CHALMERS
UNIVERSITY OF TECHNOLOGY

Life cycle assessment of a fuel cell electric vehicle with an MS-100 system

A comparison between a fuel cell electric vehicle and a battery electric vehicle

Master's thesis in Industrial Ecology

SANDRA FRANZ
ANNA LILJENROTH

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020
www.chalmers.se
Report No. E2020:077

REPORT NO. E2020:077

Life cycle assessment of a fuel cell electric vehicle with an MS-100 system

A comparison between a fuel cell electric vehicle and a battery electric vehicle

SANDRA FRANZ
ANNA LILJENROTH

Department of Technology Management and Economics
Division of Environmental Systems Analysis
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2020

Life cycle assessment of a fuel cell electric vehicle with an MS-100 system
A comparison between a fuel cell electric vehicle and a battery electric vehicle
SANDRA FRANZ
ANNA LILJENROTH

Chalmers supervisor: Anders Nordelöf, Department of Technology Management and Economics, Division of Environmental Systems Analysis

Company supervisors: Per Ekdunge and Pedro Lazaro, PowerCell Sweden AB

Examiner: Rickard Arvidsson, Department of Technology Management and Economics, Division of Environmental Systems Analysis

Report no. E2020:077
Department of Technology Management and Economics
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone +46 (0)31-772 1000

Cover: The MS-100 system in the fuel cell electric vehicle. The picture is used with permission from PowerCell Sweden AB.

Gothenburg, Sweden 2020

Life cycle assessment of a fuel cell electric vehicle with an MS-100 system
A comparison between a fuel cell electric vehicle and a battery electric vehicle

SANDRA FRANZ
ANNA LILJENROTH
Department of Technology Management and Economics
Chalmers University of Technology

Abstract

The aim was to cover knowledge gaps and extend the knowledge base for the environmental impact of two electric vehicles by conducting an attributional Life Cycle Assessment (LCA) where two vehicle options, a Battery Electric Vehicle (BEV) and a Fuel Cell Electric Vehicle (FCEV), were compared. The thesis was conducted in collaboration with the company PowerCell Sweden AB. The research question was: *What are the environmental impacts of an FCEV powered by PowerCell's MS-100 system and how does this vehicle compare with a BEV powered by a Li-ion battery with the same: powertrain performance, payload, driving range and total lifetime?*

To answer the research question an LCA case study was conducted. The study investigated four technology options, where the vehicle options were analysed with two production pathways each for the energy carrier for propulsion. The BEV was powered by either European- (RER Mix) or Swedish electricity mix (SE Mix). The FCEV was powered by hydrogen from either steam methane reforming (SMR) or wind powered electrolysis (WP-Electrolysis). The data for driving range and electricity/hydrogen consumption were obtained from simulations in the simulation tool FASTSim and were used as Life Cycle Inventory (LCI) data. The data for the LCA case study was moreover obtained from literature studies and data collection at the company PowerCell. Additionally, a sensitivity analysis was conducted to check the robustness of the Life Cycle Impact Assessment (LCIA) results. Two parameters were investigated, the platinum content in the MS-100 system and the driving range.

The environmental impacts were evaluated for seven impact categories. The LCIA results indicated that the technology options with a high share of renewable energy sources, BEV-SE Mix and FCEV-WP Electrolysis, were the preferred choices. However, for the chosen driving range the BEV-SE Mix was the most environmentally benign technology option.

The thesis was concluded with recommendations for the FCEV and MS-100 system. To be an environmentally friendly option, the FCEV should be used for extended driving ranges and should be fuelled with renewable hydrogen. For the MS-100 system, it was shown that platinum was a large contributor to the environmental impact for several of the considered environmental problems. Important environmental improvements would be to either recycle or reduce the amount of platinum.

Keywords: LCA, electric vehicle, fuel cell, battery, hydrogen

Acknowledgements

This thesis has been an interesting and educating journey already from the start. We have learned a lot and are thankful to PowerCell for giving us the opportunity to use the knowledge we have gained during our years at Chalmers University of Technology and apply them in a real-life situation.

Firstly, we would like to send a special thanks to Pedro Lazaro, Development Engineer at PowerCell, for always putting a smile on our faces while answering our millions of questions. Furthermore, we would also like to thank Per Ekdunge, Executive Vice President at PowerCell, for explaining the fuel cell technology and providing valuable information and thoughts. We would also like so send our gratitude to Lisa Kylhammar, Manager Stack Development at PowerCell, for helping us structuring the work and giving us good advices.

Moving on to the division of Environmental Systems Analysis at Chalmers University of Technology. We would like to express our gratitude to our supervisor Anders Nordelöf, Researcher, PhD, for giving us the advice and support to implement our knowledge from the textbooks into a comprehensive life cycle assessment study. It has been a pleasure to work with you since you have been genuinely interested and engaged in this thesis. Finally, we would like to thank Rickard Arvidsson, Assistant Professor, for helping us improve our thesis and finalise our work.

Additionally, all the work in this thesis has been a cooperation between the two authors and both authors have contributed equally to the work load.

Sandra Franz and Anna Liljenroth
Gothenburg, 12th of June, 2020

Abbreviations

AC	Alternating Current
ADP	Abiotic Depletion Potential
AE	Accumulated Exceedance
BE	Battery Electric
BEV	Battery Electric Vehicle
BoM	Bill of Materials
DC	Direct Current
EoL	End of Life
EV	Electric Vehicle
FASTSim	Future Automotive Systems Technology Simulator
FCE	Fuel Cell Electric
FCEV	Fuel Cell Electric Vehicle
FCS	Fuel Cell Stack
FCS system	Fuel Cell Stack System
GWP	Global Warming Potential
Li-ion battery	Lithium-ion battery
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MEA	Membrane Electrode Assembly
Ni-MH battery	Nickel-Metal Hydride battery
PEM	Polymer Electrolyte Membrane
POCP	Photochemical Ozone Creation Potential
RER-Mix	European Electricity Mix
SE-Mix	Swedish Electricity Mix
SMR	Steam Methane Reforming
WP-Electrolysis	Wind Powered Electrolysis

Contents

1
Introduction

In this chapter, a general background is presented along with the aim and problem formulation. Furthermore, general assumptions and limitations are explained.

1.1 Background

Global warming is an important topic in today's society, with rising temperatures and sea levels as devastating consequences. The transport sector is well known for its high energy intensity and large tail-pipe emissions. Transportation accounts for 24% of the direct carbon dioxide (CO_2) emissions originating from fuel combustion. The vehicles on the road are responsible for approximately three quarters of the CO_2 emissions caused by the transport sector, making it a large proportion of the sector's total emissions [1]. The transport sector needs to change in order to move forward towards a more sustainable path and achieving the Sustainable Development Goals [2]. Two important aspects presented by the International Energy Agency are the need to increase the energy efficiency of the vehicles and the need to increase the availability of low carbon fuels [1].

Electric Vehicles (EVs) are an alternative technology to the traditional combustion engine vehicles. The demand for the EVs within the transport sector is increasing both in Sweden, as well as globally [3]. The EVs remove the tail-pipe emissions in the use phase. There are several types of technologies included in the concept of EVs and two of them, Battery Electric Vehicles (BEVs) and Fuel Cell Electric Vehicles (FCEVs), are analysed in this thesis.

The general idea behind the BEV is that electricity is obtained from the grid and stored in a battery which later is used to power the electric motor of the vehicle. The origin of the electricity plays an important role in the environmental impact and therefore the BEV is evaluated operating on both Swedish and European electricity mix in this thesis.

The FCEVs have emerged as an alternative solution to the BEVs. The technology behind the fuel cell stack (FCS) is that hydrogen and oxygen react and produce electricity and water vapour. Thereby, the chemical energy in hydrogen has been converted into electrical energy. The energy is used to power the electric motor in the vehicle. In order to incorporate the FCS in the vehicle, it requires supporting equipment and this combination is referred to as a fuel cell stack system (FCS system). The Swedish fuel cell company PowerCell Sweden AB makes an FCS system called MS100. The FCS system can be used either as the main source of energy for propulsion, or to support and increase the range of battery based solutions [4]. There are some FCEVs on today´s market and there are companies within the automobile sector that show an interest in the technology. For example, AB Volvo and Daimler announced during 2020 that they will start a joint-venture that will produce fuel cells in a larger scale [5].

FCEVs use hydrogen gas as a fuel and there are several known methods for producing the hydrogen gas. Two of them are analysed in this thesis: Steam Methane Reforming (SMR) of natural gas and Wind Powered Electrolysis (WP-Electrolysis) of water. The two production methods use fossil-based and renewable energy sources respectively and the production processes have different environmental impacts. Steam reformation of natural gas is the most common hydrogen production pathway nowadays, representing 95% of the hydrogen produced in the United States and since it requires fossil resources it is considered to produce grey hydrogen [6]. There are several renewable production processes for hydrogen, however they do not have the same production capacity and are not used as extensively. This thesis investigates the renewable hydrogen production by water electrolysis driven by wind power, which is considered as green hydrogen.

PowerCell is a leading producer of FCSs and FCS systems for both stationary and mobile applications in the Nordic countries [7, 8]. The thesis is conducted in collaboration with PowerCell and investigates the environmental impacts of a simulated FCEV compared to a BEV through a Life Cycle Assessment (LCA) case study.

1.2 Aim and problem formulation

The aim is to cover knowledge gaps and create an extended knowledge base for the environmental impact of two EVs, by conducting an attributional LCA where two simulated vehicle options are compared. The vehicle options have two different powertrains, Battery Electric (BE) and Fuel Cell Electric (FCE), where the latter is modelled with PowerCell's MS-100 system incorporated. The two vehicle options are referred to as BEV and FCEV.

The environmental impacts of the BEV and FCEV are compared in an LCA case study, for seven impact categories for the entire life cycle from cradle to grave. The analysed impact categories are: (i) acidification - freshwater and terrestrial, (ii) climate change - total, (iii) eutrophication - freshwater, (iv) eutrophication - terrestrial, (v) photochemical ozone formation, (vi) resources - fossils and (vii) resources - minerals and metals.

Four technology options are investigated where the BEV and FCEV are modelled with two alternative sources, in terms of the electricity supply and the hydrogen gas production. This is to illustrate the impact of having a high share of renewable or fossil-based production of electricity or hydrogen gas in the use phase.

The thesis is performed in collaboration with PowerCell and combines information for PowerCell's MS-100 system with simulations of the use phase in a tool called FASTSim. The simulation tool FASTSim is developed and published by U.S. National Renewable Energy Laboratory [9]. The values obtained from the simulation of the BEV and FCEV are used as input data for the Life Cycle Inventory (LCI) in the LCA case study. Furthermore, literature and database data are used to complement the simulations to compile a complete LCI. The four technology options are modelled in the software openLCA with the database Ecoinvent 3.6 incorporated.

A more thorough problem formulation for the LCA case study is presented in Section 4.1. The results will be used internally by PowerCell for future development of the MS-100 system, especially for vehicle applications.

1.3 General limitations and assumptions

The thesis has consisted of a literature study, simulations of two vehicle options and an LCA case study. Assumptions and limitations are made for each of the steps. However, there are some assumptions and limitations that apply to all of the steps. The simulations of the BEV and the FCEV are based on data for a Renault Master ZE panel van, which is an electric delivery van with a total weight of 3.1 tonnes [10] and a payload of 975 kg [11]. The panel van was chosen because of its electric propulsion, the data availability and the suitable size of the vehicle for smaller goods distributions. Additionally, Renault will launch an FCEV version of the vehicle in 2020 [12].

The simulated BEV and FCEV are based on data for the Renault Master ZE, however the performance of some vehicle components such as the battery and electric motor have been modified. This in order to match the power output of PowerCell's MS-100 system. Furthermore, the BEV and the FCEV have been modelled to have the same driving range for a fully charged battery and a full hydrogen tank. These modifications were made in order to make the vehicle options comparable.

The simulation of the BEV and the FCEV in FASTSim contributes to uncertainties since it is based on a model that includes several assumptions. The simulation in FASTSim also requires assumptions to make the vehicles comparable, one example is that the total weights of the BEV and the FCEV are modified. Since the weight of the BE- and FCE powertrains differ, the total weight of the two vehicles differ. However, they are assumed to have the same payload and are able to transport the same amount of goods.

More detailed assumptions and limitations regarding the modelling of the vehicles' use phase are presented in 3.2, and for the LCA case study they are presented in Section 4.1.

2

Theory

This chapter presents the LCA framework, technical descriptions of the two vehicle options and two production pathways for hydrogen gas. Furthermore, the simulation tool FASTSim and the LCA software openLCA are described.

2.1 Life Cycle Assessment Framework

LCA is a standardised method according to ISO 14040 for determining environmental impacts of products over the entire life cycle from cradle to grave [13]. The framework is illustrated in Figure 2.1. The concept for making this type of analyses over products' entire life cycles, emerged as a consequence of the enlarged environmental awareness in several parts of the society: the public, governments and industry [14].

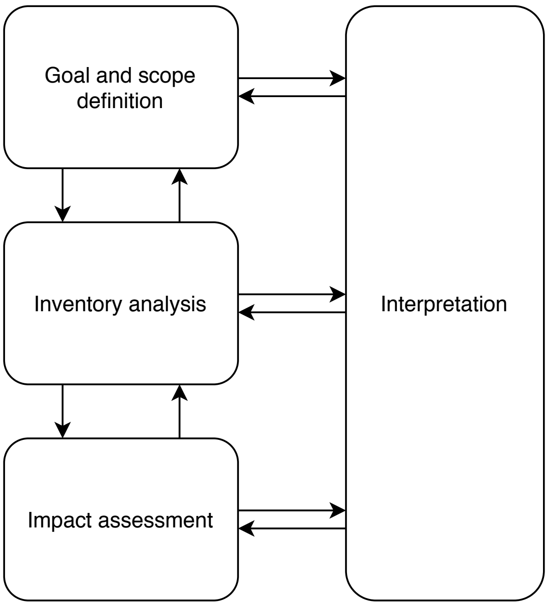

Figure 2.1: Framework for LCA according to ISO 14040 [13].

2.1.1 The four steps in LCA

According to the ISO 14040 standard, an LCA consists of four steps: goal and scope definition, inventory analysis, impact assessment and interpretation. The interpretation is integrated in all steps since it is an iterative procedure [13].

In the goal and scope definition, the framework for the assessment is set by defining which parts of the life cycle that are included and for which purpose the assessment is made [14]. Herein the functional unit of the study is defined, which is the function that the results should be related to. The functional unit also serves as a base for comparison between different products with the same function, both within the LCA and to compare with results from already performed LCAs [14]. Furthermore, it is described for whom the assessment is made and methodological choices regarding time horizon, choice of impact categories and cut-off criteria are stated [15].

The next step is the inventory analysis, in which modelling of the chosen technical system is performed, including production, transport, use, and disposal, depending on the system boundaries set in the goal and scope definition. The relevant inflows and outflows are collected for the included processes, such as material, energy, emissions and waste. The collected data is also related to the functional unit as well as described and verified in order to facilitate the interpretation of results. The result is a Life Cycle Inventory (LCI) comprising all elementary flows to and from nature as a consequence of the processes in the study [14].

Impact assessment is the phase where the LCI is translated into environmental impacts. Starting with making an impact category definition, in which the impact categories are determined, cause-effect-chains and their end-points are modelled [15]. The next step is classification, where the inventory flows are assigned to impact categories depending on their characteristics. Methane for instance, is assigned to global warming since it is a greenhouse gas [14]. Thereafter a characterization is performed where the relative contributions of each inventory flow to the environmental impact is calculated [15]. This means in practice that each resource or emission is multiplied with a characterization factor in order to determine its relative contribution. Normalization and weighting are two voluntary steps according to the ISO standard [14].

Interpretation can be seen as the most important step in the LCA, since its where all results are presented, analysed and conclusions are made. Other important parts of the interpretation in LCA are evaluations and checks, for example sensitivity analyses, uncertainty analyses and assessments of data quality [15]. Another example is a hotspot analysis, which is performed to assess the environmental impacts of each phase of the life cycle. It thereby helps with visualising and quantifying how different stages individually contribute to the environmental load of the product. The hotspot analysis can work as a basis for development of products and processes by giving guidance to which processes to prioritise [14].

2.1.2 Applications

Generally, it can be said that there are numerous applications for LCAs with a varying nature. According to the ISO standard there are four main applications: identification of improvement possibilities, decision making, choice of environmental performance indicators and market claims. One aspect that is missing in the definition is the aspect of learning. By studying a product's life cycle one can obtain a greater understanding of the processes included and the relationship between them. Consequently, another way to define the application areas of LCA is: decision making, learning and communication [15].

Another application is the comparison of products. The functional unit is central in LCA and enables the comparison between different products with the same function [15].

2.2 Electric vehicles

The technology for electrifying the transport industry has emerged as a transition into a more sustainable society in several ways, such as decreased dependence on oil, improved air quality and lower emissions of greenhouse gases [16]. There are alternatives to the fossil fuels in terms of biofuels, electricity and hydrogen that are considered renewable or more environmentally friendly during the use phase of the vehicle [17, 18]. These fuels have both advantages and disadvantages regarding production, costs, used land area and energy intensity of the fuel.

There are some drivers for the EVs in the future and one of them is the availability of electrical energy, which is not considered as a finite resource in the aspect that fossil fuels are. The term EVs is often associated with large batteries in vehicles that are charged by using a plug-in charger. The charging times are often long and the vehicles are considered to be more beneficial for city traffic rather than for longer distances, in comparison to traditional combustion vehicles [16]. In this thesis, the EVs are defined as vehicles that are powered by an electric motor. The electricity can either be stored in a battery or produced in the vehicle while driving. The main idea is that the vehicle is powered by electricity that drives the wheels [16, 19].

The EVs are often referred to as zero emission vehicles since they do not produce any direct emissions that are released into the atmosphere during the use phase [20]. This differentiates the electric vehicles from the traditional combustion vehicles with an internal combustion engine, which causes direct emissions that are released into the atmosphere during the use phase [20, 21].

In the following sections, two studied vehicle options for EVs are presented: BEVs and FCEVs. Both are promising technologies within the future transport sector. However, aspects of the cost of the vehicle, social acceptance, availability of fuel and the cost of the fuel have an impact on how they will adapt into a future society [16, 22].

2.2.1 Battery electric vehicle

A BEV is categorised as an EV since it uses an electric motor to power the vehicle. The electricity is stored in a battery that is used to power the electric motor. There are different types of batteries used in BEVs, however they have different requirements and limitations regarding for example power density, costs and safety. Lithium-ion batteries (Li-ion batteries) are commonly used in today's BEVs [23].

BEVs are proven to have several benefits compared to the traditional internal combustion engine. For example, they lack tail-pipe emissions, have high efficiency, provide sovereignty from petroleum resources and operates quieter [24]. The difference in efficiency between the two alternatives have to do with the fact that an electric motor utilises more than 90% of the stored energy for propulsion while a conventional engine utilises less than 25% of the energy content in one gallon of gasoline [25]. One gallon corresponds to 3.79 litres. Another benefit is that an electric motor can be directly connected to drive the wheels, avoiding unnecessary fuel consumption when the car is standing still or moves without needing motor power [25].

There are not only benefits with this type of technology. The driving ranges for BEVs are widely spread and this limits their potential usages. Some of them are more appropriate for city driving where home charging is possible. For long range-transport the dependency of available infrastructure and charging stations increases, where an important factor is acceptance for EVs [26]. In order to capture the actual environmental impact of EVs, it is important to consider the upstream emissions. The production of the electricity plays an important role when it comes to emissions of greenhouse gases [25]. One example is that globally, the production of both electricity and heat are very carbon-intensive processes, since they are to a large extent reliant on coal and other hydrocarbons. A drawback with EVs is the strong correlation to usage of fossil-based electricity [27]. However, this can be changed with more extensive use of renewable electricity.

When it comes to infrastructure for the EVs in Sweden, the conditions vary considerably within the country. The publicly available charging stations are not evenly spread over the country. In Västra Götaland county there are 1566 charging stations, in Stockholm county 2382 and in Norrbotten county there are only 99 stations [28]. The total amount in Sweden is 9348 stations, meaning that Stockholm county possess 25%, Västra Götaland 17% and Norrbotten county only 1%. This clearly demonstrates that the infrastructural conditions for electric vehicles vary across the country. In addition, one important aspect to have in mind is that there is no standard for the infrastructural network, meaning that not everyone is able to charge at all charging stations. Publicly available charging stations stands for only a share of the actual charging places since most cars are charged at home.

Future projections show that the number of electric cars in the car fleet will increase in the coming years, which will result in an increased demand of electricity. This is not considered as a problem from an energy point of view. However, this entails large power requirements for the grid, since the cars needs to be charged at certain hours. This could be optimised by a smart grid, which makes it possible to balance the supply of and demand for electricity. An increase of electric cars in the society will thereby require changes, and one example is that the charging patterns need to be changed [29, 30].

2.2.1.1 The components in a BEV

BEVs differ from traditional vehicles since the internal combustion engine is removed and replaced with an electric motor. Therefore, the vehicle is equipped with a traction battery pack of a large size that is charged by connecting the car with its charging port to an external power supply. An on-board charger converts the Alternating Current (AC) obtained from the electricity grid into Direct Current (DC), which is required to charge the battery pack. The traction battery is what powers the electric motor. In order for the mechanical power produced by the electric motor to drive the car forward, a transmission is required.

There are some other components that are necessary in order for the vehicle configuration to work. The power electronics controller regulates the energy provided to the electric motor, in order to manage its velocity and torque. Additionally, a system which regulates the temperature is also necessary in order to maintain conditions for optimal function. In order to provide all vehicle accessories with electricity an auxiliary battery is needed, this battery is charged by converting the high voltage DC from the battery pack to lower voltage DC with help from a DC-DC converter [31]. The components comprising a BEV are summarised in Table 2.1.

Table 2.1: Components in BEV.

Components
Battery (auxiliary)
Charge port
DC/DC converter
Electric traction motor
On-board charger
Power electronics controller
Thermal system (cooling)
Traction battery pack
Transmission

The simulated BEV is modelled in a simplified way, meaning that only a few of the components mentioned in Table 2.1 are modelled specifically on a component level. The part of the BE powertrain which is modelled with a higher precision consists of: a Li-ion battery, an inverter, an electric motor and a transmission.

Figure 2.2 illustrates which components that are included in the modelling in a more detailed manner and what is modelled more generally. A colour-coding is used to represent the similarities and differences. One important note is that the components in green and blue are modelled in this thesis, the green ones are specific for the vehicle described and the blue ones are identical for the two modelled vehicles. The components depicted in light grey and cross-hatched are important components in a BEV but are not modelled specifically, but instead as a part of an approximation representing all remaining vehicle parts and components in a "glider" dataset.

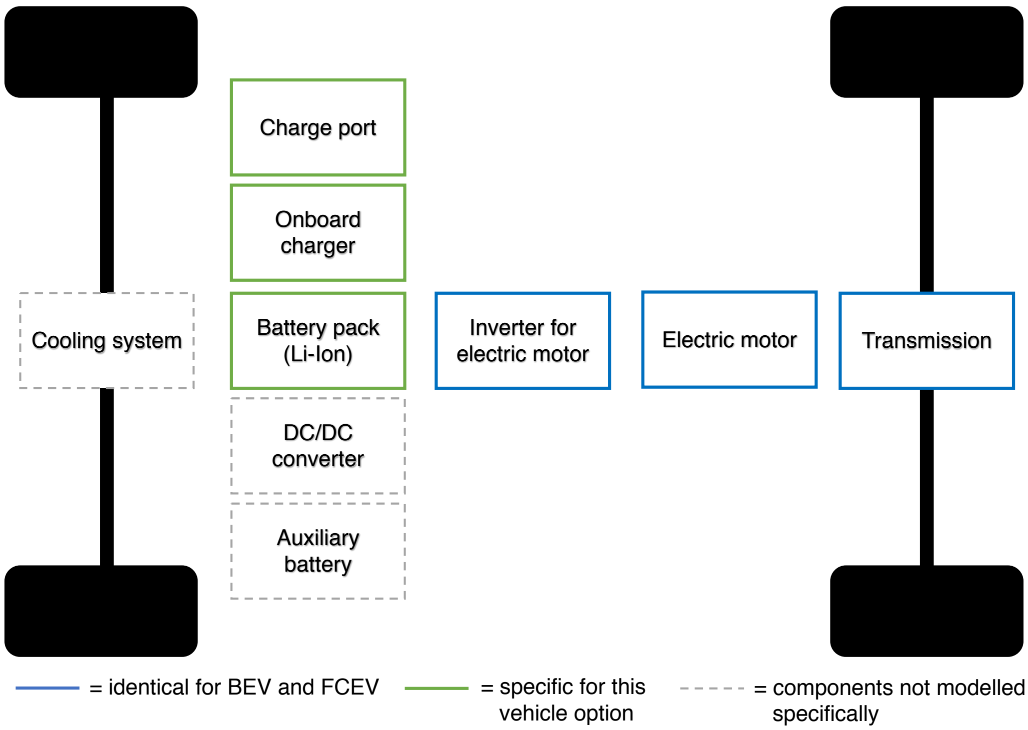

Figure 2.2: Schematic presentation of a BEV.

2.2.2 Fuel cell electric vehicle

An FCEV is categorised as an EV since it uses an electric motor to power the vehicle. A simplified description of the process occurring in the FCS in the FCEV is that the electricity is produced in an electrochemical reaction. The vehicle uses hydrogen as a fuel and converts chemical energy into energy and the by-products are heat and water vapour [19, 20].

