistic distributions in Figure 11Figure 11 where obtained, through their comparison it is possible to say that the probability of BEV total cost of ownership being inferior to that of the ICEV is about 78%.

As for V2G the results conclude that regulations up services are not economically attractive because the costs associated with this market are larger than the gains. This is mainly due to the fact that benefits from uploading energy to the grid are lower than the costs of electricity consumption and battery wear. Conversely, the regulation down power market is economically interesting mainly because there is no extra cycling on the batteries (with related battery-ware costs) and the energy charged is bought at a lower rates. This conclusion could imply that currently V2G could be more interesting for the System Operator than for the consumer, for it could reduce the need for grid stability infrastructures, such as expensive hydroelectric dams and power plants. This might lead to an increase of V2G services utility in the future if this system is widely implemented.

This said, the first research question is answered and BEV has a 78% probability of being more economical than the current ICEV technology, in the Portuguese market and from a LCC perspective, and V2G services can add monetary value to the BEV car ownership costs only when doing regulation down. The corresponding savings may amount to slightly more than 1,200 € per year.

Regarding the LCA, the key finding is that the BEV's powertrain lifecycle impact is about 30% smaller than the total lifecycle impact of a gasoline ICEV. Hence, BEV is a more appropriate choice for auto mobility environmentally speaking, and thus providing an answer to the second research question of this dissertation. The main conclusions of the study are shown on the following table.

Table 27 – LCA comparison of BEV and ICEV (source: author).

Category	ICEV LCA	BEV LCA	Difference (BEV-ICEV)
Human Health	*19%*	*43%*	*60%*
Ecosystem Quality	*9%*	*9%*	*-26%*
Resources	*73%*	*49%*	*-52%*
Total	*100%*	*100%*	*-29%*

The conclusions of this study support the claims that BEV's powertrains are more environmentally appropriate than their internal combustion engine counterparts, though the difference between them should be addressed cautiously for it might not be sufficiently wide to jump into definite conclusions. These are rather framed by the assumptions adopted in the present research but, overall, they strongly suggest towards that direction, i.e. BEV is potentially more interesting than ICEV from an LCA perspective.

5.2. Policy implications

Though this study concludes on the higher economic and environmental performance of the BEV, in terms of mobility one should keep in mind that other means of transport and particularly public transport might have higher economic and environmental performances, depending on the occupancy rates. And therefore in terms of national policy more attention to other types of mobility should also be given than indirectly promoting the use of private transport, by highlighting the reductions of car ownership LC cost potentially generated by shifting to BEV. Hence, the increase performances of BEV must not reduce the urge of solving urban mobility problems such as congestion or urban land predation by car-related activities and infrastructures. One of the current electric vehicle policies in Portugal is tax exemption for vehicles acquisition. This was a temporary measure (already left aside due to the current economic context) and was set as a means to accelerate the penetration of BEV in the Portuguese car stock. From the technological diffusion point of view, the policy measure is consistent although from an economic point of view it is not logical since BEV are more interesting than its ICEV counterparts. Apparently, the wider shift towards BEV depends on other fragilities of BEV, for instance, autonomy, battery charging time and network.

Furthermore, in terms of the Portuguese energy dependency, what would be the primary source of the extra required electricity required to power vehicles, in a scenario of pervasive diffusion of BEV? Hence, the strong support the Portuguese state was giving to BEV could imply an increase of fossil fuel consumption in the Portuguese electric mix. This said according to (Camus et al. 2011), for a 0.2 million EV penetration in Portugal in 2020 (considered a reliable scenario) would have very little impact in load profiles and electricity prices. Another energy related issue is that the capacity of BEVs for V2G, could mean that the country would not need to build the new hydroelectric dam plan because one of the supporting facts for this plan was the need for electricity regulation services. An interesting analysis to pursue after the present research would be to perform a Cost Benefit Analysis of both solutions.

Considering the impact the BEV has in mineral resources during its construction, society could be trading an oil dependency for another material dependency, lithium for example, beside fossil fuel dependency for electricity production, though this scenario is studied in (Kushnir & Sandén 2012) and (Råde & Andersson 2001), concludes that current lithium resource stocks could be sufficient for the demand, concluding that if recycling does occur then resource exhaustion does not appear to be a credible threat (though constraint to the study assumptions).

5.3. Main limitations of the study and leads for future research

For future work the author proposes the continuation of research and comparison of diesel and other alternative fuels (biofuels, gas), plug-in hybrid and fuel cell vehicles with the powertrains presented here, thus enabling to rank and categorize each technology in the Portuguese society/market, in terms of lifecycle economical and environmental performances.

On every work that is dependent on data, the question of its reliability should always be questioned. Any numerical model is dependent on the quality of data inputs, If input data is not consistent, then model results are not trustful. This said, the author believes that data and methods applied to this work are trustworthy, and therefore so are its results and conclusions if appropriately framed by the assumptions. Though some doubts could arise in some of the data inputs and methodological assumptions, particularly in the LCA, the author considers them to be small enough to yield trustful results and consistent conclusions.

In the LCC, only secondary regulation was considered has a power market for V2G. Evaluation of the profits and costs made from tertiary market is postponed for future work, but acknowledging that there is an additional source of value for V2G services in the Portuguese power market. The comparison of V2G LCA with other power generation alternatives is also proposed for future work, for example comparing a BEV (or a group of BEV's) providing V2G services to a hydroelectric dam with pumping capability or an energy reserve gas power plant.

There is another important parameter that is not addressed in this work that is the social aspect of mobility, for instance, will the consumer consider the BEV as purchasable alternative regarding their relatively low autonomy, although demonstrated here that it is more environmentally friendly and economical? These and other social aspects analyses were not addressed in this study.

6. References

De Almeida, A.T. et al., 2008. EUP Lot 11 Motors. *Technical Study for Ecodesign Directive, mandated by European Commission, Coimbra Portugal, April*, (February). Available at: http://www.eup-network.de/fileadmin/user_upload/Produktgruppen/Lots/Final_Documents/ Lot11_Motors_FinalReport.pdf [Accessed November 12, 2011].

Alves, B., 2005. *Medição da intensidade ambiental decorrente do consumo energético em deslocações urbanas de passageiros.* Universidade Ténica de Lisboa - Instituto Superior Técnico.

Arthur D. Little, I., 2002. *Guidance for Transportation Technologies : Fuel Choice for Fuel Cell Vehicles Final Report*,

Assembleia da República, 2003. Decreto-Lei n.^{o} 196/2003.

Assembleia da República, 2008. Decreto-Lei n.^{o}64/2008.

Bloomfield, L., 2001a. *Section 17.3 Batteries*, Available at: http://www.howeverythingworks.org/supplements/batteries.pdf.

Bloomfield, L., 2001b. Section 9.5 - Electric Motors. In *The Physics of Everyday Life*. John Wiley & Sons, Inc. Available at: http://www.howeverythingworks.org/supplements/electric_motors.pdf.

Camus, C., Farias, T. & Esteves, J., 2011. Potential impacts assessment of plug-in electric vehicles on the Portuguese energy market. *ENERGY POLICY*, 39(10), pp.5883-5897.

Dallinger, D., Krampe, D. & Wietschel, M., 2011. Vehicle-to-Grid Regulation Reserves Based on a Dynamic Simulation of Mobility Behavior. *Smart Grid, IEEE Transactions*, 2(2), pp.302-313. Available at: http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5756687 [Accessed November 9, 2011].

David & Banister, 2008. The sustainable mobility paradigm. *Transport Policy*, 15(2), pp.73-80. Available at: http://www.sciencedirect.com/science/article/pii/S0967070X07000820.

Delucchi, M. & Lipman, T., 2001. An Analysis of the Retail and Lifecycle Cost of Battery-Powered Electric Vehicles An Analysis of the Retail and Lifecycle Cost of Battery-Powered Electric Vehicles. *Transportation Research Part D: Transport and Environment*, 6(6), pp.371 - 404.

Delucchi, M. et al., 2000. Electric and Gasoline Vehicle Lifecycle Cost and Energy-Use Model Electric and Gasoline Vehicle Lifecycle Cost and Energy-Use Model. *eScholarship Repository, University of California*. Available at: http://repositories.cdlib.org/itsdavis/UCD-ITS-RR-99-4.

Direcção Geral de Energia e Geologia, 2010. Balanços e Indicadores Energéticos. Available at: http://www.dgge.pt?cn=68917002706771568359AAAA [Accessed September 2011].

Entidade Reguladora dos Serviços Energéticos, 2008. Manual de Procedimentos do Acerto de Contas. Available at: http://www.erse.pt/pt/electricidade/regulamentos/relacoescomerciais/Documents12 .

Entidade Reguladora dos Serviços Energéticos, 2009. *Manual de procedimentos do gestor do sistema*, Available at: http://www.erse.pt/pt/electricidade/regulamentos/operacaodasredes/Documents/Manual de Procedimentos do Gestor do Sistema.pdf.

Entidade Reguladora dos Serviços Energéticos, 2010. *Regulamento de Operação das Redes*, Available at: http://www.mercado.ren.pt/DocReg/BibRegula/ROR - 2010.pdf.

European Comission, 2011a. No Title. Available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/introduction [Accessed September 2011].

European Comission, 2011b. *White paper - Roadmap to a Single European Transport Area - Towards a competitive and resource efficient transport system*, Available at: http://ec.europa.eu/transport/strategies/2011_white_paper_en.htm.

Eurostat, 2011a. Energy Statistics. Available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/energy/introduction [Accessed September 2011].

Eurostat, 2011b. Environment Statistics. Available at: http://epp.eurostat.ec.europa.eu/portal/page/portal/environment/data/main_tables [Accessed September 2011].

Faculdade de Ciências e Tecnologia da Universidade Nova de Lisboa & Comissão de Coordenação e Desenvolvimento Regional de Lisboa e Vale do Tejo, 2006. *Planos e Programas para a melhoria da qualidade do ar na Região de Lisboa e Vale do Tejo*,

Ferrão, P., 2009. *Ecologia Industrial: Princípios e Ferramentas* 1st ed., Lisbon: IST Press.

