Grant Agreement no. 308371
ENV.2012.6.3-2 - Policy Options for a Resource-Efficient Economy

- Collaborative project -

D3.6- Report about Modelling Results from LCA Perspective

WP 3 – Modelling Results

Due date of deliverable: Month 36 (extension granted month 37)

Submission date: 20 / 10 / 2015

Start date of project: 1st October 2012 Duration: 42 months

Lead beneficiary for this deliverable: UCL

Principal Investigators: Paola Lettieri 1, Sara Evangelisti1, Carla Tagliaferri1, Teresa Domenech2, Marc Dijk3

1 University College London, Department of Chemical Engineering, Torrington Place, London WC1E 7JE, UK

2 University College London, Institute for Sustainable Resources, Central House, 14 Upper Woburn Place, London WC1H 0NN, UK

3 ICIS- Maastricht University, Kapoenstraat 2, 6200 MD Maastricht, The Netherlands

This project has received funding from the European Union's Seventh Programme for research, technological development and demonstration under grant agreement No 308371.

Dissemination Level		
PU	Public	PU

History table

Version	Date	Released by	Comments
Final version	19th October 2015	UCL	

Table of contents

List of figures

List of tables

1. Introduction

The transport sector is one of the most challenging when tackling the target of emissions reduction: currently, the CO2 emissions from the transport sector represent about 30% of the total emissions in the case of developed countries and about 23% in the case of the total man-made CO2 emissions worldwide [1]. In addition to this, it is expected that the number of light-duty vehicles in operation will rise significantly in the next decades. A study commissioned by the World Business Council for Sustainable Development (WBCSD) estimates that light-duty vehicles would increase to about 1.3 billion by 2030 and 2 billion by 2050 [2]. Hence, unless fundamental changes are made, this would drive dramatic increases in the demand for fuel supplies associated with transport, and associated impacts related to climate change, urban air quality as well as non-renewable resources depletion. This challenging context has contributed to the push towards the development of new solutions and technologies in the automotive industry. One possible solution for decreasing the carbon footprint of the transport sector is the use of low-carbon content fuels (such as cellulosic ethanol or soy biofuel) in conventional internal combustion engine vehicles, instead of the regular fuel supply [3]. However, the production of biofuel has well known drawbacks when applied to a large scale. Another option that reduces the pressure on land compared to the production of bio-energy is to move towards electric vehicles (EVs). Electric cars are promising technologies to reduce greenhouse gas emissions compared to ICEVs, thanks to the avoided or reduced requirements of diesel or gasoline as fuel supply. According to Zackrisson et al. [4], the potential saving range is between 25% for hybrid EVs, up to 50-80% for plug-in hybrid EVs and about 90% for battery EVs. Furthermore a very wide range of road vehicles can use electric power for motion: from heavy-duty vehicles- such as hybrid buses and tramways to light duty ones, including city cars, forklift trucks etc. This broad range of vehicles is associated with different battery technologies (i.e. Lithium-ion battery (Li-ion), Lithium-phosphate (Li-phosphate), Nickel Metal Hydride (NiMH), lead acid, nickel cadmium batteries) characterised by specific properties (specific power, depth of discharge (DoD), memory effect, number of charges per cycle, etc.).

The use of heavy metals for battery manufacturing, the electricity mix and the disposal of the used battery are key aspects in the life cycle of an electric vehicle that need to be carefully considered under a life cycle approach to identify sources of key environmental impacts. Wietschel et al. [5] reports an increase in electric vehicle penetrating in the future mobility markets, reaching about 1.2 million of sales in 2020. However, it is also recognised that EV are also facing the important technological challenges today. LCA can bring insights to the environmental implications associated with the manufacturing, use phase and end of life of electric cars and contribute to inform policy making in the area of resource efficient mobility.

A number of LCA studies have been published in recent years. Bettez and colleagues [6] provided a detailed inventory for the manufacturing of lithium-ion battery, designed to be adapted into a complete study of the entire EV life cycle; Ellingsen and colleagues [7] gave a more detailed description of the battery system and they worked with industrial partners to develop the inventory of their LCA. Our study its novel in two ways: 1) it incorporates the end of life of batteries and electric vehicles and 2) it considers future scenarios based on assumptions to changes in the electricity mix and the transition to a low carbon economy.

The purpose of this study was to perform an attributional life cycle assessment of the manufacturing, use and disposal phase of EVs, and compare it to the life cycle of a conventional vehicle, such as diesel ICEVs. All the components of the vehicle, including the battery system, the glider, and the power train are analysed in the hot spot analysis.

2. Life cycle assessment methodology

Life cycle assessment is one of the most developed and widely used environmental assessment tools for comparing alternative technologies when the location of the activity is already defined [8], [9]. LCA quantifies the amount of materials and energy used and the emissions and waste generated over the complete supply chain (i.e. life cycles) of goods and services [10]. Moreover, it helps determining the ''hot spots'' in the system, i.e. those activities that have the most significant environmental impact and should be improved in the first instance, thus enabling the identification of more environmentally sustainable options [11].

In LCA, a multifunctional process is defined as an activity that fulfills more than one function [12]. It is then necessary to find a rational basis for allocating the environmental burdens between the functions. The problem of allocation in LCA has been a topic of much debate (e.g. [8], [13]). The ISO standards recommend that the allocation phase should be avoided "expanding the product system to include the additional functions related to the co-products" [14]. This can be performed by broadening the system boundaries to include the avoided burdens of conventional production (i.e substitution by system expansion) [15], [16]. The same approach is recommended by the UK product labelling standard provided that it can be proved that the recovered material or energy is actually put to the use claimed [17]. As shown in Figure 1, this approach is applied in this study.

Following the methodological approach of Clift et al. [8], a pragmatic distinction is made between Foreground and Background, considering the former as 'the set of processes whose selection or mode of operation is affected directly by decisions based on the study' and the latter as 'all other processes which interact with the Foreground, usually by supplying or receiving material or energy'. The burdens evaluated here are considered under three categories [8]: direct burdens, associated with the use phase of the process/service; indirect burdens, due to upstream and downstream processes (e.g. energy provision for electricity or diesel for transportation); and avoided burdens associated with products or services supplied by the process (e.g. energy or secondary material produced by the system).

Currently more than thirty software packages exist to perform LCA analysis, with differing scope and capacity: some are specific for certain applications, while others have been directly developed by industrial organisations [18]. In this study, GaBi 6 has been used [19]. GaBi 6 contains databases developed by PE International, it incorporates industry organisations' databases (e.g. Plastics Europe, Aluminium producers, etc) and also regional and national databases (e.g. Ecoinvent, Japan database, US database, etc).

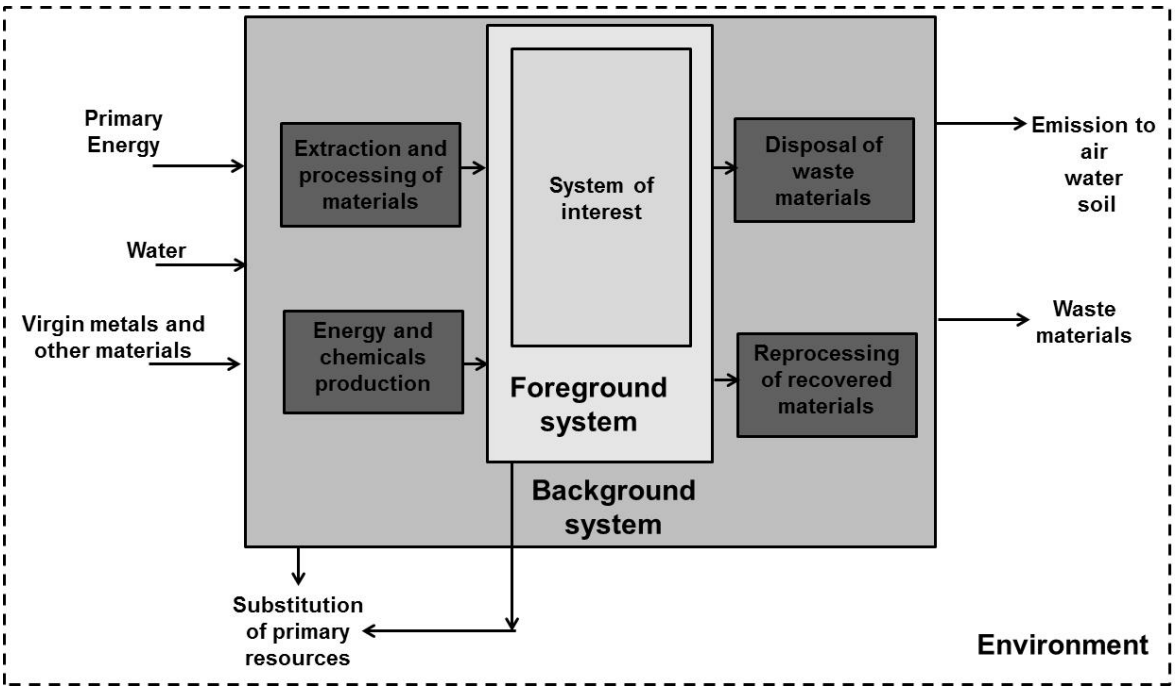


Figure 1. Life cycle assessment approach.

3. Life cycle assessment model

3.1. Goal and scope definition

The main goal of this analysis was to perform an attributional life cycle assessment of a battery electric vehicle (BEV), and compared it with the life cycle impacts of a more conventional technology, such as an internal combustion engine diesel vehicle (ICEV). Moreover, a hot spot analysis to identify the steps with the highest impacts to the total life cycle was performed. Finally, two different scenarios were considered for the end-of-life phase: a 'high recycling rate' scenario – where the total vehicle is assumed to be recovered in EU at its EoL; and a more realistic 'low recycling rate' scenario, where a fraction of the vehicles is assumed to be landfilled outside EU borders. The latter scenario more accurately represents the current situation of the vehicle EoL market in Europe, where part of the fleet exits the EU borders [20], to be sold in third countries. The study also includes a number of future scenarios for 2020, 2030, 2050, under different institutional settings, which assume different combinations of electricity grid mix. The results of the future scenarios are reported in the appendix.

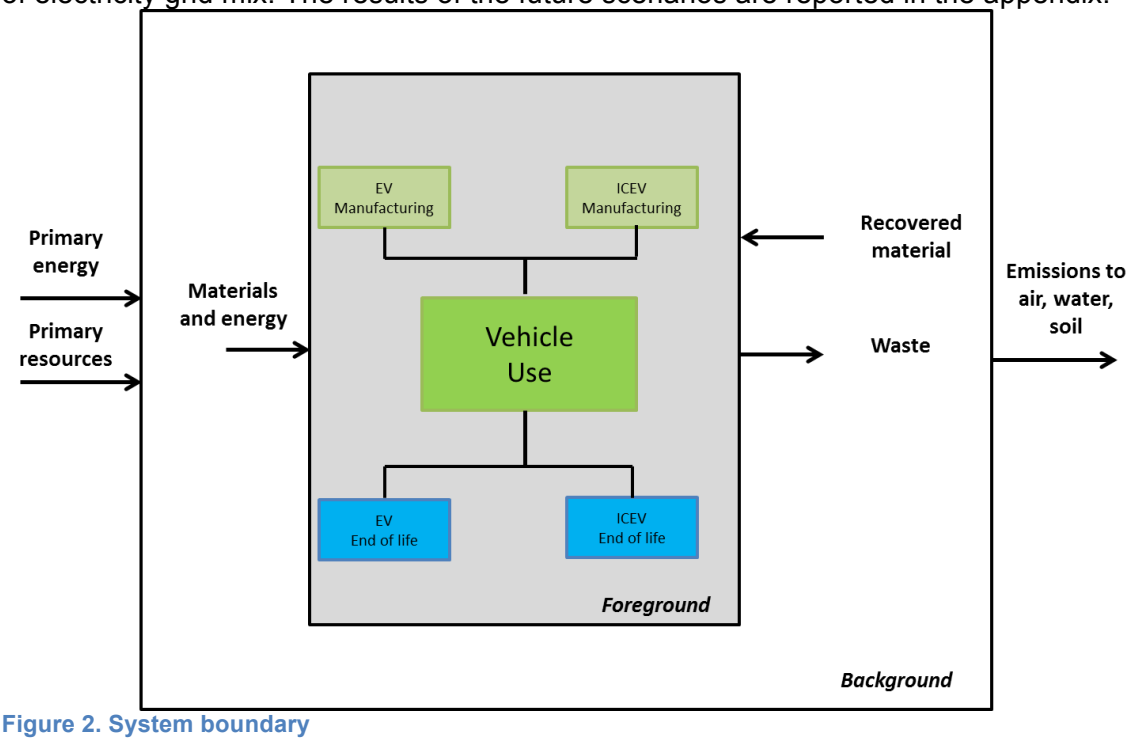


Figure 2. System boundary

A first step in the developing of the LCA has been the definition of the system boundaries. Figure 2 shows the system boundary of the system analysed. Three different phases have been considered in the analysis: the manufacturing phase – which includes the production of the batteries and all the single components up to the glider; the use phase – which includes the production of electricity needed to recharge the battery; the end of life phase – which includes from the reprocessing of the vehicle including the battery, up to the recovery of some metals. For all the phases, direct, indirect and avoided burdens have been accounted for.
The functional unit used in this study was 1 km driven by one vehicle. To account for the manufacturing and the disposal phase, an assumption of the total km driven in the entire life cycle of the vehicle was made. Based on previous studies [6], [7], a total life cycle of 150,000 km was considered for both BEVs and ICEVs.

3.2. Life cycle inventory: data sources

In this section, the inventory built for the BEV and ICEV models is presented. The inventory was based on a mix of data sources from recently published studies on BEVs and plug-in vehicles, existing dataset [19], [21], as well as reports and presentation from private companies [22].
The vehicle's models chosen as the basis for the analysis were based on commercial vehicles currently sold on the market. For the BEV, a Nissan leaf was assumed as a reference model while for the ICE a Toyota Yaris was assumed as commercial vehicle because it shows similar characteristics, in terms of size, function and style to the Nissan Leaf. Figure 3 shows the two commercial cars used as reference vehicle for the LCA model.