The energy conversion efficiency of the fuel cell is considered high compared to a conventional gasoline engine. The FCEV also has the benefit of a short charging time in comparison to charging an EV of the same size [32]. There are different types of fuel cell technologies where the electrolytes, operating temperatures and type of catalyst varies. Polymer Electrolyte Membrane (PEM) fuel cells are the most commercialised fuel cell technology today, since it has a short start up time and has a low operational temperature in comparison to the other alternative technologies [33].

The PEM fuel cell technology is considered to be well suited for transportation applications. This is because of the compactness, lightweight, high power density and high energy conversion efficiency [25]. However, one of the challenges for future commercialisation is the high costs of the technology as a whole while implementing it in a vehicle. One explanation for the high production cost is the immaturity of the technology, which results in an economic disadvantage while competing with other more established technologies [25]. BEVs are an example of a technology that are produced in larger quantities than the FCEVs.

The fuel cell technology has become more commercial and competitive over the last years and one example of this is in Japan. There are more than 200 000 installed fuel cells in Japan and the PEM fuel cell constitutes the majority of them [34]. In Sweden, there are several companies that are both active and successful within the export market such as PowerCell, Impact Coating and Sandvik. Interest is shown by experts and researchers within the field of technology which can be identified by the fact that there are projects and conferences conducted related to the fuel cell technology [34]. The FCEV is expected to be the next-generation vehicle since it does not generate greenhouse gases and air pollutants during its use phase [32].

The technology entails challenges and one of them is that FCEVs have a lot of requirements in terms of gravimetric power density, reliability, costs and volumetric power which impacts the cost effectiveness and the availability of materials suitable for production [25]. Another challenge is the fuel in terms of hydrogen. In today´s market it is considered as an expensive fuel and the infrastructure for the hydrogen fuelling stations varies a lot in different parts of the world. In Sweden, there are currently five hydrogen gas fuelling stations but there are plans to increase the number of them in the near future [35]. The EU financed project called Nordic Hydrogen Corridor aimed in 2018 at building eight hydrogen gas fuelling stations by 2020, where 32 cities showed interest in being a part of building and maintaining a hydrogen gas fuelling station. The involved parties in the initiative was Sweco (who was the project coordinator of the project), Vätgas Sverige, AGA, Hyundai and Toyota [36].

FCEVs are often expensive because of the fuel cell technology and the storage tanks that need to have good quality since the hydrogen is stored at high pressure [32]. FCEVs are expensive vehicles and thereby the cars were initially rather leased than bought by the customers. As Toyota released the Toyota MIRAI in 2014, there was a shift in ownership from leasing into buying the cars [32]. In today's market companies like Toyota, Honda and Hyundai are selling FCEVs, and there are incentives and interests indicating that the suppliers of FCEVs will increase in the future [37, 38].

2.2.2.1 The fuel cell stack system

PowerCell produces an FCS system called MS100, which can be seen as a modular unit that can be combined with an electric driveline resulting in an FCE powertrain. The MS-100 system consists of an FCS, supporting equipment and components to maintain the management during operation.

An FCS consists of a number of fuel cells that are combined and cooperate, resulting in a higher capacity for the stack than for a single cell. The technology behind the FCS can be described by the process that occurs in one of the fuel cells in the stack. In a fuel cell, the chemical energy stored in hydrogen is converted into electric energy that can be used for a range of applications. The general technology behind the PEM fuel cell is illustrated in Figure 2.3. The fuel cell consist of a Membrane Electrode Assembly (MEA), which is a PEM with a catalytic layer on each side, anode and cathode respectively. On both sides of the MEA there are gas diffusion layers and outside of these there are bipolar plates. The bipolar plates distribute the hydrogen and air on both sides of the cell and are not illustrated in Figure 2.3.

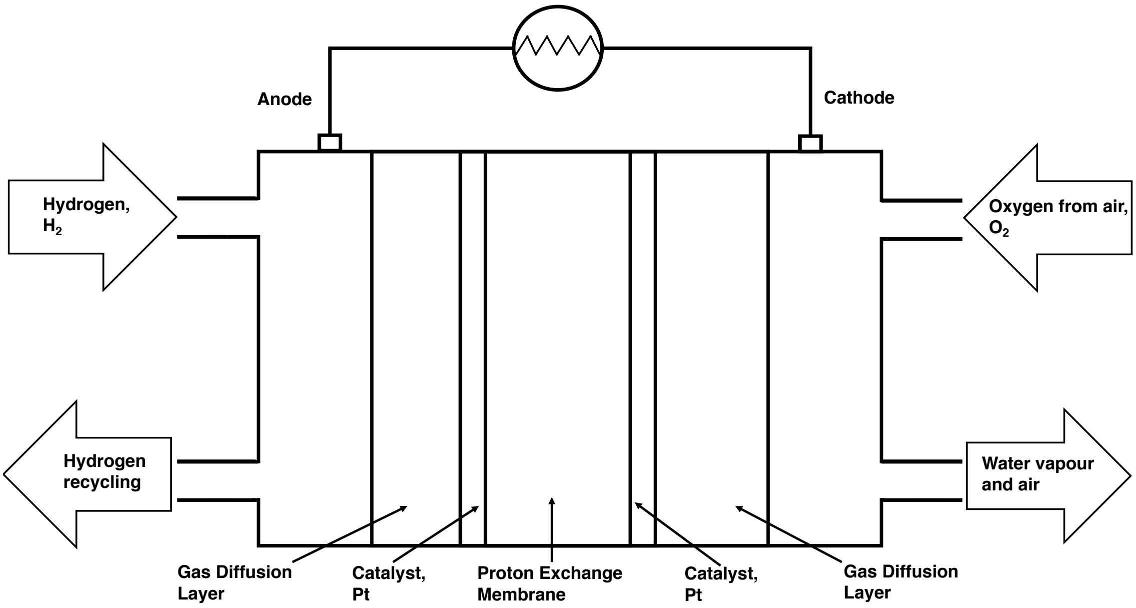

Figure 2.3: Technical description of a PEM fuel cell, illustrated with inspiration from [39, 40].

At the anode side of the fuel cell, the hydrogen molecules go through the bipolar plates and through the gas diffusion layer. The hydrogen molecules are catalysed by platinum which splits the hydrogen into two ions with a positive charge and two electrons. Thereafter the hydrogen ions go through the PEM. The electrons cannot pass through the membrane and therefore they go via the electric circuit from the anode to the cathode side of the fuel cell. On the cathode side of the fuel cell there is an inlet flow of oxygen from air. The oxygen molecules are distributed by bipolar plates and pass through the gas diffusion layer. Thereafter, they react with platinum and are split up into two negatively charged oxygen ions. Due to their negative charge, they attract the positive hydrogen ions that go through the PEM. As a result, the hydrogen ions, the electrons passing via the electric circuit and the oxygen form water by a chemical reaction. The water is transported out of the PEM fuel cell by an airflow [41, 42].

The conversion of chemical energy, stored in the hydrogen fuel, into electric energy takes place when the electrons go through the outer circuit. As this causes a current, in other words electricity, that is used to power the electric motor that drives the vehicle. However, one single fuel cell does not produce enough electrical energy to power the vehicle since it typically produces less than 1 V [43]. Therefore, many fuel cells are combined in the FCS to provide the required power. The cells in the FCS are held together by the compression plates and current collectors are used to collect the electric current.

The FCS needs a supporting system in order to provide the electric energy that powers the FCEV. Examples of the supporting components for the MS-100 system are compressors, a pump to recirculate excess hydrogen, cooling loops with pumps that cool down the MS-100 system, a humidifier that keeps the membranes moisturised and a controller unit that operates the components and electronics.

2.2.2.2 The components in an FCEV

In order to start the FCEV an auxiliary battery is needed to provide the electricity to start the vehicle, thereafter the traction battery can be engaged and power the vehicle. The FCS system generates the electric energy in form of a DC that can enter two different routes, it can either power the electric traction motor directly or charge the traction battery pack. The traction battery pack can also be used to power the electric traction motor [20].

The traction battery pack stores energy to supply to the electric traction motor, if running out of fuel. The electric traction battery pack is also used to recharge the auxiliary battery and to provide the vehicle with lower voltage power in order to run the vehicle accessories. In order for this to work, a DC/DC converter is needed since the electricity from the electric traction battery needs to be converted from high voltage DC to lower voltage DC. The electrical energy that comes from the traction battery pack and the FCS are regulated and managed by a unit called the power electronics controller. This in order to control the velocity and torque of the electric traction motor [19].

There are requirements that needs to be fulfilled in the vehicle in terms of operating temperature, pressure and humidity. In order to maintain an operating temperature within the acceptable temperature range for the components in the vehicle, the thermal system has a cooling function that is used for example in the FCS and the electric motor [19]. The performance of the FCS is related to the pressure and thereby the FCS system includes air compressors to increase the pressure of the reactants. Regarding the optimal conditions for the PEM fuel cell, the membrane requires a certain humidity in order to work properly. Therefore, a humidifier is an important component in the FCS system [43].

The FCEV uses hydrogen as a fuel, meaning that it needs a fuel filler which is a nozzle where the pressurised hydrogen can be fuelled. The nozzle is connected to the tank which is where the hydrogen is stored in the vehicle [19]. The tanks should be made of resistant and robust materials that are cheap, light and safe to use. The hydrogen is stored in gaseous form at high pressurised tanks which varies from 350-700 bar [44, 45]. It is not stored in liquid form since it is an energy intense process to liquefy hydrogen as hydrogen is liquefied at -252.8 ° C at the pressure of one atmosphere [45]. In Table 2.2 a summation of the components in an FCEV is presented.

Table 2.2: Components in an FCEV [19].

Components
Battery (auxiliary)
DC/DC converter
Electric traction motor
FCS
Fuel filler
Fuel tank for hydrogen
Power electronics controller
Thermal system (cooling)
Traction battery pack
Transmission

The simulated FCEV is modelled in a simplified way meaning that only a few of the components mentioned in Table 2.2 are modelled specifically, on a component level. The part of the FCE powertrain which is modelled with a higher precision consists of: an MS-100 system, a Ni-MH battery, an inverter, an electric motor and a transmission. Figure 2.4 illustrates which components that are included in the modelling in a more detailed manner and what is modelled more generally. A colour-coding is used to represent the similarities and differences. One important note is that the components in green and blue are modelled in this thesis, the green ones are specific for the vehicle described and the blue ones are identical for the two modelled vehicles. The components depicted in light grey and cross-hatched are important components in an FCEV but are not modelled specifically, but instead as a part of an approximation representing all remaining vehicle parts and components in a "glider" dataset.

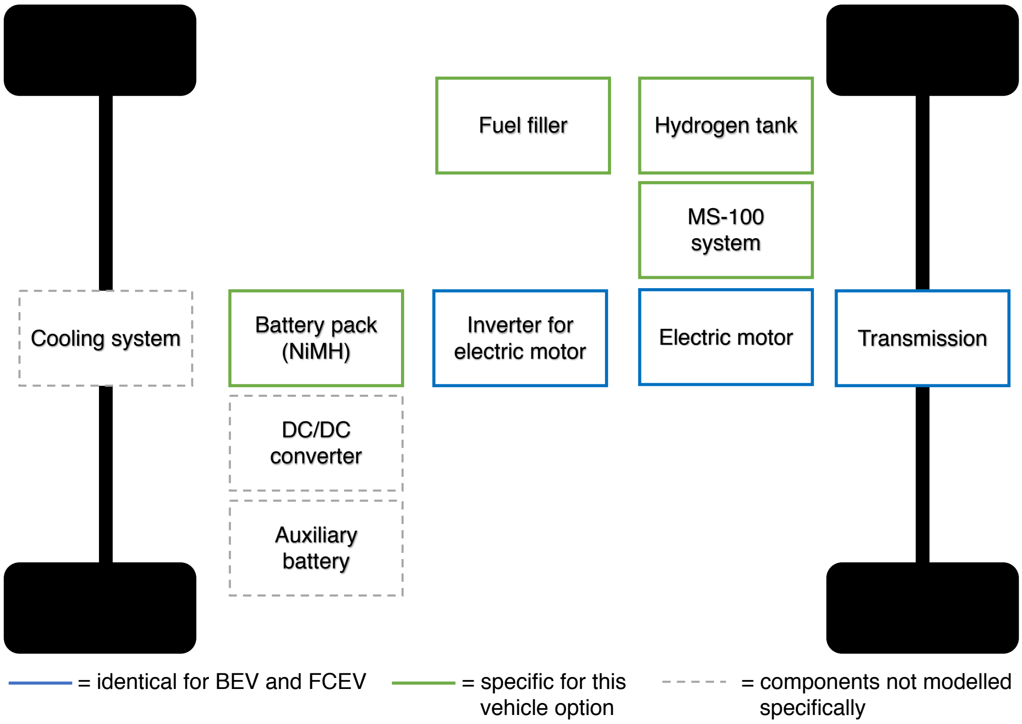

Figure 2.4: Schematic presentation of an FCEV.

2.3 Production of hydrogen gas as a fuel

There are several ways in which hydrogen gas can be produced, that vary in terms of renewability of the primary energy source and the materials and components used. The first production pathway described in this thesis is steam reformation of natural gas. This is the most commonly used method to produce hydrogen on a large scale. However, natural gas is not a renewable source of energy and the hydrogen produced is referred to as "grey". The key benefit of grey hydrogen is a low production cost.

The category of "clean" hydrogen includes both "blue" and "green" hydrogen. Blue hydrogen refers to production processes of hydrogen where the carbon emissions are captured and stored. Green hydrogen is considered as the cleanest form of hydrogen production and refers to hydrogen production generated by renewable energy sources. During such production, there should not be any carbon emissions produced. Estimates indicate that the prices for clean hydrogen are predicted to stay high relative to the prices for grey hydrogen until 2030. At the same time there are more positive estimates that indicate a more rapid decrease in the price for clean hydrogen [46].

The second production pathway for hydrogen is electrolysis of water and it is considered to be green when the supplied electricity comes from renewable generation, since only water and electricity is used. Wind powered electricity is used and therefore green hydrogen is produced. An additional benefit of integrating hydrogen production with renewable electricity production is the ability to produce hydrogen when there is excess electricity available that would not have been used otherwise. This is possible if intermittent energy sources are used for the electricity production [47].

2.3.1 Steam methane reforming of natural gas

Steam reforming of natural gas is considered as the most cost-effective and energy efficient commercialised technology for production of hydrogen, given large scale production with constant loads [48]. Hydrogen can be produced by different reforming processes and SMR is one of the most used production methods within industrial processes [49]. SMR is a production method used to produce hydrogen gas from natural gas [50]. Natural gas is a non-renewable energy source, which means that it will run out eventually [51]. Hydrogen production by SMR can in a simplified way be described in four steps: purification of natural gas, reaction with pressurised steam forming hydrogen gas, separation of carbon dioxide from the product and purification of the hydrogen gas [52].

During SMR the natural gas is converted into the gas mixture of carbon monoxide (CO) and hydrogen gas (H_2). Natural gas mainly consists of methane which is a light hydrocarbon. The natural gas is pre-treated by going through a chemical process where sulphur compounds and other impurities in the natural gas is removed by a catalytic reaction.

Thereafter, purified natural gas and pressurised steam are fed into the steam reformer [53], [54] at 1.5-3 MPa with the temperature of 850^{o}C. The reaction produces water and syngas which includes CO and carbon dioxide (CO_2) Equation 2.1 describes the reaction.

$$CH_4 + H_2O \rightarrow 3H_2 + CO \qquad \Delta H^o < 0 \tag{2.1}$$

Thereafter, a water gas shift reaction takes place. Herein the CO reacts with water to produce more hydrogen, according to Equation 2.2.

$$CO + H_2O \rightarrow H_2 + CO_2 \qquad \Delta H^o > 0 \tag{2.2}$$

The concentration of the CO in the product is approximately 0.1-0.2% [49]. Next, the CO_2 is separated from the product by liquid adsorption in a carbon dioxide removal unit [54]. Higher hydrogen purity can be reached by using for example pressure swing adsorption or membrane reactors [49].

2.3.2 Electrolysis of water

In hydrogen production by electrolysis of water, electricity is supplied to an electrolyser and water is broken down into hydrogen and oxygen. An electrolyser is, just like the PEM fuel cell, an electrochemical cell which contains an anode, a cathode and the two parts are separated by an electrolyte. The function of the electrolyte is to create an electrically conducting solution. Depending on which electrolyte material that is being used, electrolysers work differently and have different names. The three most common types used are PEM electrolysers, alkaline electrolysers and solid oxide electrolysers [47].

Alkaline water electrolysis uses an electrolyte in form of a liquid solution of sodium or potassium hydroxide. It selectively transports hydroxide ions, from the cathode to the anode. Solid oxide electrolysers utilise an electrolyte in a solid form, a ceramic material. This electrolyte instead selectively transports negatively charged oxygen ions at specific temperatures, however this requires high operating temperatures [47]. These two methods are not modelled in this thesis.

The overall equation, regardless of which type of electrolyte being used, is the same. What happens in the chemical reaction is that water is transformed or split into hydrogen gas and oxygen gas. The overall reaction is presented in Equation 2.3.

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \tag{2.3}$$

The electrolytic hydrogen production method used in this thesis is PEM water electrolysis. The reason is that there are available LCI data for this hydrogen production in the literature.

In PEM water electrolysis the electrolyte used is a solid polysulfonated membrane, for instance, Nafion [55]. The function of the membrane is to selectively transport protons between the cathode and anode. The specific reactions occurring in the PEM electrolyser are presented in Equation 2.4 and Equation 2.5. The overall reaction is the same as the one stated in Equation 2.3.

$$Anode : H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^- \tag{2.4}$$

$$Cathode : 2H^+ + 2e^- \rightarrow H_2 \tag{2.5}$$

First, water at the anode is split into protons, oxygen and electrons. The oxygen leaves in gas form. Thereafter the protons travel through the proton conducting membrane to the cathode and electrons exit through the external power circuit in order to provide the driving force for the process. This enables the protons and electrons to recombine in order to produce the hydrogen which also leaves in gas form [55, 56].

2.3.2.1 Production facility for green hydrogen

This thesis investigates a possible green production pathway for hydrogen. The modelled green production facility has been inspired by the hydrogen fuelling station in Mariestad, Sweden. This hydrogen fuelling station in Mariestad consists of several components and the most important are: a solar powerplant, an alkaline electrolyser, a battery and a hydrogen storage unit [57].

Solar power is an intermittent energy source and thereby a battery is required in the facility to store excess electricity. The renewable production facility does not produce hydrogen with the same capacity as the commercialised SMR production facilities. However, it is considered as a more sustainable production process given the assumption that the electricity needed for the electrolyser is provided from renewable energy.

Wind power is another example of an intermittent and renewable energy source. In Sweden, wind power accounted for 12% of the electricity production in 2019 [58]. Furthermore, wind power is considered as a more promising method of producing electricity in the Swedish climate, where the insolation is more limited compared to other locations. Wind powered electrolysis is a common alternative for renewable hydrogen production in LCAs for FCEVs [59, 60]. Therefore, the green hydrogen production is modelled with wind powered electricity production based on PEM electrolysis of water.

2.4 Modelling and software

This section presents FASTSim and openLCA which are the main modelling software used.

2.4.1 Future Automotive Systems Technology Simulator

The simulation tool called Future Automotive Systems Technology Simulator (FASTSim) is used to simulate the use phase for the BEV and FCEV. FASTSim can be used to simulate light- and heavy- duty vehicles. The powertrain and vehicle characteristics can be adjusted to represent the user's specific needs. Thereby the tool makes it possible to investigate whether changes in the powertrain's or the vehicle's properties have an impact on for example the performance, efficiency and battery life of the vehicle. The program allows for consideration of conventional vehicles, hybrid electric vehicles, plug-in hybrid electric vehicles, all-electric vehicles, compressed natural gas vehicles and fuel cell vehicles, allowing for comparison between different powertrains and vehicle configurations [9].

Input data can either be automatically imported or manually inserted. The input data depends on which type of vehicle that is being analysed and which test procedure that is used. The components of the powertrain and their inputs in FASTSim are summarised in Table 2.3.

Table 2.3: Powertrain components in FASTSim and some examples of inputs for each component [9].

Component	Examples of inputs
Vehicle	Drag coefficient, frontal area, glider mass
Fuel storage	Power, energy
Fuel converter	Power, base mass
Motor/Controller	Power, base mass
Battery	Power, energy, base mass
Wheel	Inertia, radius
Energy management	Level of discharge aimed at improving the fuel converter efficiency
Other components	Transmission mass, auxiliary loads

Both the vehicle and its connected components are thereafter simulated through so called speed-versus-time cycles, in which you have the possibility to change the driving cycle according to the preferred driving pattern [9]. Two examples of driving cycles are the city and highway drive cycles, which are similar to the U.S. Environmental Protection Agency's fuel economy test for light-duty vehicles. The vehicle is tested in a laboratory environment with specific conditions for the given driving cycle [61].

There are several driving cycles to choose from which enables comparison between performances depending on the conditions. For each time step the tool considers the effect of the entered parameters such as drag, rolling resistance and regenerative braking, in order to give a representative fuel consumption and performance. The plausibility of the outputs has been validated by comparing with actual available test data for a large number of vehicles [9]. In FASTSim the results from the model are illustrated together with the test results, in order to give a clear representation of the differences between them.

The outputs from the model are many and they range from concerning the performance of the car into the specific costs of certain components. Two of the most important outputs from the simulation are the adjusted fuel economy and driving range. These results are used in the LCA case study in this thesis.

2.4.2 openLCA

Resources commonly used within the LCA community are LCA software such as openLCA, SimaPro and GaBi. A software has the benefits of providing structure to the analysis and facilitate the handling of large amounts of data. The software is easily integrated with databases and can perform calculations of impact categories that otherwise would have been more time consuming. In this thesis the software openLCA is used, which has the benefits of being open sourced and free, making it easily accessible. Furthermore, it is transparent, flexible and allows for a comprehensive understanding of the life cycle with a high level of detail [62].

In order to use openLCA, an external database is incorporated to contribute with data. There are several databases to choose from, both free and paid versions, and the database Ecoinvent 3.6 is used in this thesis. The database contains large amounts of life cycle data for processes and materials. One particular benefit with Ecoinvent 3.6 is the possibility to incorporate a glider dataset. This dataset constitutes an approximate representation of all the components of a vehicle which are not associated with the propulsion technology [63]. Thereby, the collection of information for the vehicle components is facilitated.

The principle within openLCA is to create processes by adding in- and outputs as well as defining a reference flow. The reference flow defines in which unit the in- and outputs are reported, and thereby allows for up- and downscaling of the process when linked with others. When creating a new process, direct emissions originating from the process should be added as outputs. Outputs can both be emissions and also products that might be used somewhere else. Processes already existing in Ecoinvent 3.6 can be linked upstream by choosing different providers of the flow, and own processes can be linked to each other by choosing the provider of the created flow.

The purpose of creating a network of processes is to follow and track all processes down to their original elementary flows. The network of processes can be further expanded in a product system where it is defined which phases of the life cycle that should be investigated. One example is that only the production phase is included or the entire product life cycle. Several product systems can also be compared by creating a project. This allows for several comparisons between the two alternatives on a highly detailed level.

3 Methodology

This chapter presents the methodology and describes the modelling in FASTSim and openLCA. Additionally, the methodology for the sensitivity analysis is presented.

3.1 General methodology

This thesis involved several steps that overlapped during the course of the project which resulted in an iterative process. The main method used was LCA with the purpose of assessing the differences between the entire life cycle for the BEV and the FCEV. FASTSim was used to simulate the driving range as well as the electricity and hydrogen consumption, and the values were used as LCI data for the use phase in the LCA case study. Furthermore, the LCA case study was modelled in the software openLCA, with the database Ecoinvent 3.6 incorporated.

The simulation of the two vehicle options, BEV and FCEV, are based on data for the Renault Master ZE panel van [11]. The simulated vehicles are hereinafter referred to as BEV and FCEV. The objective for the simulations was to collect LCI data for the LCA case study, in terms of comparable electricity/hydrogen consumptions and driving ranges. The environmental impacts of the entire life cycle for BEV and FCEV was modelled in openLCA from cradle to grave, for the four technology options.

A sensitivity analysis was conducted for two parameters, the platinum content in the FCS in the MS-100 system and the driving range.

3.2 Modelling in FASTSim

The simulation was performed in combination with a literature study and own calculations. FASTSim was chosen as the simulation tool since it can be used to simulate the fuel consumption and range of the vehicles. The simulation tool was considered credible since the U.S. Departments of Energy's Vehicle Technologies Office stands behind it [9].

In FASTSim there is data available for a number of pre-defined vehicles, but the Renault Master ZE panel van did not exist in the simulation tool. Therefore, two other baseline vehicles were used as a basis for the simulation of BEV and FCEV. The BEV was based on a vehicle with a BE powertrain and the FCEV was based on a vehicle with an FCE powertrain. All simulations were performed with the setting of a combined value from a city driving cycle and a highway driving cycle.

3.2.1 Baseline vehicles

Before the modelling of the BEV and the FCEV, the simulation tool was validated for the two baseline vehicles. The BEV was based on a Nissan Leaf and the FCEV was based on a Toyota Mirai. The validation was performed by comparing the simulated values to the values reported in literature.