Ferrão, P. & Figueiredo, J., 2000. *A Ecologia Industrial e o automovel em Portugal*, Lisboa: Celta Editora.

Frischknecht, R. & Flury, K., 2011. Life cycle assessment of electric mobility: answers and challenges—Zurich, April 6, 2011. *The International Journal of Life Cycle Assessment*, 16(7), pp.691-695. Available at: http://www.springerlink.com/index/10.1007/s11367-011-0306-6 [Accessed April 10, 2012].

Graham, R., 2001. *Comparing the Benefits and Impacts of Hybrid Electric Vehicle Options*, Palo Alto, California.

Hill, D.M., Agarwal, A.S. & Ayello, F., 2012. Fleet operator risks for using fleets for V2G regulation. *Energy Policy*, 41(0), pp.221-231. Available at: http://www.sciencedirect.com/science/article/pii/S030142151100824X.

INTELI Inteligência em Inovação, 2010. MOBI.E Mobilidade Eléctrica. Available at: http://www.mobie.pt [Accessed September 7, 2011].

Institute for Environment and Sustainability, 2010. *ILCD Handbook - General guide on LCA - Detailed guidance*, Ispra - Itally.

Kempton, W., 2000. Electric-drive vehicles for peak power in Japan. *Energy Policy*, 28. Available at: http://www.sciencedirect.com/science/article/pii/S0301421599000786 [Accessed November 10, 2011].

Kempton, W. & Tomić, J., 2005. Vehicle-to-grid power fundamentals: Calculating capacity and net revenue. *Journal of Power Sources*, 144(1), pp.268-279. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0378775305000352 [Accessed July 6, 2011].

Kushnir, D. & Sandén, B. a., 2012. The time dimension and lithium resource constraints for electric vehicles. *Resources Policy*. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0301420711000754 [Accessed April 4, 2012].

Majeau-Bettez, G., Hawkins, T.R. & Stromman, A.H., 2011. Life Cycle Environmental Assessment of Lithium-Ion and Nickel Metal Hydride Batteries for Plug-In Hybrid and Battery Electric Vehicles (vol 45, pg 4548, 2011). *ENVIRONMENTAL SCIENCE & TECHNOLOGY*, 45(12), p.5454.

Moura, Filipe, 2009. *CAR ORGAN TRANSPLANT - ANTICIPATING ENERGY AND ENVIRONMENTAL BENEFITS OF CLEANER TECHNOLOGIES*. Universidade Técnica de Lisboa - Instituto Superior Técnico.

Moura, Filipe, 2006. Interim Report Driving energy system transformation with “ vehicle-to-grid ” power Approved by Leo Schrattenholzer. *Program*.

Nissan, 2011. Nissan LEAF ™ Specifications. Available at: http://www.nissanusa.com/ev/media/pdf/specs/FeaturesAndSpecs.pdf.

Norris, G., 2001. Integrating life cycle cost analysis and LCA. *The International Journal of Life Cycle Assessment*, 6(2), pp.118-120. Available at: http://dx.doi.org/10.1007/BF02977849.

PRé Consultants, 2011. Eco-indicator 99 impact assessment method for LCA. Available at: http://www.pre-sustainability.com/content/eco-indicator-99 [Accessed September 2011].

REN, 2011. Sistema de Informação de Mercados de Energia Eléctrica. Available at: http://www.mercado.ren.pt/Paginas/default.aspx [Accessed July 21, 2011].

Råde, I. & Andersson, B.A., 2001. Requirement for metals of electric vehicle batteries. *Journal of Power Sources*, 93(1–2), pp.55-71. Available at: http://www.sciencedirect.com/science/article/pii/S0378775300005474.

Stamp, A., Lang, D.J. & Waeger, P.A., 2012. Environmental impacts of a transition toward e-mobility: the present and future role of lithium carbonate production. *JOURNAL OF CLEANER PRODUCTION*, 23(1), pp.104-112.

Swiss Centre for Life Cycle Inventories, 2007. ecoinvent data v2.0. Available at: www.ecoinvent.ch.

Tchobanoglous, G., Theisen, H. & Vigil, S., 1993. *Integrated Solid Waste Management: Engineering Principles and Management Issues* Internatio., London: McGraw-Hill Education - Europe.

The Boston Consulting Group, 2010. *Batteries for Electric Cars - Challenges, Opportunities, and the Outlook to 2020*, Available at: http://www.bcg.com/documents/file36615.pdf .

Turton, H. & Moura, F, 2008. Vehicle-to-grid systems for sustainable development: An integrated energy analysis. *Technological Forecasting and Social Change*, 75(8), pp.1091-1108. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0040162507002053 [Accessed August 23, 2011].

United Nations Statistics Division, 2010. Environmental Indicators: GHGs. Available at: http://unstats.un.org/unsd/environment/air_greenhouse_emissions.htm [Accessed September 2011].

United States Department of Energy, Office of Transportation & Air Quality & United States Environmental Protection Agency, 2012. Electric Vehicles. Available at: http://www.fueleconomy.gov/feg/evtech.shtml [Accessed January 2012].

Vieira, J., Moura, Filipe & Viegas, J.M., 2007. Transport policy and environmental impacts: The importance of multi-instrumentality in policy integration. *Transport Policy*, 14(5), pp.421-432. Available at: http://www.sciencedirect.com/science/article/pii/S0967070X07000406.

Volkswagen Group Research - Environment Affairs Product, 2009. *The TSI Engine Environmental Commendation Background Report*, Wolfsburg.

Volkswagon, 2011. Dados Técnicos e Equipamentos VW Golf.

XVIII Governo Constitucional, 2010. *Estratégia Nacional para a Energia 2020*, Zackrisson, M., Avellán, L. & Orlenius, J., 2010. Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues. *Journal of Cleaner Production*, 18(15), pp.1519-1529. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0959652610002167 [Accessed August 9, 2011].

7. Annex

7.1. ICEV sensitivity analysis

Summary Statistics for Total ICEV

Statistics		**Percentile**	
Minimum	-12,974.51 €	**5%**	- 8,246.24 €
Maximum	-2,005.99 €	**10%**	-7,557.42 €
Mean	-5,611.94 €	**15%**	-7,111.13 €
Std Dev	1,447.72 €	**20%**	-6,751.37 €
Variance	2095884.331	**25%**	-6,473.11 €
Skewness	-0.637784269	**30%**	- 6,243.39 €
Kurtosis	3.552386037	**35%**	-6,020.99 €
Median	- 5,456.79 €	**40%**	-5,821.31 €
Mode	-5,728.37 €	**45%**	-5,635.16 €
Left X	- 8,246.24 €	**50%**	-5,456.79 €
Left P	5%	**55%**	-5,268.42 €
Right X	- 3,516.62 €	**60%**	-5,096.27 €
Right P	95%	**65%**	- 4,931.65 €
Diff X	4,729.63 €	**70%**	-4,760.63 €
Diff P	90%	**75%**	- 4,575.63 €
#Errors	0	**80%**	- 4,381.78 €
Filter Min	Off	**85%**	- 4,149.12 €
Filter Max	Off	**90%**	-3,894.15 €
#Filtered	0	**95%**	-3,516.62 €

Regression and Rank Information for Total ICEV

Rank	**Name**	**Regr**	**Corr**
1	Total km in lifecycle	-0.564	-0.563
2	Years the device will last	0.430	0.409
3	New Car Price	-0.412	-0.408
4	Price of Gasoline	-0.337	-0.332
5	Vehicle efficiency	-0.312	-0.305
6	Annualization interest rate	-0.223	-0.202
7	Maintenance cost	-0.147	-0.150
8	Car Salvage price	0.063	0.056
9	Taxes	-0.031	-0.033
10	Financing Interest rate	-0.027	-0.040

Rank	**Name**	**Description**
#1	Total km in lifecycle	Triangular distribution (lower limit=40000;mode=300000;upper limit=500000)
#2	Years the device will last	Triangular distribution (lower limit=10;mode=15;upper limit=20;)
#3	New Car Price	Triangular distribution (lower limit=13000;mode= 22000; upper limit=45000)
#4	Price of Gasoline	Triangular distribution (lower limit=0.8;mode=1.5;upper limit=2.3)
#5	Vehicle efficiency	Triangular distribution (lower limit=4;mode=6;upper limit=10)
#6	annualization interest rate	Triangular distribution (lower limit=0.01;mode=0.03;upper limit=0.05)
#7	Maintenance cost	Normal distribution (μ=10970;σ=2500)

#8	Car Salvage price	Triangular distribution (lower limit=500;mode=2500;upper limit=6000)
#9	Taxes	Triangular distribution (lower limit=500;mode=1581;upper limit=3000)
#10	Financing Interest rate	Triangular distribution (lower limit=0.005;mode=0.03;upper limit=0.1)

7.2. BEV with no V2G sensitivity analysis

Summary Statistics for Total no V2G

Statistics		**Percentile**	
Minimum	- 9,780.83 €	**5%**	-6,183.76 €
Maximum	- 1,150.43 €	**10%**	-5,655.52 €
Mean	- 4,213.85 €	**15%**	-5,322.33 €
Std Dev	1,097.54 €	**20%**	-5,075.41 €
Variance	1204594.574	**25%**	-4,876.57 €
Skewness	-0.557954089	**30%**	-4,698.86 €
Kurtosis	3.523357569	**35%**	-4,538.70 €
Median	- 4,122.88 €	**40%**	-4,390.62 €
Mode	-3,870.36 €	**45%**	-4,253.75 €
Left X	-6,183.76 €	**50%**	- 4,122.88 €
Left P	5%	**55%**	-3,985.86 €
Right X	-2,588.78 €	**60%**	-3,860.76 €
Right P	95%	**65%**	-3,732.81 €
Diff X	3,594.99 €	**70%**	-3,586.14 €
Diff P	90%	**75%**	-3,439.18 €
#Errors	0	**80%**	-3,277.05 €
Filter Min	Off	**85%**	-3,105.25 €
Filter Max	Off	**90%**	-2,884.10 €
#Filtered	0	**95%**	-2,588.78 €