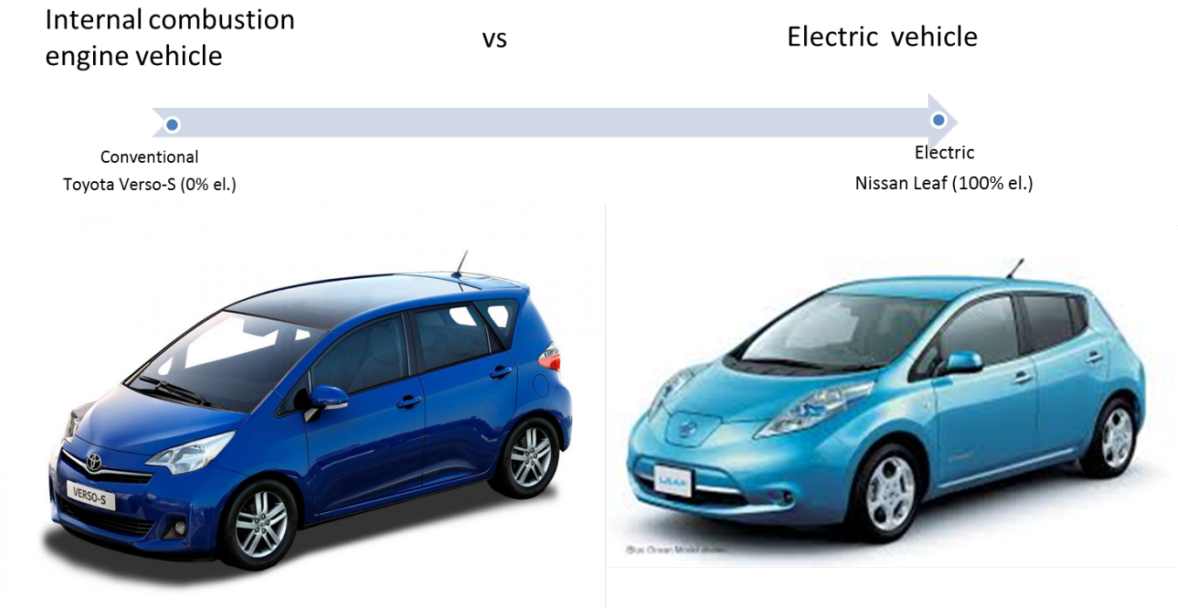


Figure 3. Commercial vehicles assumed in the LCA models.

Two different models were considered for the BEV life cycle analysis, in order to test the robustness of the results. The first model (EV I) was based on the study published by Bettez et al. [6]. In their study, Bettez and colleagues based the LCA inventory on average literature data for the manufacturing of the battery. The second model (EV II) was based on the study published by Ellingsen et al. [7]. Their inventory was based on an existing battery, and the dataset for this was built with a mix of average and commercial data supplied by the battery manufacturing industry.
In total, 44 flows, 123 processes and 116 macro-units were modelled for the EVI and EVII to build the LCA models of this project.

3.3. Manufacturing phase

The vehicle is composed by several units, which can be divided in sub-units up to the single component. As shown in Figure 4, the two main macro-units, which compose the vehicle, are the powertrain (electric motor and battery system for the BEV and the internal combustion engine for the ICEV) and the glider. For both ICEV and BEV, the glider was based on Ecoinvent 2.1 [21]. Table 1 shows a list of the components included in the glider inventory.

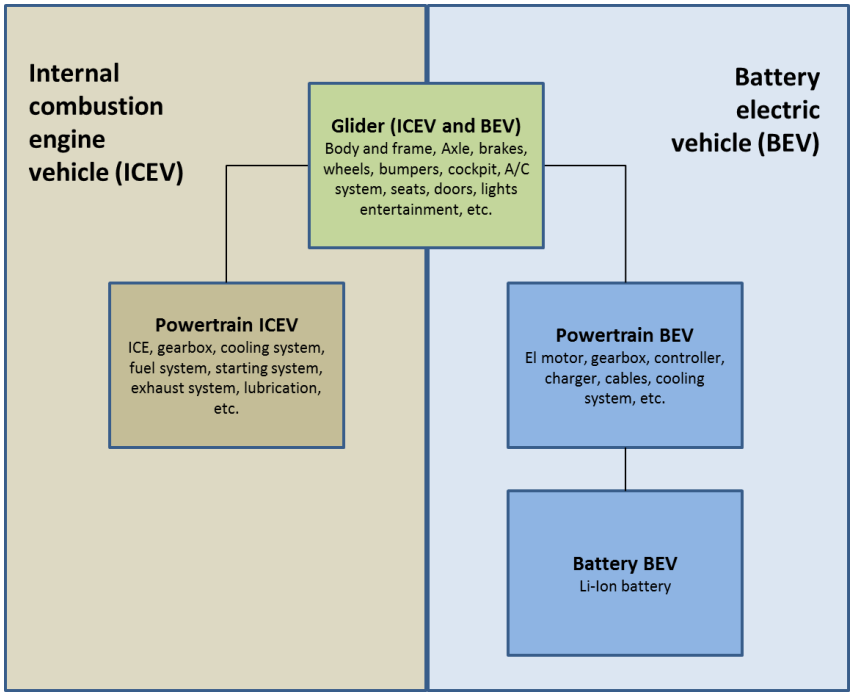


Figure 4. Macro units and components of an ICEV and BEV [23].

Table 1. Components included in the glider (for both BEV and ICEV) [21], [23].

Unit	Component
Body&Frame	Chassis and body
Body&Frame	Gaskets
Body&Frame	Front screen
Body&Frame	Zinc coating
Body&Frame	Insulation
Body&Frame	Paint
Body&Frame	Wiper liquid (Glycol/WateEr)
Axle	Front axle steering
Axle	Axle Rear axle
Breaks	Brake shoes, disks, supports
Breaks	Brake pressure hoses
Breaks	Brake oil
Breaks	Brake shoes, supports
Wheels	Rims
Wheels	Tyres
Bumper	Dampers and springs
Air Conditioning	Compressor
Air Conditioning	Air distribution
Air Conditioning	Adapters
Air Conditioning	Refrigerant R134a
Cockpit	Cockpit
Safety (Belts, AirbagBse)	lts airbags
Interior / Linings	Linings

Interior / Linings	Insulation
Seats	Seat structure
Seats	Seat covers
Doors	Frames
Doors	Windows side and rear
Electrics / Lights	Lights
Electrics / Lights	Cables
Electrics / Lights	El. Motors St. 50%
Electrics / Lights	El. Motors Al 30%
Electrics / Lights	El. Motors Cu 20%
Electronics	Electronics

Battery Electric Vehicle

The powertrain of the battery electric vehicle includes all the units of the BEV excluding the glider (see Figure 3). In total, the weight of the glider and the powertrain excluding the battery was 1307 kg and 1271 kg for EVI and EVII, respectively, in order to match a total weight for the BEV equal to the Nissan leaf. The weight of the Li-Ion battery was 214 and 250 kg for EVI and EVII, corresponding to a specific power of 112 and 106 Wh/kg. Table 2 shows the characteristics of the Nissan Leaf, which is the electric vehicle assumed in this study for the BEV.

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

Nissan Leaf		
Curb weight	kg	1521
Length	cm	444.5
Width	cm	177
Height	cm	155
Body style		5-door hatchback
Electric motor	kW	80
Battery (Li-Ion)	kWh	24
Range	km (EPA[1])	117
	km (NEDC[2])	175
Energy per km	Wh (NEDC)	173

Note: [1] Environmental Protection Agency; [2] New European Driving Cycle.

3.3.1. Battery system

Figure 5 shows the flow diagram of the battery system. This is composed by four units: the cooling system; the battery cell; the packaging; and the battery management system (BMS).

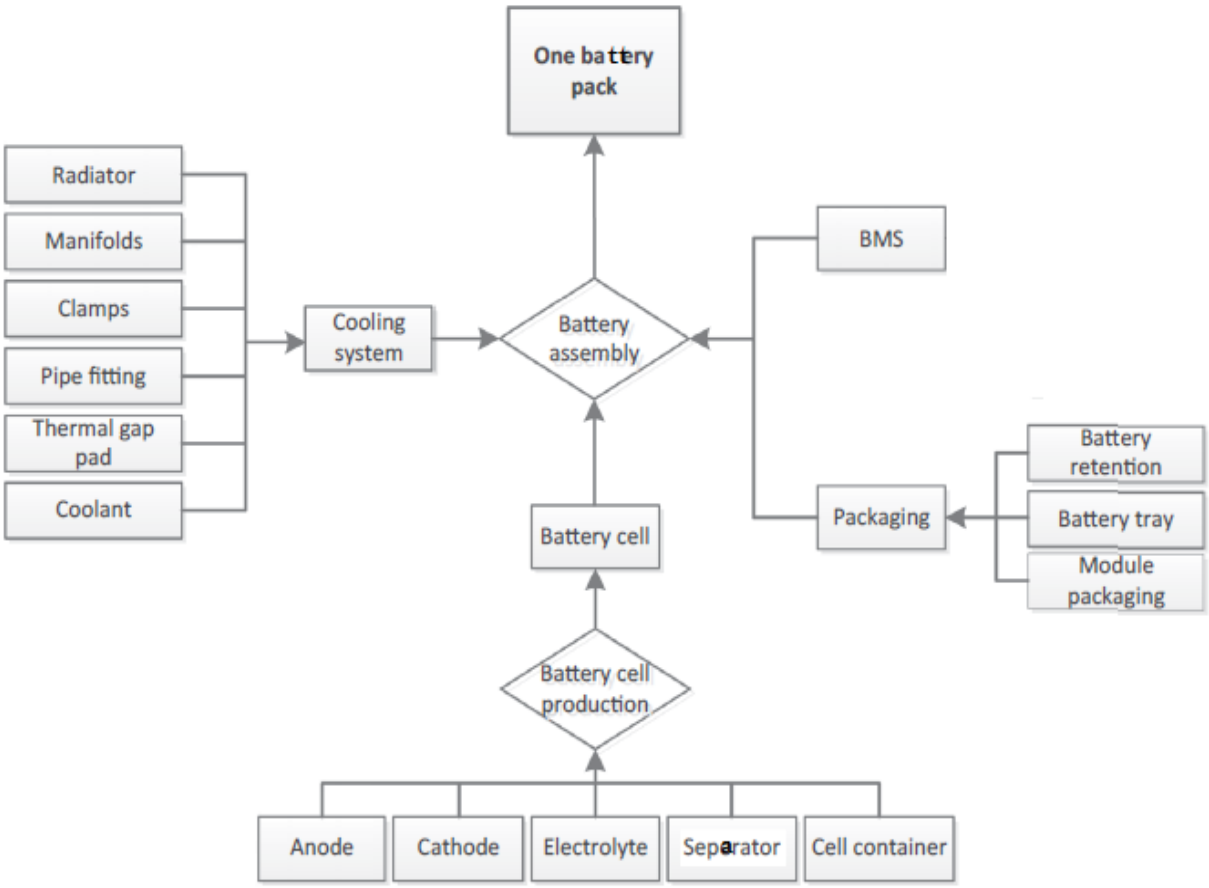


Figure 5. Process flows of the Battery system [7].

The battery system is the core of the BEV. For this analysis, we have assumed a Li-ion battery type. The battery system is composed by several components, which were all modelled originally in this study based on the inventory developed by Majeau-Bettez et al. [6] – for the EVI, and Ellingsen et al. [7] – for the EVII. The battery is composed by several modules, each one made up by a specific number of cells based on the required energy output of the battery system.
The main differences amongst the two models are in terms of materials and quantities involved in the manufacturing phase, and in the energy assumed for the manufacturing of the battery system.
The energy required for the manufacturing of the battery system can vary greatly amongst the literature, from 3.1 to 1060 MJ/kWh [7]. In particular, the value of the energy requirement for manufacturing is considerably different for the two battery models analysed. Ellingsen et al. [7] assumed an energy requirement of 586 MJ/kWh based on industrial data, while Majeau-Bettez et al. [6] reported an energy consumption between 371 and 473 MJ/kWh based on industry reports. Moreover, while Ellingsen et al. [7] refers to the energy required to manufacture the battery cell, the figure assumed by Majeau-Bettez et al. [6] included also the energy for the battery system assembling.
Figure 6 and 7 show the mass distribution amongst the battery components for EVI and EVII. For both models, the main component of the battery pack is the cell. It is worth noticing that originally Majeau-Bettez et al. [6] did not include the cooling system as a component of the battery pack. For a balanced comparison between the two models, this study includes the cooling system as defined by Ellingsen et al. [7] also in EVI model.

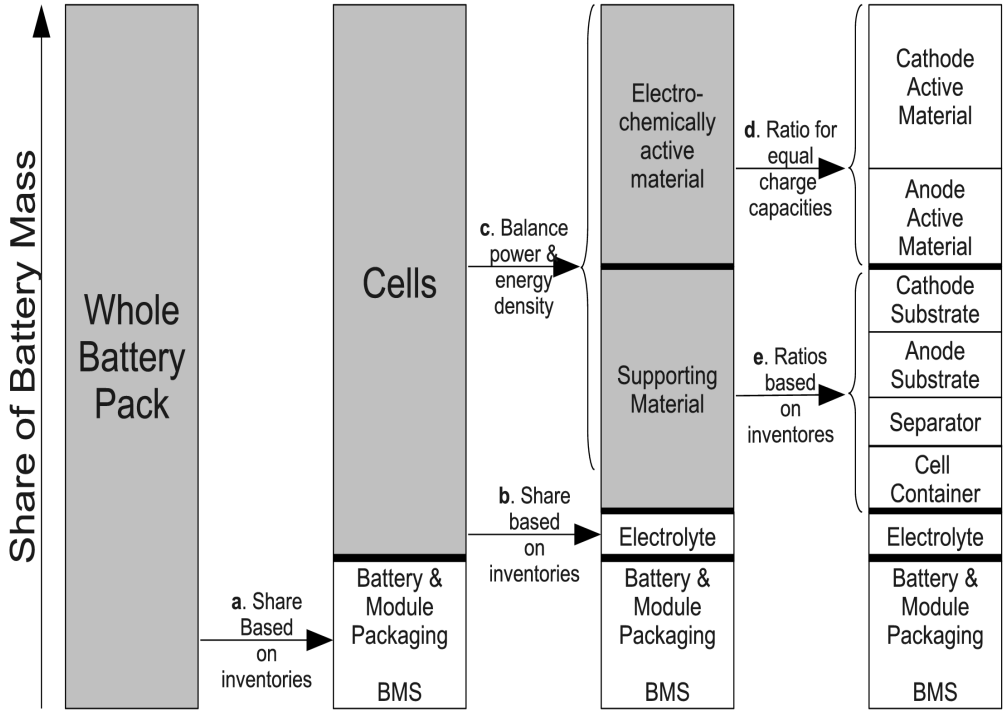


Figure 6. Mass distribution for EVI battery system [6].