The baseline vehicles were tested by running the simulation tool with the existing datasets, with a modification of the total weight of the vehicle. This approach was used because the Renault Master ZE was not included in the simulation tool and instead the data for the simulation of the BEV and the FCEV is based on values from literature. The simulated values and the driving ranges reported in literature are illustrated in Table 3.1.

Table 3.1: Comparison of driving ranges and the electricity/hydrogen consumption for two baseline vehicles.

Vehicle	Simulated value	Reported value
Nissan Leaf		
Driving range	164.0 km	170.0 km [64]
Electricity consumption	19.0 kWh/100 km	16.5 kWh/100 km [64]
Toyota Mirai		
Driving range	471.0 km	502.0 km [65]
Hydrogen consumption	1.10 kg H_2/100 km	0.76 kg H_2/100 km [66]

The values in Table 3.1 show that there is a difference between the simulated value in FASTSim and the reported values from literature. One explanation for the deviation can be that the driving cycles and conditions varies during the test phase.

3.2.1.1 Simulation of panel van

A simulation of the panel van was performed to compare the reported and simulated values for driving range and electricity consumption. The existing datasets for the Nissan Leaf were used as a starting point, but modified with specific technical data for the panel van. The data used in the simulation is illustrated in Table 3.2. The data in Table 3.2 was also used for the simulations of the BEV and FCEV in Section 3.2.2 and Section 3.2.2.2.

Table 3.2: Technical data for the simulated panel van.

Component	**Amount**	**Unit**	**Reference**
Panel van			
Drag coefficient	0.34	-	[67]
Frontal area	4.06	m^2	[67]
Wheel base	4.33	m	[10]
Tire radius	0.41	m	[10]

The simulation of the panel van was based on technical data for the Renault Master ZE panel van. However, the power of the battery was not known and was therefore approximated to be the same power as the electric motor. The data for the simulation in FASTSim are presented in Table 3.3.

Table 3.3: Data used for the modelling of the panel van in FASTSim.

Component	**Amount**	**Unit**	**Reference**
Panel van			
Total weight	3100	kg	[10]
Performance			
Battery power	57	kW	
Battery capacity	33	kWh	[11]
Electric motor power	57	kW	[11]

The data presented in Table 3.2 and Table 3.3 were combined and used as inputs for FASTSim to modify the default values provided by the simulation tool for the Nissan Leaf. The simulated and reported values for the panel van are presented in Table 3.4. The comparison was made in order to analyse whether the simulation tool would provide tolerable results when analysing larger sized vehicles.

Table 3.4: Comparison of driving ranges for the simulated and reported values for the Renault Master ZE panel van.

Vehicle	**Simulated value**	**Reported value**
Driving range	104.6 km	120.0 km, [11]
Electricity consumption	32.8 kWh/100 km	28.0 kWh/100 km, [68]

Table 3.4 shows that there is a difference between the simulated and reported values from literature. However, the simulation tool was assumed to make acceptable simulations of the panel van.

3.2.2 Simulation of BEV and FCEV

The BEV and the FCEV are based on the simulation for the panel van and have same function in terms of powertrain performance, payload and size. The total weights of the vehicles were modified in order to assure that the weight of the components in the BE- and FCE powertrain were included. The total weight, T_{weight}, was calculated according to Equation 3.1.

$$T_{weight} = C_{weight} + P_{weight} \tag{3.1}$$

The curb weight, C_{weight}, was defined as the total weight of the vehicle, excluding the driver and with a battery or fuel tank charged or filled to 90% [69]. The payload, P_{weight}, was assumed to include a driver with the weight of 75 kg and goods of 900 kg.

The curb weight of the BEV and FCEV differs, since the curb weight includes the weight of the powertrain. However, the glider includes the components of a vehicle that are not associated with the propulsion technology and are thereby identical for the BEV and FCEV [63]. The weight of the glider, G_{weight}, was calculated for the panel van according to Equation 3.2.

$$G_{weight} = T_{weight} - B_{weight} - EM_{weight} - MC_{weight} - P_{weight} - TR_{weight} \tag{3.2}$$

The weight of the powertrain, PT_{weight}, was assumed to be the sum of the weight of the battery, B_{weight}, the electric motor, EM_{weight}, the motor controller, MC_{weight} and the transmission, TR_{weight}. The motor controller is used to convert voltage between the battery and the electric motor. Another word for motor controller is inverter. The transmission was defined as the gearbox including the supporting mechanical system.

The following calculations for the BEV and the FCEV use the denotations presented in Table 3.5.

Table 3.5: Denotations for the components in the calculations.

Component	**Denotation**
Battery	B_{weight}
Curb weight	C_{weight}
Electric motor	EM_{weight}
Glider	G_{weight}
Motor controller	MC_{weight}
Payload	P_{weight}
Powertrain	PT_{weight}
Transmission	TR_{weight}
Total weight	T_{weight}

The weight of the glider for the panel van was calculated according to Equation 3.2 with the values presented in Table 3.6. The weight was calculated to 1666 kg.

Table 3.6: Values for calculation of the glider weight for the panel van.

Component	Amount	Unit	Reference
Panel van			
Payload	975	kg	[11]
Total weight	3100	kg	[10]
BE powertrain			
Battery (33 kWh)	255	kg	[11]
Electric motor (57 kW)	36	kg	[70]
Motor controller	8	kg	[71]
Transmission	160	kg	[9]
Calculated weight			
Glider	1666	kg	

Some components are assumed identical for the BEV and FCEV, in order to perform a comparable study. Therefore, the weight of the electric motor and the motor controller had to be recalculated. This was because the FCEV has an FCS with a power output of 100 kW. Thereby, the weight of electric motor and the motor controller was obtained from two calculation programs [70, 71]. The components and their respective weights are presented in Table 3.7.

Table 3.7: Identical components and weights used for the simulation of BEV and FCEV.

Component	Amount	Unit	Reference
Electric motor (100 kW)	45	kg	[70]
Glider	1666	kg	
Motor controller	11	kg	[71]
Payload	975	kg	[11]
Transmission	160	kg	[9]

3.2.2.1 Simulation of BEV

The total weight was required in order to simulate the BEV. The total weight is calculated according to Equation 3.1. Since the curb weight, C_{weight}, is defined as the sum of the glider weight, G_{weight}, and the weight of the powertrain, PT_{weight}, the equation was rearranged into Equation 3.3. This was done by adding the payload, P_{weight}, to the curb weight in order to obtain the total weight of the BEV.

$$T_{weight} = G_{weight} + P_{weight} + PT_{weight} \tag{3.3}$$

The required weights of the components in the BE powertrain in Equation 3.3 are presented in Table 3.8.

Table 3.8: The weights of the components in the BEV.

Component	Amount	Unit	Reference
Panel van			
Glider	1666	kg	
Payload	975	kg	[11]
Electric powertrain			
Battery (80 kWh)	404	kg	
Electric motor (100 kW)	45	kg	[70]
Motor controller	11	kg	[71]
Transmission	160	kg	[9]
Calculated weight			
Curb weight	2286	kg	
Total weight	3261	kg	

The powertrain, PT_{weight}, was assumed to consist of a battery, electric motor, motor controller and transmission. The battery referred to in Table 3.8 is a Li-ion battery. The weight and the capacity of the battery was obtained by a literature study in combination with an iterative approach. Data from the calculation software BATPAC was used to make a linearisation, based on four existing Li-ion batteries [72]. A mathematical expression was obtained based on the relationship between the weight and capacity of the Li-ion battery, that is presented in Section A.1.1.1.2 in Appendix A. Thereafter, the total weight of the BEV was calculated according to Equation 3.3. The data used for simulation of BEV is presented in Table 3.9.

Table 3.9: Data used for simulation of BEV.

Component	Amount	Unit	Reference
BEV			
Total weight	3261	kg	
Performance			
Battery energy	80	kWh	
Battery power	100	kW	
Motor power	100	kW	

The simulated driving range and electricity consumption are presented in Table 5.1 in Section 5.1. The obtained driving range for the BEV was used as a fixed value for the FCEV simulation. This was to make the BEV and the FCEV comparable in terms of driving range.

3.2.2.2 Simulation of FCEV

The total weight of the FCEV was calculated from Equation 3.3. The FCE powertrain was assumed to include a battery, an electric motor, a MS-100 system, a hydrogen tank, a motor controller and a transmission. The battery in the powertrain was a Nickel-Metal Hydride battery (Ni-MH battery) with a power of 1.6 kWh. This was based on the Toyota Mirai which has a motor power of 113 kW [66]. The data for the fuel converter also known as the MS-100 system is obtained from PowerCell.

The simulation of the hydrogen tank was made in an iterative process, since the required amount of hydrogen to provide the same driving range as for the BEV was unknown. The required amount of hydrogen gas for driving the given distance had an impact on the size and weight of the tank. Hence, the total weight of the FCEV was dependent on the weight of the hydrogen tank, which had an impact on the driving range.

To simulate the hydrogen tank, data was collected for different sizes of hydrogen tanks. It was found that the storage capacity of the hydrogen tank was approximately 97% of the total storage [73]. The storage capacity used in this thesis was however, 95% in order to facilitate the calculations.

The total weight of the FCEV was calculated by an iterative approach where the total weights for the FCEV and the hydrogen tank were considered as fixed values and the fuel storage energy in FASTSim was systematically changed until it reached the given distance. Thereafter, the simulated hydrogen fuel consumption was obtained and recalculated into 3.8 kg hydrogen gas with a hydrogen tank size of 4 kg. Given the amount of hydrogen and the weight of the tank, the total weight of the FCEV was calculated. The weights for the FCEV, the FCE powertrain and the calculated values for the curb weight and total weight are presented in Table 3.10.

Table 3.10: The weights of the components in the FCEV.

Component	**Amount**	**Unit**	**Reference**
Panel van			
Glider	1666	kg	
Payload	975	kg	[11]
FCE powertrain			
Battery (1.6 kWh)	54	kg	[74]
Electric motor (100 kW)	45	kg	[70]
MS-100 system	187	kg	
Hydrogen tank incl. 3,8 kg hydrogen gas	77	kg	
Motor controller	11	kg	[71]
Transmission	160	kg	[9]
Calculated weight			
Curb weight	2200	kg	
Total weight	3175	kg	

The data used for the simulation of the FCEV is presented in Table 3.11. The data for the fuel storage was represented by the MS-100 system. Consequently, all data for the simulation regarding the MS-100 system was provided by PowerCell.

Table 3.11: Data used for simulation of FCEV.

Component	**Amount**	**Unit**	**Reference**
FCEV			
Total weight	3175	kg	
Performance			
Battery energy	1.60	kWh	[74]
Battery power	33	kW	[9]
Motor power	100	kW	
Fuel storage			
Fuel storage energy	128	kWh	
Fuel and fuel storage mass	1.50	kWh/kg	[75]
Fuel converter power	100	kW	
Fuel converter time to full power	5	s	

The fuel and fuel storage mass were assumed to be the energy in the fuel divided by the weight of the tank. The value of 1.50 kWh/kg in Table 3.11 was obtained from literature [75]. The simulated driving range and hydrogen consumption are presented in Table 5.1 in Section 5.

3.2.2.3 Simulation of BEV with an extended driving range

The total weight of the BEV with an extended driving range was calculated based on the component weights in Table 3.8, with modified values for the total weight of the vehicle and the weight of the Li-ion battery. The driving range was extended by increasing the storage capacity for the Li-ion battery. The storage capacity was doubled, which resulted in a Li-ion battery of 160 kWh and 808 kg. The weights of the components in the BEV with an extended driving range are presented in Table 3.14.

Table 3.12: The weights of the components in the BEV with an extended driving range.

Component	**Amount**	**Unit**	**Reference**
Panel van			
Glider weight	1666	kg	
Payload	975	kg	[11]
BE powertrain			
Battery (160 kWh)	808	kg	[74]
Electric motor (100 kW)	45	kg	[70]
Motor controller	11	kg	[71]
Transmission	160	kg	[9]
Calculated weight			
Curb weight	2690	kg	
Total weight	3665	kg	

The simulation of the BEV with an extended driving range was performed in the same way as described in Section 3.2.2.1 with the exception of the value for the Li-ion battery energy and the total weight of the vehicle. The input data for the simulation in FASTSim is presented in Table 3.13.

Table 3.13: Data used for simulation of BEV with an extended driving range.

Component	Amount	Unit	Reference
Panel van			
Total weight	3665	kg	
Performance			
Battery energy	160	kWh	
Battery power	100	kW	
Motor power	100	kW	

The simulated driving range and electricity consumption are presented in Table 5.1 in Section 5.

3.2.2.4 Simulation of FCEV with an extended driving range

The total weight of the FCEV with an extended driving range was calculated based on the component weights in Table 3.10, with modified values for the total weight of the vehicle and the hydrogen tank. The driving range was extended by increasing the storage capacity of the hydrogen tank. The storage capacity was doubled, which resulted in a storage tank of 8 kg, with the storage capacity of 7.6 kg hydrogen gas and a fuel storage energy of 259 kWh. The weights of the components in the FCEV with an extended driving range are presented in Table 3.14.

Table 3.14: The weights of the components in the FCEV with an extended driving range.

Component	Amount	Unit	Reference
Panel van			
Glider weight	1666	kg	
Payload	975	kg	[11]
FCE powertrain			
Battery (1,6 kWh)	54	kg	[74]
Electric motor (100 kW)	45	kg	[70]
MS-100 system	187	kg	
Hydrogen tank with 7,6 kg hydrogen gas	154	kg	
Motor controller	11	kg	[71]
Transmission	160	kg	[9]
Calculated weight			
Curb weight	2277	kg	
Total weight	3252	kg	

The simulation of the FCEV with an extended driving range was performed in the same way as described in Section 3.2.2.2 with the exception of the value for fuel storage energy. The fuel storage energy was obtained by the iterative approach as mentioned in Section 3.2.2.2. The input data for the simulation in FASTSim is presented in Table 3.15.

Table 3.15: Data used for simulation of FCEV with an extended driving range.

Component	**Amount**	**Unit**	**Reference**
Panel van			
Total weight	3252	kg	
Performance			
Battery energy	1.60	kWh	[74]
Battery power	33	kW	
Motor power	100	kW	
Fuel storage			
Fuel storage energy	259	kWh	
Fuel and fuel storage mass	1.50	kWh/kg	[75]
Fuel converter power	100	kW	
Fuel converter time to full power	5	s	

The simulated driving range and hydrogen consumption are presented in Table 5.1 in Section 5.

3.3 Modelling in openLCA

To model the entire life cycle from cradle to grave of the four technology options, a LCI was required. The data collection and assumptions are presented and described in Section 4.2.

When the LCI data were collected, the next step was to model the processes and flows in openLCA. The reason for using a software for the impact assessment calculations was that it facilitates the data management and calculations, since performing all these calculations by hand would have been very time consuming.

The purpose with the modelling in openLCA was to get a representative picture of the environmental impacts of the four technology options. Processes were thoroughly researched before included in the model and own processes were created when there was not any representative process available.

The most common problem faced in the modelling was that the inventory did not match the content of the incorporated database Ecoinvent 3.6. Either it was a material that did not exist in the database or there were several variants of the same process. When this type of problem occurred, either a new process was created or the material was approximated by a material with similar properties.

One general methodological choice for the modelling of complex components was that their materials were added, together with general machining processes such as injection moulding for plastic materials and metal working for metals. This simplification was used since the exact machining processes were unknown. Additional limitations and assumptions for the LCA case study are described in the Section 4.

For the modelling of the four technology options in openLCA, the choice of providers of the flows was an important choice. The choice of flows in terms of the geographical system boundaries are further described in Section 4. The most preferred choice was to choose market processes with European conditions. Market processes can be described as a consumption mix of a specific reference product in a chosen geographical region. By using market processes, average transports of the chosen product within this region are also added [76]. The hierarchy used when identifying providers in Ecoinvent 3.6 is presented in Table 3.16.

Table 3.16: Hierarchy when choosing providers in Ecoinvent 3.6.

Hierarchy	**Provider**
1st	Market process - European conditions
2nd	Market process - Global conditions
3rd	Production process - European conditions
4th	Production process - Global conditions

3.4 Sensitivity analysis

A sensitivity analysis was performed since there was an interest to investigate the impacts of varying the platinum content in the FCS and extending the driving range. This analysis was performed for the two technology options with a high share of renewable sources, BEV-SE Mix and FCEV-WP Electrolysis.

In the first analysis, the platinum content in the FCS was varied by a parameter for three levels of platinum. The platinum content in the FCS is of interest to PowerCell since they are continuously improving their FCSs. Therefore, it was desired to look further into the consequences of changing the content as well as the effects of recycling the platinum.

In the second analysis, the environmental impacts of extending the driving range was investigated by doubling the storage capacity of the Li-ion battery and the hydrogen tank. The doubling of the capacity increased the driving range to a different extent for the BEV than the FCEV. Thereby, the vehicles were no longer comparable regarding the driving range and thereby did not have the same function. This was simulated in FASTSim to obtain the driving range and electricity/hydrogen consumption.

4
Life Cycle Assessment case study

In this chapter, the LCA case study conducted according to the LCA framework is described. This is presented in three sections: goal and scope definition, inventory analysis and impact assessment results.

4.1 Goal and scope definition

In this section the goal, context, scope and modelling requirements of the LCA case study are presented, along with assumptions and limitations.

4.1.1 Goal and context

The goal of the LCA case study is to find the environmental impacts of an FCEV equipped with an MS-100 system in comparison to a BEV with the same function and size. The intended application is to cover knowledge gaps and create an extended knowledge base for the environmental impact of the BEV and FCEV. Furthermore, the results of the LCA case study will be used by PowerCell for internal communication and as a base for future development of an FCEV with the MS-100 system.

The research question to be answered is: *What are the environmental impacts of an FCEV powered by PowerCell's MS-100 system and how does this vehicle compare with a BEV powered by a Li-ion battery with the same: powertrain performance, payload, driving range and total lifetime?* This is investigated by comparing two vehicle options, BEV and FCEV, which are identical except for the powertrains and each combined with two alternative production pathways for producing the energy carrier for the propulsion. The alternative routes are different electricity generation for charging and different hydrogen production processes. The four technology options are presented in Table 4.1.

Table 4.1: The four technology options included in the LCA case study.

Vehicle option	**Production pathway for producing the energy carrier for propulsion**	**Denotation**
BEV	European electricity mix	BEV-RER Mix
BEV	Swedish electricity mix	BEV-SE Mix
FCEV	Steam methane reforming of natural gas	FCEV-SMR
FCEV	Wind powered electrolysis	FCEV-WP Electrolysis

4.1.2 Scope and modelling requirements

The selected vehicle for the LCA case study is a panel van, modelled based on the Renault Master ZE, with an assumed lifetime of 250 000 vehicle km ($v \cdot km$). Two vehicle options are modelled with a BE- and an FCE powertrain, respectively. The life cycle scope of the four technology options is presented in two flowcharts in Figure 4.1 and Figure 4.2. The case study is conducted in collaboration with PowerCell and thereby specific data has been used for the MS-100 system, while the data for the Li-ion battery is more general and collected from literature.

The LCA case study is attributional, and the life cycle scope stretches from cradle to grave, with the modelling based on current technologies. Thereby, the system is studied with a short time horizon, as it is today. The reason is that the technology for BEVs and FCEVs is progressing rapidly. The case study also includes a sensitivity analysis which investigates two parameters. In the first analysis, the platinum content in the FCS is varied by a parameter for three levels of platinum. Furthermore, the environmental consequences of using primary platinum resources and the benefits of recycling platinum are investigated. The second analysis investigates the environmental impacts of extending the driving range, by doubling the storage capacity of the Li-ion battery and the hydrogen tank.

The LCA case study uses Ecoinvent 3.6 for background data, using the system model called *Allocation, cut-off by classification*, which applies the cut-off approach also called the recycled content approach [77]. This means that the processes and process flows used in Ecoinvent 3.6 includes secondary raw materials.

The life cycle is modelled as to include the waste separation procedures such as shredding of the materials at the End of Life (EoL). Thereby, the burden of the waste separation processes for the input processes are accounted for. However, not all upgrading procedures which are a part of recycling or any credits for recycled materials are considered.

The investigated life cycles for the BEV and the FCEV are divided into four subsystems that are defined and explained in Table 4.2. The subsystems are used to separate and illustrate different system boundaries.

Table 4.2: The modelled subsystems in the LCA case study.

Subsystem	**Defined in the LCA case study**
Natural system	System containing resources and energy resources.
Background system	System including the generic data from Ecoinvent 3.6
Technical system under investigation	The modelled system in the LCA case study based on communication with PowerCell and literature studies.
Core system	PowerCells production of the MS-100 system.

4.1.2.1 The modelled system for the BEV

The BEV is modelled as shown in the flowchart in Figure 4.1 and is presented in three phases: production phase, use phase and EoL phase. The flowchart illustrates the inputs of resources and energy resources from the natural system into the background system. It also presents the outflows in terms of emissions from the background system to the natural system.

The *background system* contains the generic processes from Ecoinvent 3.6 used as inputs for the modelling of the *technical system under investigation*. The process inputs from the *background system* to the *technical system under investigation* includes secondary raw materials from other products. There is also a flow of secondary raw materials leaving the *technical system under investigation* into the *background system*. This is because of the methodological choice of using the cut-off approach. There is also a waste flow from the *technical system under investigation* to the *background system*, which corresponds to all the generated waste for the modelled processes.

The *technical system under investigation* is presented in three phases that are illustrated as dotted lines. The boxes illustrate processes and the arrows between the boxes illustrate transport of process flows between the processes. The transports are modelled based on generic processes and assumed distances, which are described more in detail in Section 4.2. The production phase is the first phase and illustrates the three main components for the BEV: the Li-ion battery, other powertrain parts and the glider. They go through the steps of extraction, production of materials and parts, production of the BE powertrain and the production of the complete BEV. During the second phase, the use phase, the BEV uses electricity from either European or Swedish supply mix. The electricity consumption for the BEV was obtained from the results from the simulation of the BEV that is presented in Section 5.1. The BEV is also assumed to get maintenance during its lifetime.

After the BEV has driven 250 000 km it was assumed to be worn out. In the third phase, the EoL phase, the Li-ion battery is dismantled whereas the remaining vehicle, including the powertrain goes to shredding. The Li-ion battery is directly transported to a specific treatment and recycling facility, while the remaining vehicle components are shredded before being transported to the facility.

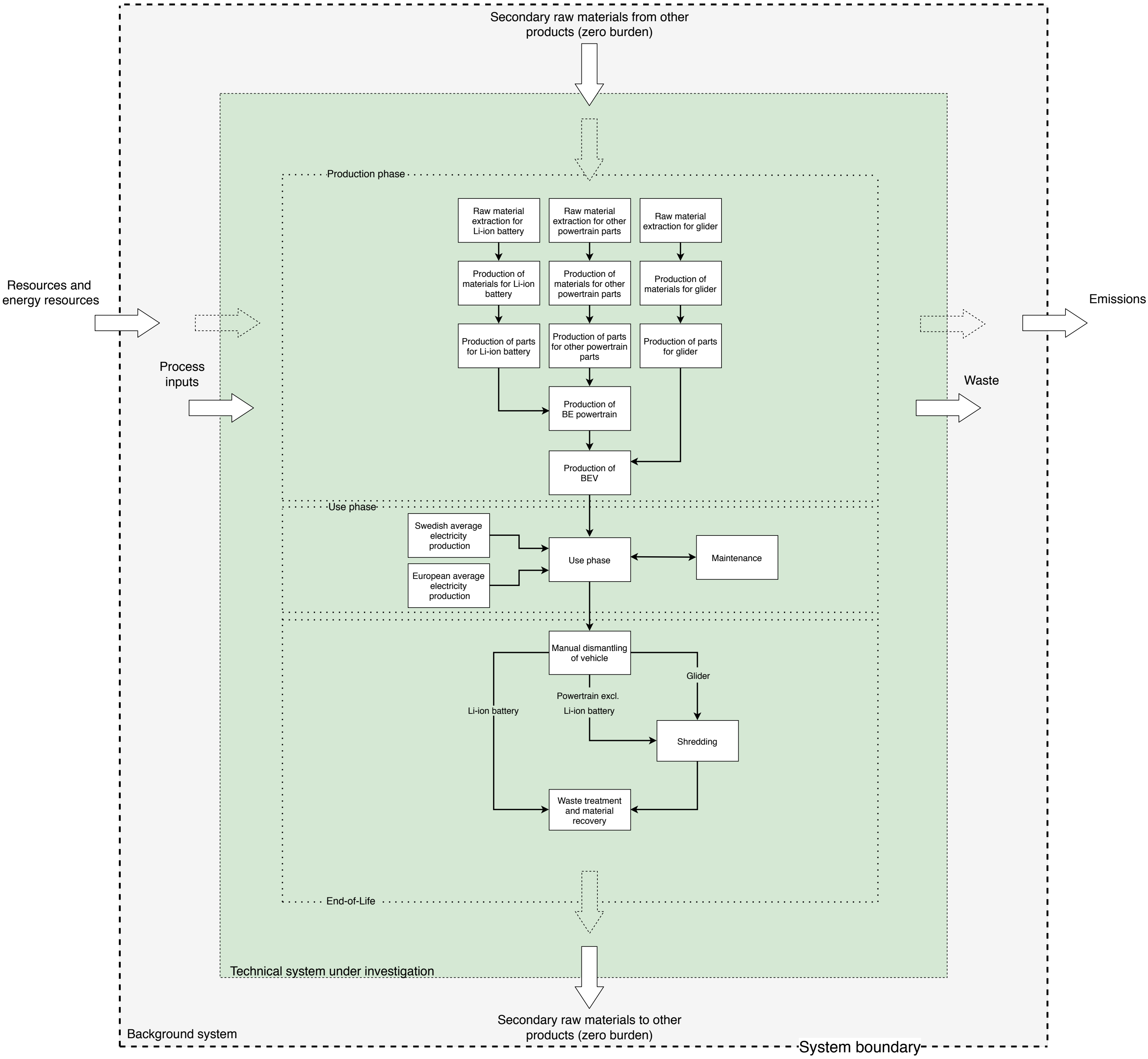

Figure 4.1: Flow chart for Battery Electric Vehicle.