Regression and Rank Information for Total no V2G

Rank	**Name**	**Regr**	**Corr**
1	New Car Price	-0.581	-0.584
2	Years the device will last	0.427	0.413
3	Total km in lifecycle	-0.399	-0.392
4	Efficiency	-0.376	-0.364
5	Annualization interest rate	-0.219	-0.228
6	Price of electricity for a private consumer	-0.149	-0.140
7	Maintenance cost	-0.142	-0.143
8	DoD	-0.119	-0.107
9	Car Salvage price	0.092	0.103
10	percentage of BEV maintenance lower then ICEV	0.084	0.085
11	Charger + battery efficiency (infra)	0.053	0.061
12	Financing Interest rate	-0.041	-0.032
13	Taxes	-0.035	-0.055
14	Unit cost of battery	-0.013	0.002

Rank	Name	Description
#1	New Car Price	Triangular distribution (lower limit=15000;mode=35000; upper limit=50000)
#2	Years the device will last	Triangular distribution (lower limit=10;mode=15;upper limit=20)
#3	Total km in lifecycle	Triangular distribution (lower limit=40000;mode=300000;upper limit=500000)
#4	Efficiency	Triangular distribution (lower limit=0.05;mode=0.14;upper limit=0.3)
#5	Annualization interest rate	Triangular distribution (lower limit=0.01;mode=0.03;upper limit=0.05)
#6	Price of electricity for a private consumer	Triangular distribution (lower limit=0.06;mode=0.13;upper limit=0.23)
#7	Maintenance cost	Normal distribution (μ=10970;σ=2500)
#8	DoD	Triangular distribution (lower limit=0.2;mode=0.8; upper limit=0.95)
#9	Car Salvage price	Triangular distribution (lower limit=500;mode=2000;upper limit=6000)
#10	percentage of BEV maintenance lower then ICEV	Triangular distribution (lower limit=0;mode=0.25;upper limit=0.5)
#11	Charger + battery efficiency (infra)	Triangular distribution (lower limit0.7;mode=0.8;upper limit=0.95)
#12	Financing Interest rate	Triangular distribution (lower limit=0.005; mode=0.03;upper limit=0.1)
#13	Taxes	Triangular distribution (lower limit=0;mode=0; upper limit=2000)
#14	Unit cost of battery	Triangular distribution (lower limit=150;mode=220;upper limit=400)
#15	Es	Normal distribution (μ=25;σ=2.4)
#16	cost of a home charger	Triangular distribution (lower limit=1000;mode=5000;upper limit=10000)
#17	% domestic charge	Triangular distribution (lower limit=0.25;mode=0.8;upper limit=1)

7.3. BEV regulation up sensitivity analysis

Summary Statistics for Total reg up

Statistics		Percentile	
Minimum	- 10,612.52 €	**5%**	-6,317.87 €
Maximum	- 1,344.46 €	**10%**	-5,805.30 €
Mean	- 4,378.37 €	**15%**	-5,496.69 €
Std Dev	1,099.30 €	**20%**	-5,261.03 €
Variance	1208451.336	**25%**	-5,065.85 €
Skewness	- 0.489538838	**30%**	-4,888.57 €
Kurtosis	3.490809506	**35%**	-4,731.33 €
Median	-4,296.52 €	**40%**	- 4,583.43 €
Mode	-3,730.08 €	**45%**	-4,436.60 €
Left X	-6,317.87 €	**50%**	-4,296.52 €
Left P	5%	**55%**	-4,161.86 €
Right X	-2,720.41 €	**60%**	-4,025.25 €
Right P	95%	**65%**	-3,885.71 €
Diff X	3,597.46 €	**70%**	-3,740.08 €
Diff P	90%	**75%**	-3,601.30 €
#Errors	0	**80%**	-3,443.52 €
Filter Min	Off	**85%**	-3,261.32 €
Filter Max	Off	**90%**	-3,045.05 €
#Filtered	0	**95%**	-2,720.41 €

Regression and Rank Information for Total reg up			
Rank	**Name**	**Regr**	**Corr**
1	New Car Price	-0.578	-0.580
2	Years the device will last	0.420	0.394
3	Total km in lifecycle	-0.406	-0.385
4	DoDmax	-0.275	-0.273
5	Annualization interest rate	-0.234	-0.214
6	vehicle efficiency	-0.225	-0.212
7	Price of electricity for a private consumer	-0.175	-0.169
8	Maintenance cost	-0.139	-0.126
9	dd	0.096	0.088
10	Car Salvage price	0.089	0.108
11	percentage of BEV maintenance lower then ICEV	0.086	0.079
12	drb	0.081	0.081
13	Charger + battery efficiency (infra)	0.050	0.054
14	Unit cost of battery €/kWh	-0.044	-0.031

Rank	**Name**	**Description**
#1	New Car Price	Triangular distribution (lower limit=15000;mode=35000;upper limit=50000)
#2	Years the device will last	Triangular distribution (lower limit=10;mode=15;upper limit=20)
#3	Total km in lifecycle	Triangular distribution (lower limit=40000;mode=300000;upper limit=500000)
#4	DoDmax	Triangular distribution (lower limit=0.2;mode=0.8;upper limit=0.95)
#5	annualization interest rate	Triangular distribution (lower limit=0.01;mode=0.03;upper limit=0.05)
#6	vehicle efficiency	Triangular distribution (lower limit=0.05;mode=0.14;upper limit=0.3)
#7	Price of electricity for a private consumer	Triangular distribution (lower limit=0.06;mode=0.13;upper limit=0.23)
#8	Maintenance cost	Normal distribution (μ=10970;σ=2500)
#9	dd	Triangular distribution (lower limit=0;mode=33.16; upper limit=80)
#10	Car Salvage price	Triangular distribution (lower limit=500;mode=2000;upper limit=6000)
#11	percentage of BEV maintenance lower then ICEV	Triangular distribution (lower limit=0;mode=0.25;upper limit=0.5)
#12	drb	Triangular distribution (lower limit=5;mode=50;upper limit=70)
#13	Charger + battery efficiency (infra)	Triangular distribution (lower limit=0.7;mode=0.8;upper limit=0.95)
#14	unit cost of battery €/kWh	Triangular distribution (lower limit=150;mode=220;upper limit=400)
#15	Financing Interest rate	Triangular distribution (lower limit=0.005;mode=0.03;upper limit=0.1)
#16	Taxes	Triangular distribution (lower limit=0;mode=0;upper limit=2000)
#17	pcap (€/kW-h)	Triangular distribution (lower limit=0

		;mode=0.0230535553278686; upper limit=0.06)
#18	Rd_c up	Triangular distribution (lower limit=0.05; mode=0.277797761924197; upper limit=0.5)
#19	pel (€/kWh)	Triangular distribution (lower limit= 0.01; mode=0.055572308072692; upper limit=0.1)
#20	Es (kWh DC)	Normal distribution (μ=25;σ=2.4)
#21	% domestic charge	Triangular distribution (lower limit=5;mode=15;upper limit=25)
#22	cost of a home charger (€)	Triangular distribution (lower limit=1000;mode=5000;upper limit=10000)
#23	Inversion efficiency	Triangular distribution (lower limit=0.75; mode=0.92; upper limit =0.98)
#24	cost of a public charger (€)	Triangular distribution (lower limit =1500;mode=7000;upper limit=20000)

7.4. BEV regulation down sensitivity analysis

Summary Statistics for Total reg down

Statistics		**Percentile**	
Minimum	- 9,779.29 €	**5%**	-6,087.31 €
Maximum	-148.42 €	**10%**	-5,588.16 €
Mean	-4,095.90 €	**15%**	-5,279.63 €
Std Dev	1,144.99 €	**20%**	-5,022.26 €
Variance	1311012.634	**25%**	-4,813.99 €
Skewness	-0.416178577	**30%**	-4,627.73 €
Kurtosis	3.38194052	**35%**	-4,471.66 €
Median	-4,025.46 €	**40%**	-4,308.18 €
Mode	-3,897.27 €	**45%**	-4,163.61 €
Left X	-6,087.31 €	**50%**	-4,025.46 €
Left P	5%	**55%**	-3,885.50 €
Right X	-2,361.36 €	**60%**	-3,737.30 €
Right P	95%	**65%**	-3,599.63 €
Diff X	3,725.95 €	**70%**	-3,451.95 €
Diff P	90%	**75%**	-3,302.57 €
#Errors	0	**80%**	-3,130.83 €
Filter Min	Off	**85%**	-2,927.48 €
Filter Max	Off	**90%**	-2,685.32 €
#Filtered	0	**95%**	-2,361.36 €

Regression and Rank Information for Total reg down

Rank	**Name**	**Regr**	**Corr**
1	New Car Price	- 0.552	- 0.560
2	Years the device will last	0.413	0.416
3	Total km in lifecycle	- 0.378	- 0.361
4	Erecharge	- 0.307	- 0.319
5	dd	0.236	0.219
6	annualization interest rate	-	-

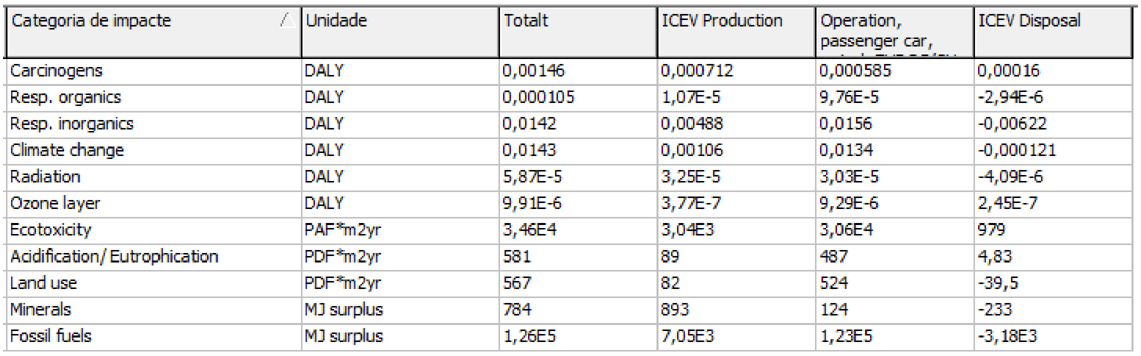
		0.211	0.222
7	vehicle efficiency	- 0.192	- 0.178
8	Maintenance cost	- 0.142	- 0.121
9	Price of electricity for a private consumer	- 0.127	- 0.121
10	DoDmax	- 0.111	- 0.128
11	Car Salvage price	0.086	0.089
12	percentage of BEV maintenance lower then ICEV	0.084	0.074
13	Charger + battery efficiency (infra)	0.047	0.054
14	Es	0.045	0.025