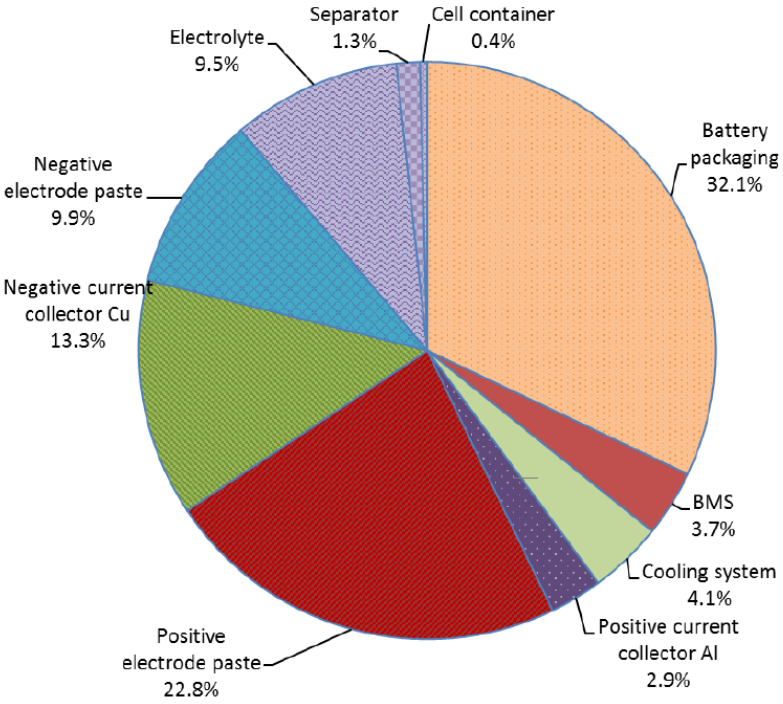


Figure 7. Mass distribution for EVII battery system [7].

3.3.2. Cooling system

The thermal management of the battery is done by the cooling system. This is made by six sub-components: radiator, manifolds, clamps & fasteners, pipe fitting, thermal gap pad, and coolant [7]. The main component is the aluminium radiator, which accounts for the 30% of the total aluminium used in the battery system [7]. The cooling system is the same for EVI and EVII model.

3.3.3. Battery cell

Figures 8-12 show the process flow for the manufacturing of the cell for EVI. As shown in Figure 5, the cell is composed by five components: anode, cathode, separator, electrolyte and cell container. The electricity requirement for the manufacturing of the cell in EVI includes the coating of the electrode pastes to metallic foils used as current collectors, welding of current collectors to tabs, filling of electrolyte, and initial charging of the finished cell. However, as noted by Ellingsen et al. [7], the main consumption is associated to the operation of various dry rooms that are vital to the quality of the battery cells. This explains also the difference in energy consumption assumed in EVI and EVII.

The anode is composed of a copper current collector with a coat of negative electrode paste (Figure 8). The negative electrode paste consists mainly of synthetic graphite, but also contains small amounts of binders. The cathode (Figure 9) is composed of an aluminium current collector with a coat of positive electrode paste. The positive electrode paste consists mainly of the positive active material, Li(NixCoyMnz)O2, and small amounts of carbon black and a binder. The cell container consists of a multilayer pouch and tabs (Figure 12). The pouch is placed around the cell components, with one end left open for electrolyte filling. After the electrolyte has been added and evenly distributed between the cathode, separator, and anode, the cell is sealed. For each cell, a copper tab is welded to the negative current collector and an aluminium tab welded to the positive current collector. The tabs pass through the walls of the sealed pouch and connect the cell to bar-shaped conductors, referred to as busbars [7].

Each of the battery cells has an outer and an inner frame, which includes heat transfer plates. These plates contribute to more than 60% of the total aluminium use in the studied battery.

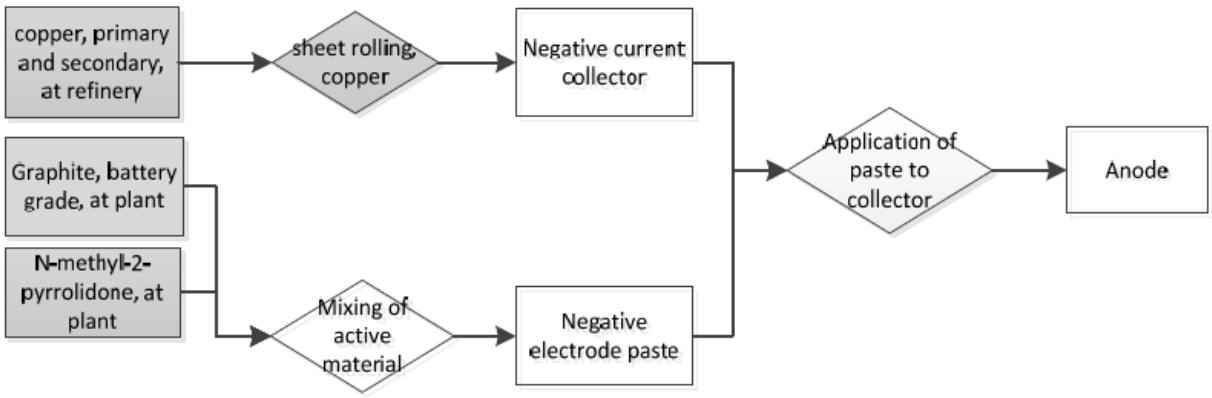


Figure 8. Anode manufacturing [6].

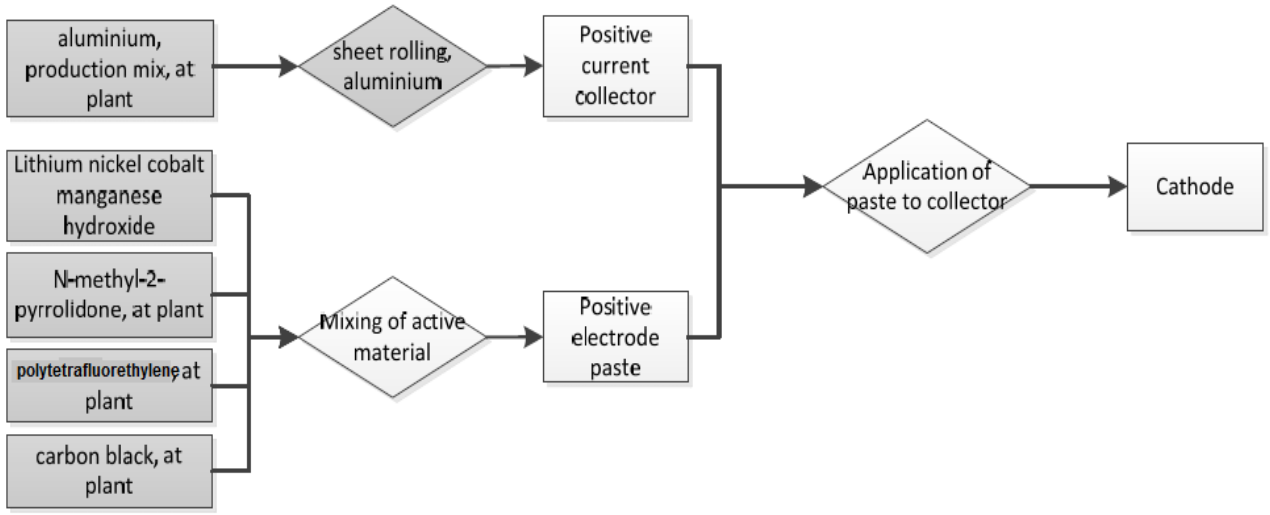


Figure 9.Cathode manufacturing [6].

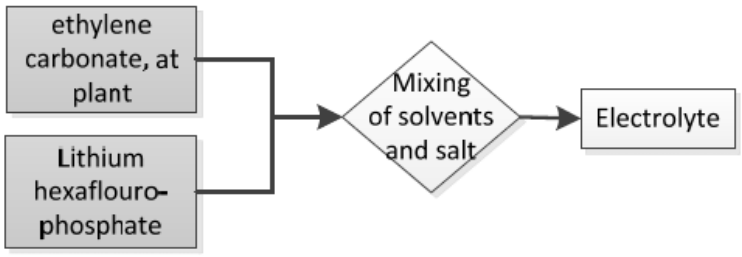


Figure 10.Electrolyte manufacturing [6].

Figure 11. Separator manufacturing [6].

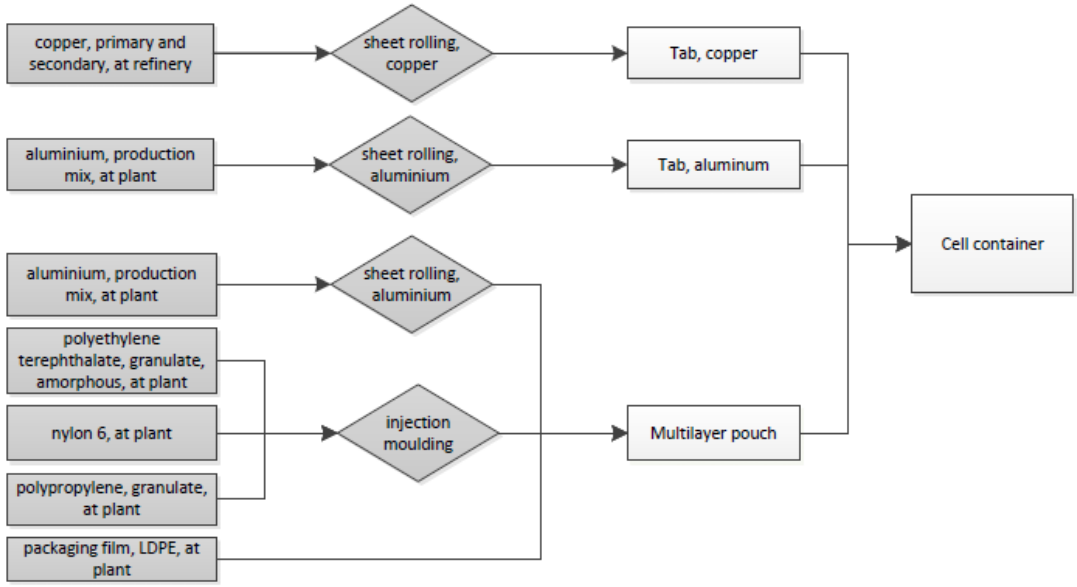


Figure 12. Cell container manufacturing [6].

3.3.4. Packaging

The packaging is divided into three components: module packaging; battery retention; and battery tray. The first consists of inner and outer frames, the busbars, the module fasteners and the module lid. There are several battery modules in one battery, and the battery retention system keeps the battery modules in place within the battery tray, using straps, restraints, and foams. In addition, eight heat transfer plates made of steel are considered a part of the battery retention system. All battery components are placed inside a steel battery tray, which is closed with a sealed lid [7].

3.3.5. Battery management system

The BMS includes battery module boards (BMBs), the Integrated Battery Interface System (IBIS), fasteners, a high-voltage (HV) system, and a low-voltage system. Usually BMBs are placed under the module lid and their role is to monitor the voltage and temperature of the battery cells. The IBIS is the master controller of the BMBs and it is in charge of the battery charge and discharge strategies.

ICEV

The inventory for the ICEV manufacturing phase is based on Ecoinvent 2.2 database [21]. They referred to a life cycle inventory analysis based on a “Golf A4, 1.4 l Otto” [24]. The whole life cycle inventory as reported by Ecoinvent was scaled up to match the total weight of the Toyota Yaris, which was 1500 kg. The emissions to air during the manufacturing process are assumed to result from stationary combustion processes at the factory site [21].

3.4. Use phase

In the use phase, we have accounted for the emissions due to the use of the vehicles (direct emissions) and for the emissions due to the production of the fuel (indirect emissions), i.e. electricity for BEV and diesel for ICEV.

BEV

The energy consumption reported in the literature can vary significantly depending on the assumptions made of battery cycles or lifetime. In our study, we assumed a lifetime of 150,000 for the BEV, in line with the study of Notter et al. [23]. The electric

energy needed to drive 1 km was assumed to be equal to 0.56 MJ/km, based on Ecoinvent 2.2 [21], with a powertrain efficiency of 80% in a standard driving cycle (New European Driving Cycle, NEDC). This is similar to the consumption reported by Notter et al. [23], which shows an electrical consumption of 17 kWh for 100 km, referred to a combination of the urban (12.8 kWh/100km) and extra-urban (16.8 kWh/100km) energy consumption in a NEDC, plus the consumption of heating and air conditioning during one year. A slightly lower electrical consumption was assumed in Ellingsen et al. and Majeau-Bettez et al. [6], [7], corresponding at 3,000 cycles for the battery lifetime, and equals to 0.5 MJ/km. In order to analyse the sensitivity of the environmental results to the power train efficiency a scenario analysis was performed. For this analysis, the power train efficiency ranged between 50% and 90% according to a fixed battery output of 0.448 MJ/km- i.e. the energy available for the vehicle. We calculated the energy input required by the battery for the different power train efficiencies chosen according to a linear relation.

$$power\ train\ efficiency = \frac{energy\ available\ for\ the\ vehicle}{energy\ input\ at\ the\ battery}$$

3.4.1. Electricity

In this study we have assumed an electricity production mix representative of the average European electricity grid. The inventory was based on GaBi database [19]. The mix of primary sources considered is shown in Figure 13. The European mix has as a reference year 2011. It is dominated by nuclear energy (mainly from France), hard coal and natural gas, which alone constitute around 64% of the total primary energy.