4.1.2.2 The modelled system for the FCEV

The FCEV is modelled as shown in the flowchart in Figure 4.2 and the *core system* is modelled with more specific data since it was obtained from PowerCell. The *core system* constitutes what is otherwise often referred to as the foreground system in LCA. The flowchart in Figure 4.2 illustrates the resources, inputs, flows of secondary raw materials from or to other products with zero burden, waste outputs and emissions for the system in the same way as for the BEV in Section 4.1.2.2. The transports are modelled based on generic processes and assumed distances, which are described more in detail in Section 4.2.

The modelling differs for the BEV and the FCEV regarding the *technical system under investigation* since there are more processes modelled for the FCEV. The modelling includes the FCS, auxiliary components for the MS-100 system, other powertrain components, the fuel tank and the glider.

The *core system* includes the processes production of parts and the assembly of the FCE-system that PowerCell governs and can influence. PowerCell can choose their suppliers and set demands on quality and performance. The MS-100 system is assembled in PowerCell's facility. In the second phase, the use phase, the FCEV is modelled with two different production pathways for the hydrogen production, SMR and WP Electrolysis. The use phase includes the entire life cycle of the hydrogen production meaning that it takes the construction, production and dismantling of the supply chain facilities into account. The FCEV is also assumed to get maintenance during its lifetime.

After the FCEV has driven 250 000 $v{\cdot}km$ it is considered to be worn out. In the third phase, the EoL phase, the FCEV is dismantled into the MS-100 system, which is further dismantled into an FCS and the auxiliary components of the MS-100 system. The platinum in the FCS is assumed to be dismantled and recovered. The benefit from the recycling of platinum is not accounted for because of the methodological choice of using the cut-off approach. However, the effects of recycling platinum are further elaborated in the sensitivity analysis in Section 5.3.

The auxiliary components, the fuel tank and the glider are shredded. These components as well as the remaining parts of the FCEV are transported to a facility for the waste treatment and material recovery.

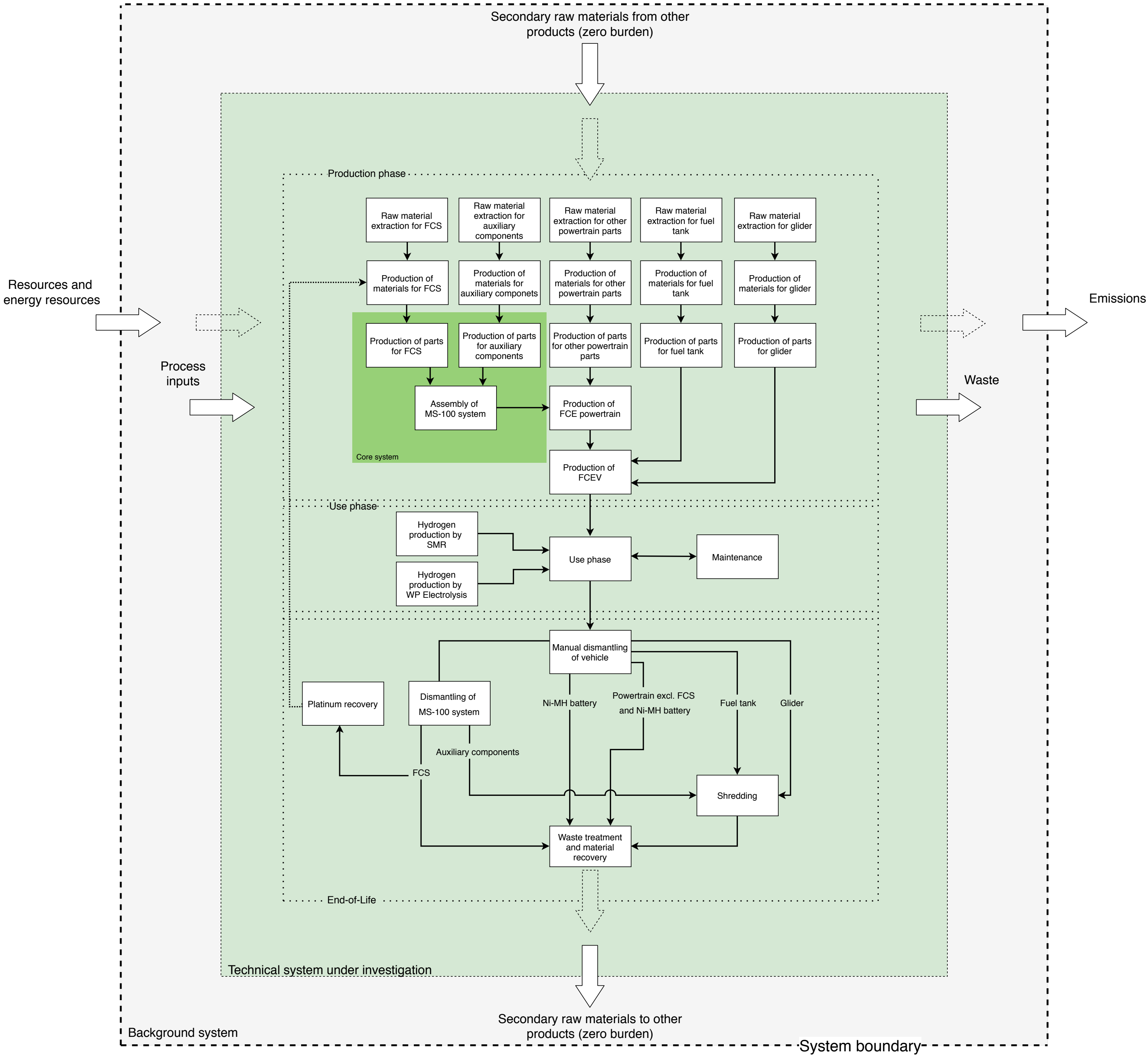

Figure 4.2: Flow chart for FCEV.

4.1.2.3 Functional unit

The functional unit of the LCA case study is expressed in vehicle kilometres, $v \cdot km$, driven by the vehicles in the use phase. This is used as the basis for comparison.

4.1.2.4 Selection of impact assessment methods and analysed impact categories

The method for impact assessment used is ILCD 2.0 2018 midpoint, provided by Ecoinvent 3.6. A set of methods identified by an expert group to provide the best available indicators for various environmental problems.

International Reference Life Cycle Data System (ILCD) is an international forum within the LCA society with the goal of providing robustness, consistency and quality assurance of life cycle data and its corresponding studies [78]. Furthermore ILCD is continuously reviewed by Joint Research Centre (JRC) which is a service within the European Commission [79]. Thereby, this method package was considered legitimate. Categories on midpoint level were selected since they are easy to analyse and interpret, relative to results on endpoint level.

The impact categories used are therefore included in this method package. The choice of impact categories was based on the impact categories chosen for a similar type of LCA conducted for Toyota Mirai, where Toyota Mirai was compared to other vehicle options [60]. Thereby, the same impact categories were analysed in this thesis since they were already stated as of importance for FCEVs. Additionally, it was considered as an advantage that the results could be compared.

Seven impact categories are used in this thesis: (i) acidification - freshwater and terrestrial, (ii) climate change - total, (iii) eutrophication - freshwater, (iv) eutrophication - terrestrial, (v) photochemical ozone formation, (vi) resources - fossils and (vii) resources - minerals and metals. They are presented in the following paragraphs. For eutrophication, both freshwater and terrestrial eutrophication are described. For resource use, fossil as well as minerals and metal resource use are described.

4.1.2.4.1 Acidification

Acidification can be described as the phenomenon when the chemical balances, both in terrestrial and aquatic areas are disrupted, resulting in a decreased pH value. Acidification in land and water can lead to both direct and indirect effects. A direct effect is that the reproduction of fishes is negatively affected. Furthermore, a change in pH can lead to changes in concentrations of nutrients leading to indirect negative effects for the surrounding plants and animals [80]. Furthermore, acidification can cause leaching of toxic metals out of soils and rocks, damage to forests as well as damage to buildings and monuments [15].

Acidification is indicated as Accumulated Exceedance (AE). This indicator describes the difference in critical load exceedance caused by deposition of acidifying substances in sensitive land and aquatic areas [81]. The most important acidifying substances are sulphur dioxide (SO_2), nitrous oxides (NO_x), hydrochloric acid (HCl) and ammonia (NH_3). Their common characteristic is their ability to form acidifying H^+ ions [15]. For this reason, the unit of the indicator is mol H^+ equivalents. Within the ILCD method package, both terrestrial and freshwater acidification is considered and belongs to the overall category ecosystem quality.

4.1.2.4.2 Climate change

Global warming can be described as the phenomenon when the radiation balance of the Earth is changing, meaning that infrared energy is trapped in the atmosphere and resulting in increased temperature. This is due to emissions of greenhouse gases that absorbs infrared radiation which otherwise would have left the Earth [82]. The most common greenhouse gas is CO_2, but other important ones are methane (CH_4), chlorofluorocarbons (CFCs) and nitrous oxide (N_2O) [15].

Global warming is measured in the category climate change by the indicator Global Warming Potential (GWP), which is defined as the ratio between the increased infrared absorption caused by the emissions accounted for, and the increased infrared absorption caused by 1 kg of carbon dioxide, which is used as the reference. In other words the GWP of a substance describes its potential contribution to climate change. Some greenhouse gases stay longer in the atmosphere than others and therefore GWPs are calculated and given for several time horizons, and in this case study GWP100 is used. The GWPs that are used within the scope of LCA are developed by the UN Intergovernmental Panel on Climate Change (IPCC). The unit of GWP is given in kg of CO_2 equivalents [15]. In this case study, climate change total is used which comprises all the categories: biogenic, fossil and land use.

4.1.2.4.3 Eutrophication

Eutrophication can be described as the phenomenon when the biological productivity of land and aquatic areas starts to increase due to the high availability of growth promoting factors such as sunlight, carbon dioxide and fertilizers. High levels of certain nutrients can also cause alteration of species composition. A consequence of eutrophication is for example algal blooms which negatively affects the water quality and clarity. Anoxic zones in waterbodies can also occur due to oxygen depletion caused by microbial decomposition of the blooms [15, 83].

The most important pollutants causing eutrophication are nitrogen and phosphorus. Eutrophication in aquatic and terrestrial areas differ. In terrestrial areas, eutrophication is measured by the indicator Accumulated Exceedance (AE) of nitrogen, with the unit of mol N equivalents. In contrast, the indicator used in aquatic freshwater is the portion of phosphorus ending up in freshwater compartments, with the unit of kg P equivalents. In this case study, both freshwater and terrestrial eutrophication is considered and they belong to the overall category ecosystem quality [79].

4.1.2.4.4 Photochemical ozone formation

Ozone (O_3) can be considered both beneficial and hazardous depending on its location in the air [84]. When it is present in the lower atmosphere, on a ground level, it is considered as a harmful pollutant due to its ability to negatively affect plants, human health and the built environment. It is formed due to photochemical oxidation of volatile organic compounds ($VOCs$) and carbon monoxide (CO) in the presence of nitrogen oxides (NO_x) and sunlight [85]. On the other hand, when present at a high altitude in the atmosphere, in the stratosphere, it is beneficial since it eliminates more than 99% of the harmful ultraviolet radiation coming from the sun and is a vital part of the ozone layer [15, 84].

Tropospheric ozone is the ozone considered within the indicator Photochemical Ozone Creation Potential (POCP). Photooxidants, like ozone gives rise to photochemical smog or summer smog which is harmful for both humans and nature [15]. POCP gives the photochemical ozone creation potential of one VOC relative to other VOCs [86]. The unit is kg of NMVOC equivalents, which is an abbreviation for non-methane volatile organic compounds. In the ILCD method package POCP belongs to the human health overall category [79].

4.1.2.4.5 Resource use

The resources covered within this impact category are abiotic resources, more specifically minerals, metals and fossil fuels. Abiotic resources are considered as non-living resources that are not recreated by themselves. Examples of abiotic resources are fossil fuels such as crude oil, iron ore and metals [15, 87].

Depletion of abiotic resources is often measured by the Abiotic Depletion Potential (ADP) which is calculated as a quotient between the extraction rate and the available amount of reserves, the resulting value is related to antimony [87]. In the ILCD package of Life Cycle Impact Assessment (LCIA) methods there are two indicators covering abiotic resources. Firstly, ADP ultimate reserves considering minerals and metals. Secondly, ADP fossil fuels considering fossil-based fuels. The reference unit of ADP ultimate reserves is kg of antimony (Sb) equivalents, while the unit of ADP fossil fuels is given in MJ [79]. This impact category brings significant insecurities because of difficulties in estimating correct sizes of reserves [87].

Table 4.3: The midpoint LCIA categories used in this LCA case study.

Impact category	**Indicator**	**Unit**
Climate change		
Climate change, total	Global Warming Potential (GWP100)	kg CO_2 eq.
Ecosystem quality		
Acidification *freshwater and terrestrial*	Accumulated Exceedance (AE)	mol H^+ eq.
Eutrophication, *freshwater*	Fraction of nutrients reaching freshwater end compartment (P)	kg P eq.
Eutrophication, *terrestrial*	Accumulated Exceedance (AE)	mol N eq.
Human health		
Photochemical ozone formation	Photochemical Ozone Creation Potential (POCP)	kg NMVOC eq.
Resources		
Resource use, *Minerals and Metals*	Abiotic resource depletion (ADP ultimate reserves)	kg Sb eq.
Resource use, *Energy carriers*	Abiotic resource depletion - fossil fuels (ADP fossil fuels)	MJ

4.1.2.5 Other system boundaries

In addition to the subsystems linked to the life cycle of each technology option explained in Sections 4.1.2.1 and 4.1.2.2, and the boundary to the natural system there are also boundaries in terms of time and geography. In terms of time scope, the LCA case study investigates current technologies. PowerCell´s MS-100 system is a prototype undergoing continuous improvements and development and the data used in the modelling represents the MS-100 system as it is today. The data used for the modelling of the other components in the system are assumed to be representative for today's production technologies.

The components in the MS-100 system are primarily modelled with a European origin, since PowerCell have their main suppliers in Europe. However, there are not European datasets available for all the components in Ecoinvent 3.6 and in such cases global datasets are used. A global system boundary is used for the modelling of the production phase of the other components in the system and the EoL phase.

The geographical boundary for the use phase was set to be Sweden in dialogue with PowerCell. The BEV and FCEV were assumed to be produced in Sweden. The production of the energy carriers for propulsion was also assumed to take place in Sweden, for the technology options: BEV-SE Mix, FCEV-SMR and FCEV-WP Electrolysis. However, the technology option BEV-RER Mix was modelled with a more carbon intensive electricity mix based on the average electricity production in a

European country. The geographical boundary for the first phase of EoL is assumed to take place in Sweden since there are facilities for EoL treatment of vehicles. The rest of the treatment processes used global datasets from Ecoinvent 3.6.

The transports in the modelled system are generic distances that are included in the market processes that has been used for the modelling, if available. The modelling is performed according to the case study's hierarchy that is described in Table 3.16 in Section 3.3.

4.1.2.6 Data quality requirements

The quality for the data used in the LCA case study is evaluated based on the relevance, reliability and accessibility. The data for the MS-100 system is considered relevant since it is collected from PowerCell. However, the MS-100 system is a prototype and information for sub-components was not fully available. Due to confidentiality some suppliers did not report all amounts of materials included in the components. Specific assumptions for the modelling of components are presented in Section 4.2.

The quality of data for the technology options differs in relevance since they vary in age and geographical location, but the information used was considered to be the best available data. The older datasets were used based on a trade-off between the reliability of the data and whether it represented the technology in a good way or not. Datasets with a high reliability was preferred over newer datasets with lower reliability.

There is also the aspect of accessibility. Detailed data of technologies and production processes are often confidential and not disclosed to the public. The accessibility also impacted the choice of origin for the process flows in the modelling. In order to make consistent choices, the hierarchy described in Table 3.16 in Section 3.3 was used.

4.1.2.7 Assumptions and limitations

The LCA case study includes several assumptions and limitations in order to make it timely feasible and to focus on the aim. The overarching assumptions and limitations are described in this section to give a general overview. However, there are several assumptions for specific steps in the modelling which are described more in detail for the concerned processes in Section 4.2.

The FCEV was modelled to manage the capacity of the MS-100 system and thereby the BEV was simulated to have the same function in terms of powertrain performance. Excluding the powertrain, the BEV and the FCEV are assumed equal for all components and larger structures in the vehicles, for example chassis, frame and body. Even so, when adding the BE- and FCE powertrains the total weight of the simulated vehicles differ. The focus of the modelling of the components in the simulated vehicles were set on the electric motor, the inverter, the transmission, the

Li-ion battery, the Ni-MH battery and the MS-100 system. An aggregated glider dataset is assumed to represent all of the components and sub-parts that are not a part of the two powertrains. This is a simplification since the collection of all the materials for the components in the BEV and the FCEV are outside the scope of the case study.

It is further assumed that both the BEV and the FCEV are assembled in Sweden and the transport of the MS-100 system to the vehicle assembly is neglected. The MS-100 system is produced in PowerCell's production facility in Gothenburg. The case study included district heating and waste from the facility, however the electricity was only considered for the activation of the MS-100 system. The reason is that PowerCell conducts a lot of research and development of their products. Thereby the allocation factor used for district heating and waste did not result in a representative approximation of the electricity used for the MS-100 system.

The main difference in the modelling of the vehicle options is in the production and EoL treatment of the powertrains. Data for the electricity consumption and the hydrogen consumption of the vehicles is obtained from the simulation in FAST-Sim. This entails uncertainties since the values are simulated and not obtained for an existing vehicle.

The BEV and the FCEV are assumed to be worn out and ready for disposal after 250 000 $v \cdot km$. This is a simplification since some components would not last during the entire lifetime and others would not be worn out during the lifetime. Maintenance of the BEV and the FCEV was approximated by a generic process for an electric passenger car in Ecoinvent 3.6, and no further maintenance has been considered. Another important assumption is that the MS-100 system is manually dismantled in a treatment facility. This was assumed since there are a lot of valuable components and materials in the MS-100 system, such as platinum which is an expensive and scarce metal.

The case study includes two production pathways each for the BEV and FCEV for production of electricity and hydrogen. The chosen production pathways have an impact on the results for the case study. However, the selected technologies are considered to be representative on today´s market.

The supporting infrastructure for the FCEV in terms of a hydrogen fuelling station was modelled. However, a representative charging station for the BEV was not found. Thereby, the fuelling station for the FCEV is only presented in the LCIA results in Section 4.3, but is excluded from the comparisons of the selected LCIA results in Section 5.2.

4.2 Life Cycle Inventory Analysis

In this section the modelling of the BEV and the FCEV is presented. The life cycle is divided into the three phases: production phase, use phase and EoL phase. The process flows and most of the processes used for the modelling originate from the database Ecoinvent 3.6 with the system model *Allocation cut-off by classification* [77, 88]. Methodological choices such as the hierarchy when choosing processes in Ecoinvent 3.6 are further described in Section 3.3. The datasets in form of unit processes used for the modelling are presented in Section A.1 in Appendix A. More detailed modelling regarding for example the MS-100 system is presented in Appendix B.

4.2.1 Production phase

In this section, the modelling of the production phase for the BEV and the FCEV are described. This includes the assembly of the vehicles and the production of the included components. The unit processes for vehicle assembly are presented in Table A.1 and A.10 in Appendix A.

4.2.1.1 BEV

This section presents the modelling of the BEV in terms of the assembly of the vehicle and a more detailed modelling of the Li-ion battery.

4.2.1.1.1 Modelling of the assembly of the BEV
The assembly of the BEV consists of several processes. The BEV consists of a glider, a charger and a BE powertrain which are presented in Table A.1 in Appendix A. The glider is modelled with an existing process in Ecoinvent 3.6 and one important aspect to keep in mind is that the dataset was constructed for a smaller car than the analysed panel van. The BE powertrain comprises a Li-ion battery, an electric motor, an inverter and a transmission.

The datasets for the electric motor, inverter and transmission are identical for the BEV and the FCEV. The components are assumed to be transported from Stuttgart to Gothenburg by a lorry, a distance of 1293 km. There is also a transport for the Li-ion battery, since it is assumed to be produced in China and is transported to Gothenburg by a container ship, a distance of 21 370 km.

4.2.1.1.2 Modelling of Li-ion battery
The size of the Li-ion battery has a large impact on the electricity consumption and therefore, an approximation of the weight was required. In order to obtain the weight of the Li-ion battery, a literature study was performed in order to collect data for existing Li-ion batteries [72]. The data gathered consisted of energy and weights for a few Li-ion batteries and was thereafter plotted in a graph in order to visualize the relationship between weight and energy. An approximative linear relationship was obtained and used to calculate the weight of a Li-ion battery with

the energy of 80 kWh. The energy of 80 kWh for the Li-ion battery was obtained by the iterative process in FASTSim where the driving distance for the vehicles where set to 264 km. The values for the existing Li-ion batteries and the linearisation are presented in Figure A.1 in Appendix A.

The modelling of the Li-ion battery in openLCA was based on an already existing Li-ion battery process in Ecoinvent 3.6 called *market for battery, Li-ion, rechargeable, prismatic | Cutoff U, GLO*. However, the data for the battery cells was considered to be outdated and was replaced by a dataset for NMC111 battery cells [89]. The guiding principle for the modelling were to use global processes in order to match the global status of the battery process used. The NMC111 battery cells are modelled to be produced with Chinese electricity since China is a large producer of Li-ion batteries. The modelling of the Li-ion battery is presented in Table A.2 in Appendix A.

4.2.1.2 FCEV

This section presents the modelling of the assembly for the FCEV. Firstly, the assembly of the FCEV is presented and the MS-100 system, Ni-MH battery and hydrogen tank are described more thoroughly. Furthermore, along with the modelling of the MS-100 system, the activation of the system as well as the energy and waste for PowerCell's production facility are presented.

4.2.1.2.1 Modelling of the assembly of FCEV

The assembly of the FCEV consists of several processes. The FCEV consists of a glider, a fuel receptacle, a hydrogen tank and an FCE powertrain. The FCE powertrain comprises a Ni-MH battery, an electric motor, an inverter and a transmission. The electric motor, inverter, transmission and hydrogen tank are assumed to be transported by a lorry from Stuttgart to Gothenburg, a distance of 1293 km. There is also a transport for the Ni-MH battery, since it is assumed to be produced in Japan and is transported to Gothenburg by a container ship, a distance of 25 200 km. The modelling of the assembly is presented in Table A.10 in Appendix A.

4.2.1.2.2 Modelling of MS-100 system

In order to model the FCEV, information regarding the FCS and MS-100 system was collected. This was manually inventoried at PowerCell's own production site in Gothenburg, where components were inspected and weighted. The starting point was the BoM acquired from PowerCell, in which all components and their respective supplier was stated. The BoM list was complemented with technical specifications and complementary data. The data was provided by PowerCell and regarded the weight of the components in the BoM list.

For the modelling of the components in the MS-100 system, qualified guesses were made when the material or the ratio between the material was unknown. The assumptions were for example based on density ratios for the materials, visual inspection and stated relationships for similar components. Because of the limited time frame and the given system boundaries, only the main components and the components for which there was available data were considered.

There are several complex technical components in the MS-100 system, however there was a lack of detailed information. Therefore, several assumptions were made throughout the data collection for the MS-100 system. One example is that electrical components were assumed to have 30% electronics and 70% housing. This assumption was used since the relationship was stated for a specific product in a technical specification. The technical specification cannot be disclosed due to confidentiality reasons. Another assumption is that small amounts of materials in the components, for example, coating have been neglected.

The MS-100 system is a prototype that is still under development and therefore there were some difficulties with the data collection. The reason is that there was no set standard for the incorporation of the MS-100 system in a vehicle, because the systems are adapted to the customer needs. Thereby, the modelling of the MS-100 system was based on PowerCell's assessment of necessary components for the application in a vehicle. Furthermore, there was a lack of detailed information regarding materials and weights for the components since the suppliers did not disclose this type of information due to confidentiality. The data for the modelling of the MS-100 system is presented in an aggregated form in Table A.11 in Appendix A due to confidentiality reasons. The full dataset is presented in Appendix B.

In order to obtain optimal function of the FCS it has to be activated. The main reason is that the function of the proton conducting membrane is improved. For this procedure an inert gas is required in order to clean the system, as well as oxygen, hydrogen and coolant as for the operation of the FCS. This process also consumes electricity. Since PowerCell purchases green electricity, the electricity required for this process has been modelled as label certified electricity in Ecoinvent 3.6.

After activating the FCS, it is incorporated in the MS-100 system. The system is tested to see that it fulfils the customer requirements. The modelled process for the activation of the FCS and the MS-100 system is presented in an aggregated table for the entire MS-100 system in Table A.12 in Appendix A. However, the amounts are not disclosed in Appendix A, but are presented in Appendix B.