Rank	Name	Description
#1	New Car Price	Triangular distribution (lower limit=15000;mode=35000;upper limit=50000)
#2	Years the device will last	Triangular distribution (lower limit=10;mode=15;upper limit=20)
#3	Total km in lifecycle	Triangular distribution (lower limit=40000; mode=300000;upper limit=500000)
#4	Erecharge	Triangular distribution (lower limit=0;mode=0;upper limit=15)
#5	dd	Triangular distribution (lower limit= 0;mode= 33.16;upper limit= 80)
#6	annualization interest rate	Triangular distribution (lower limit=0.01;mode=0.03;upper limit=0.05)
#7	vehicle efficiency	Triangular distribution(lowerlimit=0.05;mode=0.14; upper limit=0.3)
#8	Maintenance cost	Normal distribution (μ=10970;σ=2500)
#9	Price of electricity for a private consumer	Triangular distribution (lower limit=0.06;mode=0.13;upper limit=0.23)
#10	DoDmax	Triangular distribution (lower limit=0.2;mode=0.8;upper limit=0.95)
#11	Car Salvage price	Triangular distribution (lower limit=500;mode=2000;upper limit=6000)
#12	percentage of BEV maintenance lower then ICE	Triangular distribution (lower limit=0;mode=0.25;upper limit=0.5)
#13	Charger + battery efficiency (infra)	Triangular distribution (lower limit=0.7;mode=0.8;upper limit=0.95)
#14	Es	Normal distribution (μ=25;σ=2.4)
#15	Financing Interest rate	Triangular distribution (lower limit=0.005;mode=0.03;upper limit=0.1)
#16	Taxes	Triangular distribution (lower limit=0;=mode=0;upper limit=2000)
#17	pcap (€/kW-h)	Triangular distribution (lower limit=0;mode=0.0230535553278686 ;upper limit= 0.06)
#18	Rd_c down	Triangular distribution (lower limit= 0.05; mode=0.134219637813518; upper limit=0.5)
#19	Unit cost of battery	Triangular distribution (lower limit=150; mode=220; upper limit=400)
#20	% domestic charge	Triangular distribution (lower limit=5;mode=15;upper limit=25)
#21	cost of a home charger (€)	Triangular distribution (lower limit= 1000;mode=5000;upper limit=10000)

#22	pel (€/kWh)	Triangular distribution (lower limit=0.01; mode=0.0242135619767757; upper limit=0.04)
#23	cost of a public charger (€)	Triangular distribution (lower limit=5; mode=10; upper limit=15)

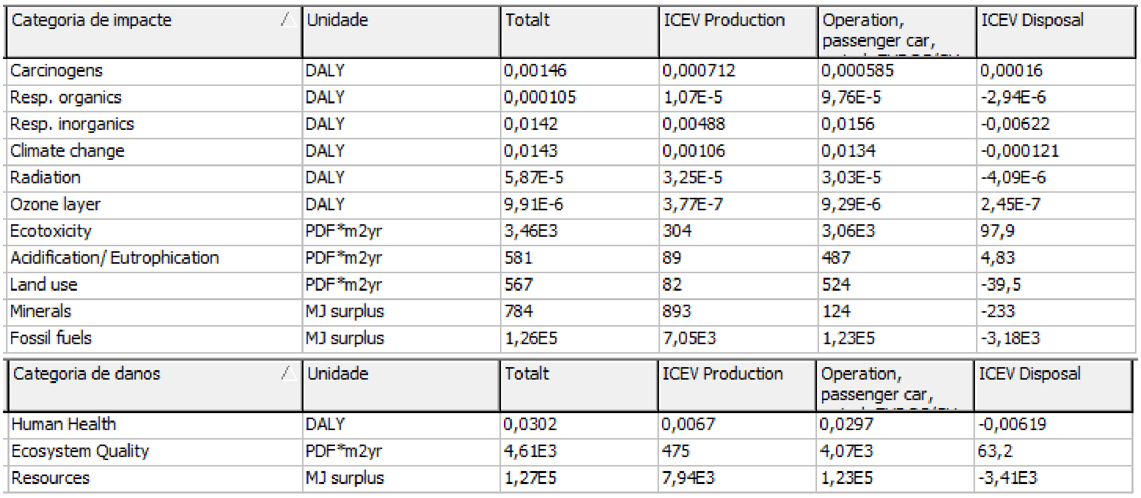
7.5. Lifecycle Impact Assessment of a ICEV

Characterization



Categoria de impacte	Unidade	Totalt	ICEV Production	Operation, passenger car,	ICEV Disposal
Carcinogens	DALY	0,00146	0,000712	0,000585	0,00016
Resp. organics	DALY	0,000105	1,07E-5	9,76E-5	-2,94E-6
Resp. inorganics	DALY	0,0142	0,00488	0,0156	-0,00622
Climate change	DALY	0,0143	0,00106	0,0134	-0,000121
Radiation	DALY	5,87E-5	3,25E-5	3,03E-5	-4,09E-6
Ozone layer	DALY	9,91E-6	3,77E-7	9,29E-6	2,45E-7
Ecotoxicity	PAF*m2yr	3,46E4	3,04E3	3,06E4	979
Acidification/ Eutrophication	PDF*m2yr	581	89	487	4,83
Land use	PDF*m2yr	567	82	524	-39,5
Minerals	MJ surplus	784	893	124	-233
Fossil fuels	MJ surplus	1,26E5	7,05E3	1,23E5	-3,18E3

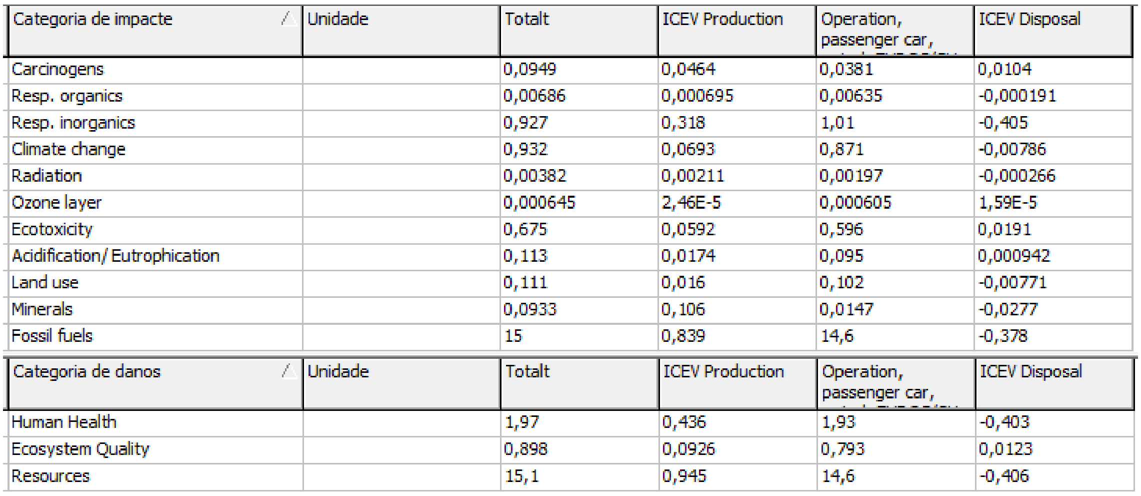
Damage Assessment



Categoria de impacte	Unidade	Totalt	ICEV Production	Operation, passenger car,	ICEV Disposal
Carcinogens	DALY	0,00146	0,000712	0,000585	0,00016
Resp. organics	DALY	0,000105	1,07E-5	9,76E-5	-2,94E-6
Resp. inorganics	DALY	0,0142	0,00488	0,0156	-0,00622
Climate change	DALY	0,0143	0,00106	0,0134	-0,000121
Radiation	DALY	5,87E-5	3,25E-5	3,03E-5	-4,09E-6
Ozone layer	DALY	9,91E-6	3,77E-7	9,29E-6	2,45E-7
Ecotoxicity	PDF*m2yr	3,46E3	304	3,06E3	97,9
Acidification/ Eutrophication	PDF*m2yr	581	89	487	4,83
Land use	PDF*m2yr	567	82	524	-39,5
Minerals	MJ surplus	784	893	124	-233
Fossil fuels	MJ surplus	1,26E5	7,05E3	1,23E5	-3,18E3

Categoria de danos	Unidade	Totalt	ICEV Production	Operation, passenger car,	ICEV Disposal
Human Health	DALY	0,0302	0,0067	0,0297	-0,00619
Ecosystem Quality	PDF*m2yr	4,61E3	475	4,07E3	63,2
Resources	MJ surplus	1,27E5	7,94E3	1,23E5	-3,41E3