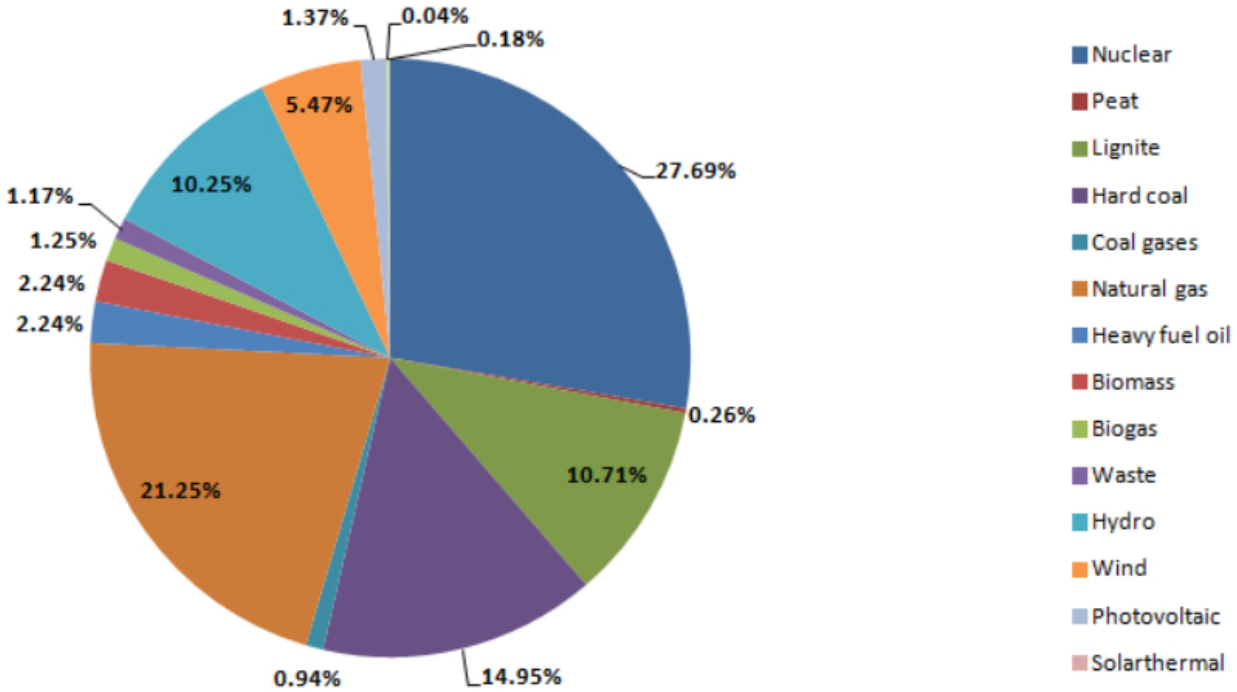


Figure 13. European primary sources mix for electricity production [19].

ICEV

For the ICEV use phase we assumed the same lifetime of the BEV, which was 150,000 km. The fuel consumption assumed was 50.04 mL/km, based on Ecoinvent

2.2 [21]. A EURO 5[1] vehicle was assumed, in accordance to the most recent European regulations on the subject.

3.4.2. Diesel

The production of diesel was based on Gabi database [19]. The data set covers the entire supply chain of the refinery products. European specific downstream (refining) technologies, feedstock (crude oil) and product (diesel fuel, etc.) properties, like sulphur contents are considered. The biogenic components blended to the fossil fuel are also included in the model according to the GaBi database [19].

3.5. End-of-Life phase

BEV

The disposal of the battery electric vehicle has been modelled considering the glider and the powertrain excluding the battery, and the disposal of the Li-Ion battery. The first set of components was assumed to follow the same disposal route as defined in the Ecoinvent database (See ICEV).

The disposal of the Li-Ion battery was modelled according to a state of the art technology developed by Umicore [22]. This process includes two pathways: pyro-metallurgical treatment and hydrometallurgical treatment. Given the lack of inventory data, we have assumed the hydro and pyro-metallurgical processes in the Ecoinvent database as proxy of the Umicore process (see Figure 14).

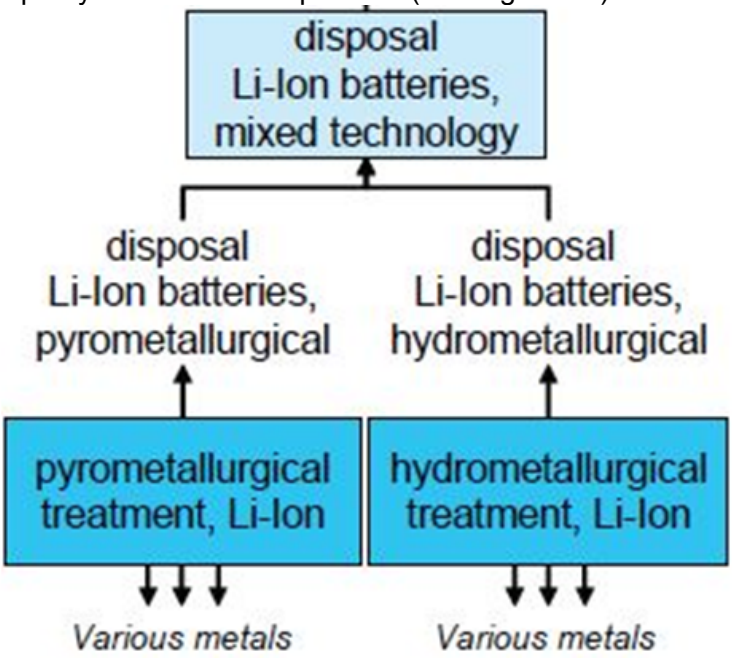


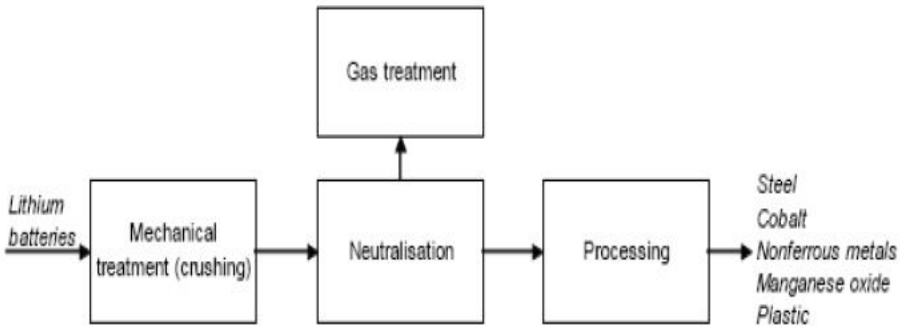
Figure 14. Disposal of one Li-Ion battery in the Ecoinvent database (based on Hischier [25]).

The Umicore process is a single-furnace pyro-metallurgical treatment method for the treatment of Li-Ion batteries and Li-polymer cells, as well as nickel metal hydride (NiMH) batteries [26]. The main purpose of the process is the recovery of cobalt and/or nickel. Cobalt is commonly found in lithium-ion and lithium-polymer batteries, whereas nickel is mainly introduced into the process through the treatment of NiMH batteries. Figure 15 shows the pyrometallurgical process as assumed in the Ecoinvent database.

[1] European emission standards define the acceptable limits for exhaust emissions of new vehicles sold in EU member states. The emission standards are defined in a series of European Union directives staging the progressive introduction of increasingly stringent standards.

The slag is mainly formed by compounds containing aluminium (Al), silicon (Si), calcium (Ca) and to some extent iron (Fe). In the process, lithium also ends up in the slag in the form of lithium oxide. The slag can be used in the construction or concrete industry [26]; however, in this model, slag use was not considered. The alloy fraction is predominantly made up of residual iron, copper, cobalt, and possibly nickel. The alloy is subsequently leached with sulfuric acid in a hydrometallurgical step which extracts metals like cobalt, copper, nickel and iron [26] as shown in Figure 16.

Figure 15. Pyrometallurgical process as modelled in the Ecoinvent database 2.2 (based on Hischier and Gallen Hischier [25].)



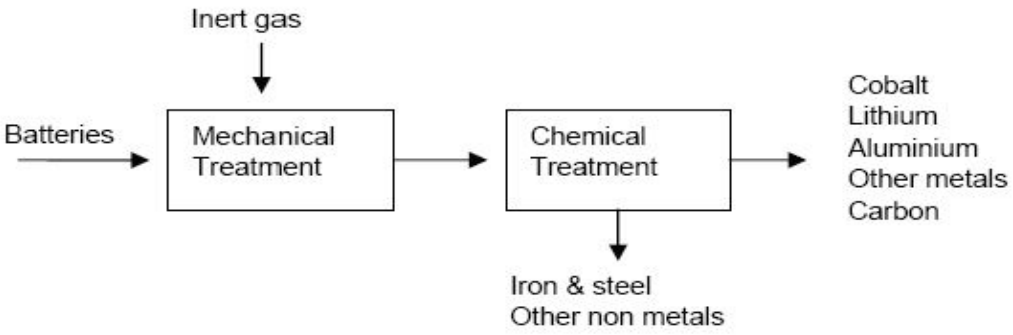


Figure 16- Hydrometallurgical process as modelled in the Ecoinvent database 2.2 (based on Hischier Hischier [25]).

The recovery rate of the metals from the pyro and hydrometallurgical processes were based on data elaborated by Vadenbo [26] for the Umicore process. Considering 1 kg of Li-Ion battery, the recovery rate for the following metals were considered:

- 7.7% Co (Pyro)
- 13.6% Co (Hydro)
- 9.6% Cu (Pyro)
- 10.8% Steel (Pyro)
- 6.6% Steel (Hydro)
- 6% Ni (Hydro)

To account for the avoided burdens due the recovery of these metals, primary production processes were considered in the system expansion.

ICEV

The disposal of the ICEV is based on Ecoinvent database [21]. It accounted for 100% recycling of aluminium, copper and steel contained in the vehicle. The rest of the materials were assumed to be sent to an incineration plant after dismantling [21].

3.6. Scenario analysis: landfill

A scenario analysis was performed for the disposal phase of BEV and ICEV. Two main scenarios were modelled assuming a high recycling rate and a low recycling rate. In the 'high recycling rate' scenario the entire fleet was assumed to be recycled and disposed within the EU borders, according to the previously described EoL phase. Conversely, in the 'low recycling rate' scenario, only 57% of the fleet was assumed to be disposed in EU [20]; part of the fleet was considered to be sold outside the EU borders [20] and track was lost of it. However, in order to account for the EoL of these vehicles, in the 'low recycling rate' scenario 43% of the fleet was assumed to end up in a landfill outside EU. To model this, the 'Landfill of ferro metals' process was considered, according to GaBi database [19].

4. Results and discussion

4.1. High recycling rate scenario

Table 3 shows the normalised results[2] of the 'high recycling rate' scenarios (assumed as the baseline) for EVI, EVII and ICEV based on the functional unit (i.e. 1 km driven per vehicle). The total impacts of the three cases have been normalised using the regionalised CML European factors reported in the appendix [19].
The impact indicators related to water (Marina Aquatic Eco-toxicity Potential-MAETP- and Fresh Water Aquatic Eco-toxicity Potential -FAETP) of EVI and EVII are significantly higher than all other normalised impact indicators; the Human Toxicity Potential (HTP) and the ADP element follow in order of magnitude. The reason of the increased values of those results for the EV models has to be found in the use of precious and non-precious metals during manufacturing. It is common that LCA analysis of processes involving the use of metals show high impacts in the water-related categories [27]. This is related to the extraction and processing of the metal itself.
In this report, special attention is paid to the impact Global Warming Potential (GWP), as this is one of the key policy focus;. The ADP fossil is also analysed to quantify the impact on depletion of fossil resources and thus on use of primary energy; furthermore, the HTP is considered because of the impact of this category on human health. All other environmental indicators are reported in the appendix for further information.

Table 3. Normalised results of the 'high recycling rate' scenarios for EVI, EVII and ICEV.

Total normalized impacts	*EV I*	*EV II*	*ICE*
Abiotic Depletion (ADP elements)	5.24E-13	1.79E-13	5.64E-14
Abiotic Depletion (ADP fossil)	3.77E-14	3.80E-14	6.65E-14
Acidification Potential (AP)	3.57E-14	3.76E-14	3.87E-14
Eutrophication Potential (EP)	9.76E-15	7.64E-15	9.62E-15
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	1.62E-12	1.56E-12	8.86E-14
Global Warming Potential (GWP 100 years)	2.30E-14	2.13E-14	3.21E-14
Human Toxicity Potential (HTP inf.)	1.75E-13	1.42E-13	8.36E-14
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	4.06E-12	3.16E-12	8.70E-13
Ozone Layer Depletion Potential (ODP, steady state)	3.09E-14	2.02E-16	1.28E-16
Photochem. Ozone Creation Potential (POCP)	3.14E-14	3.25E-14	-5.35E-14
Terrestric Ecotoxicity Potential (TETP inf.)	8.36E-15	8.23E-15	1.36E-14

2 In the normalisation phase of LCA, the results are referred as relative magnitude for each impact category. In this study the normalisation was performed according to the European regionalised impacts reported in the GaBi database (EU25+3, year 2000, incl biogenic carbon (region equivalents).