The assembly of the MS-100 system was modelled to take place in PowerCell´s facility in Gothenburg. Data for the production facility regarding the heating of the building and the waste generated are included in the LCA case study. However, there were no data available for the exact amounts of waste for each MS-100 system and therefore, an allocation factor was used for the approximation. The allocation factor is based on the total output of the produced FCS and FCS systems for PowerCell during 2019, divided by the output of the MS-100 system. The allocation factor was also used to allocate the total heating of the facility to the MS-100 system, however the allocation factor is not disclosed to the public due to confidentiality reasons.

The data for energy and waste related to the production of the MS-100 system are presented in Table A.13 in Appendix A.

4.2.1.2.3 Modelling of Ni-MH battery

Two datasets from different life cycle inventories were used to model the Ni-MH battery present in the FCEV. The data for the assembly of the Ni-MH battery was combined with a dataset for the positive and negative electrode and electrolyte [90, 91]. The datasets for the modelling of the Ni-MH battery is presented in Table A.14 in Appendix A.

The production of the Ni-MH battery was assumed to be taking place in Japan, since it is where most Ni-MH batteries are produced today. Therefore, global processes were used and Japanese electricity. Furthermore, in order to model the Li-ion and Ni-MH battery similarly the same market transports were used for both of them.

4.2.1.2.4 Modelling of fuel tank

In order to obtain information for the modelling of the hydrogen tank two different sources were combined. The first one was a technical assessment of compressed hydrogen storage tank systems by Hua et al. from 2010 [73], that provided information regarding weight and materials for a 700-bar hydrogen tank with 5.6 kg of usable hydrogen. This information was used in combination with the life cycle inventory provided by a data article by Rossi et al. from 2019 [92]. The data article supplemented with exact processes to choose in the Ecoinvent database.

To model the required tank size for the FCEV the data had to be re-scaled. This was achieved by calculating the relative material content for the provided tank size and use the same relationship for the simulated tank size. The inventory for the modelled hydrogen tank is presented in Table A.15 in Appendix A. The dataset from the data article was modified to some extent since the electricity was modelled as European.

4.2.2 Use phase

For the modelling of the use phase, both the operation of the vehicle and the production of the electricity and hydrogen are included. A Well-To-Tank analysis studies extraction of energy resources, production of energy carriers and distribution of them but not the energy conversion in the motor. In a Tank-To-Wheel analysis, only the energy conversion in the motor and its connecting emissions and wear and tear are included. Combined they are referred to as a Well-to-Wheel analysis [93].

Both the electricity generation and the hydrogen production are modelled from Well-to-Wheel in this case study. Thereby, they are followed from their resource extraction through their production and also through their energy conversion. However, neither of the two vehicle options produce any direct emissions in the use phase.

There are some dissimilarities regarding the modelling of the infrastructure for the production of the electricity and hydrogen. This is since the data availability for the production and decommissioning are described in different extent in the datasets used.

4.2.2.1 BEV

In this section the modelling of the use phase for the two technology options, BEV-RER Mix and BEV-SE Mix, for the BEV are presented.

4.2.2.1.1 Modelling of the use phase for BEV

The use phase for the BEV is modelled to include the electricity production, Swedish and European electricity mix, and maintenance of the vehicle. Both the electricity and the maintenance are modelled with already existing process in Ecoinvent 3.6. One important aspect to have in mind is that the infrastructure for the charging station is not considered. This decision was mainly taken due to lack of appropriate data. The assumption can be justified by the high share of electric vehicles being charged at home and the less extensive infrastructure required in comparison with a hydrogen fuelling station.

The modelling of the use phase for the BEV-RER Mix and BEV-SE Mix are presented in Table A.16 and Table A.17 in Appendix A.

4.2.2.2 FCEV

In this section the modelling of the use phase for the two technology options, FCEV-SMR and FCEV-WP Electrolysis, for the FCEV are presented.

4.2.2.2.1 Modelling of the use phase for FCEV

There are two production processes for hydrogen in this LCA case study, SMR of natural gas and hydrogen production from wind powered electrolysis. The two production processes are modelled to include the construction of the facility, the production of the hydrogen and the deconstruction of the facility.

The hydrogen from the two production processes are modelled to be fuelled to the vehicle in from a fuelling station. The station is modelled in the same way for the two technology options, except for the input of the hydrogen gas. For the hydrogen gas produced from SMR the production is assumed to take place in Sweden and the hydrogen gas is transported in pipelines to the fuelling station. The wind powered hydrogen production was assumed to take place next to the fuelling station and did not consider any additional transports.

The fuelling station for the hydrogen gas was modelled even though the charging station for the BEVs was not considered. The reason is that there was an interest of analysing the environmental impact of the fuelling station, which is presented in the LCIA results in Section 4.3, however it is not included in the selected LCIA results in Section 5.2.

4.2.2.2.1.1 Hydrogen production from SMR

The SMR of natural gas was modelled with a dataset where the hydrogen plant had a production capacity of 1.5 million Nm^3/day and the plant's lifetime was 20 years [53]. The dataset was obtained from an LCA of hydrogen production via SMR of natural gas by Spath and Mann conducted in 2001. The dataset was considered as valid even though it was published twenty years ago. The reason was that the dataset was often referred to in similar studies.

The data used for the modelling of the SMR production of hydrogen was re-calculated to the reference flow of m^3H_2. This was done by using the density of hydrogen of 0.0899 kg/Nm^3 and the density for natural gas of 0.717 kg/Nm^3 [53,94]. The density for natural gas varies for different literature sources depending of the composition. An average value for the density of natural gas was used in this study. The modelling included the construction of the facility and the operation of the production process per kg of H_2, and is presented in Table A.20 in Appendix A.

The produced hydrogen was then assumed to be transported in pipelines from Stenungsund to the fuelling station in Gothenburg, a distance of 50 km. This assumption was made since there is an industrial district in Stenungsund with several chemical industries. The transportation process was approximated from an existing process in Ecoinvent 3.6 called *market for natural gas, high pressure | natural gas, high pressure| Cutoff U, SE*. The process was reconstructed to transport hydrogen gas instead of natural gas. The emissions from the original transport process were neglected since they were related to emissions of natural gas during transport. The data for the modified values for the modelling of the transport of hydrogen is presented in Table A.21 in Appendix A.

The fuelling station was modelled based on a dataset from 2008 for an existing fuelling station in Reykjavik by Maack [48]. The dataset for the modelled fuelling station includes a compressor, maintenance of the fuelling station, a storage module for hydrogen gas and walls and foundation. It also considers the dismantling of the station. The data used for the modelling is presented in Table A.22 in Appendix A.

4.2.2.2.1.2 Hydrogen production from wind powered electrolysis

The wind powered production plant for hydrogen gas was modelled with a dataset with the production capacity of 1440 Nm^3/day and a lifetime of 15 years [48]. Thereby the capacity for the wind powered electrolysis is significantly lower than for the SMR of natural gas. This is reasonable since the electrolyser produces hydrogen for local use while the SMR production is a central production site distributing to several users.

The modelling of the wind powered production of hydrogen was based on a dataset from 2008 for an electrolytic hydrogen fuelling station by Maack [48]. The wind powered hydrogen production includes the material inputs for the PEM-electrolyser and operation of the electrolyser. The data used for the modelling is presented in Table A.23 in Appendix A.

Since the hydrogen is assumed to be produced on site the transports are neglected. The data used for the modelling of the fuelling station is essentially the same as for the fuelling station for the hydrogen produced by SMR, with the exception of the electricity used to power the operation of the fuelling station. The data used for the modelling is presented in Table A.24 in Appendix A.

4.2.3 EoL phase

The focus of the EoL modelling were put on the BEV and the FCEV and additionally manual dismantling of the FCS itself. Since the functional unit of the LCA case study is $v \cdot km$ the EoL of the hydrogen production pathways have not been modelled other than what is already included in the datasets that are being used.

In order to facilitate the modelling, processes already present in Ecoinvent 3.6 database have been used to the highest extent possible. However, modelling based on existing processes in Ecoinvent 3.6 are not fully disclosed, but the modified inputs and outputs are presented in Appendix A and Appendix B.

One example of a process used for the modelling is *treatment of used glider, passenger car, shredding | Cutoff U, GLO*, which have been used for both of the vehicle options. The batteries, both Li-ion and Ni-MH, have been modelled separately since they are required to be treated separately due to legislation. The FCS is also treated separately since is contains valuable metals such as platinum.

4.2.3.1 BEV

This section presents the modelling of the EoL phase for the BEV. The BEV was manually dismantled and thereafter the BE powertrain excluding the NiMH-battery was treated.

4.2.3.1.1 Manual disassembly of BEV
The BEV was manually disassembled in a manual treatment facility. It was assumed that the BEV was transported to the car dismantler that was located in Jönköping, 150 km from Gothenburg. The manual treatment facility was approximated by an existing process called *manual dismantling of used electric passenger car | Cutoff U, GLO* in Ecoinvent 3.6.

In the disassembly process the BEV was separated into a glider, a Li-ion battery and a BE powertrain excluding the Li-ion battery. The disassembly process is presented in Table A.25 in Appendix A. There are two waste processes for the used Li-ion battery, hydrometallurgical treatment and pyrometallurgical treatment, that are used since the two treatment processes are assumed to have an equal share of the market.

4.2.3.1.2 Treatment of BE powertrain

The treatment process of the BE powertrain excluding the Li-ion battery was approximated with the process called *treatment of used glider, passenger car, shredding | Cutoff U, GLO* in Ecoinvent 3.6. However, a minor modification was made to the treatment process regarding the provider of the waste plastic mixture that was set to have the geographical boundary of Europe. The reason was that the treatment was assumed to take place in Sweden. The modelling for the treatment of the used BE powertrain without the Li-ion battery is presented in Table A.26 in Appendix A.

4.2.3.2 FCEV

This section presents the modelling of the EoL phase for the FCEV. The EoL phase for the FCEV is modelled more thoroughly than for the BEV since it was of interest to investigate the environmental impact of treating the MS-100 system. Hence, the FCEV goes through four main steps: manual disassembly, treatment of the FCE powertrain, dismantling of the FCS and platinum recovery from the FCS.

4.2.3.2.1 Manual disassembly of FCEV

The FCEV was manually disassembled in a manual treatment facility. As for the BEV, the FCEV was transported to the car dismantler in Jönköping and the manual treatment facility was approximated by the existing process called *manual dismantling of used electric passenger car | Cutoff U, GLO* in Ecoinvent 3.6. In the disassembly process the FCEV was separated into an FCS, a Ni-MH battery, an FCE powertrain excluding the Ni-MH battery and FCS as well as a glider. The disassembly process is presented in Appendix A in Table A.27.

4.2.3.2.2 Treatment of FCE powertrain

The treatment of the FCE powertrain excluding the Ni-MH battery and FCS was modelled in accordance with the treatment process for the BE powertrain excluding the Li-ion battery. The modelling is presented in Table A.28 in Appendix A.

The FCS was manually dismantled, and the materials were separated into their respective material categories. The modelling for the disassembly of the FCS is only presented in Appendix B due to confidentiality. The reasoning behind the modelling is that the materials were divided into three categories: metals, plastic and electronics. The metals were assumed to be recycled to 95% with 5% losses. The recycled content was considered as a product flow and the losses as waste flows. For electronics, 100% were considered as a product flow and for plastics 100% were considered as a mixture of plastic waste.

4.2.3.2.2.1 Platinum recovery from FCS

The platinum in the FCS was recovered and was modelled in a separate process where it was assumed to be recycled to 70% with 30% losses [92]. The data for the modelling of the recovery of platinum from the FCS is presented in Table A.29 in Appendix A.

4.3 LCIA results

In this section the results from the LCIA are presented for each impact category analysed: acidification, climate change, eutrophication, photochemical ozone formation and resources. The results from the LCIA are presented for the three life cycle phases: production phase, use phase and the EoL phase. Within the phases there are subdivisions that present the impacts of components or systems which were considered interesting and would facilitate the comparison of the four technology options.

The LCIA results are presented for each impact category in Tables 4.4-4.10. The remaining powertrain is defined as all the components in the powertrain excluding the Li-ion battery for the BEV and the MS-100 system for the FCEV. It also includes an electric charger for the BE powertrain and a fuel receptacle for the FCE powertrain. Furthermore, in the use phase of the FCEVs a fuelling station was modelled. This is because the supporting infrastructure for an FCEV requires a more complex fuelling station, that for example requires storage of large amounts of hydrogen under high pressure underground. The requirements of a charging station for a BEV are less extensive, since the vehicle runs on electricity. The fuelling station is therefore presented since it is a requirement for the proper functioning of an FCEV, however an equivalent option for the BEV was not found.

In this section the LCIA results from the LCA case study are presented and discussed on a more general level, allowing for further analysis of selected LCIA results in Section 5.2.

4.3.1 Acidification - freshwater and terrestrial

The LCIA results for the impact category acidification - freshwater and terrestrial are presented in Table 4.4.

Table 4.4: LCIA results for acidification - freshwater and terrestrial.

Life cycle phases	**BEV-RER Mix**	**BEV-SE Mix**	**FCEV-SMR**	**FCEV-WP Electrolysis**
Acidification - freshwater and terrestrial [$mmol\ H^{+}eq./v \cdot km$]				
Production phase				
Li-ion battery	8.26E-01	8.26E-01	-	-
MS-100 system	-	-	1.32E+00	1.32E+00
Tank	-	-	8.34E-03	8.34E-03
Glider	2.43E-01	2.43E-01	2.43E-01	2.43E-01
Remaining powertrain	9.62E-02	9.62E-02	4.47E-01	4.47E-01
Total contribution:	1.17E+00	1.17E+00	2.02E+00	2.02E+00
Use phase				
Electricity/Hydrogen	7.91E-01	1.05E-01	6.25E-01	2.77E-01
Fuelling station	-	-	6.20E-02	6.20E-02
Maintenance	1.87E-02	1.87E-02	1.87E-02	1.87E-02
Total contribution:	8.10E-01	1.24E-01	7.06E-01	3.57E-01
EoL				
EoL	1.93E-02	1.93E-02	1.06E-02	1.06E-02
Total contribution:	1.93E-02	1.93E-02	1.06E-02	1.06E-02
Total life cycle contribution:	1.99E+00	1.31E+00	2.73E+00	2.38E+00

The results in Table 4.4 show that the two technology options including a BEV have a lower environmental impact considering the entire life cycle. The technology option with the lowest environmental impact is BEV-SE Mix and this is mainly sourced to the Swedish electricity mix with a high share of renewable energy sources. The main difference between the two BEVs is found in the use phase. The European electricity mix has a higher share of fossil-based energy than the Swedish electricity mix. However, the production- and EoL phase are similar for the BEVs.

Generally, the technology options including an FCEV have a larger environmental impact during its entire life cycle than the BEVs, because of their production phase. The technology option FCEV-SMR has a larger environmental impact than FCEV-WP Electrolysis because of its fossil-based hydrogen production.

The selected LCIA results for this impact category are illustrated in Figure 5.1 and are further discussed in Section 5.2.

4.3.2 Climate change - total

The LCIA results for the impact category climate change - total are presented in Table 4.5.

Table 4.5: LCIA results for climate change - total.

Life cycle phases	**BEV-RER Mix**	**BEV-SE Mix**	**FCEV-SMR**	**FCEV-WP Electrolysis**
Climate change - total [$g\ CO_2eq./v \cdot km$]				
Production phase				
Li-ion battery	2.79E+01	2.79E+01	-	-
MS-100 system	-	-	2.90E+01	2.90E+01
Tank	-	-	1.73E+00	1.73E+00
Glider	4.27E+01	4.27E+01	4.27E+01	4.27E+01
Remaining powertrain	7.19E+00	7.19E+00	1.01E+01	1.01E+01
Total contribution:	7.78E+01	7.78E+01	8.36E+01	8.36E+01
Use phase				
Electricity/Hydrogen	1.37E+02	1.75E+01	1.94E+02	1.48E+01
Fuelling station	-	-	1.07E+01	1.07E+01
Maintenance	3.83E+00	3.83E+00	3.83E+00	3.83E+00
Total contribution:	1.40E+02	2.13E+01	2.09E+02	2.93E+01
EoL				
EoL	6.64E+00	6.64E+00	6.40E+00	6.40E+00
Total contribution:	6.64E+00	6.64E+00	6.40E+00	6.40E+00
Total life cycle contribution:	2.25E+02	1.06E+02	2.99E+02	1.19E+02

Table 4.5 indicates that the environmental impact of the entire life cycle is highest for the technology options with a high share of fossil-based energy sources, FCEV-SMR and BEV-RER Mix. Furthermore, the technology options with a high share of renewable energy sources, BEV-SE Mix and FCEV-WP Electrolysis are comparable in terms of environmental impact.

The fuelling station is included in the total life cycle contribution for the FCEVs and results in an additional environmental burden that is not included in the BEVs. By subtracting the impact of the fuelling station, the total life cycle contribution of the FCEV-WP Electrolysis is 1.08E+02, which is close to the total life cycle contribution of the BEV-SE Mix 1.06E+02.

The selected LCIA results for this impact category are illustrated in Figure 5.2 and are further discussed in Section 5.2.

4.3.3 Eutrophication - freshwater

The LCIA results for the impact category eutrophication - freshwater are presented in Table 4.6.

Table 4.6: LCIA results for eutrophication - freshwater.

Life cycle phases	**BEV-RER Mix**	**BEV-SE Mix**	**FCEV-SMR**	**FCEV-WP Electrolysis**
Eutrophication - freshwater [$g\ P\ eq./v \cdot km$]				
Production phase				
Li-ion battery	2.89E-02	2.89E-02	-	-
MS-100 system	-	-	3.11E-02	3.11E-02
Tank	-	-	1.00E-03	1.00E-03
Glider	2.61E-02	2.61E-02	2.61E-02	2.61E-02
Remaining powertrain	5.99E-03	5.99E-03	7.71E-03	7.71E-03
Total contribution:	6.10E-02	6.10E-02	6.59E-02	6.59E-02
Use phase				
Electricity/Hydrogen	1.36E-01	1.14E-02	9.71E-03	9.89E-03
Fuelling station	-	-	3.92E-03	3.92E-03
Maintenance	1.43E-03	1.43E-03	1.43E-03	1.43E-03
Total contribution:	1.37E-01	1.28E-02	1.51E-02	1.52E-02
EoL				
EoL	1.10E-03	1.10E-03	6.89E-04	6.89E-04
Total contribution:	1.10E-03	1.10E-03	6.89E-04	6.89E-04
Total life cycle contribution:	1.99E-01	7.50E-02	8.17E-02	8.19E-02

Table 4.6 illustrates that the technology option BEV-RER Mix has the highest environmental impact of the entire life cycle, while BEV-SE Mix has the lowest. The difference between the two technology options is mainly due to the electricity production. The total environmental impact of the FCEVs is approximately in the same magnitude, despite their different production pathways for hydrogen.

An interesting observation is that the total contribution of the production phase is in the same magnitude for the four technology options, in contrast to previously mentioned impact categories.

4.3.4 Eutrophication - terrestrial

The LCIA results for eutrophication - terrestrial are presented in Table 4.7.

Table 4.7: LCIA results for the impact category eutrophication - terrestrial.

Life cycle phases	**BEV-RER Mix**	**BEV-SE Mix**	**FCEV-SMR**	**FCEV-WP Electrolysis**
Eutrophication - terrestrial [$mmol\ N\ eq./v \cdot km$]				
Production phase				
Li-ion battery	5.48E-01	5.48E-01	-	-
MS-100 system	-	-	1.73E+00	1.73E+00
Tank	-	-	1.49E-02	1.49E-02
Glider	4.53E-01	4.53E-01	4.53E-01	4.53E-01
Remaining powertrain	1.96E-01	1.96E-01	2.31E-01	2.31E-01
Total contribution:	1.20E+00	1.20E+00	2.43E+00	2.43E+00
Use phase				
Electricity/Hydrogen	1.24E+00	2.36E-01	2.89E+00	2.14E-01
Fuelling station	-	-	1.37E-01	1.37E-01
Maintenance	3.56E-02	3.56E-02	3.56E-02	3.56E-02
Total contribution:	1.27E+00	2.72E-01	3.06E+00	3.87E-01
EoL				
EoL	3.92E-02	3.92E-02	2.89E-02	2.89E-02
Total contribution:	3.92E-02	3.92E-02	2.89E-02	2.89E-02
Total life cycle contribution:	2.51E+00	1.51E+00	5.52E+00	2.85E+00

Table 4.7 indicates that the environmental impact differs widely between the four technology options. FCEV-SMR has a significantly larger impact for its entire life cycle than the other technology options. This is mainly due to the usage and extraction of natural gas for the hydrogen production by SMR. For this impact category, the FCEVs have the highest total environmental impact and the BEVs have the lowest. The technology option BEV-SE Mix is the preferred option.

4.3.5 Photochemical ozone formation

The LCIA results for photochemical ozone formation are presented in Table 4.8.

Table 4.8: LCIA results for the impact category photochemical ozone formation.

Life cycle phases	**BEV-RER Mix**	**BEV-SE Mix**	**FCEV-SMR**	**FCEV-WP Electrolysis**
Photochemical ozone formation [$g\ NMVOC\ eq./v \cdot km$]				
Production phase				
Li-ion battery	1.73E-01	1.73E-01	-	-
MS-100 system	-	-	4.23E-01	4.23E-01
Tank	-	-	4.94E-03	4.94E-03
Glider	1.91E-01	1.91E-01	1.91E-01	1.91E-01
Remaining powertrain	5.81E-02	5.81E-02	8.68E-02	8.68E-02
Total contribution:	4.22E-01	4.22E-01	7.05E-01	7.05E-01
Use phase				
Electricity/Hydrogen	3.14E-01	5.38E-02	8.84E-01	8.45E-02
Fuelling station	-	-	4.66E-02	4.66E-02
Maintenance	2.70E-01	2.70E-01	2.70E-01	2.70E-01
Total contribution:	5.83E-01	3.23E-01	1.20E+00	4.01E-01
EoL				
EoL	1.04E-02	1.04E-02	8.05E-03	8.05E-03
Total contribution:	1.04E-02	1.04E-02	8.05E-03	8.05E-03
Total life cycle contribution:	1.02E+00	7.56E-01	1.21E+00	1.11E+00

Table 4.8 shows that FCEV-SMR is the technology option with the highest environmental impact. One aspect worth noting is the high contribution from maintenance in the use phase, which is mainly due to emissions of ethylene and high use of synthetic rubber. Furthermore, the FCEV-WP Electrolysis is competitive with the BEV-RER Mix in terms of environmental impact of the entire life cycle. The technology option BEV-SE Mix has the lowest impact.

It is also shown that the contribution of the Li-ion battery for the BEVs is significantly lower than of the MS-100 system and tank for the FCEVs. The reason for comparing the Li-ion battery and the MS-100 system and tank is that they provide the same function in the vehicle, in terms of powering the electric motor.

4.3.6 Resources - fossils

The LCIA results for the impact category resources - fossils are presented in Table 4.9.

Table 4.9: LCIA results for resources - fossils.

Life cycle phases	**BEV-RER Mix**	**BEV-SE Mix**	**FCEV-SMR**	**FCEV-WP Electrolysis**
Resources - fossils [$MJ\ /v \cdot km$]				
Production phase				
Li-ion battery	3.97E-01	3.97E-01	-	-
MS-100 system	-	-	5.16E-01	5.16E-01
Tank	-	-	4.07E-02	4.07E-02
Glider	6.18E-01	6.18E-01	6.18E-01	6.18E-01
Remaining powertrain	1.01E-01	1.01E-01	1.35E-01	1.35E-01
Total contribution:	1.12E+00	1.12E+00	1.31E+00	1.31E+00
Use phase				
Electricity/Hydrogen	3.17E+00	1.93E+00	3.40E+01	2.19E-01
Fuelling station	-	-	1.45E-01	1.45E-01
Maintenance	7.98E-02	7.98E-02	7.98E-02	7.98E-02
Total contribution:	3.25E+00	2.01E+00	3.43E+01	4.44E-01
EoL				
EoL	3.65E-02	3.65E-02	3.26E-02	3.26E-02
Total contribution:	3.65E-02	3.65E-02	3.26E-02	3.26E-02
Total life cycle contribution:	4.40E+00	3.16E+00	3.56E+01	1.79E+00

Table 4.9 illustrates the impact of the high use of fossil-based resources for hydrogen production by SMR, which differentiates FCEV-SMR from the other technology options. The electricity production for the BEV-RER Mix includes fossil-based energy resources and hence it has the second largest impact within the use phase. The BEV-SE Mix has the third largest environmental impact within the use phase, which is due to the high share of renewable energy sources in the Swedish electricity mix. The FCEV-WP Electrolysis uses a lower amount of fossil resources and is therefore the most preferred technology option in this impact category.

4.3.7 Resources - minerals and metals

The LCIA results for resources - minerals and metals are presented in Table 4.10.

Table 4.10: LCIA results for the impact category resources - minerals and metals.