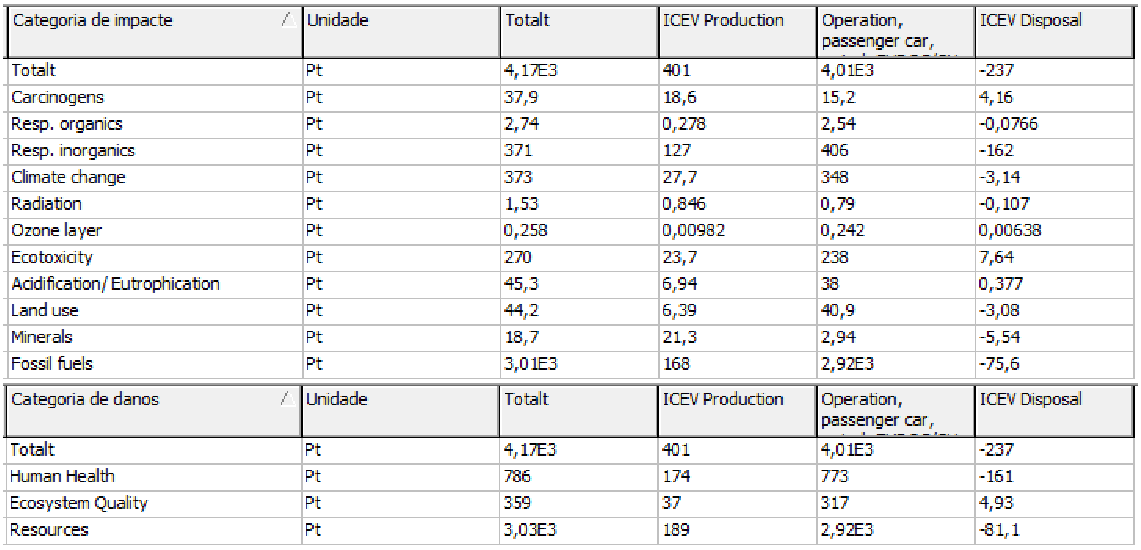
Normalization



Categoria de impacte	Unidade	Totalt	ICEV Production	Operation, passenger car,	ICEV Disposal
Carcinogens		0,0949	0,0464	0,0381	0,0104
Resp. organics		0,00686	0,000695	0,00635	-0,000191
Resp. inorganics		0,927	0,318	1,01	-0,405
Climate change		0,932	0,0693	0,871	-0,00786
Radiation		0,00382	0,00211	0,00197	-0,000266
Ozone layer		0,000645	2,46E-5	0,000605	1,59E-5
Ecotoxicity		0,675	0,0592	0,596	0,0191
Acidification/ Eutrophication		0,113	0,0174	0,095	0,000942
Land use		0,111	0,016	0,102	-0,00771
Minerals		0,0933	0,106	0,0147	-0,0277
Fossil fuels		15	0,839	14,6	-0,378

Categoria de danos	Unidade	Totalt	ICEV Production	Operation, passenger car,	ICEV Disposal
Human Health		1,97	0,436	1,93	-0,403
Ecosystem Quality		0,898	0,0926	0,793	0,0123
Resources		15,1	0,945	14,6	-0,406

Single Score

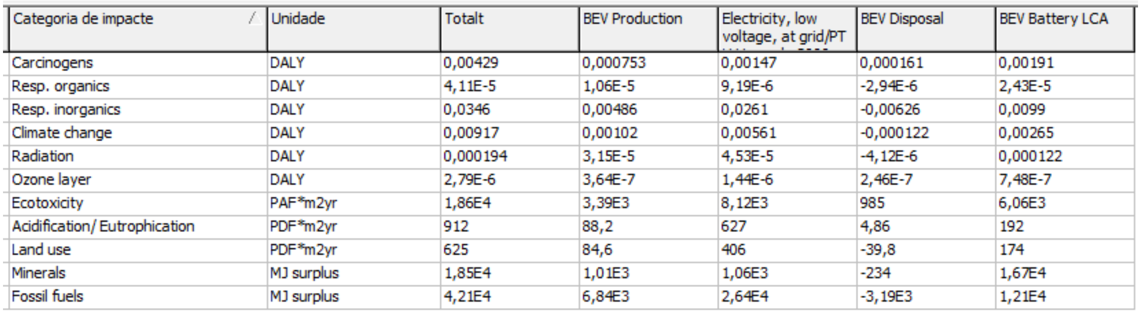


Categoria de impacte	Unidade	Totalt	ICEV Production	Operation, passenger car,	ICEV Disposal
Totalt	Pt	4,17E3	401	4,01E3	-237
Carcinogens	Pt	37,9	18,6	15,2	4,16
Resp. organics	Pt	2,74	0,278	2,54	-0,0766
Resp. inorganics	Pt	371	127	406	-162
Climate change	Pt	373	27,7	348	-3,14
Radiation	Pt	1,53	0,846	0,79	-0,107
Ozone layer	Pt	0,258	0,00982	0,242	0,00638
Ecotoxicity	Pt	270	23,7	238	7,64
Acidification/ Eutrophication	Pt	45,3	6,94	38	0,377
Land use	Pt	44,2	6,39	40,9	-3,08
Minerals	Pt	18,7	21,3	2,94	-5,54
Fossil fuels	Pt	3,01E3	168	2,92E3	-75,6

Categoria de danos	Unidade	Totalt	ICEV Production	Operation, passenger car,	ICEV Disposal
Totalt	Pt	4,17E3	401	4,01E3	-237
Human Health	Pt	786	174	773	-161
Ecosystem Quality	Pt	359	37	317	4,93
Resources	Pt	3,03E3	189	2,92E3	-81,1

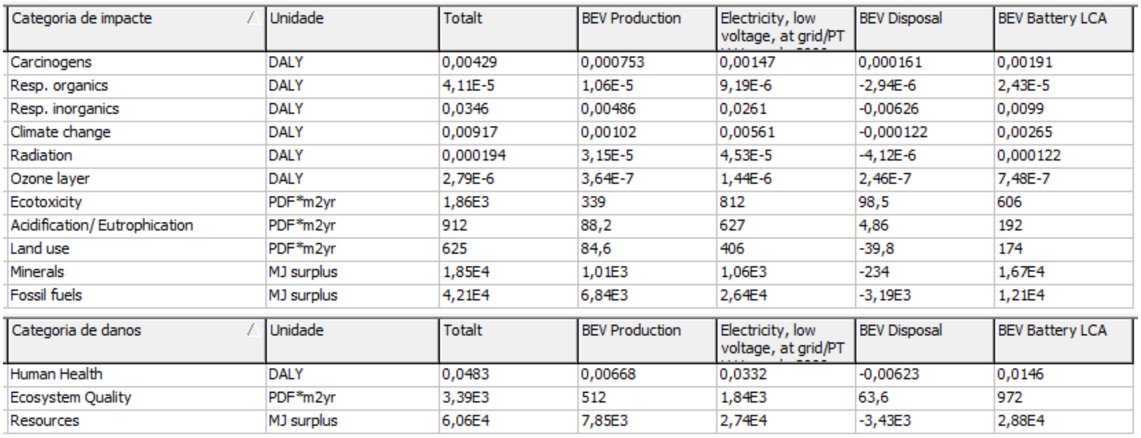
7.6. Lifecycle Impact Assessment of a BEV

Characterization



Categoria de impacte	Unidade	Totalt	BEV Production	Electricity, low voltage, at grid/PT	BEV Disposal	BEV Battery LCA
Carcinogens	DALY	0,00429	0,000753	0,00147	0,000161	0,00191
Resp. organics	DALY	4,11E-5	1,06E-5	9,19E-6	-2,94E-6	2,43E-5
Resp. inorganics	DALY	0,0346	0,00486	0,0261	-0,00626	0,0099
Climate change	DALY	0,00917	0,00102	0,00561	-0,000122	0,00265
Radiation	DALY	0,000194	3,15E-5	4,53E-5	-4,12E-6	0,000122
Ozone layer	DALY	2,79E-6	3,64E-7	1,44E-6	2,46E-7	7,48E-7
Ecotoxicity	PAF*m2yr	1,86E4	3,39E3	8,12E3	985	6,06E3
Acidification/ Eutrophication	PDF*m2yr	912	88,2	627	4,86	192
Land use	PDF*m2yr	625	84,6	406	-39,8	174
Minerals	MJ surplus	1,85E4	1,01E3	1,06E3	-234	1,67E4
Fossil fuels	MJ surplus	4,21E4	6,84E3	2,64E4	-3,19E3	1,21E4

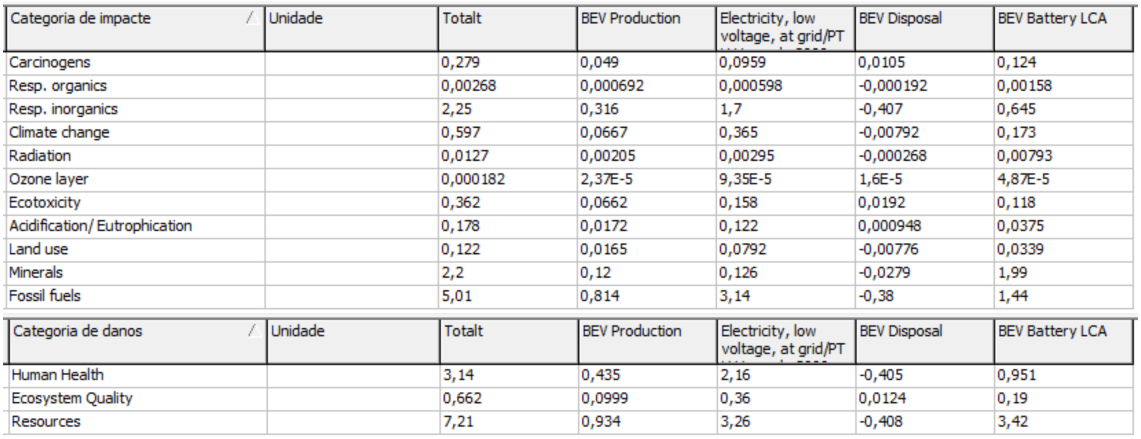
Damage Assessment



Categoria de impacte	Unidade	Totalt	BEV Production	Electricity, low voltage, at grid/PT	BEV Disposal	BEV Battery LCA
Carcinogens	DALY	0,00429	0,000753	0,00147	0,000161	0,00191
Resp. organics	DALY	4,11E-5	1,06E-5	9,19E-6	-2,94E-6	2,43E-5
Resp. inorganics	DALY	0,0346	0,00486	0,0261	-0,00626	0,0099
Climate change	DALY	0,00917	0,00102	0,00561	-0,000122	0,00265
Radiation	DALY	0,000194	3,15E-5	4,53E-5	-4,12E-6	0,000122
Ozone layer	DALY	2,79E-6	3,64E-7	1,44E-6	2,46E-7	7,48E-7
Ecotoxicity	PDF*m2yr	1,86E3	339	812	98,5	606
Acidification/ Eutrophication	PDF*m2yr	912	88,2	627	4,86	192
Land use	PDF*m2yr	625	84,6	406	-39,8	174
Minerals	MJ surplus	1,85E4	1,01E3	1,06E3	-234	1,67E4
Fossil fuels	MJ surplus	4,21E4	6,84E3	2,64E4	-3,19E3	1,21E4