Figure 17 shows the GWP of the three different technologies analysed for the high recycling rate scenario; the total impacts are broken down into the manufacturing, use and disposal phases and the results are reported for functional unit.
The total GWPs of the two EV models are very similar (0.12 kg of CO_2eq for EVI and 0.11 kg of CO_2eq for EVII) whereas the GWP of the ICEV is 45% higher (0.16 kg of CO_2eq). The higher GWP of the ICEV is due to the higher impact associated with the use phase: the disposal phase of the three models is similar in the three models; However, the manufacturing phase of the ICEV has a substantially lower GWP compared to EV, being the use determinant of the total trend of the results for the ICEV. The higher GWP of the use phase of the ICEV model is associated to the greater amount of greenhouse gas emitted during the use of diesel as fuel when compared to the production and use of the current EU electricity mix for electric vehicles. For all three models the use phase determines the major contribution to the total GWP (61% for EVI, 66% for EVII and 89% for ICEV). The disposal phase accounts for both the 'disruptive' burdens associated with the disposal of car elements and reprocessing of metals and the 'beneficial' burden associated with recycling, in Figure 17. For all the scenarios analysed, this phase has an overall positive contribution to environment thanks to the allocation of avoided burdens, according to the system expansion method, associated with the recovery of metals and other resources contained in cars. However, this phase has a small weight in the total environmental burdens of the technologies analysed, as the benefits of metal recycling are significantly reduced by the burdens of the energy intensive reprocessing processes.

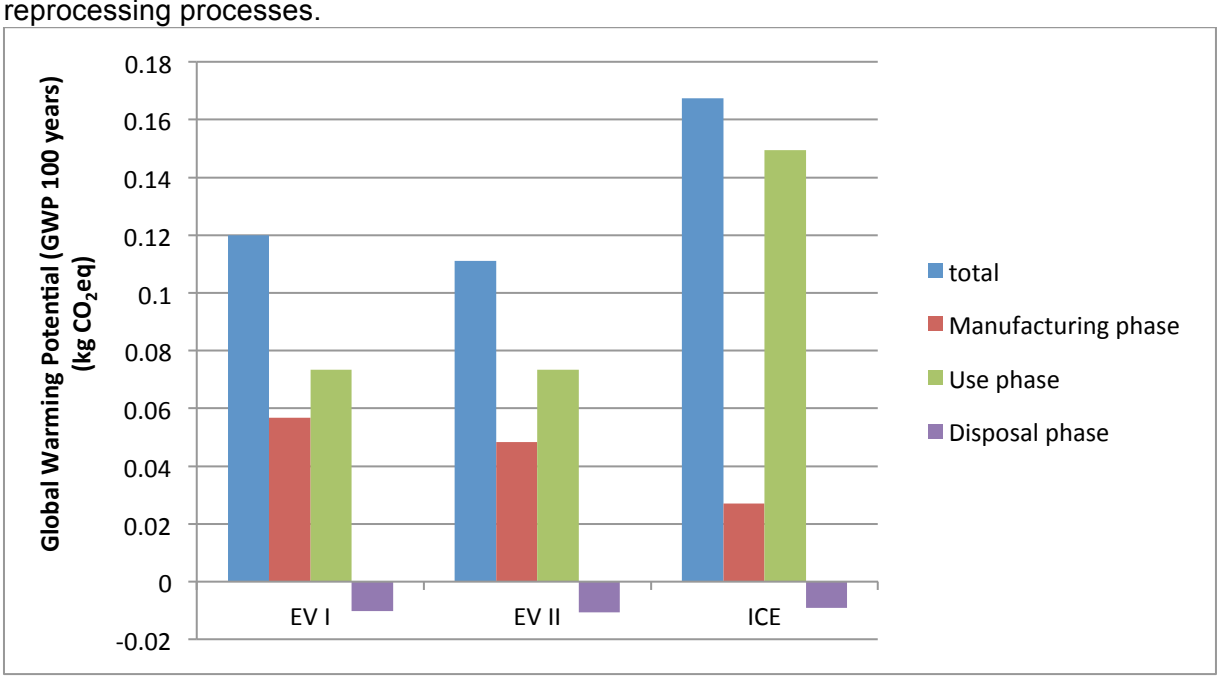


Figure 17. GWP of the EVI, EVII and ICEV for high recycling rate scenario.

Given that manufacturing phase of the EVs has substantially higher GWP than the manufacturing phase of the ICEV, a further analysis has been performed of the two EV models to identify the key phases or hot spots of the manufacturing process. The analysis concludes that about half of the total GWP of the manufacturing phase is associated to the manufacturing of the battery pack. A detailed hot spot analysis of the EV battery pack model is presented in Figure 18 and 19 for EVI and EVII. The main contributor to the GWP of the battery pack for EVI is the manufacturing of the positive electrode paste, as also found in Bettez et al. [6]. In particular, the indirect burdens associated with the production of the tetrafluoroethylene- a chemical used for

the manufacturing of this paste- contribute to 78% of the GWP of the positive electrode paste. The hot spot analysis for the manufacturing of the battery pack for EVII is shown in Figure 19. In this case, the energy used for the battery assembly determines more than 55% of the total GWP of the battery pack. Table 4 lists the main differences in the EVI and EVII model which explain the different GWP impact associated with the two manufacturing phases.

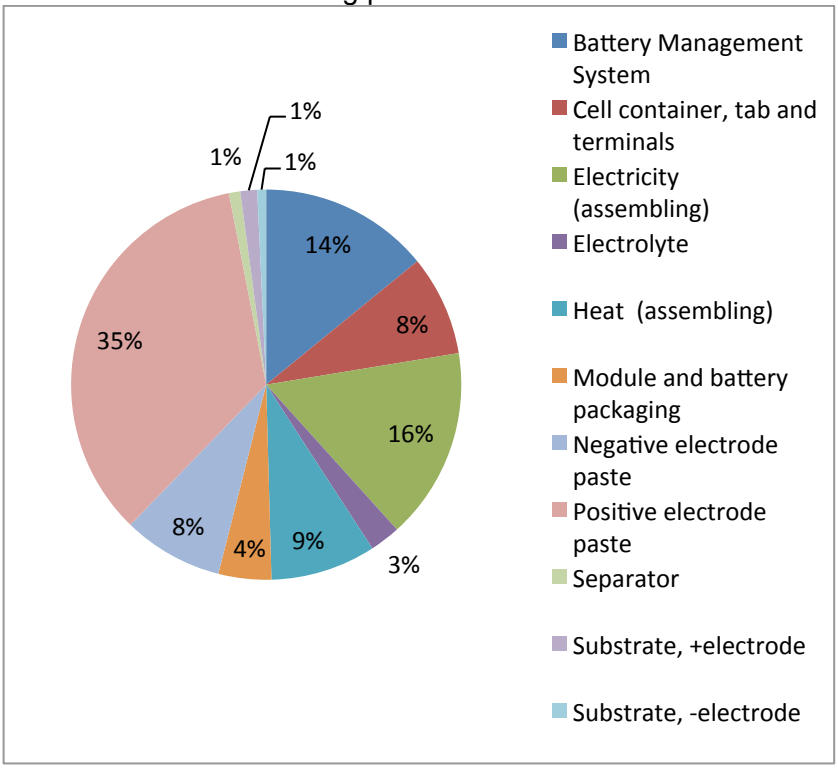


Figure 18. GWP hot spot analysis of the EVI battery manufacturing phase for the high recycling rate scenario.

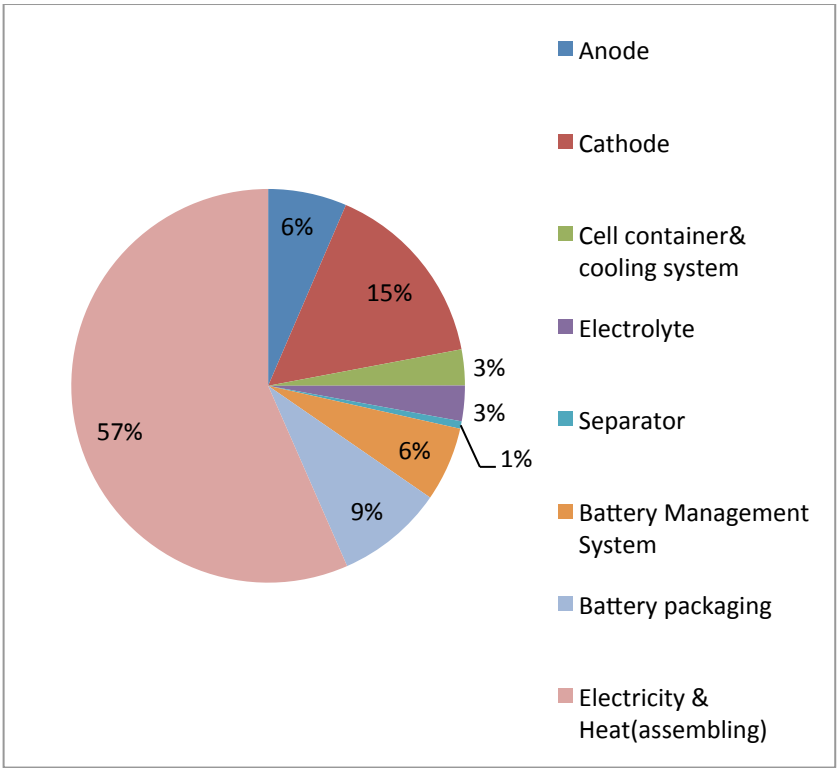


Figure 19. GWP hot spot analysis of the EVII battery manufacturing phase for the high recycling rate scenario.

Table 4. Materials and quantities considered for the manufacturing of the battery in EVI and EVII model.

	EVI (Bettez et al., 2011)	quantities for 1 kg of battery (kg)	**EVII (Ellingson et al., 2013)**	quantities for 1kg of battery(kg)
	material		material	
Battery cell				
Positive electrode paste	**Active material positive electrode paste LiNi0.4Co0.2Mn0.4O2**	0.202	**Active material positive electrode paste LiNi0.4Co0.2Mn0.4O2**	0.218
	Carbon black	0.012	Carbon black	0.005
	N-methyl-2-pyrrolidone	0.065	N-methyl-2-pyrrolidone	0.095
	tetrafluoroethylene	0.019	polyvinylfluoride	0.009
	water, decarbonised	380		
	Negative electrode paste			
Negative electrode paste	graphite, battery grade	0.089	graphite, battery grade	0.096
	N-methyl-2-pyrrolidone	0.026	N-methyl-2-pyrrolidone	0.094
	tetrafluoroethylene	0.005	acrylic acid	0.002
			carboxymethyl cellulose, powder	0.002
Electricity for assemblin g(MJ)	Electricity(MJ)	27		100.8
Heat for assemblin g(MJ)	Heat(MJ)	30		/

The total ADP is reported in Figure 20. The trend of the results is similar to the GWP. The main contribution to the total depletion of energy resources happens during the use phase; particularly, for the case of ICEV this is associated to the diesel consumption (hence fossil resources). In the case of the EV models, the impact of the manufacturing phase is comparable to the impact of the use phase and the burden is almost equally spread among the battery manufacturing and the manufacturing of the rest of the vehicle. The energy requirements for the battery assembly explain most of the ADP of EVI and EVII (37% of the total ADP of the battery manufacturing for EVI and 52% of the total ADP of battery manufacturing for EVII) as shown in Figures 21 and 22.

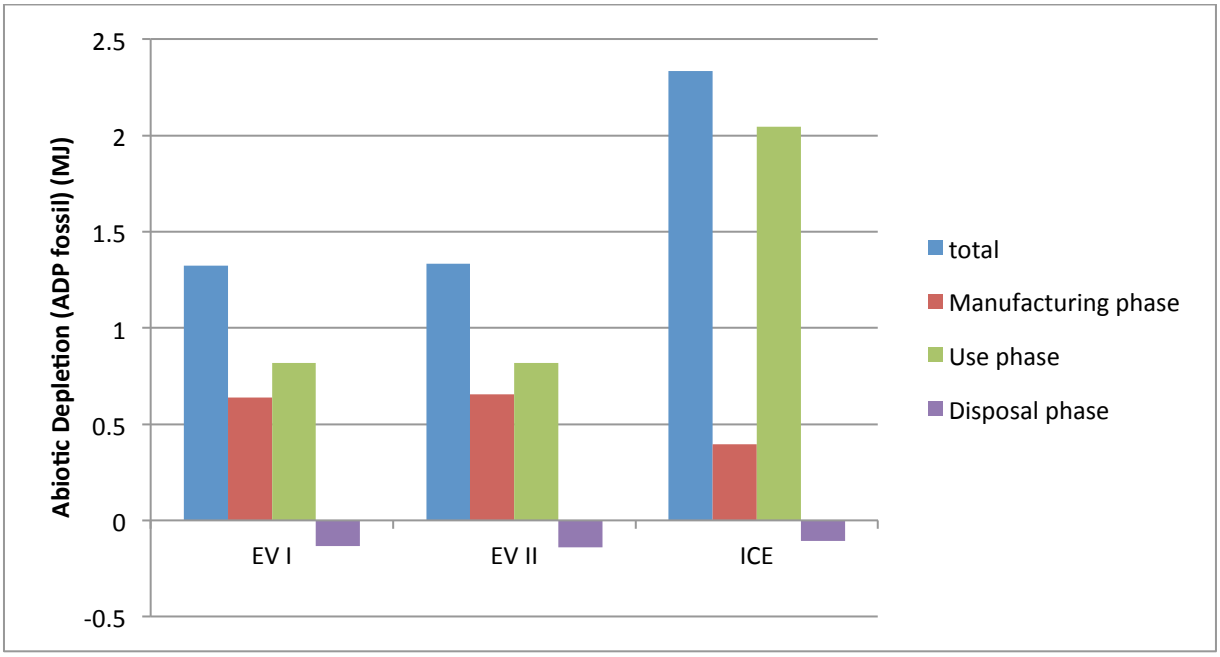

Abiotic Depletion (ADP fossil) (MJ)
2.5
2
1.5
1
0.5
0
-0.5
EV I
EV II
ICE
total
Manufacturing phase
Use phase
Disposal phase

Figure 20. ADP of the EVI, EVII and ICEV for high recycling rate scenario.