Life cycle phases	**BEV-RER Mix**	**BEV-SE Mix**	**FCEV-SMR**	**FCEV-WP Electrolysis**
Resources - minerals and metals [$mg\ Sb\ eq./v \cdot km$]				
Production phase				
Li-ion battery	9.37E+00	9.37E+00	-	-
MS-100 system	-	-	3.16E+00	3.16E+00
Tank	-	-	1.72E-02	1.72E-02
Glider	4.91E+00	4.91E+00	4.91E+00	4.91E+00
Remaining powertrain	9.41E-01	9.41E-01	8.95E-01	8.95E-01
Total contribution:	1.52E+01	1.52E+01	8.98E+00	8.98E+00
Use phase				
Electricity/Hydrogen	9.93E-01	6.47E-01	5.36E-01	1.71E+00
Fuelling station	-	-	3.11E-01	3.11E-01
Maintenance	5.03E-01	5.03E-01	5.03E-01	5.03E-01
Total contribution:	1.50E+00	1.15E+00	1.35E+00	2.52E+00
EoL				
EoL	2.06E-01	2.06E-01	9.79E-02	9.79E-02
Total contribution:	2.06E-01	2.06E-01	9.79E-02	9.79E-0
Total life cycle contribution:	1.69E+01	1.66E+01	1.04E+01	1.16E+01

Table 4.10 indicates that the technology options including a BEV generally perform worse. The environmental impact of the Li-ion battery in the production phase is significantly higher than the environmental impact of the MS-100 system and tank. For the FCEVs the hydrogen production by wind powered electrolysis has the largest environmental impact within the use phase. This is due to the high resource requirements for the production and maintenance of the electrolyser.

The selected LCIA results for this impact category are illustrated and further discussed in Figure 5.3 in Section 5.2.

5

Results and discussion

In this chapter the results from the simulation of the vehicles in FASTSim and the selected LCIA results from the LCA case study are presented and discussed. A sensitivity analysis is presented for two parameters and thereafter a general discussion is presented along with recommendations for further research.

5.1 Results from use phase simulations

The simulated electricity consumption/hydrogen consumption for the BEV and FCEV, with the lifetime of 250 000 $v \cdot km$ is presented in Table 5.1. The results are presented for two alternatives for the BEV and the FCEV, respectively.

Table 5.1: Simulation results in FASTSim.

Vehicle option	Amount	Unit
BEV		
Original Li-ion battery		
Driving range	264	km
Electricity consumption	31.9	kWh/100 km
Lifetime electricity consumption	79 844	kWh
Doubled storage capacity for Li-ion battery		
Driving range	497	km
Electricity consumption	33.8	kWh/100 km
Lifetime electricity consumption	84 531	kWh
FCEV		
Original hydrogen tank		
Driving range	264	km
Hydrogen consumption	1.44	kg H_2/100 km
Lifetime hydrogen consumption	3 597	kg H_2
Doubled storage capacity for hydrogen tank		
Driving range	528	km
Hydrogen consumption	1.46	kg H_2/100 km
Lifetime hydrogen consumption	3 639	kg H_2

The first alternative in Table 5.1, includes the original equipment and the second one includes the necessary equipment for extending the range. This is achieved by doubling the storage capacity of the Li-ion battery for the BEV and of the hydrogen tank for the FCEV.

The results in Table 5.1 show that the range of the BEV when doubling the storage capacity of the Li-ion battery does not increase as much as when doubling the storage capacity of the hydrogen tank in the FCEV. The results also show that the electricity consumption increases for a BEV with doubled storage capacity of the Li-ion battery, to a larger extent than the hydrogen consumption does for an FCEV with doubled storage capacity of the hydrogen tank. The life time electricity consumption and the life time hydrogen consumption are used as input data for the modelling of the vehicle's life cycles in openLCA.

Worth noting is that the function of the vehicle is no longer the same in terms of driving range when extending the range, however the powertrain performance, payload and total lifetime remain the same.

5.2 Selected LCIA results

In this section the selected LCIA results are presented in Figure 5.1-5.3 and discussed more thoroughly. The selected impact categories are acidification, climate change and resources. The impact categories were considered as relevant to discuss and are commonly used in LCA studies. In Section 4.3 the LCIA results are presented and analysed for all analysed impact categories. However, they were discussed more generally allowing for further analysis of selected LCIA results in this section.

The results illustrated in Figures 5.1-5.3 present an aggregated value for the MS-100 system and the tank. The reason is that they provide a comparable function to the Li-ion battery in terms of providing energy to the electrical motor. Another distinction from the LCIA results is that the fuelling station for the FCEVs is excluded. The fuelling station is excluded to make the results comparable with each other. This simplification was necessary since corresponding data for a charging station for the BEVs was not found.

5.2.1 Acidification - freshwater and terrestrial

The results for the impact category acidification - freshwater and terrestrial are presented in Figure 5.1. The two technology options including a BEV have the lowest environmental in this impact category. The production of the Li-ion battery and especially the production of the battery cells, has a significant impact of the entire life cycle. This is mainly sourced to the extraction and refinery of for example nickel, cobalt and copper. The main difference between the technology options for the BEVs is found in the category electricity (WTW). This is mainly because the European electricity mix has a larger share of fossil-based energy than the Swedish electricity mix.

In contrast, the technology options including an FCEV contribute with the highest environmental impact. The FCEVs have an extensive impact that is mainly sourced to the mine operation, extraction and refinery of platinum in the FCS in the MS-100 system.

The remaining powertrain of the FCEVs has a higher environmental impact than for the BEVs since it includes a NiMH-battery. The NiMH-battery is included in the remaining powertrain since it is necessary for the functioning of the vehicle. However, the NiMH-battery is not the main energy source for propulsion of the vehicle.

There is a difference in the production of the hydrogen (WTW) for the FCEVs. The environmental impact for the technology option FCEV-SMR is associated with the extraction and use of natural gas, as well as the direct emissions from the SMR process. For the technology option FCEV-WP Electrolysis the production of the electrolyser is the main contributor to the environmental impact of the hydrogen production. This is mainly sourced to the large amounts of nickel used.

To conclude, FCEV-SMR and FCEV-WP Electrolysis have a higher environmental impact than BEV-RER Mix and BEV-SE Mix. The production of electricity (WTW) and hydrogen (WTW) for the technology options is also of importance within the impact category. The technology option with the lowest environmental impact is the BEV-SE Mix while the FCEV-SMR has the highest environmental impact.

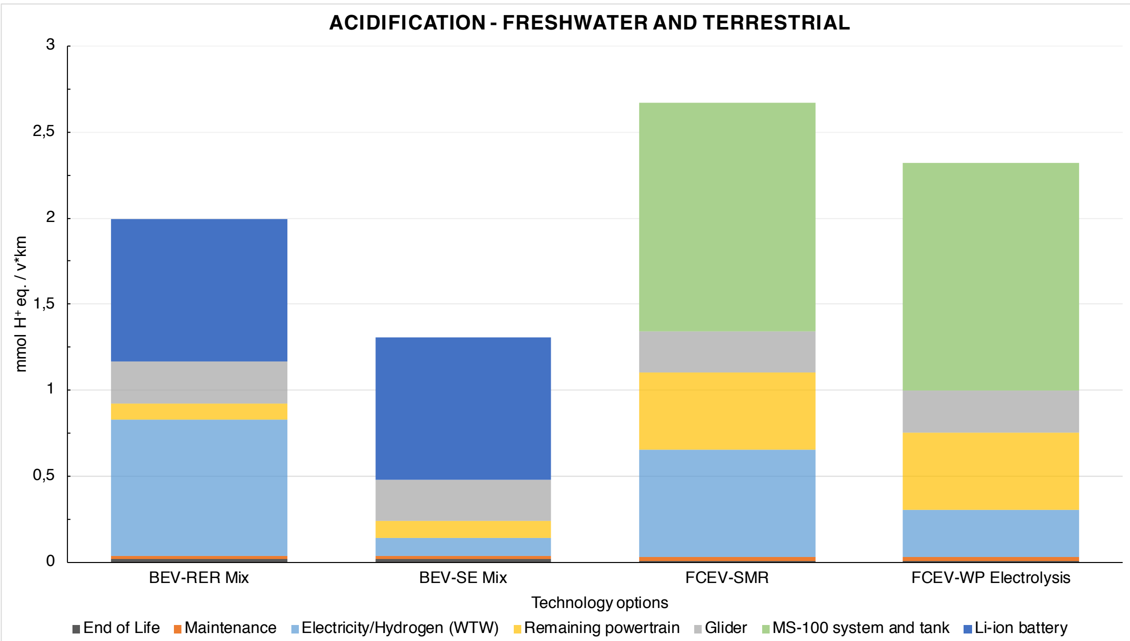

Figure 5.1: Selected LCIA results for acidification, considering the entire life cycle.

5.2.2 Climate change - total

The results for the impact category climate change - total are presented in Figure 5.2. There is no significant difference between the four technology options in the production phase. However, the main difference is found in the category electricity/hydrogen (WTW). The technology options with a high share of fossil-based energy sources, BEV-RER Mix and FCEV-SMR, contribute to a high environmental impact. For the BEV it can be explained by the high share of fossil-based energy in the European electricity mix. For the FCEV, the reason is the extraction and use of natural gas that is a fossil resource. Additionally, there are direct emissions of for example carbon dioxide and methane during the SMR process.

In contrast, the technology options with a high share of renewable energy sources, BEV-SE Mix and FCEV-WP Electrolysis have a significantly lower environmental impact. For the BEV the reason is that the Swedish electricity mix has a high share of renewable energy sources. For the FCEV there is a contribution from hydrogen (WTW) even though it uses wind power. This can be explained by the production of the electrolyser and is mainly sourced to nickel, chromium steel and copper. For this impact category, the BEV-SE Mix and FCEV-WP Electrolysis are roughly equal in terms of environmental impact.

Worth noting is that the modelled production of hydrogen by wind powered electrolysis is on a small scale relative to the hydrogen production by SMR. This has an influence on the environmental impact per kilogram of hydrogen since the processes have different production capacities and lifetimes.

To conclude, the BEV-RER and FCEV-SMR have higher environmental impact than BEV-SE Mix and FCEV-WP Electrolysis. However, there is no clear answer to whether the BEV-SE Mix or FCEV-WP Electrolysis is the preferred technology option. Thereby the technology options that use a higher share of renewable energy sources are considered as the most favourable options.

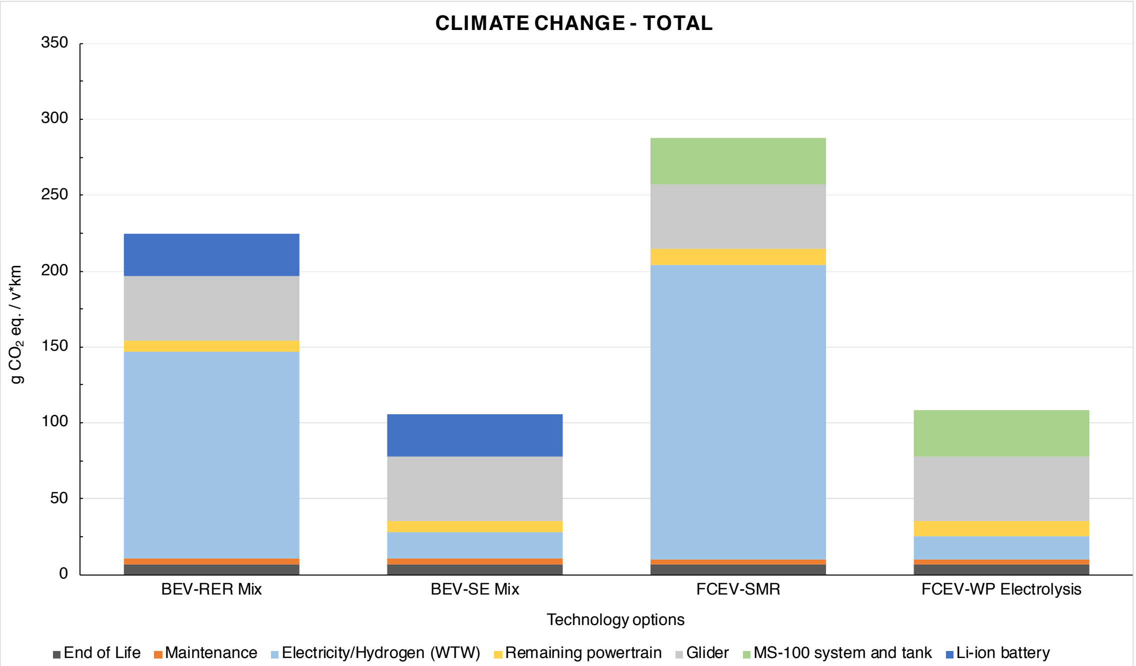

Figure 5.2: Selected LCIA results for climate change - total, considering the entire life cycle.

5.2.3 Resources - minerals and metals

The results for the impact category resources - minerals and metals are presented in Figure 5.3. The technology options including a BEV have the highest environmental impact. The main contributor is the production of the Li-ion battery and especially the battery cells. This is sourced to the use of scarce metals such as cobalt and copper. One important aspect to keep in mind is the difference in weight between the Li-ion battery and the MS-100 system.

In contrast, the technology options including an FCEV have the lowest environmental impact. For the FCEV the MS-100 system and tank are not the main contributors to the life cycle as the Li-ion battery is for the BEV. However, the main contributor within the MS-100 system is platinum in the FCS. In the hydrogen production for the FCEV-WP Electrolysis the environmental impact is mainly sourced to the use of zinc for prevention of corrosion on the wind turbines. The FCEV-SMR has the lowest environmental impact which is in contrast to the previously presented results. The reason is the high production capacity of the SMR process.

The glider is modelled in the same way for the four technology options and thereby contributes equally to the life cycles. The production of the glider has a large environmental impact because its production requires large quantities of both electronics and metals.

To conclude, the BEV-RER Mix and BEV-SE Mix have a higher environmental impact than FCEV-SMR and FCEV-WP Electrolysis, where FCEV-SMR is the preferred technology option.

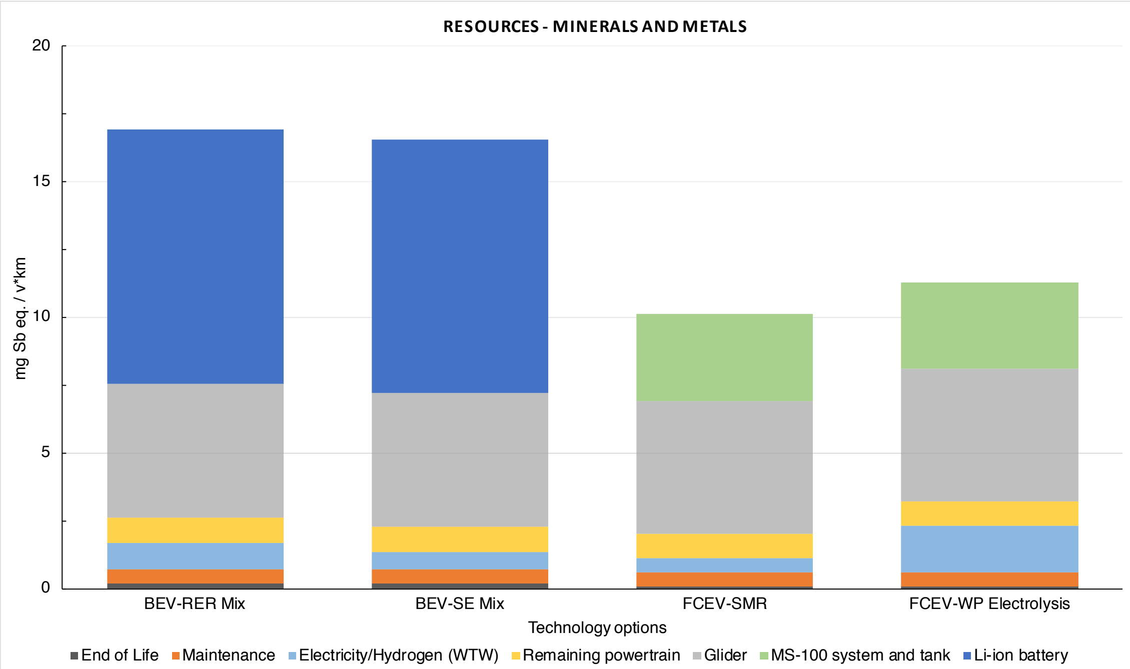

Figure 5.3: Selected LCIA results for resources - minerals and metals , considering the entire life cycle.

5.3 Sensitivity analysis

In this section two parameters are investigated to analyse the sensitivity of the data used. The sensitivity parameters are the platinum content in the FCS and the impact of extending the driving range. This is done for the two technology options BEV-SE Mix and FCEV-WP Electrolysis. The reason for choosing them was that they have a high share of renewable energy sources which is promising for the future of the automotive sector. The results are presented for three impact categories: acidification, climate change and resources.

5.3.1 Three levels of platinum content

In the first analysis, three levels of platinum content are investigated. The platinum content is doubled for each level and the levels are referred to as low, medium and high. The corresponding values for the three levels are presented in Appendix B. The platinum level referred to as medium has been used for all other simulations of the FCEVs in the previously presented results. There was also of interest to PowerCell to analyse the environmental consequences of recycling the platinum in the FCS. Thereby, the effects of recycling platinum have been investigated for three modelling alternatives, that are presented in Table 5.2.

Table 5.2: The analysed modelling alternatives.

Modelling alternative	Denotation	Description
Recycled content of platinum	RC, Pt	Recycled content of platinum is used for process in- and outflows
Primary content platinum	Prim, Pt	Primary platinum content is used for process in- and outflows
Primary content of platinum with credit for recycling	Prim+Cred, Pt	Primary platinum content is used for process in- and outflows and the credit for recycling and secondary use of platinum is accounted for

The sensitivity analysis includes three modelling alternatives for the platinum content. In order to take credit for the recycling into account, only primary materials can be used. The modelling was based on the cut-off approach and thereby recycled materials were included in the used raw materials. Therefore, the platinum input was modified to include primary platinum, to enable modelling of the recycling process for platinum.

This first modelling alternative is referred to as "RC, Pt" since the process inputs for platinum include recycled content. However, the environmental burden of the recycling of the platinum is included in the modelled system since the platinum is not modelled to go to secondary use. The second modelling alternative is referred to as "Prim, Pt" since primary platinum is used for the modelling. Thereby the environmental burden of the recycling was included. The third modelling alternative is referred to as "Prim+Cred, Pt" and was based on the modelling for the "Prim, Pt" with the difference that the credit for the recycled platinum was accounted for. Thereby, the environmental benefit of secondary use of the platinum was included.

The results of the sensitivity analysis for the three levels of platinum content and the three modelling alternatives for the recycling are presented in Figures 5.4 - 5.6.

5.3.1.1 Acidification - freshwater and terrestrial

Figure 5.4 shows a significant difference in environmental impact of the entire life cycle for the three levels of platinum. This goes in line with the results presented in Figure 5.1 in Section 5.2, where the platinum content in the FCS plays a significant role in the total environmental impact of the FCEV. The results presented in Figure 5.4 shows that the platinum content is a sensitive parameter which matter both in the production phase, as well as in the total life cycle of the vehicle.

The results in Figure 5.4 for the modelling alternatives for "RC, Pt" and "Prim, Pt" implies that a large share of the platinum on the market originates from primary platinum. This is since the total environmental impact of the two alternatives is rather similar even though the origin is changed from partly including recycled content to only including primary platinum. For the modelling alternative "RC, Pt" it is shown that the environmental benefit of recycling the platinum and receive credit for the secondary use, increases with the amount of platinum used in the FCS.

The EoL phase is a small contributor to the environmental impact of this impact category. However, this is not shown for the modelling alternative "Prim+Cred, Pt" since it is illustrated as negative. This is due to the environmental benefits of the credit for the recycling of platinum. The contribution from EoL is not negative, but the environmental burden of the EoL phase is smaller than the environmental benefit of the recycling and the secondary use of platinum. This results in a decreased total environmental impact of the entire life cycle. Thereby, the total impact for "Prim+Cred, Pt" is lower than the other two modelling alternatives.

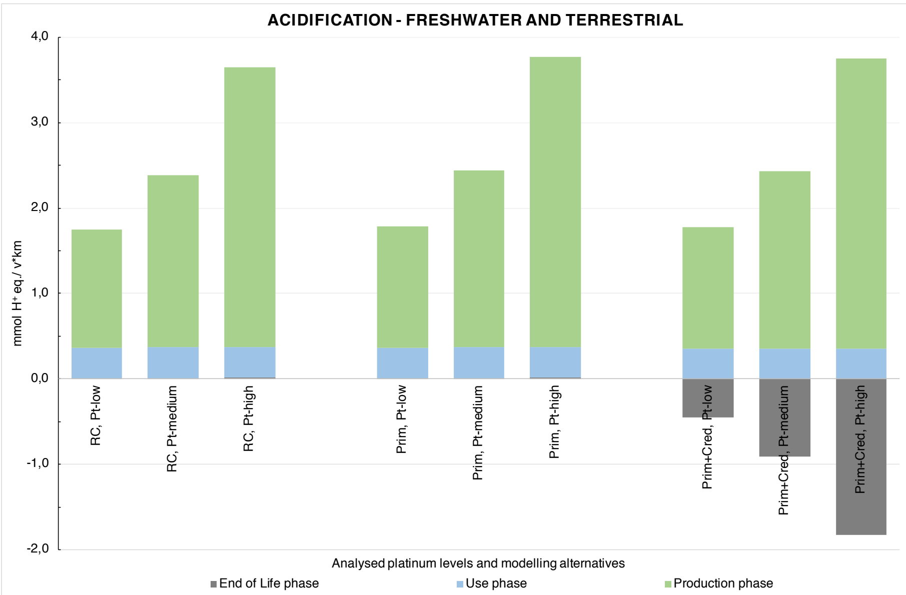

Figure 5.4: Results for acidification for three different platinum levels.

5.3.1.2 Climate change - total

Figure 5.5 illustrates that the change in platinum content does not have the same impact on the results as presented in Figure 5.4. This goes hand in hand with the results presented in Figure 5.2 in Section 5.2, where the impact of the MS-100 system is considered rather small compared to the entire life cycle. This implies that the content of platinum is not as sensitive regarding climate change as within the impact category acidification.

What also can be concluded from the results in Figure 5.2 is that the processes in the EoL phase contribute to the environmental impact to a larger extent than they did for the impact category acidification. Thereby the benefits of recycling platinum and receiving credit for secondary use are not as significant for this impact category. However, the advantages of recycling the platinum still increases with the amount of platinum used in the FCS.

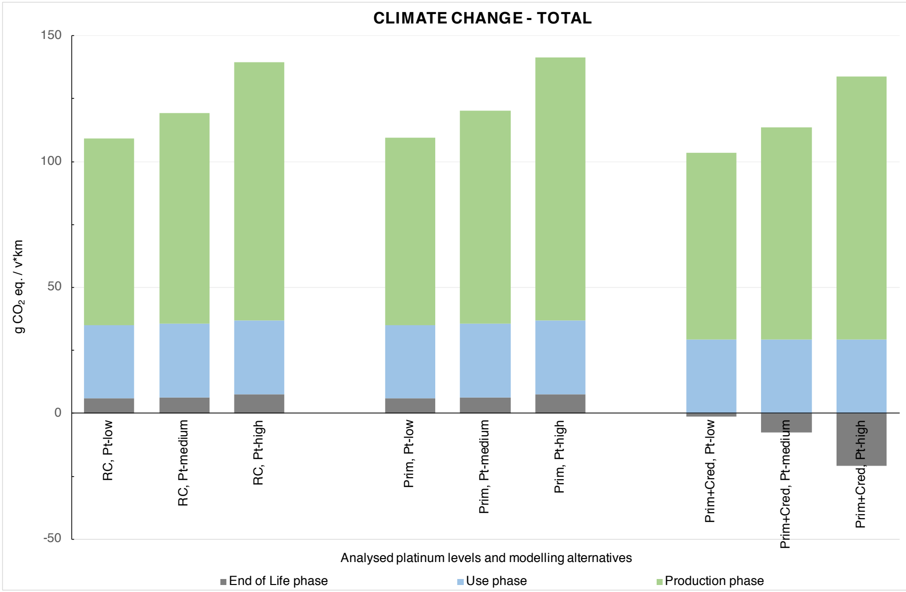

Figure 5.5: Results for climate change for three different platinum levels.

5.3.1.3 Resources - minerals and metals

Figure 5.6 illustrates that the change in platinum content does not have the same impact on the results as presented in Figure 5.4-5.5. Changing the platinum content does not have a significant impact of the results. This agrees with the results presented in Figure 5.3 in Section 5.2 where the MS-100 system is not the main contributor within the production phase. Hence, a change in platinum content should not have an extensive impact of the entire life cycle. This implies that results while changing the content of platinum are rather robust.

This impact category focuses on the scarcity of the element by comparing the amounts used with the total reserve available. The analysed platinum content in the MS-100 system is small compared to the reserves. Hence, the impact of changing the level of platinum has a small effect within this impact category.

The results in Figure 5.6 show that the EoL phase is a rather small contributor to the entire life cycle. The benefits associated with secondary use of platinum are lower in this impact category, than in the impact categories of acidification and climate change. Therefore, the total environmental impact is not reduced to the same extent.