Categoria de danos	Unidade	Totalt	BEV Production	Electricity, low voltage, at grid/PT	BEV Disposal	BEV Battery LCA
Human Health	DALY	0,0483	0,00668	0,0332	-0,00623	0,0146
Ecosystem Quality	PDF*m2yr	3,39E3	512	1,84E3	63,6	972
Resources	MJ surplus	6,06E4	7,85E3	2,74E4	-3,43E3	2,88E4

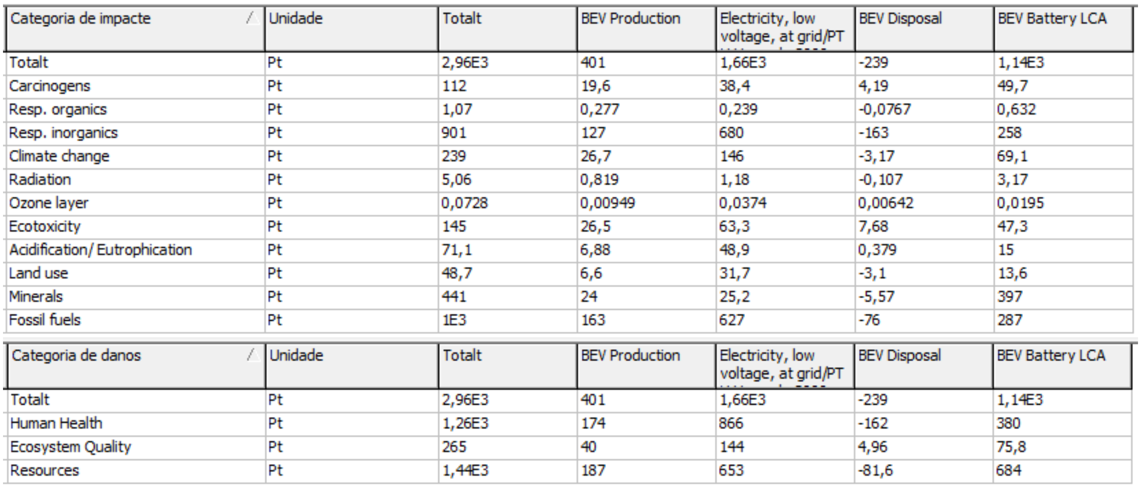
Normalization



Categoria de impacte	Unidade	Totalt	BEV Production	Electricity, low voltage, at grid/PT	BEV Disposal	BEV Battery LCA
Carcinogens		0,279	0,049	0,0959	0,0105	0,124
Resp. organics		0,00268	0,000692	0,000598	-0,000192	0,00158
Resp. inorganics		2,25	0,316	1,7	-0,407	0,645
Climate change		0,597	0,0667	0,365	-0,00792	0,173
Radiation		0,0127	0,00205	0,00295	-0,000268	0,00793
Ozone layer		0,000182	2,37E-5	9,35E-5	1,6E-5	4,87E-5
Ecotoxicity		0,362	0,0662	0,158	0,0192	0,118
Acidification/ Eutrophication		0,178	0,0172	0,122	0,000948	0,0375
Land use		0,122	0,0165	0,0792	-0,00776	0,0339
Minerals		2,2	0,12	0,126	-0,0279	1,99
Fossil fuels		5,01	0,814	3,14	-0,38	1,44

Categoria de danos	Unidade	Totalt	BEV Production	Electricity, low voltage, at grid/PT	BEV Disposal	BEV Battery LCA
Human Health		3,14	0,435	2,16	-0,405	0,951
Ecosystem Quality		0,662	0,0999	0,36	0,0124	0,19
Resources		7,21	0,934	3,26	-0,408	3,42

Single Score

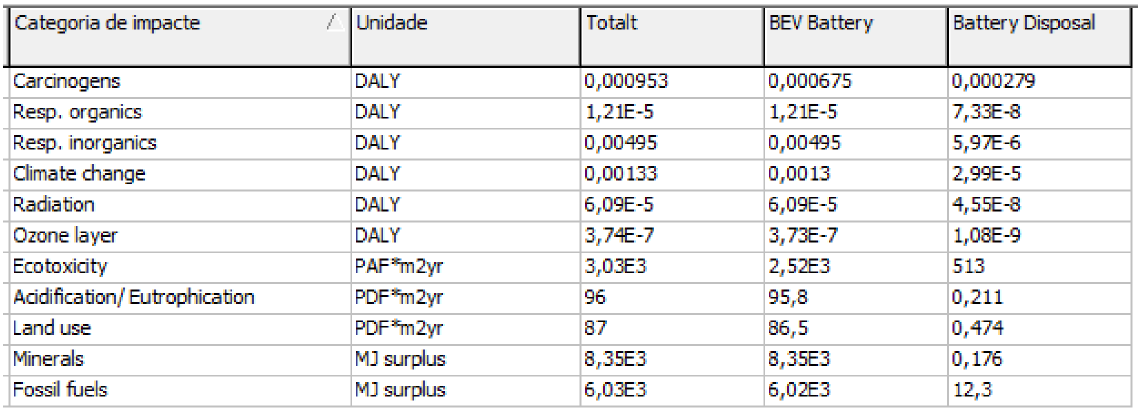


Categoria de impacte	Unidade	Totalt	BEV Production	Electricity, low voltage, at grid/PT	BEV Disposal	BEV Battery LCA
Totalt	Pt	2,96E3	401	1,66E3	-239	1,14E3
Carcinogens	Pt	112	19,6	38,4	4,19	49,7
Resp. organics	Pt	1,07	0,277	0,239	-0,0767	0,632
Resp. inorganics	Pt	901	127	680	-163	258
Climate change	Pt	239	26,7	146	-3,17	69,1
Radiation	Pt	5,06	0,819	1,18	-0,107	3,17
Ozone layer	Pt	0,0728	0,00949	0,0374	0,00642	0,0195
Ecotoxicity	Pt	145	26,5	63,3	7,68	47,3
Acidification/ Eutrophication	Pt	71,1	6,88	48,9	0,379	15
Land use	Pt	48,7	6,6	31,7	-3,1	13,6
Minerals	Pt	441	24	25,2	-5,57	397
Fossil fuels	Pt	1E3	163	627	-76	287

Categoria de danos	Unidade	Totalt	BEV Production	Electricity, low voltage, at grid/PT	BEV Disposal	BEV Battery LCA
Totalt	Pt	2,96E3	401	1,66E3	-239	1,14E3
Human Health	Pt	1,26E3	174	866	-162	380
Ecosystem Quality	Pt	265	40	144	4,96	75,8
Resources	Pt	1,44E3	187	653	-81,6	684

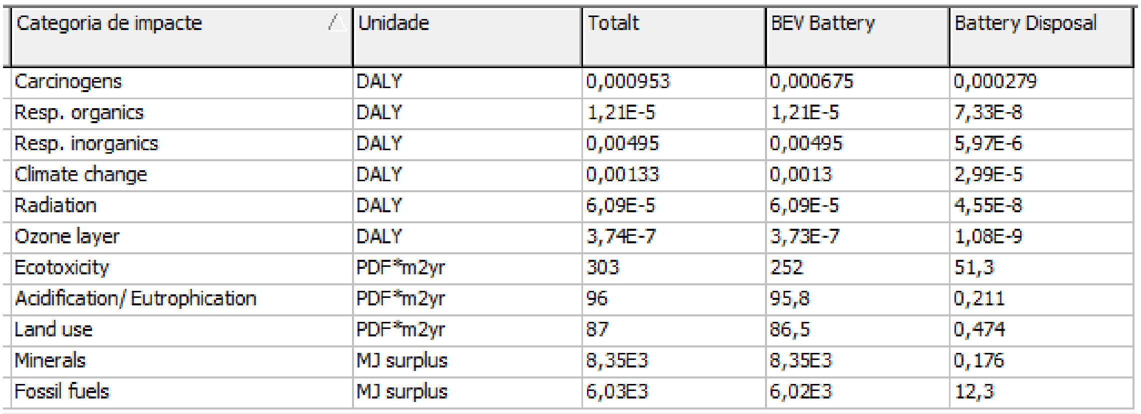
7.7. Lifecycle Impact Assessment of one battery

Characterization

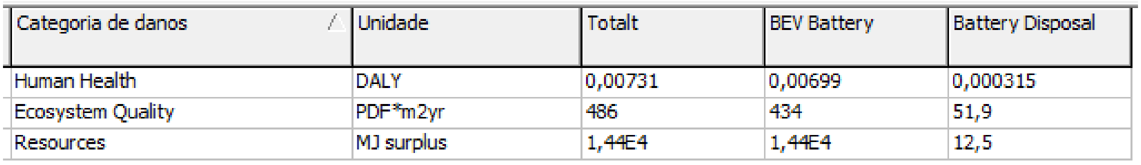


Categoria de impacte	Unidade	Totalt	BEV Battery	Battery Disposal
Carcinogens	DALY	0,000953	0,000675	0,000279
Resp. organics	DALY	1,21E-5	1,21E-5	7,33E-8
Resp. inorganics	DALY	0,00495	0,00495	5,97E-6
Climate change	DALY	0,00133	0,0013	2,99E-5
Radiation	DALY	6,09E-5	6,09E-5	4,55E-8
Ozone layer	DALY	3,74E-7	3,73E-7	1,08E-9
Ecotoxicity	PAF*m2yr	3,03E3	2,52E3	513
Acidification/ Eutrophication	PDF*m2yr	96	95,8	0,211
Land use	PDF*m2yr	87	86,5	0,474
Minerals	MJ surplus	8,35E3	8,35E3	0,176
Fossil fuels	MJ surplus	6,03E3	6,02E3	12,3