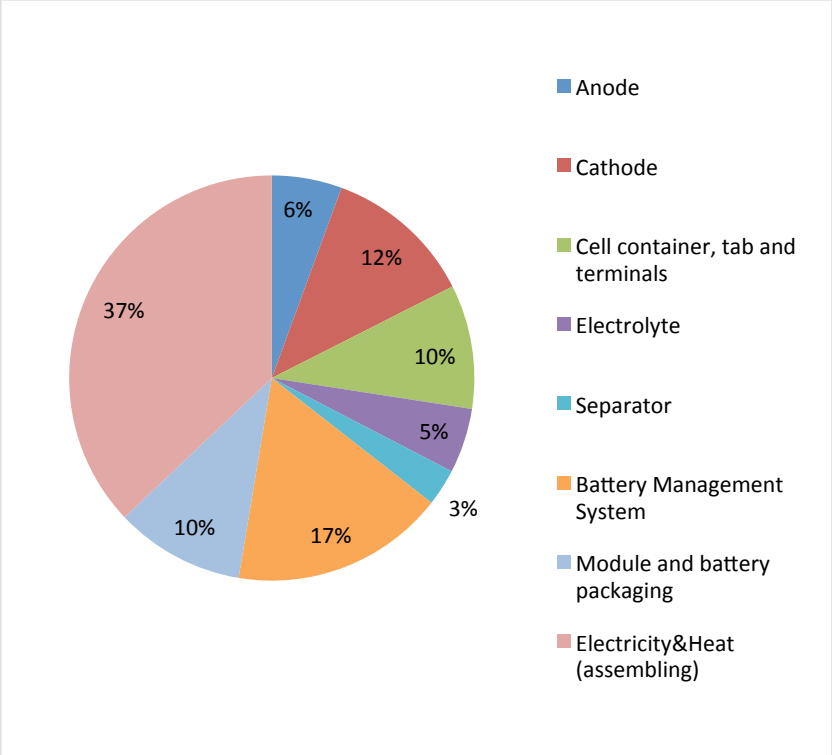


Figure 21. ADP hot spot analysis of the EVI battery manufacturing phase for the high recycling rate scenario.

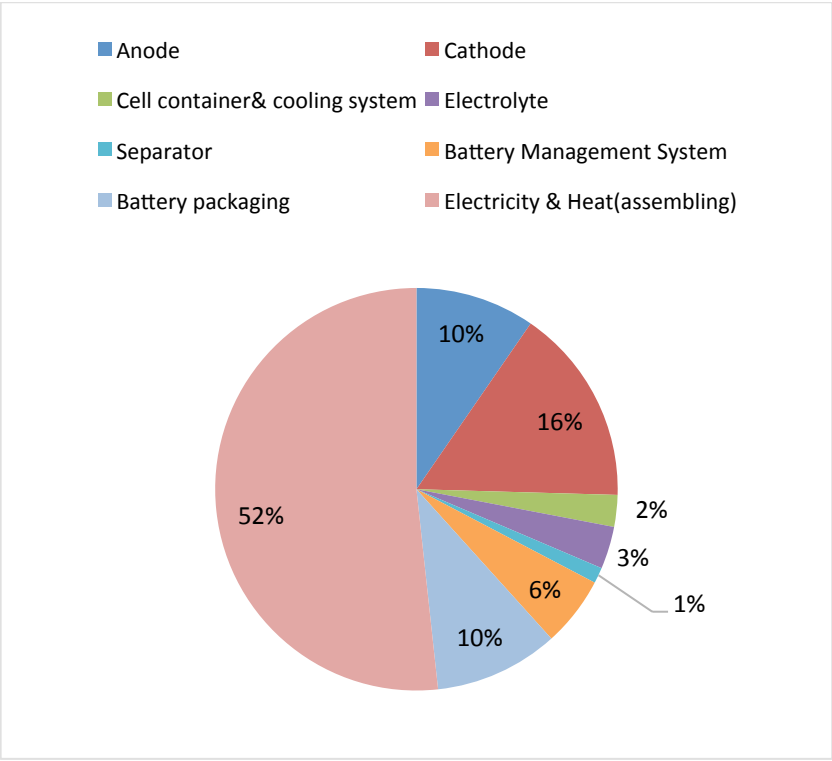


Figure 22. ADP hot spot analysis of the EVII battery manufacturing phase for the high recycling rate scenario.

Remarkably different are the results obtained for HTP as shown in Figure 23. For this impact category, the total burden of the two EV models is significantly higher than in

the ICEV model. The main impacts are associated with the manufacturing phases of the EVs, and in particular, with the chemical and metals production processes used in the manufacturing phase, which are associated with the toxicological impacts greater than the toxicological impacts of emissions associated with the production of electricity, required during the vehicle use. The detailed hot spot analysis of the batteries manufacturing is reported in Figures 24 and 25. In opposition to what reported for the other indicators, the HTPs of the EVI and EVII disposal phases are more than double than that of the disposal phase of ICEV.

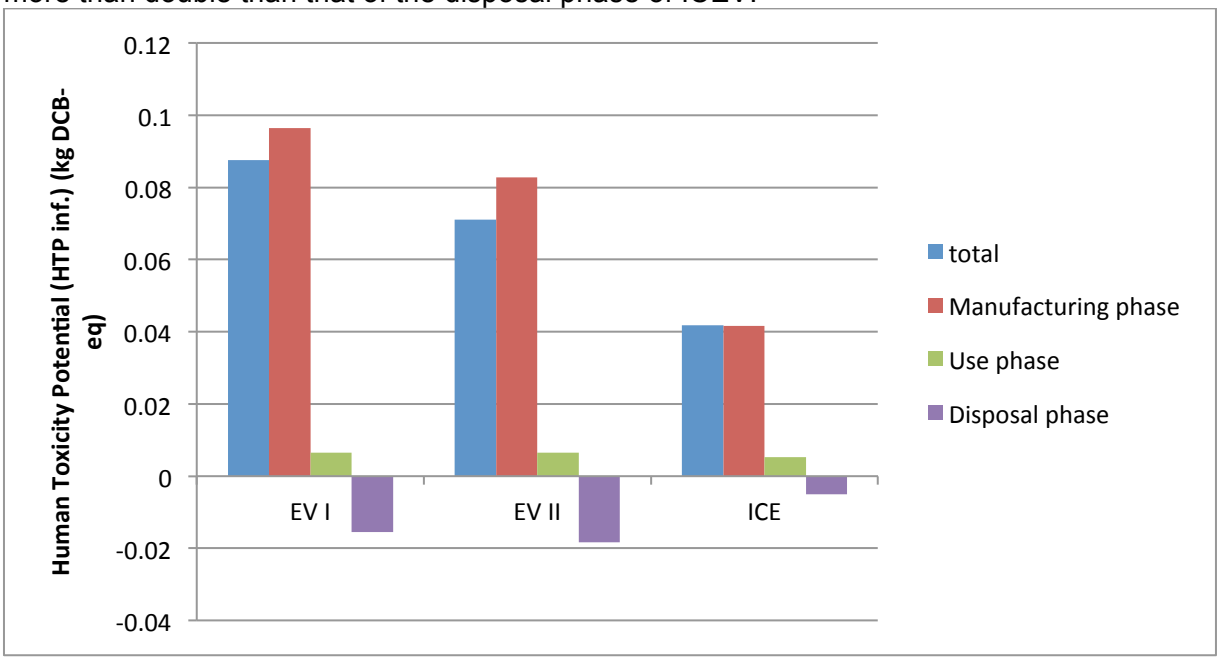


Figure 23. HTP of the EVI, EVII and ICEV for high recycling rate.

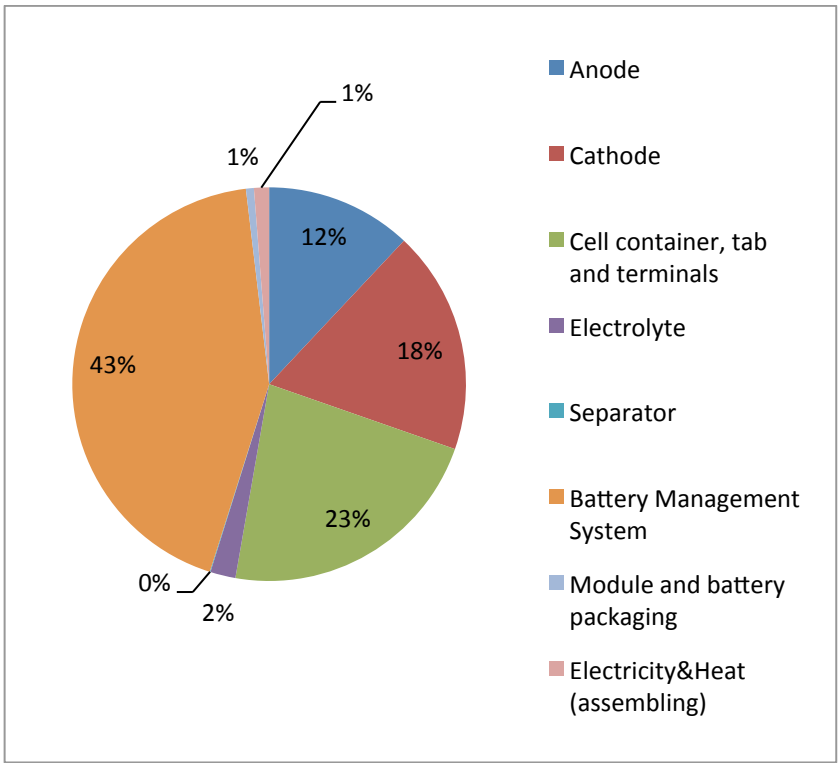


Figure 24. HTP hot spot analysis of the EVI manufacturing phase for the high recycling rate scenario.

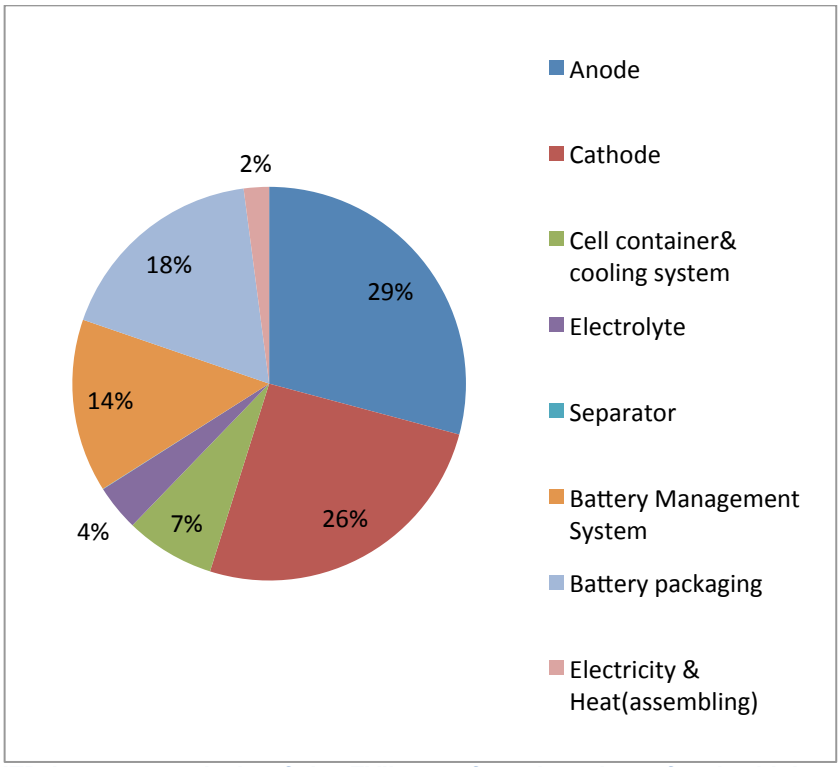


Figure 25. HTP hot spot analysis of the EVII manufacturing phase for the high recycling rate scenario.

Further aggregated results for the base scenario of EVI, EVII and ICEV are reported in the appendix. The hot spot analysis of the EVI, EVII and ICEV for all environmental indicators is also reported in the appendix as well as the burdens of the manufacturing, use and disposal phases.
Furthermore, Figure 26 shows the GWP of the EVI model (high recycling rate scenario) for different power train efficiency. Increasing the power train efficiency, hence improving the EV technology, would produce a reduction of the total environmental impacts. For example, increasing the power train efficiency from 50 to 80% would result in a 30% decreasing of the total GWP.

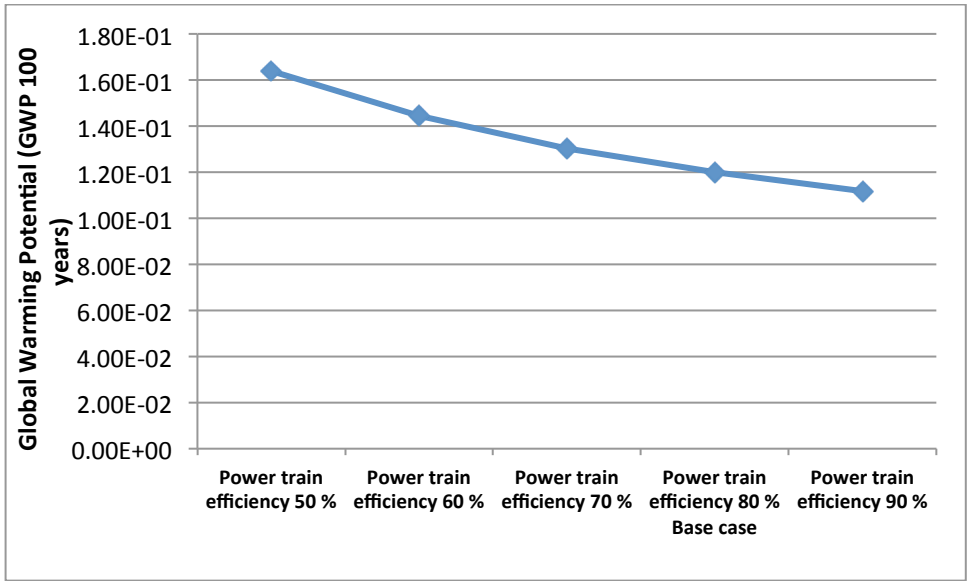


Figure 26. GWP of the EVI model for different power train efficiencies (high recycling rate scenario).

4.2. Low recycling rate scenario

This section reports the results of the low recycling scenario, based on the assumptions noted above. Table 5 summarises main results for the low recycling rate scenario. The GWP, ADP and HTP results of both scenarios for EVI, EVII and ICEV are reported for comparison. As noted previously, the disposal phase has a small weight in the total environmental impacts, therefore, a change of the modelling assumptions to better reflect the current end of life context in Europe, does not lead to a significant variation of the results (see Table 5).