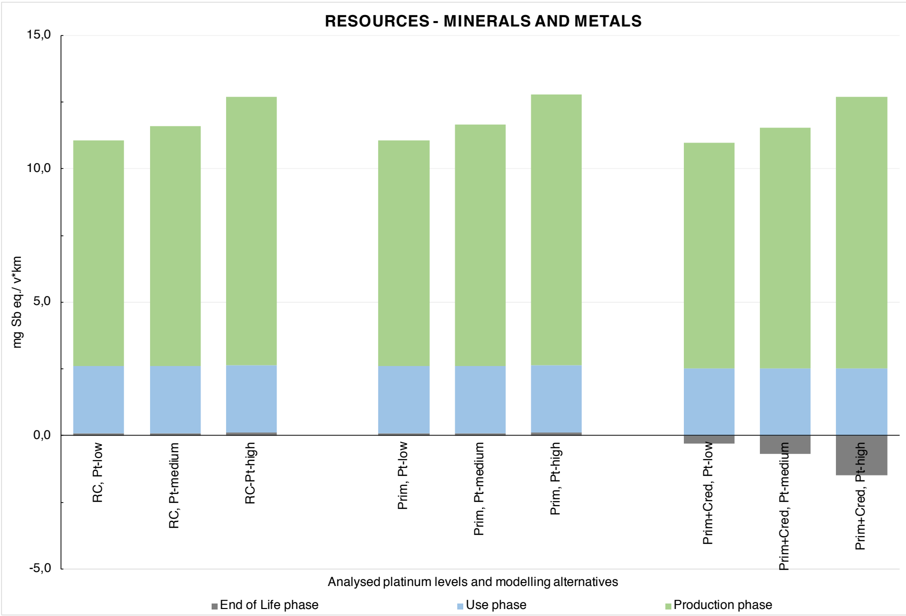

Figure 5.6: Results for resources - minerals and metals for three different platinum levels.

To conclude, the platinum in the FCS in the MS-100 system is used in rather small amounts. The sensitivity of this parameter depends on which impact category that is analysed. Thereby, the conclusion is that an increase in platinum content increases the environmental impact of the total life cycle. Regarding the modelling alternatives for platinum, the results imply that there are environmental benefits of recycling platinum. However, the magnitude of these benefits varies with the platinum content in the FCS.

5.3.2 The driving range of the vehicles

The second analysis investigated the environmental impacts of an extended driving range. This was done since the LCA case study had a fixed driving range based on the capacity for the BEV. However, longer driving ranges are desired for transport vehicles in order to make the transports time-efficient. The extension of the driving range was achieved by doubling the storage capacity of the Li-ion battery and the hydrogen tank. For the BEV the electricity consumption increased significantly while the hydrogen consumption was approximately the same for the FCEV, the results are shown in Table 5.1. This resulted in longer driving range for the FCEV than for the BEV and thereby they no longer had the same function in terms of driving range. One explanation is the large difference in weight between the Li-ion battery and the hydrogen tank.

The environmental impacts of the extension of the driving range were evaluated in openLCA. The results are presented in Figures 5.7-5.9.

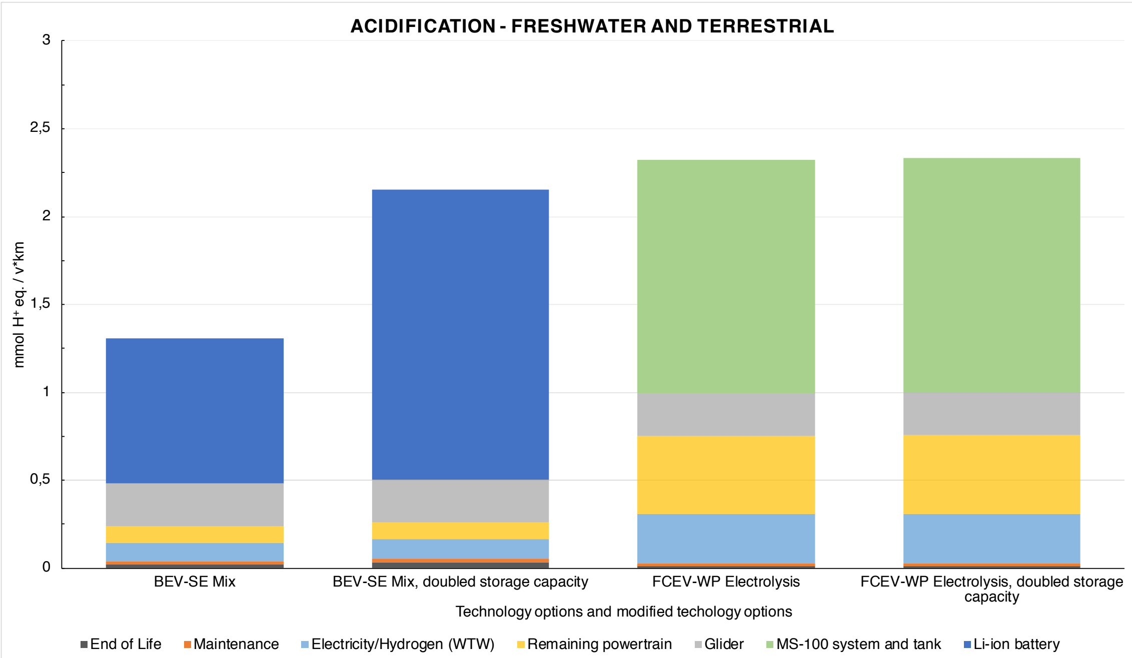

Figure 5.7: Results for acidification - freshwater and terrestrial when analysing the impact of extending the driving range.

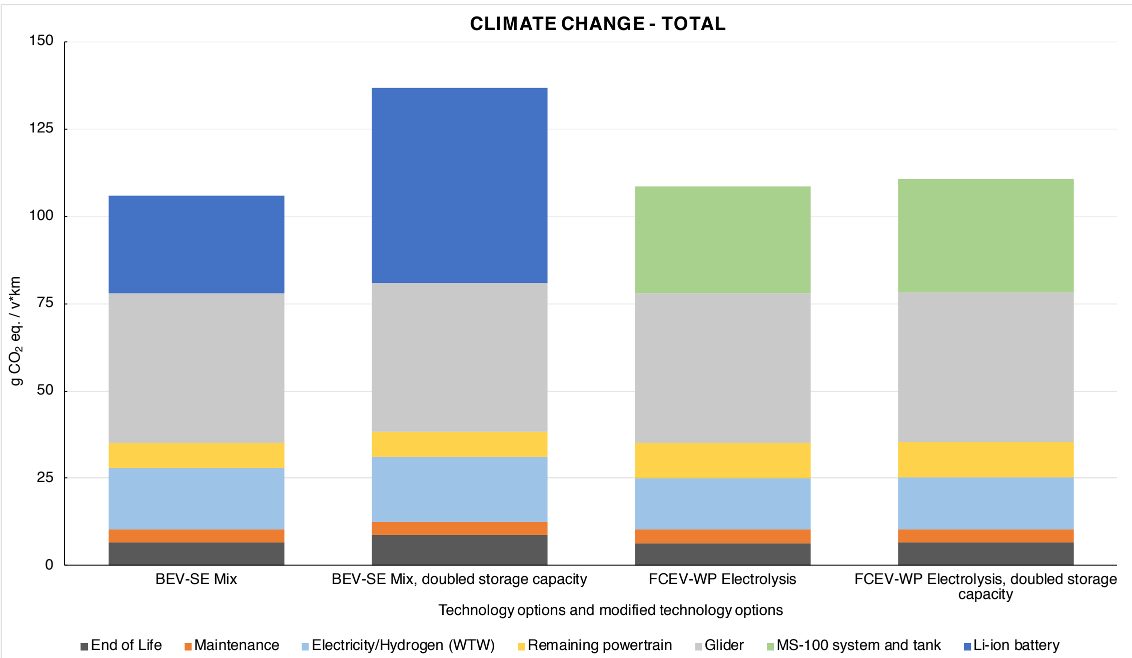

Figure 5.8: Results for climate change - total when analysing the impact of extending the driving range.

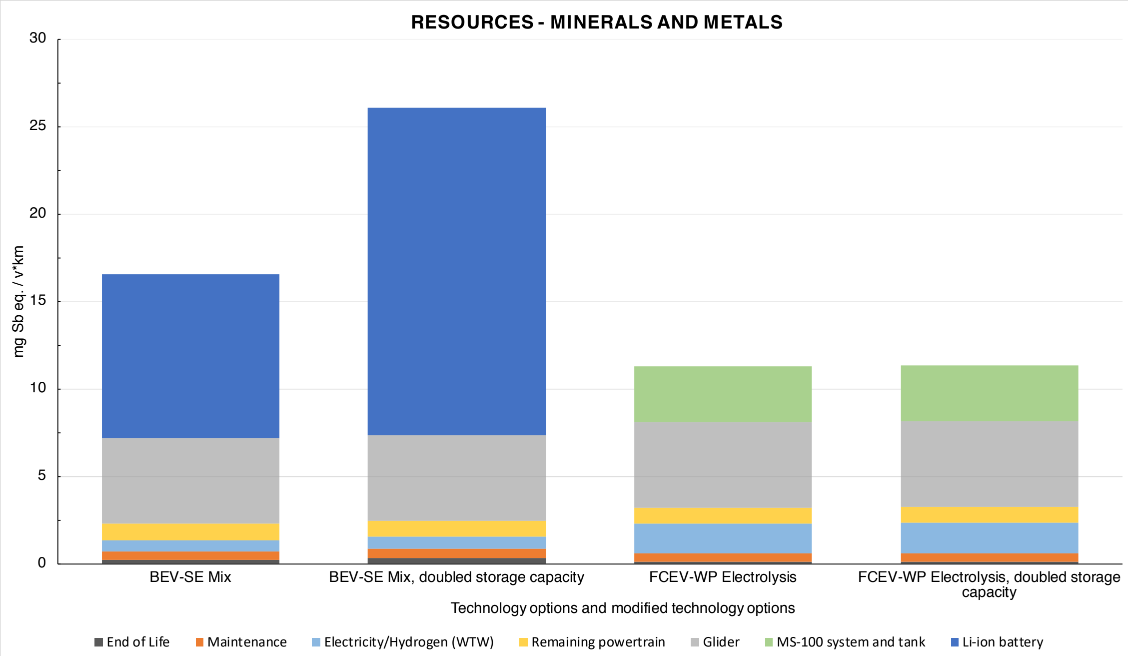

Figure 5.9: Results for resources - minerals and metals when analysing the impact of extending the driving range.

The results for the three impact categories indicate that the BEV-SE Mix doubled storage capacity of the Li-ion battery has a larger impact on the total life cycle than the BEV-SE Mix. However, the FCEV-WP Electrolysis with doubled storage capacity of the hydrogen tank is approximately the same as for the FCEV-WP Electrolysis. This implies that the environmental impact of the BEV-SE Mix is more sensitive to an extended driving range than the FCEV-WP Electrolysis.

To conclude the results, show that the range of an FCEV-WP Electrolysis can be extended without a significant increase in hydrogen consumption or environmental impact. In contrast to the BEV, where both the electricity consumption and environmental impact increased significantly.

5.4 General discussion

The aim was to investigate the environmental impacts of an FCEV powered by PowerCell's MS-100 system compared to a BEV powered by a Li-ion battery. The case study compared two EVs, namely FCEVs and BEVs, and this choice was made since EVs are considered to be on the rise in the transport sectors and do not have any tail-pipe emissions in the use phase. This distinguishes the EVs from the vehicles with conventional internal combustion engines which are dominating the transport sector today. The choice of vehicles for comparison has a large influence on the results. The BEV was chosen on PowerCell's recommendation since it is a technology that is commonly used today and is predicted to expand even more in the future.

To analyse the entire life cycle of the vehicle options the electricity and hydrogen consumption was required. The vehicles were simulated in FASTSim which provides uncertainty to the LCA case study, since the simulation tool includes several estimations and simplifications. The modelling of the four technology options in openLCA also involved simplifications since only the main components of the powertrain was modelled thoroughly. The simplifications contribute with uncertainties but were considered necessary for fulfilling the aim. Thereby, the vehicle options were modelled with the same level of detail.

The LCA case study included a large share of data which varied in time and geography. One example is that the SMR of natural gas is based on the numbers of an American production plant, while the hydrogen production from wind powered electrolysis is based on a hydrogen fuelling station in Reykjavik. The simplifications and generalisations are necessary due to lack of site-specific and regional data. This has an impact on the results since the plant for the SMR of natural gas has a larger production capacity than the renewable production of hydrogen powered by wind power. Thereby, the environmental impact of the production facility is distributed over larger production quantities. This is however reasonable since the production of hydrogen by wind powered electrolysis occurs at the fuelling station and for local use compared to the centralised SMR production.

The thesis is conducted in collaboration with PowerCell and thereby specific data for the MS-100 system has been used. There is not any current standard for the application of a MS-100 system in a vehicle and therefore the analysed system is not fully comprehensive. The analysed MS-100 system is based on technical specifications and recommendations from PowerCell regarding what is required for the implementation in a vehicle. However, there are components that are not considered, and one example is the power electronics required for the connection of the MS-100 system to the vehicle. In order to perform a more comprehensive LCA case study of the MS-100 system for an application in a vehicle, the knowledge about components and materials from cradle to gate should to be improved. There is also a need for more detailed information regarding minor processes and adjustments in the production facility.

The LCIA results from the LCA case study are presented for seven impact categories that were found to be frequently used in similar LCA studies and are associated with common environmental problems in today's society. It is important to use several impact categories in order to present a broad perspective. In the LCA case study, the analysed impact categories have shown that different technology options are more or less preferable from an environmental point of view. The BEV-SE Mix have proven to be the most favourable choice in most of the impact categories. This is mainly due to the high share of renewable energy sources in the Swedish electricity mix and the chosen driving range. However, the technology option FCEV-WP Electrolysis also showed promising results. For example, in the impact categories climate change - total and eutrophication - freshwater the two technology options are comparable in environmental impact. On the other hand, for the impact category resources -

fossils FCEV-WP Electrolysis has the lowest environmental impact among the four technology options.

Generally, the LCIA results favour the technology options with a high share of renewable energy sources. The FCEV is modelled with electricity produced from wind powered electrolysis. This implies both advantages and disadvantages since wind is an intermittent energy source, meaning that it depends on the wind conditions. An ideal scenario would be to combine the location of the fuelling station with a large wind farm, so hydrogen can be produced when there is an excess of electricity. There are several renewable production pathways for hydrogen and one example is the solar powered fuelling station in Mariestad. Thereby, it was considered interesting to investigate a solar powered electricity source for the electrolysis. A smaller study was conducted to investigate the effect of supplying the electrolyser with electricity from photovoltaic solar panels. This was done by changing the electricity input for the technology option FCEV-WP Electrolysis from wind to solar power. However, to be able to reach the same production capacity as the wind powered production, a larger electrolyser was needed. This resulted in a higher environmental impact of the hydrogen production when considering the larger electrolyser and photovoltaic solar panels.

As the LCA case study shows, the MS-100 system is not the main contributor to the environmental impact of the entire life cycle of the FCEV. This implies that there is a need for developing supporting technology for the FCEV, including the production of hydrogen gas and supporting infrastructure. However, these factors cannot be directly controlled by PowerCell. The results from the LCA case study show that platinum is the largest contributor in terms of environmental impacts of the MS-100 system, for several of the investigated impact categories. Thereby, it could be of interest to PowerCell to reduce the amount of platinum in the FCS, which was investigated in the sensitivity analysis. This is something PowerCell continuously works with while improving the technology for the MS-100 system. Furthermore, it is shown that there are environmental advantages of recycling platinum and that they increase with the amount of platinum used in the FCS. However, the results vary among the evaluated impact categories. In order to continue the development of the technology for FCS there is a need to decrease the platinum content as well as to improve the possibilities for recycling smaller quantities of platinum. Platinum is a scarce resource and therefore the incentive for recycling should not be dependent on the amounts used.

The LCIA results and the sensitivity analysis have shown that platinum is a sensitive parameter and thereby, the dataset used for the modelling of platinum is of importance. This is also the case for the modelling of the Li-ion battery where metals such as cobalt, copper and nickel are used. The approximations and assumptions that are used in the generic datasets obtained from Ecoinvent 3.6 have an impact on the results and should be further analysed for a more comprehensive and detailed analysis. The information in the datasets might be more or less up to date and originate from processes with different degrees of data availability, meaning that it is difficult to say how representative the datasets are. However, this was outside the scope of this analysis since the main focus was on comparison of the vehicle options.

The simulation of vehicle options, BEV and the FCEV, is based on the Renault Master ZE panel van which is a transport vehicle. Desirable qualities of a transport vehicle is the ability to transport goods and to have long driving ranges. Therefore, it was investigated, in a sensitivity analysis, how an extension of the driving range would influence the results. As shown in the results of the sensitivity analysis the FCEV-WP Electrolysis is the preferred choice for an extended driving range, from an environmental perspective. This implies that FCEVs could be beneficial to use in the transport sector for long driving distances. In the future, FCEVs might be able to replace the transport vehicles driven on fossil-based fuels that are associated with large tail-pipe emissions.

5.5 Recommendation for further research

The maturity of the technology for FCEVs has an impact on the results of the LCA case study. This is because the data availability is considered low in comparison to the availability of data for BEVs. Therefore, it would be of interest to model the two vehicle options more detailed. For example, by including a more comprehensive list of vehicle components instead of using the glider dataset. This also applies for the required equipment to connect the MS-100 system to a vehicle.

The core of this thesis was to investigate the environmental impact of an FCEV with an MS-100 system in comparison to a BEV equipped with a Li-ion battery. The results imply that the environmental impact of the MS-100 system, generally constituted a small share of the total impact. Thereby, it could be of interest for PowerCell to conduct an LCA for the MS-100 system to enable comparison with other FCS systems on the market.

The sensitivity analysis showed that there are environmental benefits of recycling platinum, however for smaller amounts of platinum the benefits are less significant. Thereby, it would be interesting to investigate the demand and possibilities for implementing a recycling system for FCS.

The hydrogen production has been proven to be of importance in this LCA case study. Therefore, it would be interesting to investigate alternative renewable production pathways and the potential for implementing them on the Swedish market. This could be evaluated in aspects of demand, profitability and the environmental impacts of construction and operation.

6
Conclusion

The thesis has provided an extended knowledge base regarding the environmental impacts of the two vehicle options, BEV and FCEV. The results showed that the technology options with a high share of renewable energy sources in the production of the energy carrier for propulsion have a lower environmental impact than the technology options with a high share of fossil-based energy sources. This implies that in the future both BEV and FCEV have benefits associated with reducing the share of fossil-based energy sources.

The technology options with a high share of renewable energy sources, BEV-SE Mix and FCEV-WP Electrolysis, were considered as the preferred choices in terms of environmental impact. However, for the chosen driving range the BEV-SE Mix has the lowest environmental impact for several of the investigated environmental problems, with the exception of resource depletion, and is considered to be the most environmentally benign technology option.

The use phase of the vehicles has shown to be an important contributor to environmental impact, however the production phase is also a significant contributor to some of the environmental problems investigated. For example, the production phase for the FCEV causes larger amounts of acidifying emissions than the BEV, however when considering resource depletion of metals and minerals the situation is reversed. For climate change, the production phases of the BEV and FCEV are almost comparable in their contribution to global warming. The EoL phase on the other hand, has shown to be a small contributor to the environmental impact in comparison to the production- and use phase of the vehicles.

This thesis was conducted in collaboration with the company PowerCell and therefore some recommendations are provided for the future use of the FCEV and the MS-100 system. The FCEV has higher environmental benefits associated with extending the driving range than the BEV. Furthermore, the FCEV should be fuelled with renewable hydrogen in order to be an environmentally friendly option. For the MS-100 system it is shown that platinum is a large contributor to the environmental impact for several of the considered environmental problems. Therefore, important environmental improvements would be to either recycle or reduce the amount of platinum used in the FCS in the MS-100 system.

References

[1] Tracking Transport 2019. Paris: International Energy Agency (IEA), 2020. Available from: https://www.iea.org/reports/tracking-transport-2019.

[2] Sustainable Development Goals: Knowledge Platform. United Nations (UN), 2020. Available from: https://sustainabledevelopment.un.org/?menu=1300.

[3] Emilsson E, Dahllöf L. Lithium-Ion Vehicle Battery Production Status 2019 on Energy Use, CO2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling. IVL Swedish Environmental Research Institute, 2019. Available from: https://www.ivl.se/download/18.14d7b12e16e3c5c36271070/1574923989017/C444.pdf.

[4] Offer G.J, Howey D, Contestabile M, Clague R, and Brandon N.P. Comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles in a future sustainable road transport system. *Energy Policy*, 38(1):24–29, 2010. doi: 10.1016/j.enpol.2009.08.040.

[5] TT, NyTeknik.Nu satsar Volvo och Daimler på bränsleceller, 2020. Available from: https://www.nyteknik.se/fordon/nu-satsar-volvo-och-daimler-pa-bransleceller-6993981.

[6] Office of energy efficiency & renewable energy. Hydrogen Production: Natural Gas Reforming, 2020. Available from: https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming.

[7] Midroc. Nordic leading cleantech company PowerCell converts toxic waste from olive oil production into electricity, 2014. Available from: https://www.midroc.se/nyheter/2014/nordic-leading-cleantech-company-powercell-converts-toxic-waste-to-electricity/.

[8] Årsredovisning 2016. PowerCell Sweden AB, 2016. Available from: https://www.powercell.se/wordpress/wp-content/uploads/2018/12/arsredovisning-2016-55646powercellarsredovisning2016.pdf.

[9] Brooker A, Gonder J, Wang L, Wood E, Lopp S, and Ramroth L. FASTSim: A Model to Estimate Vehicle Efficiency, Cost and Performance. *SAE Technical Papers*, 2015-April(April):21–23, 2015. doi:10.4271/2015-01-0973.

[10] Groupe Renault. Renault MASTER - Practical, tough and versatile, 2019. Available from: https://www.johnbanks.co.uk/renault/brochures/master.pdf.

[11] Groupe Renault. Renault Master Z.E., 2018. Available from: https://www.pvi.fr/Default.aspx?SiteSearchID=3305PageID=13454649.

[12] Groupe Renault. Groupe Renault introduced hydrogen into its light commercial vehicles range, 2019. Available from: https://en.media.groupe.renault.com/news/groupe-renault-introduces-hydrogen-into-its-light-commercial-vehicles-range-5c08-989c5.html.

[13] International Organization for Standardization (ISO). ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework, 2006. Available from: https://www.iso.org/standard/37456.html.

[14] V. Manickam I.V. Muralikrishna. Chapter Five - Life Cycle Assessment. In V. Manickam I.V Muralikrishna, editor, *Environmental Management*, pages 57–75. Butterworth-Heinemann, 2017. doi: 10.1016/B978-0-12-811989-1.00005-1.

[15] Baumann H and Tillman A.M. *The Hitch Hiker's Guide to LCA - An orientation in life cycle assessment methodology and application.* Studentlitteratur AB, Lund, 1:9 edition, 2004.

[16] Sandén B, Wallgren P, editors. Perspektiv på eldrivna fordon 2015. Version 2.0. Göteborg: Chalmers; 2015. Available from: https://www.chalmers.se/sv/styrkeomraden/energi/Documents/Perspektiv%20pa%20ny%20teknik/PerspektivpaEldrivnafordon2015v2.0.pdf.

[17] U.S. Department of Energy. Alternative Fuels Data Center: Alternative Fuels and Advanced Vehicles, 2020. Available from: https://afdc.energy.gov/fuels/.

[18] U.S. Energy Information Administration (EIA). Biofuels explained: Biofuels explained ethanol and biodiesel, 2019. Available from: https://www.eia.gov/energyexplained/biofuels/.

[19] U.S. Department of Energy. Alternative fuels data center: How do fuel cell electric vehicles work using hydrogen?, 2020. Available from: https://afdc.energy.gov/vehicles/how-do-fuel-cell-electric-cars-work.

[20] Arnold N. Hydrogen fuel cell cars: what you need to know, 2020. Available from: https://www.bmw.com/en/innovation/how-hydrogen-fuel-cell-cars-work.html.

[21] U.S. Department of Energy. Alternative Fuels Data Center: Emissions from Hybrid and Plug-In Electric Vehicles, 2020. Available from: https://afdc.energy.gov/vehicles/electricemissions.html.

[22] Fuel Cell Today. Fuel Cell Applications - Fuel and Infrastructure, 2020. Available from: http://www.fuelcelltoday.com/applications/fuel-and-infrastructure.

[23] Perner A and Vetter J. Lithium-ion batteries for hybrid electric vehicles and battery electric vehicles. In *Advances in Battery Technologies for Electric Vehicles*, pages 173–190. Elsevier, 2015. doi: 10.1016/B978-1-78242-377-5.00008-X.

[24] Ehsani M, Gao Y, Gay S.E, and Emadi A. *Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design.* CRC Press, 2005.

[25] Alaswad A, Baroutaji A, Achour H, Carton J, Al Makky Ahmed, and Olabi A.G. Developments in fuel cell technologies in the transport sector. *International Journal of Hydrogen Energy*, 41(37):16499–16508, 2016. doi: 10.1016/j.ijhydene.2016.03.164.

[26] Salah K and Kama N. Unification requirements of electric vehicle charging infrastructure. *International Journal of Power Electronics and Drive Systems*, 7(1):246–253, 2016. doi: 10.11591/ijpeds.v7.i1.pp246-253.

[27] Bicer Y and Dincer I. Life cycle environmental impact assessments and comparisons of alternative fuels for clean vehicles. *Resources, Conservation and Recycling*, 132(2018):141–157, 2018. doi: 10.1016/j.resconrec.2018.01.036.

[28] Power Circle. Elbilsstatistik, 2019. Available from: https://www.elbilsstatistik.se/laddinfrastatistik.