Damage Assessment

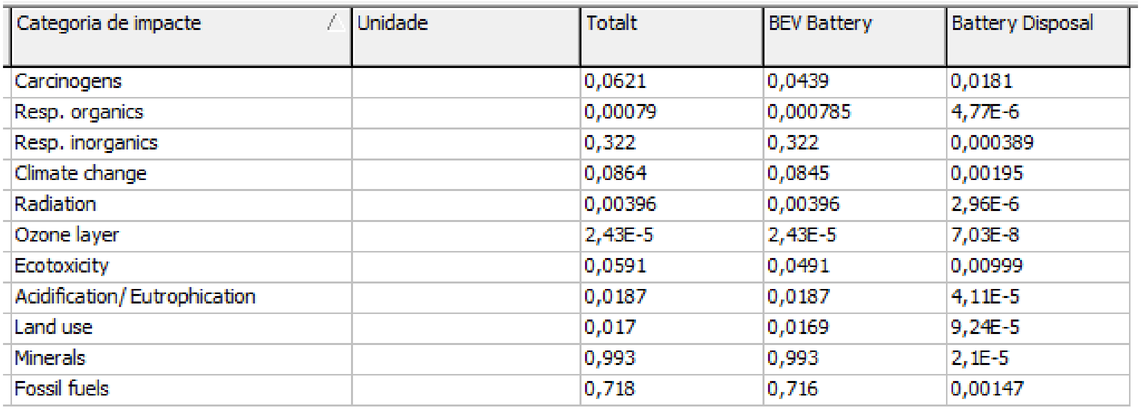


Categoria de impacte	Unidade	Totalt	BEV Battery	Battery Disposal
Carcinogens	DALY	0,000953	0,000675	0,000279
Resp. organics	DALY	1,21E-5	1,21E-5	7,33E-8
Resp. inorganics	DALY	0,00495	0,00495	5,97E-6
Climate change	DALY	0,00133	0,0013	2,99E-5
Radiation	DALY	6,09E-5	6,09E-5	4,55E-8
Ozone layer	DALY	3,74E-7	3,73E-7	1,08E-9
Ecotoxicity	PDF*m2yr	303	252	51,3
Acidification/ Eutrophication	PDF*m2yr	96	95,8	0,211
Land use	PDF*m2yr	87	86,5	0,474
Minerals	MJ surplus	8,35E3	8,35E3	0,176
Fossil fuels	MJ surplus	6,03E3	6,02E3	12,3

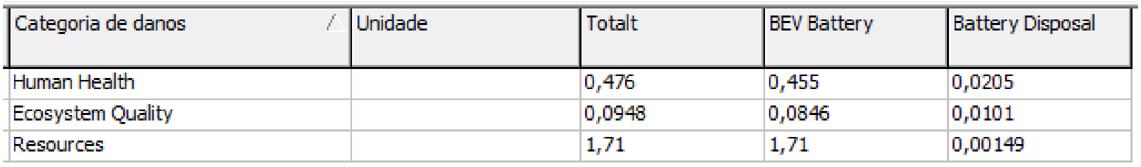


Categoria de danos	Unidade	Totalt	BEV Battery	Battery Disposal
Human Health	DALY	0,00731	0,00699	0,000315
Ecosystem Quality	PDF*m2yr	486	434	51,9
Resources	MJ surplus	1,44E4	1,44E4	12,5

Normalization

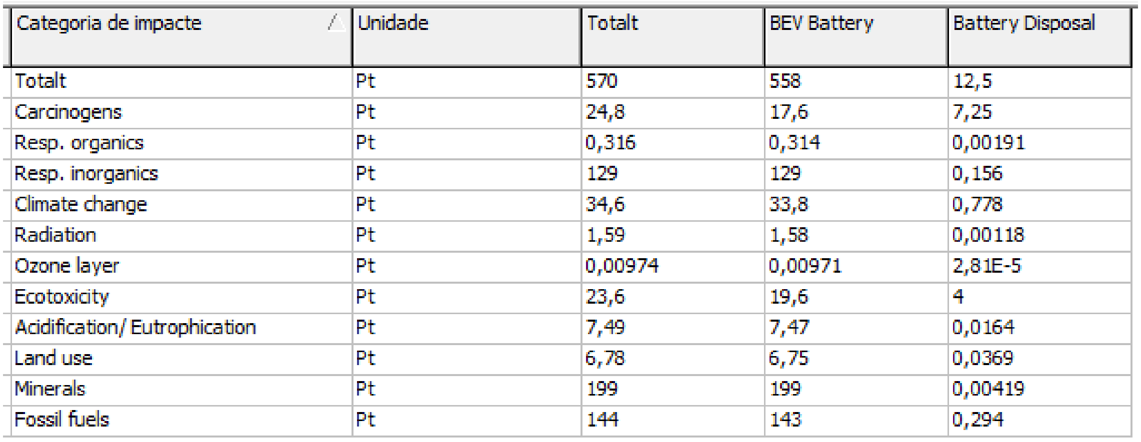


Categoria de impacte	Unidade	Totalt	BEV Battery	Battery Disposal
Carcinogens		0,0621	0,0439	0,0181
Resp. organics		0,00079	0,000785	4,77E-6
Resp. inorganics		0,322	0,322	0,000389
Climate change		0,0864	0,0845	0,00195
Radiation		0,00396	0,00396	2,96E-6
Ozone layer		2,43E-5	2,43E-5	7,03E-8
Ecotoxicity		0,0591	0,0491	0,00999
Acidification/ Eutrophication		0,0187	0,0187	4,11E-5
Land use		0,017	0,0169	9,24E-5
Minerals		0,993	0,993	2,1E-5
Fossil fuels		0,718	0,716	0,00147

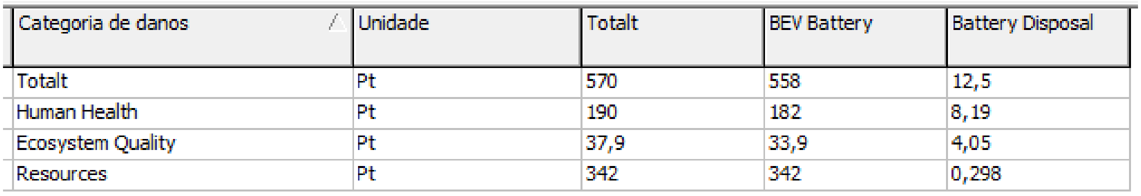


Categoria de danos	Unidade	Totalt	BEV Battery	Battery Disposal
Human Health		0,476	0,455	0,0205
Ecosystem Quality		0,0948	0,0846	0,0101
Resources		1,71	1,71	0,00149

Single Score



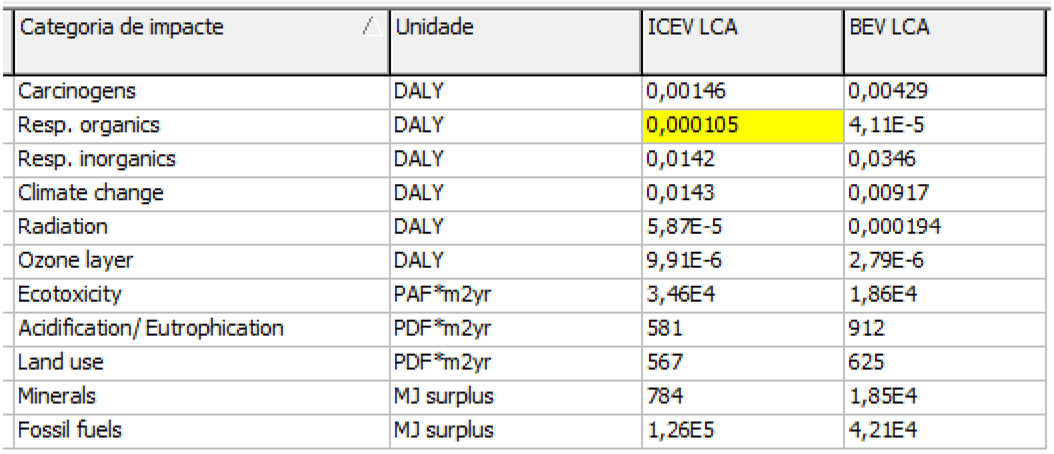
Categoria de impacte	Unidade	Totalt	BEV Battery	Battery Disposal
Totalt	Pt	570	558	12,5
Carcinogens	Pt	24,8	17,6	7,25
Resp. organics	Pt	0,316	0,314	0,00191
Resp. inorganics	Pt	129	129	0,156
Climate change	Pt	34,6	33,8	0,778
Radiation	Pt	1,59	1,58	0,00118
Ozone layer	Pt	0,00974	0,00971	2,81E-5
Ecotoxicity	Pt	23,6	19,6	4
Acidification/ Eutrophication	Pt	7,49	7,47	0,0164
Land use	Pt	6,78	6,75	0,0369
Minerals	Pt	199	199	0,00419
Fossil fuels	Pt	144	143	0,294



Categoria de danos	Unidade	Totalt	BEV Battery	Battery Disposal
Totalt	Pt	570	558	12,5
Human Health	Pt	190	182	8,19
Ecosystem Quality	Pt	37,9	33,9	4,05
Resources	Pt	342	342	0,298