Table 5. High- low recycling rate scenario non-normalised results comparison.

	High recycling rate			low recycling rate		
Non normalised results	**EV I**	**EV II**	**ICE**	**EV I**	**EV II**	**ICE**
CML2001 - Apr. 2013, Abiotic Depletion (ADP fossil) [MJ]	1.3E+00	1.3E+00	2.3E+00	1.3E+00	1.3E+00	2.4E+00
CML2001 - Apr. 2013, Global Warming Potential (GWP 100 years) [kg CO2-Equiv.]	1.2E-01	1.1E-01	1.7E-01	1.2E-01	1.1E-01	1.7E-01
CML2001 - Apr. 2013, Human Toxicity Potential (HTP inf.) [kg DCB-Equiv.]	8.8E-02	7.1E-02	4.2E-02	8.8E-02	7.1E-02	4.4E-02

4.3. Comparison of results with literature

Finally, the total GWPs for EVI and EVII calculated in this study are compared with results reported in published LCA studies on EV in the literature. As shown in Figure 27, the results obtained in the current study are well aligned with the lower end of the range found in the literature. Results from older studies are placed in the upper range of the literature results, while more recent studies report results in the lower range. This can be explained by improvement in higher energy production efficiencies, adoption of more advanced technologies and higher share of renewable energy in the electricity mix, which have contributed to the decrease of the total GWP of EVs and ICEVs.

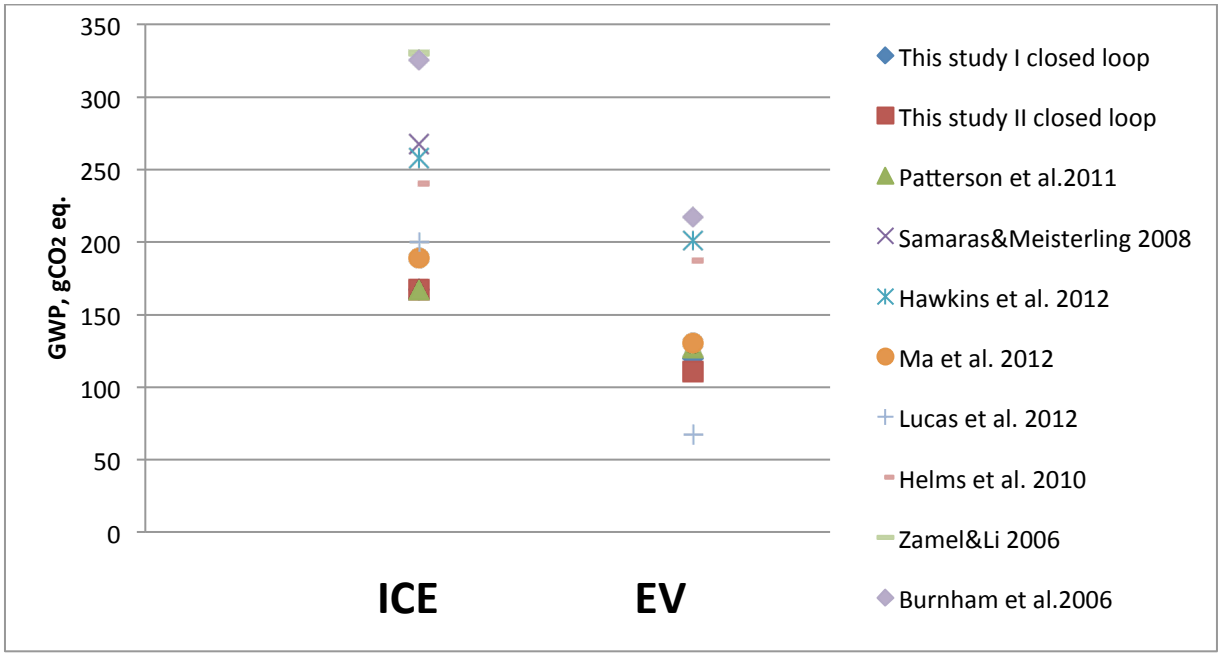


Figure 27. Comparison with literature.

5. Conclusions

The transport sector is one of the most challenging when tackling the targets on emissions reduction: developing technologies in the automotive industry, such as electric and fuel cell vehicles, associated with the use of low-carbon content fuels are appealing solutions to potentially reduce greenhouse gas emissions.

This study reported the results of a life cycle assessment analysis of an electric passenger vehicle using a Lithium-ion battery compared to an internal combustion engine vehicle. The analysis has covered all the phases of the vehicle from the extraction of resources to the disposal/ recycling of components at the end of its use life. A hot spot analysis has been performed to identify key phases of the entire vehicle life cycles in terms of environmental impacts. Three major phases have been identified to contribute to the total environmental impacts: manufacturing, use and disposal. A further break down of the impacts associated to those phases has been reported in the hot spot analysis. Battery production and assembling have proven to be main contributors to environmental impacts for EVs. Two models for the manufacturing of the EV have been produced, based on different inventory data.

Overall, the results show that ICEVs have a higher contribution to global warming than the BEVs. This result, that one may have expected, is explained by the differences in the use phase of the vehicles. GWP is significantly higher (by almost 50%) in the use phase of ICEVs compared to EVs. However, this trend is inverted in the case of the manufacturing phase, where GWP of BEVs is almost double that of the ICEV. The higher global warming impact of the EV manufacturing is explained by a more complex propelling system that includes the battery manufacturing. In general, the manufacturing phase of EVs has a significantly greater impact than that of ICEVs, associated with the production, use and depletion of metals, chemicals and energy required in the production and assembling of the battery system.

The picture is though quite different is the focus is shifted towards impact categories associated with toxicity. HTP results are substantially higher in the case of EVs compared with ICEVs. This result is again linked with the use of metals and chemicals for the battery manufacturing, which have relevant implications not only in terms of human toxicity but also water contamination.

A novel contribution of the present study is the introduction of the end of life/ disposal phase of vehicles. Two different disposal scenarios have been analysed: a high recycling rate scenario and a low recycling rate scenario. In the high recycling rate scenario, the vehicle fleet is totally assumed to be disposed within EU, following existing stringent standards on recovery and recycling of resources. The low recycling rate model assumes that part of the vehicle fleet that leaves the EU, mainly as second hand car exports, an scenario that more truly reflects the current situation of end of life vehicles in the EU. In this, it has been considered that vehicles are landfilled when they reach the end of their use life. This scenario though assumes that vehicles are put on landfills that comply with EU standards. This assumption is justified by the lack of data on the real fate of exported vehicles. It is therefore likely that negative burdens of the disposal phase may have been underestimated. In general, though, the end of life phase has a small weight to the overall environmental impact of cars and therefore only a negligible variation of the results have been reported for the two scenarios. Even though the disposal phase has a minor impact on the total environmental burdens, future research is needed to better understand the environmental impacts of improper treatment of vehicles at the end of their use life outside EU boundaries.

This study has demonstrated that EVs have an important role to play in reducing GHG associated with global warming and addressing more local air quality problems in cities. However, the study also shows that the manufacturing phase of EVs still

represents the major impediment to the total environmental performance of the technology, given the greater impacts and GHG emissions associated to the manufacturing phase of EVs compared to ICEVs. The study also demonstrates that EVs have important drawbacks associated with the significantly higher toxicity impacts, mainly due to battery manufacturing and assembling. Technological improvements are therefore required to address and try to minimize environmental impacts associated with the battery of EVs. Fundamental research has still to be developed on the subject that tackles how future changes in the energy mix and improvements of the technological efficiencies could contribute to a reduction of the GWP of the BEV manufacturing phase decreasing the difference with the manufacturing phase of the ICEV and the potential for substitution of material, higher recyclability and recovery of critical metals and chemical binders in the battery of EVs to reduce their toxicity.

References

[1] UNECE, “Climate Change and Sustainable Transport - Transport - UNECE,” 2015. [Online]. Available: http://www.unece.org/?id=9890. [Accessed: 14-Sep-2015].

[2] World Business Council for Sustainable Development, “Mobility 2030: Meeting the challenges to sustainability,” 2004.

[3] C. Samaras and K. Meisterling, “Life cycle assessment of greenhouse gas emissions from plug-in hybrid vehicles: implications for policy.,” *Environ. Sci. Technol.*, vol. 42, no. 9, pp. 3170–6, May 2008.

[4] M. Zackrisson, L. Avellán, and J. Orlenius, “Life cycle assessment of lithium-ion batteries for plug-in hybrid electric vehicles – Critical issues,” *J. Clean. Prod.*, vol. 18, no. 15, pp. 1519–1529, Nov. 2010.

[5] M. Wietschel, P. Plötz, A. Kühn, and T. Gnann, “Market evolution scenarios for electric vehicles,” 2013.

[6] G. Majeau-Bettez, T. R. Hawkins, and A. H. Strømman, “Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles.,” *Environ. Sci. Technol.*, vol. 45, no. 10, pp. 4548–54, May 2011.

[7] L. A.-W. Ellingsen, G. Majeau-Bettez, B. Singh, A. K. Srivastava, L. O. Valøen, and A. H. Strømman, “Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack,” *J. Ind. Ecol.*, vol. 18, no. 1, pp. 113–124, Feb. 2014.

[8] R. Clift, A. Doig, and G. Finnveden, “THE APPLICATION OF LIFE CYCLE ASSESSMENT TO INTEGRATED SOLID WASTE MANAGEMENT,” *Process Saf. Environ. Prot.*, vol. 78, no. July, pp. 279–287, 2000.

[9] R. Clift, “System Approaches: Life Cycle Assessment and Industrial Ecology,” in *Pollution: Causes, Effects and Control*, 5th ed., R.M. Harrison Royal Society of Chemistry, London, 2013.

[10] H. Baumann and A.-M. Tillman, *The Hitch Hiker’s Guide to LCA. An orientation in life cycle assessment methodology and application*. Lund, Sweden, Studentlitteratur, 2004.

[11] R. Clift, “Sustainable development and its implications for chemical engineering,” *Chem. Eng. Sci.*, vol. 61, pp. 4179–4187, 2006.

[12] T. Ekvall and G. Finnveden, “Allocation in ISO 14041—a critical review,” *J. Clean. Prod.*, vol. 9, pp. 197–208, 2001.

[13] R. Heijungs and J. B. Guinée, “Allocation and ‘what-if’ scenarios in life cycle assessment of waste management systems.,” *Waste Manag.*, vol. 27, no. 8, pp. 997–1005, Jan. 2007.

[14] ISO 14040, *International Standard, In: Environmental Management – Life Cycle Assessment – Principles and Framework*. 2006.

[15] ILCD, *European Commission-Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook- Recommendations for Life Cycle Impact Assessment in the European context.*, First. Publications Office of the European Union., 2011.

[16] O. Eriksson, G. Finnveden, T. Ekvall, and A. Björklund, "Life cycle assessment of fuels for district heating: A comparison of waste incineration, biomass- and natural gas combustion," *Energy Policy*, vol. 35, no. 2, pp. 1346–1362, Feb. 2007.

[17] BSI, "Specification for the Assessment of the Life Cycle Greenhouse GasEmissions of Goods and Services," 2011.

[18] S. Manfredi and R. Pant, "Supporting environmentally sound decisions for waste management: A technical guide to Life Cycle Thinking (LCI) and Life Cycle Assessment (LCA) for waste experts and LCA practitioners," 2011.

[19] Thinkstep, "GaBi 6 software-system and databases for life cycle engineering. Stuttgart, Echterdingen (see www.pe-europe.com)." 2015.

[20] G. Mehlhart, C. Merz, L. Akkermans, and J. J. Jorgensen, "European second-hand car market analysis Final Report," 2011.

[21] Swiss Centre for Life Cycle Inventories, "Ecoinvent: the life cycle inventory data, Version 3.0. Swiss Centre for Life Cycle Inventories, Duebendorf." 2014.

[22] Umicore, "Battery recycling," 2015. [Online]. Available: http://www.umicore.com/en/industries/automotive/umicore-battery-recycling/. [Accessed: 14-Sep-2015].

[23] D. A. Notter, M. Gauch, R. Widmer, P. Wäger, A. Stamp, R. Zah, and H.-J. Althaus, "Contribution of Li-ion batteries to the environmental impact of electric vehicles.," *Environ. Sci. Technol.*, vol. 44, no. 17, pp. 6550–6, Sep. 2010.

[24] M. Leuenberger and R. Frischknecht, "Life Cycle Assessment of Battery Electric Vehicles and Concept Cars," 2010.

[25] R. Hischier and E. Gallen, "Disposal of electric and electronic equipment (e-Waste)," 2007.

[26] C. Vadenbo, "Prospective Environmental Assessment of Lithium Recovery in Battery Recycling," 2009.

[27] M. Pizzol, P. Christensen, J. Schmidt, and M. Thomsen, "Eco-toxicological impact of 'metals' on the aquatic and terrestrial ecosystem: A comparison between eight different methodologies for Life Cycle Impact Assessment (LCIA)," *J. Clean. Prod.*, vol. 19, no. 6–7, pp. 687–698, Apr. 2011.

Appendix

NORMALISATION FACTORS

Table A1. Normalisation factor for Europe [19].

CML2001 - Apr. 2013, EU25+3, year 2000, incl biogenic carbon (region equivalents)		
Abiotic Depletion (ADP elements)	6040000	kg Sb-Equiv.
Abiotic Depletion (ADP fossil)	3.51E+13	MJ
Acidification Potential (AP)	1.68E+10	kg SO2-Equiv.
Eutrophication Potential (EP)	1.85E+10	kg Phosphate-Equiv.
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	2.09E+11	kg DCB-Equiv.
Global Warming Potential (GWP 100 years)	5.21E+12	kg CO2-Equiv.
Global Warming Potential (GWP 100 years), excl biogenic carbon	5.21E+12	kg CO2-Equiv.
Human Toxicity Potential (HTP inf.)	5E+11	kg DCB-Equiv.
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	4.45E+13	kg DCB-Equiv.
Ozone Layer Depletion Potential (ODP, steady state)	10200000	kg R11-Equiv.
Photochem. Ozone Creation Potential (POCP)	1.73E+09	kg Ethene-Equiv.
Terrestric Ecotoxicity Potential (TETP inf.)	1.16E+11	kg DCB-Equiv.