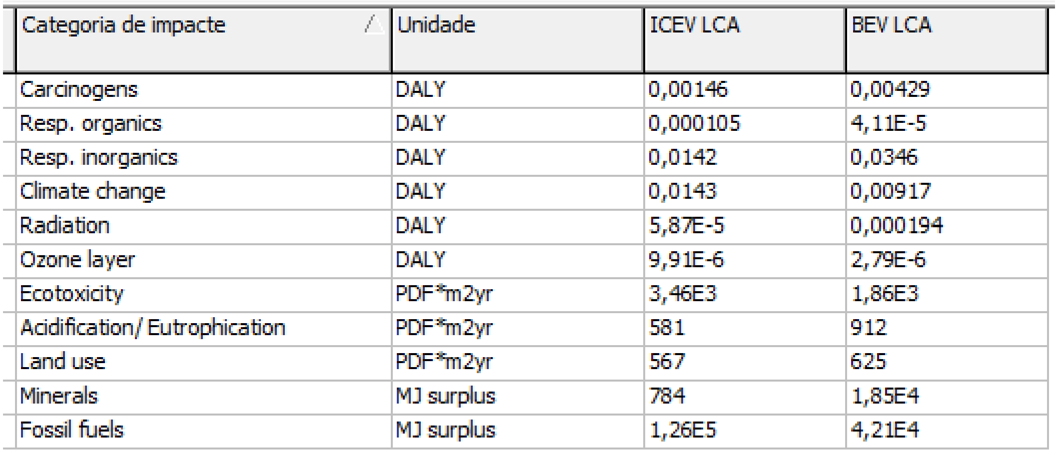
7.8. Lifecycle comparison

Characterization

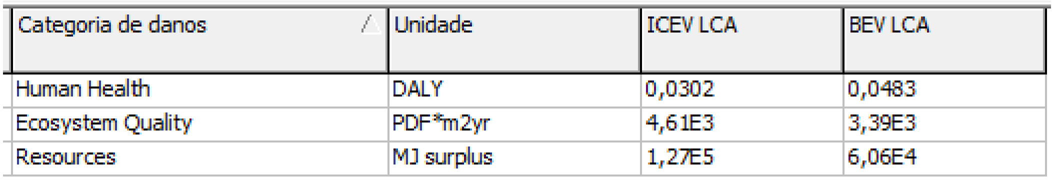


Categoria de impacte	Unidade	ICEV LCA	BEV LCA
Carcinogens	DALY	0,00146	0,00429
Resp. organics	DALY	0,000105	4,11E-5
Resp. inorganics	DALY	0,0142	0,0346
Climate change	DALY	0,0143	0,00917
Radiation	DALY	5,87E-5	0,000194
Ozone layer	DALY	9,91E-6	2,79E-6
Ecotoxicity	PAF*m2yr	3,46E4	1,86E4
Acidification/ Eutrophication	PDF*m2yr	581	912
Land use	PDF*m2yr	567	625
Minerals	MJ surplus	784	1,85E4
Fossil fuels	MJ surplus	1,26E5	4,21E4

Damage Assessment

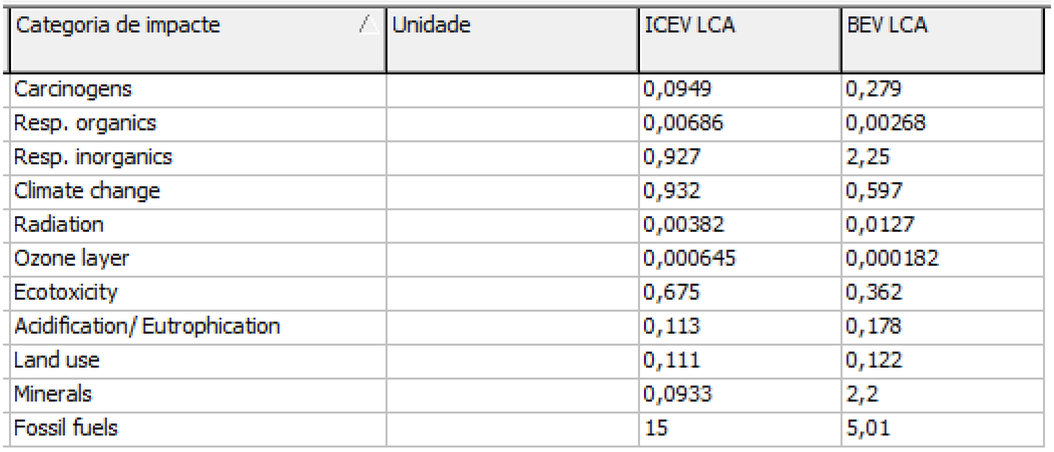


Categoria de impacte	Unidade	ICEV LCA	BEV LCA
Carcinogens	DALY	0,00146	0,00429
Resp. organics	DALY	0,000105	4,11E-5
Resp. inorganics	DALY	0,0142	0,0346
Climate change	DALY	0,0143	0,00917
Radiation	DALY	5,87E-5	0,000194
Ozone layer	DALY	9,91E-6	2,79E-6
Ecotoxicity	PDF*m2yr	3,46E3	1,86E3
Acidification/ Eutrophication	PDF*m2yr	581	912
Land use	PDF*m2yr	567	625
Minerals	MJ surplus	784	1,85E4
Fossil fuels	MJ surplus	1,26E5	4,21E4

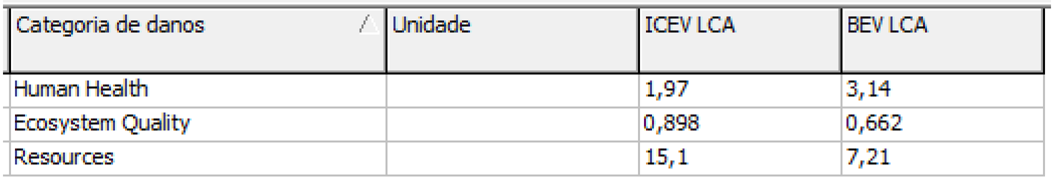


Categoria de danos	Unidade	ICEV LCA	BEV LCA
Human Health	DALY	0,0302	0,0483
Ecosystem Quality	PDF*m2yr	4,61E3	3,39E3
Resources	MJ surplus	1,27E5	6,06E4

Normalization

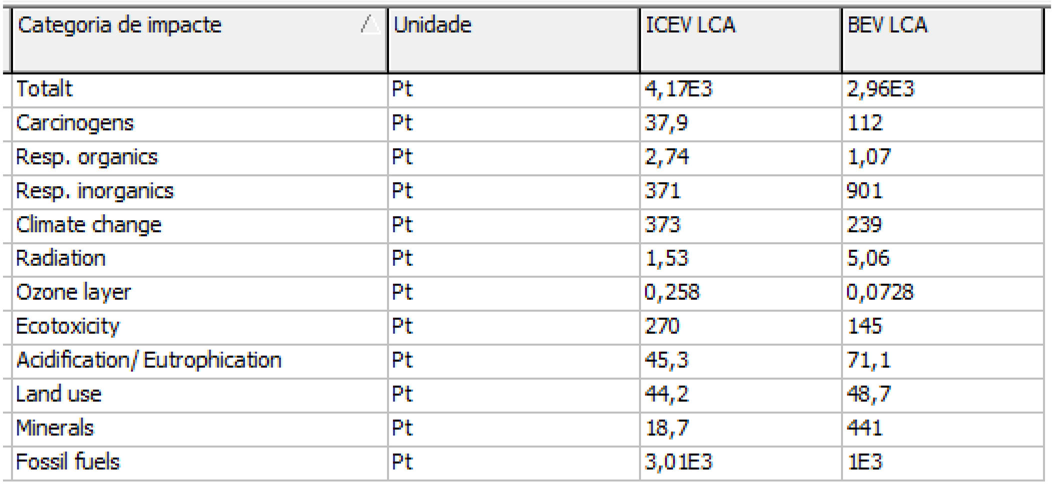


Categoria de impacte	Unidade	ICEV LCA	BEV LCA
Carcinogens		0,0949	0,279
Resp. organics		0,00686	0,00268
Resp. inorganics		0,927	2,25
Climate change		0,932	0,597
Radiation		0,00382	0,0127
Ozone layer		0,000645	0,000182
Ecotoxicity		0,675	0,362
Acidification/ Eutrophication		0,113	0,178
Land use		0,111	0,122
Minerals		0,0933	2,2
Fossil fuels		15	5,01

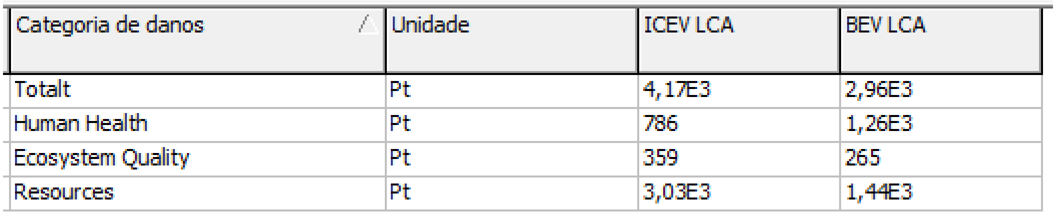


Categoria de danos	Unidade	ICEV LCA	BEV LCA
Human Health		1,97	3,14
Ecosystem Quality		0,898	0,662
Resources		15,1	7,21

Single Score



Categoria de impacte	Unidade	ICEV LCA	BEV LCA
Totalt	Pt	4,17E3	2,96E3
Carcinogens	Pt	37,9	112
Resp. organics	Pt	2,74	1,07
Resp. inorganics	Pt	371	901
Climate change	Pt	373	239
Radiation	Pt	1,53	5,06
Ozone layer	Pt	0,258	0,0728
Ecotoxicity	Pt	270	145
Acidification/ Eutrophication	Pt	45,3	71,1
Land use	Pt	44,2	48,7
Minerals	Pt	18,7	441
Fossil fuels	Pt	3,01E3	1E3



Categoria de danos	Unidade	ICEV LCA	BEV LCA
Totalt	Pt	4,17E3	2,96E3
Human Health	Pt	786	1,26E3
Ecosystem Quality	Pt	359	265
Resources	Pt	3,03E3	1,44E3