HIGH RECYCLING RATE SCENARIO

Table A2. Normalised results of the high recycling rate scenarios for EVI, EVII and ICEV. The normalisation was performed according to the European regionalised impacts reported in the GaBi database (EU25+3, year 2000, incl biogenic carbon (region equivalents) [19]).

Total normalized impacts	***EV I***	***EV II***	***ICE***
Abiotic Depletion (ADP elements)	5.24E-13	1.79E-13	5.64E-14
Abiotic Depletion (ADP fossil)	3.77E-14	3.80E-14	6.65E-14
Acidification Potential (AP)	3.57E-14	3.76E-14	3.87E-14
Eutrophication Potential (EP)	9.76E-15	7.64E-15	9.62E-15
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	1.62E-12	1.56E-12	8.86E-14
Global Warming Potential (GWP 100 years)	2.30E-14	2.13E-14	3.21E-14
Global Warming Potential (GWP 100 years), excl biogenic carbon	2.31E-14	2.13E-14	3.24E-14
Human Toxicity Potential (HTP inf.)	1.75E-13	1.42E-13	8.36E-14
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	4.06E-12	3.16E-12	8.70E-13
Ozone Layer Depletion Potential (ODP, steady state)	3.09E-14	2.02E-16	1.28E-16
Photochem. Ozone Creation Potential (POCP)	3.14E-14	3.25E-14	-5.35E-14
Terrestric Ecotoxicity Potential (TETP inf.)	8.36E-15	8.23E-15	1.36E-14

Table A3. Non normalised results of the high recycling rate scenarios for EVI, EVII and ICEV.

Total Non normalized impacts	EV I	EV II	ICE
Abiotic Depletion (ADP elements)	3.16E-06	1.08E-06	3.41E-07
Abiotic Depletion (ADP fossil)	1.32E+00	1.33E+00	2.33E+00
Acidification Potential (AP)	6.02E-04	6.34E-04	6.51E-04
Eutrophication Potential (EP)	1.81E-04	1.41E-04	1.78E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	3.38E-01	3.27E-01	1.85E-02
Global Warming Potential (GWP 100 years)	1.20E-01	1.11E-01	1.67E-01
Global Warming Potential (GWP 100 years), excl biogenic carbon	1.20E-01	1.11E-01	1.69E-01
Human Toxicity Potential (HTP inf.)	8.76E-02	7.11E-02	4.18E-02
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	1.81E+02	1.41E+02	3.87E+01

Ozone Layer Depletion Potential (ODP, steady state)	3.16E-07	2.06E-09	1.31E-09
Photochem. Ozone Creation Potential (POCP)	5.43E-05	5.63E-05	-9.26E-05
Terrestric Ecotoxicity Potential (TETP inf.)	9.69E-04	9.54E-04	1.58E-03

Table A4. Non-normalised hot spot analysis of the high recycling rate scenarios for EVI.

Non Normalised results of EVI	Life Cycle Assessment EV I	Life Cycle Assessment EV I	Life Cycle Assessment EV I	Life Cycle Assessment EV I
		DISPOSAL PHASE EV I	Manufacturing phase EV - I	USE PHASE EV I
Abiotic Depletion (ADP elements)	3.16E-06	-1.52E-07	3.30E-06	1.29E-08
Abiotic Depletion (ADP fossil)	1.323358	-0.13291	0.638127	0.818137
Acidification Potential (AP)	0.000602	-0.00013	0.000362	0.00037
Eutrophication Potential (EP)	0.000181	-2.73E-05	0.000188	2.01E-05
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	0.337551	0.29447	0.042733	0.000348
Global Warming Potential (GWP 100 years)	0.119959	-0.0102	0.056787	0.07337
Global Warming Potential (GWP 100 years), excl biogenic carbon	0.120127	-0.01035	0.056886	0.07359
Human Toxicity Potential (HTP inf.)	0.08762	-0.0154	0.096423	0.006594
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	180.8028	46.31753	125.6159	8.869417
Ozone Layer Depletion Potential (ODP, steady state)	3.16E-07	4.41E-11	3.16E-07	5.46E-11
Photochem. Ozone Creation Potential (POCP)	5.43E-05	-1.10E-05	4.38E-05	2.15E-05
Terrestric Ecotoxicity Potential (TETP inf.) [kg DCB-Equiv.]	0.000969	-4.14E-05	0.000846	0.000165

Table A5. Non-normalised hot spot analysis of the high recycling rate scenarios for EVII.

Non Normalised results of EVII	Life Cycle Assessment EV II	Life Cycle Assessment EV II	Life Cycle Assessment EV II	Life Cycle Assessment EV II
		DISPOSAL PHASE EV II	Manufacturing phase EV -II	USE PHASE EV II
Abiotic Depletion (ADP elements)	1.08E-06	-1.77E-07	1.24E-06	1.29E-08

Abiotic Depletion (ADP fossil)	1.333272	-0.13948	0.654615	0.818137
Acidification Potential (AP)	0.000634	-0.00015	0.000412	0.00037
Eutrophication Potential (EP)	0.000141	-3.19E-05	0.000153	2.01E-05
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	0.326822	0.293648	0.032826	0.000348
Global Warming Potential (GWP 100 years)	0.111026	-0.01073	0.048389	0.07337
Global Warming Potential (GWP 100 years), excl biogenic carbon	0.111187	-0.01089	0.048491	0.07359
Human Toxicity Potential (HTP inf.)	0.071055	-0.01827	0.082734	0.006594
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	140.6742	44.01747	87.78726	8.869417
Ozone Layer Depletion Potential (ODP, steady state)	2.06E-09	1.99E-11	1.98E-09	5.46E-11
Photochem. Ozone Creation Potential (POCP)	5.63E-05	-1.20E-05	4.67E-05	2.15E-05
Terrestric Ecotoxicity Potential (TETP inf.)	0.000954	-4.67E-05	0.000836	0.000165

Table A6. Non-normalised hot spot analysis of the high recycling rate scenarios for ICEV.

Non Normalised results of ICEV	Life Cycle Assessment ICE	Life Cycle Assessment ICE	Life Cycle Assessment ICE	Life Cycle Assessment ICE
		Disposal phase ICE vehicle	Manufacturing phase ICE vehicle	Use phase ICE vehicle
Abiotic Depletion (ADP elements)	3.41E-07	-2.35E-09	3.37E-07	5.82E-09
Abiotic Depletion (ADP fossil)	2.33E+00	-1.06E-01	3.96E-01	2.04E+00
Acidification Potential (AP)	0.000651	-2.97E-05	0.000189	0.000492
Eutrophication Potential (EP)	0.000178	-1.43E-06	5.54E-05	0.000124
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	0.018512	0.000997	1.65E-02	0.001031
Global Warming Potential (GWP 100 years)	0.167497	-0.00903	0.027168	0.149357
Global Warming Potential (GWP 100 years), excl biogenic carbon	0.168697	-0.00911	0.027239	0.150572
Human Toxicity Potential (HTP inf.)	0.041798	-0.00505	0.04156	0.005283

Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	38.72158	-3.52749	40.21308	2.035991
Ozone Layer Depletion Potential (ODP, steady state)	1.31E-09	7.63E-11	1.23E-09	6.10E-13
Photochem. Ozone Creation Potential (POCP)	-9.26E-05	-5.36E-06	3.16E-05	-1.19E-04
Terrestric Ecotoxicity Potential (TETP inf.)	1.58E-03	-1.43E-05	4.97E-04	1.10E-03

LOW RECYCLING RATE SCENARIO

Table A7. Normalised results of the low recycling rate scenarios for EVI, EVII and ICEV. The normalisation was performed according to the European regionalised impacts reported in the GaBi database (EU25+3, year 2000, incl biogenic carbon (region equivalents) [19]).

Total normalized impacts	EV I	EV II	ICE
Abiotic Depletion (ADP elements)	5.24E-13	1.79E-13	5.66E-14
Abiotic Depletion (ADP fossil)	3.79E-14	3.81E-14	6.79E-14
Acidification Potential (AP)	3.58E-14	3.77E-14	3.95E-14
Eutrophication Potential (EP)	9.77E-15	7.64E-15	9.66E-15
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	1.62E-12	1.56E-12	8.65E-14
Global Warming Potential (GWP 100 years)	2.31E-14	2.14E-14	3.29E-14
Global Warming Potential (GWP 100 years), excl biogenic carbon	2.31E-14	2.14E-14	3.32E-14
Human Toxicity Potential (HTP inf.)	1.75E-13	1.42E-13	8.79E-14
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	4.06E-12	3.16E-12	9.05E-13
Ozone Layer Depletion Potential (ODP, steady state)	3.09E-14	2.02E-16	1.25E-16
Photochem. Ozone Creation Potential (POCP)	3.15E-14	3.26E-14	-5.21E-14
Terrestric Ecotoxicity Potential (TETP inf.)	8.39E-15	8.26E-15	1.37E-14

Table A8. Non normalised results of the low recycling rate scenarios for EVI, EVII and ICEV.

Total Non normalized impacts	EV I	EV II	ICE
Abiotic Depletion (ADP elements)	3.16E-06	1.08E-06	3.42E-07
Abiotic Depletion (ADP fossil)	1.33E+00	1.34E+00	2.38E+00
Acidification Potential (AP)	6.03E-04	6.35E-04	6.65E-04
Eutrophication Potential (EP)	1.81E-04	1.41E-04	1.79E-04
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	3.38E-01	3.27E-01	1.81E-02
Global Warming Potential (GWP 100 years)	1.20E-01	1.11E-01	1.72E-01
Global Warming Potential (GWP 100 years), excl biogenic carbon	1.20E-01	1.12E-01	1.73E-01
Human Toxicity Potential (HTP inf.)	8.76E-02	7.11E-02	4.40E-02
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	1.81E+	1.41E+	4.03E+

	02	02	01
Ozone Layer Depletion Potential (ODP, steady state)	3.16E-07	2.06E-09	1.27E-09
Photochem. Ozone Creation Potential (POCP)	5.44E-05	5.64E-05	-9.02E-05
Terrestric Ecotoxicity Potential (TETP inf.)	9.73E-04	9.58E-04	1.59E-03

Table A9. Non-normalised hot spot analysis of the low recycling rate scenarios for EVI.

Non Normalised results of EVI	Manufacturing phase EV - I	USE PHASE EV I	Disposal EVI
Abiotic Depletion (ADP elements)	3.30E-06	1.29E-08	-1.52E-07
Abiotic Depletion (ADP fossil)	6.38E-01	0.818137	-1.28E-01
Acidification Potential (AP)	3.62E-04	0.00037	-1.29E-04
Eutrophication Potential (EP)	1.88E-04	2.01E-05	-2.72E-05
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	4.27E-02	0.000348	2.94E-01
Global Warming Potential (GWP 100 years)	0.056787	0.07337	-9.83E-03
Global Warming Potential (GWP 100 years), excl biogenic carbon	0.056886	0.07359	-9.98E-03
Human Toxicity Potential (HTP inf.)	9.64E-02	0.006594	-1.54E-02
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	125.6159	8.869417	4.64E+01
Ozone Layer Depletion Potential (ODP, steady state)	3.16E-07	5.46E-11	4.41E-11
Photochem. Ozone Creation Potential (POCP)	4.38E-05	2.15E-05	-1.09E-05
Terrestric Ecotoxicity Potential (TETP inf.)	8.46E-04	0.000165	-3.75E-05

Table A10. Non-normalised hot spot analysis of the low recycling rate scenarios for EVII.

Non Normalised results of EVII	Manufacturing phase EV -II	USE PHASE EV II	Disposal phase EVII
Abiotic Depletion (ADP elements)	1.24E-06	1.29E-08	-1.8E-07
Abiotic Depletion (ADP fossil)	0.654615	0.818137	-0.13413
Acidification Potential (AP)	0.000412	0.00037	-0.00015
Eutrophication Potential (EP)	0.000153	2.01E-05	-3.2E-05
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	0.032826	0.000348	0.293649
Global Warming Potential (GWP 100 years)	0.048389	0.07337	-0.01036

Global Warming Potential (GWP 100 years), excl biogenic carbon	0.048491	0.07359	-0.01052
Human Toxicity Potential (HTP inf.)	0.082734	0.006594	-0.01826
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	87.78726	8.869417	44.05274
Ozone Layer Depletion Potential (ODP, steady state)	1.98E-09	5.46E-11	1.99E-11
Photochem. Ozone Creation Potential (POCP)	4.67E-05	2.15E-05	-1.2E-05
Terrestric Ecotoxicity Potential (TETP inf.)	0.000836	0.000165	-4.3E-05

Table A11. Non-normalised hot spot analysis of the low recycling rate scenarios for ICEV.

Non Normalised results of ICEV	Manufacturing phase ICE vehicle	Use phase ICE vehicle	Disposal ICEV
Abiotic Depletion (ADP elements)	3.37E-07	5.82E-09	-1.3E-09
Abiotic Depletion (ADP fossil)	0.39646	2.043698	-0.05767
Acidification Potential (AP)	0.000189	0.000492	-1.6E-05
Eutrophication Potential (EP)	5.54E-05	0.000124	-7.5E-07
Freshwater Aquatic Ecotoxicity Pot. (FAETP inf.)	0.016485	0.001031	0.000569
Global Warming Potential (GWP 100 years)	0.027168	0.149357	-0.00496
Global Warming Potential (GWP 100 years), excl biogenic carbon	0.027239	0.150572	-0.00501
Human Toxicity Potential (HTP inf.)	0.04156	0.005283	-0.00287
Marine Aquatic Ecotoxicity Pot. (MAETP inf.)	4.02E+01	2.04E+00	-1.99326
Ozone Layer Depletion Potential (ODP, steady state)	1.23E-09	6.10E-13	4.35E-11
Photochem. Ozone Creation Potential (POCP)	3.16E-05	-0.00012	-3E-06
Terrestric Ecotoxicity Potential (TETP inf.)	0.000497	0.001101	-6.2E-06