[29] Ringdahl L. Elbilarna är våra stora bovar – och otippade räddare. *Svenska Dagbladet Näringsliv*. 2019, November. Available from: https://www.svd.se/elbilar-kan-vara-raddningen-for-vart-osakra-elnat.

[30] Nohrstedt L. Studie: Elnätet måste bli smartare för att klara elbilar. *Ny Teknik*. 2019, July. Available from : https://www.nyteknik.se/energi/studie-elnatet-maste-bli-smartare-for-att-klara-elbilar-6964937.

[31] U.S. Department of Energy. Alternative fuels data center: How do all-electric cars work?, 2014. Available from: https://afdc.energy.gov/vehicles/how-do-all-electric-cars-work.

[32] Pistoia G. Chapter 5 - Vehicle Applications: Traction and Control Systems. In Pistoia G, editor, *Battery Operated Devices and Systems*, pages 321–378. Elsevier, 2009. doi: 10.1016/B978-0-444-53214-5.00005-4.

[33] Deloitte China. Fueling the Future of Mobility Hydrogen and fuel cell solutions for transportation. 1, 2020. Available from: https://www2.deloitte.com/content/dam/Deloitte/cn/Documents/finance/deloitte-cn-fueling-the-future-of-mobility-en-200101.pdf.

[34] Swedish Electromobility Centre. Annual report 2018, 2018. Available from: http://emobilitycentre.se/wp-content/uploads/2019/10/Swedish-Electromobility-Centre-Annual-report-2018.pdf.

[35] Vätgas Sverige. Tankstationer, 2020. Available from: http://www.vatgas.se/tanka/.

[36] Vätgas Sverige. 32 svenska städer vill ha vätgastankstation, 2020. Available from: http://www.vatgas.se/2018/01/03/32-svenska-stader-vill-ha-vatgastankstation/.

[37] National Geographic. Fuel Cells Information, Facts, and Technology, 2020. Available from: https://www.nationalgeographic.com/environment/global-warming/fuel-cells/.

[38] Chalmers. Nyväckt intresse för bränsleceller i fordonsindustrin, 2016. Available from: https://www.chalmers.se/sv/styrkeomraden/transport/nyheter/Sidor /Nyv%C3%A4ckt-intresse-f%C3%B6r-br%C3%A4nsleceller.aspx.

[39] Intelligent Energy. Fuel cells, 2020. Available from: https://www.intelligent-energy.com/our-products/stationary-power/fuel-cells/.

[40] Kavitha K, Radhakrishnan P, and Ashok A. Chapter 41.2 - Nanomaterials for Fuel Cell Technology. In *Handbook of Nanomaterials for Industrial Applications*, Micro and Nano Technologies, pages 751 – 767. Elsevier, 2018. doi:10.1016/B978-0-12-813351-4.00043-2.

[41] Hydrogenics. Fuel Cells, 2020. Available from: https://www.hydrogenics.com/technology-resources/hydrogen-technology/fuel-cells/.

[42] Lepiller C. Pragma Industries. Fuel Cell explained, 2019. Available from: https://www.pragma-industries.com/technology/fuel-cell-explained/.

[43] U.S Department of Energy - Office of Energy Efficiency & Renewable Energy. Fuel Cell Systems, 2020. Available from: https://www.energy.gov/eere/fuelcells/fuel-cell-systems.

[44] U.S Department of Energy - Office of Energy Efficiency & Renewable Energy . Hydrogen Storage, 2020. Available from: https://www.energy.gov/eere/fuelcells/hydrogen-storage.

[45] Abderezzak B. Introduction to Hydrogen Technology. In Abderezzak B, editor, *Introduction to Transfer Phenomena in PEM Fuel Cell*, pages 1–51. Elsevier, 2018. doi: 10.1016/B978-1-78548-291-5.50001-9.

[46] The clean hydrogen future has already begun. Paris: International Energy Agency (IEA), 2019. Available from: https://www.iea.org/commentaries/the-clean-hydrogen-future-has-already-begun.

[47] U.S Department of Energy - Office of Energy Efficiency & Renewable Energy. Hydrogen Production: Electrolysis, 2020. Available from: https://www.energy.gov/eere/fuelcells/hydrogen-production-electrolysis.

[48] Maack M. Generation, of the energy carrier hydrogen in context with electricity buffering generation through fuel cells. *Icelandic New Energy*, 2008. Available from: http://www.needs-project.org/RS1a/RS1a%20D8.2%20Final %20report%20on%20hydrogen.pdf.

[49] Vozniuk O, Tanchoux N, Millet JM, Albonetti S, Di Renzo F, and Cavani F. Chapter 14 - Spinel Mixed Oxides for Chemical-Loop Reforming: From Solid State to Potential Application. In Albonetti S, Perathoner S, and Quadrelli EA, editors, *Studies in Surface Science and Catalysis*, volume 178, pages 281–302. Elsevier Inc., 1 2019. doi: 10.1016/B978-0-444-64127-4.00014-8.

[50] Deng C, Zhu M, Zhou Y, and Feng X. Optimal Synthesis of Multi-Component Refinery Hydrogen Network. 44:1069–1074, 1 2018. doi: 10.1016/B978-0-444-64241-7.50173-7.

[51] Morse E, National Geographic. Non-renewable energy, 2013. Available from: https://www.nationalgeographic.org/encyclopedia/non-renewable-energy/.

[52] Vätgas Sverige. Bränslecellen – så funkar den!, 2020. Available from: http://www.vatgas.se/faktabank/bransleceller/.

[53] Spath PL and Mann MK. Life Cycle Assessment of Hydrogen Production via Natural Gas Steam Reforming. Technical report, National Renewable Laboratory (NREL), 2001. Available from: www.nrel.gov/docs/fy01osti/27637.pdf.

[54] Pini M, Breglia G, Venturelli M, Montorsi L, Milani M, Neri P, and Ferrari AM. Life cycle assessment of an innovative cogeneration system based on the aluminum combustion with water. *Renewable Energy*, 154:532–541, 7 2020. doi:10.1016/j.renene.2020.03.046.

[55] Shiva Kumar S and Himabindu V. Hydrogen production by PEM water electrolysis – A review. *Materials Science for Energy Technologies*, 2(3):442–454, 2019. doi:10.1016/j.mset.2019.03.002.

[56] Smolinka T. Fraunhofer ISE. PEM Water Electrolysis - Present Status of Research and development. *18th World Hydrogen Energy Conference*, pages 1–23, 2010. Available from: https://businessdocbox.com/Metals/68482016-Pem-water-electrolysis-present-status-of-research-and-development.html.

[57] Nilsson Energy. Systemöversikt av vätgastankstation i Mariestad, 2020. Available from: https://energiforsk.se/media/26432/mariestad-off-grid-vatgastankstation.pdf.

[58] Energimyndigheten. 2019 rekordår för svensk elproduktion, 2020. Available from: http://www.energimyndigheten.se/nyhetsarkiv/2020/2019-rekordar-for-svensk-elproduktion/.

[59] Chen Y, Hu X, and Liu J. Life cycle assessment of fuel cell vehicles considering the detailed vehicle components: Comparison and scenario analysis in China based on different hydrogen production schemes. *Energies*, 12(15):3031, 2019. doi: 10.3390/en12153031.

[60] Toyota Motor Corporation. The MIRAI Life Cycle Assessment Report. 2015. Available from: https://global.toyota/pages/globaltoyota/sustainability/esg/challenge2050 /challenge2/lifecycleassessmentreporten.pdf.

[61] U.S. Environmental Protection Agency. Detailed Test Information, 2020. Available from: https://www.fueleconomy.gov/feg/fetestschedules.shtml.

[62] Green Delta. openLCA - the Life Cycle and Sustainability Modeling Suite, 2020. Available from: http://www.openlca.org/openlca/.

[63] Del Duce A, Gauch M, and Althaus HJ. Electric passenger car transport and passenger car life cycle inventories in ecoinvent version 3. *International Journal of Life Cycle Assessment*, 21(9):1314–1326, 2016. doi: 10.1007/s11367-014-0792-4.

[64] Electric Vehicle Database. Nissan Leaf 24 kWh (2015-2018) price and specifications - EV Database, 2018. Available from: https://ev-database.org/car/1020/Nissan-Leaf-30-kWh.

[65] Toyota Motor Corporation. 2017 Mirai Product Information, 2017. Available from: https://www.toyota.com/mirai/assets/core/Docs/Mirai%20Specs.pdf.

[66] Toyota Motor Corporation.Toyota Mirai Technical Specification, 2020. Available from: https://media.toyota.co.uk/wp-content/filesmf/14449195 32151015MToyotaMiraiTechSpecFinal.pdf.

[67] Kühlwein J. Driving Resistances of Light-Duty Vehicles in Europe: Present Situation, Trends and Scenarios for 2025. *The International Council on Clean Transportation (ICCT)*, (December):1–46, 2016. Available from: https://theicct.org/sites/default/files/publications/ICCTLDV-Driving-Resistances-EU121516.pdf.

[68] ECOMOTORS INC. and EVCOMPARE. Renault Master Z.E, 2020. Available from: https://evcompare.io/trucks-and-vans/renault/renaultmasterze/.

[69] Groupe Renault. New Renault MASTER, 2020. Available from: http://dsg-renault.co.uk/uploads/documents/master.pdf.

[70] Nordelöf A, Alatalo M, and Ljunggren Söderman M. A scalable life cycle inventory of an automotive power electronic inverter unit—part I: design and composition. *International Journal of Life Cycle Assessment*, 24(1):78–92, 2019. doi: 10.1007/s11367-018-1503-3.

[71] Nordelöf A, Alatalo M, and Ljunggren Söderman M. A scalable life cycle inventory of an automotive power electronic inverter unit—part I: design and composition. *International Journal of Life Cycle Assessment*, 24(1):78–92, 2019. doi: 10.1007/s11367-018-1503-3.

[72] Nelson PA, Gallagher KG, Ahmed S, Dees DW, Susarla N, Bloom ID, Kubal JJ, and Song J. BatPaC Model Software. *Argonne National Laboratory*, 2020. Available from: https://www.anl.gov/tcp/batpac-battery-manufacturing-cost-estimation.

[73] Hua TQ, Ahluwalia RK, Peng JK, Kromer M, Lasher S, McKenney K, Law K, and Sinha J. Technical assessment of compressed hydrogen storage tank systems for automotive applications. *International Journal of Hydrogen Energy*, 36(4):3037–3049, 2011. doi: 10.1016/j.ijhydene.2010.11.090.

[74] Argonne National Laboratory. Technology Assessment of a Fuel Cell Vehicle: 2017 Toyota Mirai, Report # ANL/ESD-18/12. Technical report, 2018. Available from: https://publications.anl.gov/anlpubs/2018/06/144774.pdf.

[75] U.S. Department of Energy Office of Energy Efficiency & Renewable Energy. DOE Technical Targets for Onboard Hydrogen Storage for Light-Duty Vehicles, 2020. Available from: https://www.energy.gov/eere/fuelcells/doe-technical-targets-onboard-hydrogen-storage-light-duty-vehicles.

[76] ecoinvent. What is a market and how is it created?, 2020. Available from: https://www.ecoinvent.org/support/faqs/methodology-of-ecoinvent-3/what-is-a-market-and-how-is-it-created.html.

[77] ecoinvent. Allocation cut-off by classification, 2020. Available from: https://www.ecoinvent.org/database/system-models-in-ecoinvent-3/cut-off-system-model/allocation-cut-off-by-classification.html.

[78] European Commission - Joint Research Centre - Institute for Environment and Sustainability: International Reference Life Cycle Data System (ILCD) Handbook - Nomenclature and other conventions. First edition 2010. EUR 24384 EN. Luxembourg. Publications Office of the European Union; 2010. doi: 10.2788/96557.

[79] Fazio S, Castellani V, Sala S, Schau EM, Secchi M, Zampori L, Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods, EUR 28888 EN, European Commission, Ispra, 2018, ISBN 978-92-79-76742-5, doi:10.2760/671368, JRC109369.

[80] Swedish University of Agricultural Sciences. Försurning, 2016. Available from: https://www.slu.se/institutioner/energi-teknik/forskning/lca/vadar/forsurning/.

[81] European Commission. LCIA Method data set overview page, 2011. Available from: https://eplca.jrc.ec.europa.eu/EUFRP/showLCIAMethod.xhtml;jsessionid=9F24EEE9400484EAD975E74ED0B427F0?uuid=f6cbd466-253f-4145-a4bb-8dae7d266e89stock=default.

[82] Swedish University of Agricultural Sciences. Klimatpåverkan, 2016. Available from: https://www.slu.se/institutioner/energi-teknik/forskning/lca/vadar/klimatpaverkan/.

[83] Chislock MF, Doster E, Zitomer RA and Wilson AE. Eutrophication: Causes, Consequences, and Controls in Aquatic Ecosystems. Nature Education Knowledge 4(4):10, 2013. Available from: https://www.nature.com/scitable/knowledge/library/eutrophication-causes-consequences-and-controls-in-aquatic-102364466/.

[84] Swedish University of Agricultural Sciences. Marknära ozon, 2016. Available from: https://www.slu.se/institutioner/energi-teknik/forskning/lca/vadar/marknara-ozon/.

[85] European Commission C, 2013, Commission Recommendation of 9 April 2013 on the use of common methods to measure and communicate the

life cycle environmental performance of products and organisations. OJ L124, 04.05.2013, pp. 1-210. Available from:https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX%3A32013H0179from=EN.

[86] Altenstedt J and Pleijel K. POCP for individual VOC under European conditions, IVL report B-1305. Technical report, IVL - Swedish Environmental Research Institute, Gothenburg, 1998. Available from: https://www.ivl.se/download/18.343dc99d14e8bb0f58b7368/1445515409320/B1305.pdf.

[87] Swedish University of Agricultural Sciences. Abiotiska resurser, 2016. Available from: https://www.slu.se/institutioner/energi-teknik/forskning/lca/vadar/abiotiska-resurser/.

[88] Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, and Weidema B. The ecoinvent database version 3 (part I): overview and methodology. *International Journal of Life Cycle Assessment*, 21(9):1218–1230, 9 2016. doi: 10.1007/s11367-016-1087-8.

[89] Lewrén A. Life cycle assessment of nickel-rich lithium-ion battery for electric vehicles A comparatative LCA between the cathode chemistries NMC 333 and NMC 622. 2019. Available from: https://hdl.handle.net/20.500.12380/300644.

[90] Mahmud MAP, Huda N, Farjana SH, and Lang C. Comparative life cycle environmental impact analysis of lithium-ion (LiIo) and nickel-metal hydride (NiMH) batteries. *Batteries*, 5(1):22, 2019. doi: 10.3390/batteries5010022.

[91] Majeau-Bettez G, Hawkins TR, and Strømman AH. Life cycle environmental assessment of lithium-ion and nickel metal hydride batteries for plug-in hybrid and battery electric vehicles. *Environmental Science and Technology*, 45(10):4548–4554, 2011. doi: 10.1021/es103607c.

[92] Rossi F, Parisi ML, Maranghi S, Basosi R, and Sinicropi A. Life Cycle Inventory datasets for nano-grid configurations. *Data in Brief*, 28:104895, 2020. doi: 10.1016/j.dib.2019.104895.

[93] Nordelöf A, Messagie M, AM Tillman, Ljunggren Söderman M, and Van Mierlo J. Environmental impacts of hybrid, plug-in hybrid, and battery electric vehicles—what can we learn from life cycle assessment? *International Journal of Life Cycle Assessment*, 19(11):1866–1890, 2014. doi: 10.1007/s11367-014-0788-0.

[94] Quader MA and Ahmed S. Bioenergy with carbon capture and storage (BECCS): Future prospects of carbon-negative technologies. In *Clean Energy for Sustainable Development: Comparisons and Contrasts of New Approaches*, chapter 4, pages 91–140. 2017. doi: 10.1016/B978-0-12-805423-9.00004-1.

[95] WEH GmbH Precision connectors. Receptacle for hydrogen car, 2020. Available from: https://www.weh.com/weh-receptacle-tn1-h-for-refuelling-of-cars-series.html.

A

Appendix A

A.1 Life cycle inventory modelling

This section presents the data collection for the life cycle inventory in Section 4.2. The data is presented for the BEV and the FCEV in the three modelled life cycle phases: production phase, use phase and EoL phase.

All used process flows in the model originate from the database Ecoinvent 3.6 with the system model *Allocation cut-off by classification* [77], [88]. The used processes have mainly originated from Ecoinvent 3.6 depending on availability. However, some processes had to be self-created in a simplified manner based on literature studies and modelled with flows from Ecoinvent 3.6. The self-created processes have a reference to the table where the original process is presented.

In the following tables, the reference flow of the modelled processes is written in bold. The modelling is presented in form of unit processes in Ecoinvent 3.6.

A.1.1 Production phase

In this section, the production phases for the two vehicles, BEV and FCEV, are presented. This includes the assembly of the vehicles and the production of the included components.

A.1.1.1 BEV

A.1.1.1.1 Modelling of the assembly of BEV
The assembly of the BEV is modelled as the production and assembly of glider and BE powertrain, the Li-ion battery is modelled more thoroughly. The modelling is presented in Table A.1. The Li-ion battery for the BEV is modelled according to the process *market for battery, Li-ion, rechargeable, prismatic| Cutoff U, GLO* in Ecoinvent 3.6 [88]. However, the modelling of the battery cell was replaced since another more detailed data set was used, which is presented in Table A.2. The transmission is approximated by 160 kg of low-alloyed steel.

Table A.1: Assembly of BEV.

Flow	Amount	Unit	Provider	Ref.
Inputs				
charger, electric passenger car	6.20E+00	kg	market for charger, electric passenger car|GLO	[88]
glider, passenger car	1.67E+03	kg	market for glider, passenger car|GLO	[88]
BE powertrain BEV				
battery, Li-ion, rechargeable, prismatic, NMC111 battery cell	4.04E+02	kg	market for battery, Li-ion, rechargeable, prismatic NMC111 battery cell|GLO	[88] Table A.2
Inverter unit, IGBT PE, 10.9 kg motor controller	1.00E+00	Item(s)	Production of inverter unit, IGBT PE motor controller, 10.9 kg|RER	[71]
metal working,average steel product manufacturing	1.60E+02	kg	market for metal working, average for steel product manufacturing|GLO	[88]
Nd(Dy)FeB PMSM 44.9 kg	1.00E+00	Item(s)	Production of Nd(Dy)FeB PMSM 44.9 kg|RER	[70]
steel, low alloyed	1.60E+02	kg	market for steel, low alloyed |GLO	[88]
transport, freight, lorry, 16-32 metric ton, EURO4	2.79E+05	kg·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RER	[88]
transport, freight, sea, container ship	8.63E+06	kg·km	market for transport, freight, sea, container ship|GLO	[88]
Outputs				
Assembly of BEV	1.00E+00	Item(s)		

A.1.1.1.2 Modelling of Li-ion battery

The weight of the Li-ion battery in Table A.1 was calculated from an equation received from a linearisation of the relationship between the energy and the weight of Li-ion batteries. The result is illustrated in Figure A.1, the energy of 80 kWh was used to calculate the weight. The values used for the linearisation was obtained from the program BatPac [72].

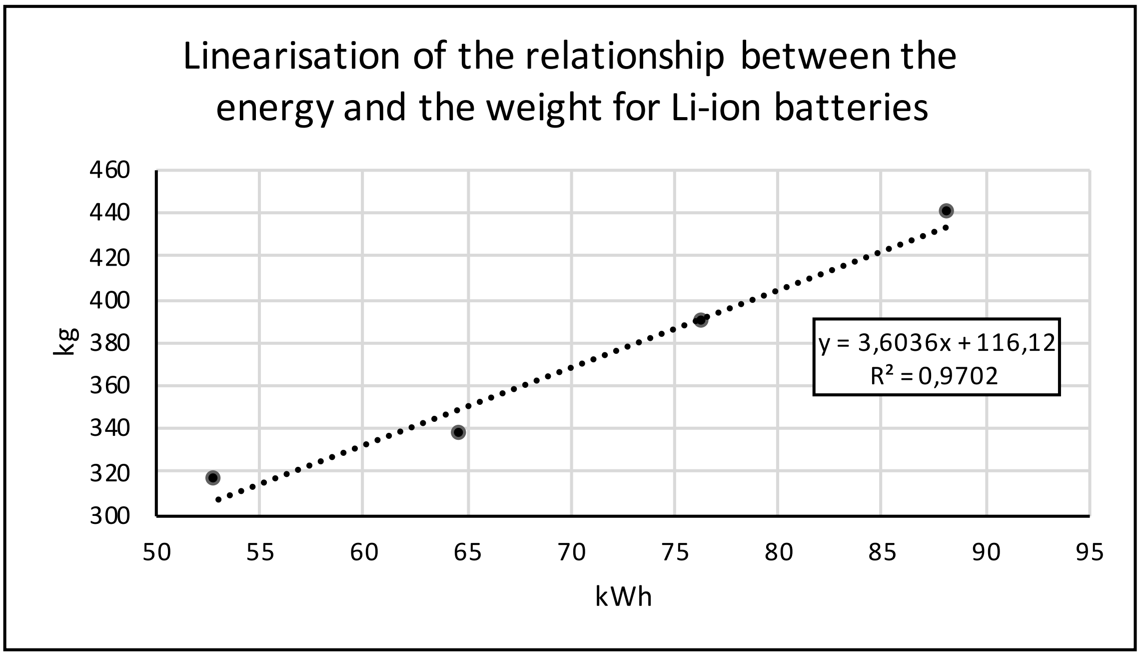

Figure A.1: The linearisation of the relationship between energy and weight for Li-ion batteries.

The modelling of the Li-ion battery was based on the already existing process within Ecoinvent 3.6 *market for battery, Li-ion, rechargeable, prismatic | Cutoff U, GLO*. The process was mainly modified by using a more detailed data set for the battery cell (NMC111) [89]. The modelling of the NMC111 battery cell included several data sets which are presented in Table A.2-A.9, and the assembly of the NMC111 battery cell for the market process for the Li-ion battery is presented in Table A.2.

Table A.2: Assembly of Li-ion battery cell (NMC111).

Flow	Amount	Unit	Provider	Ref.
Inputs				
Anode for NMC111-cell	3.20E-01	kg	Anode for NMC111 cell	Table A.3
Cathode for NMC111-cell	4.60E-01	kg	Cathode for NMC111 cell	Table A.4
Cell container	5.20E-02	kg	Cell container	Table A.8
electricity, medium voltage	4.80E+00	MJ	market group for electricity, medium voltage|CN	[89]
Electrolyte for NMC111-cell	1.50E-01	kg	Electrolyte for NMC111 cell	[89]
heat, district or industrial, natural gas	1.10E+01	MJ	heat and power co-generation, natural gas, conventional power plant,100MW electrical|RoW	[89]
heat, district or industrial, natural gas	1.12E+01	MJ	heat and power co-generation, natural gas, conventional power plant,100MW electrical|RoW	[89]
injection moulding	1.28E-02	kg	market for injection moulding|GLO	[89]
injection moulding	3.20E-03	kg	market for injection moulding|GLO	[89]
polyethylene, high density, granulate	3.20E-03	kg	market for polyethylene, high density, granulate|GLO	[89]
polypropylene, granulate	1.28E-02	kg	market for polypropylene, granulate|GLO	[89]
tap water	5.30E+00	kg	market group for tap water|GLO	[89]
Outputs				
Battery cell for Li-ion battery, NMC111-cell	1.00E+00	kg		
wastewater, from residence	2.01E-03	m^3	market for wastewater, from residence|RoW	[89]

Table A.3: Assembly of anode (NMC111-cell).

Flow	Amount	Unit	Provider	Ref.
Inputs				
coal tar	1.48E-01	kg	market for coal tar|GLO	[89]
copper	3.50E-01	kg	market for copper|GLO	[89]
electricity, medium voltage	9.26E+00	MJ	market group for electricity, medium voltage|CN	[89]
heat, district or industrial, natural gas	3.33E+00	MJ	heat and power co-generation, natural gas, conventional power plant, 100MW electrical|RoW	[89]
injection moulding	3.25E-02	kg	market for injection moulding|GLO	[89]
petroleum coke	5.87E-01	kg	market for petroleum coke|GLO	[89]
polyvinylfluoride	3.25E-02	kg	market for polyvinylfluoride|GLO	[89]
sheet rolling, copper	3.50E-01	kg	market for sheet rolling, copper|GLO	[89]
Outputs				
Anode	1.00E+00	kg		
Carbon dioxide	2.72E-01	kg		[89]
Nitrogen oxides	5.74E-03	kg		[89]
Particulates, < 10 um	2.53E-03	kg		[89]
Particulates, < 2.5 um	1.30E-03	kg		[89]
Sulfur oxides	3.95E-02	kg		[89]

Table A.4: Assembly of cathode (NMC111-cell).

Flow	Amount	Unit	Provider	Ref.
Inputs				
Active cathode material	7.92E-01	kg	Active cathode material	Table A.5
aluminium, primary, ingot	1.10E-01	kg	market for aluminium, primary, ingot|RoW	[89]
carbon black	5.34E-02	kg	market for carbon black|GLO	[89]
injection moulding	4.45E-02	kg	market for injection moulding|GLO	[89]
polyvinylfluoride	4.45E-02	kg	market for polyvinylfluoride|GLO	[89]
sheet rolling, aluminium	1.10E-01	kg	market for sheet rolling, aluminium|GLO	[89]
Outputs				
Cathode	1.00E+00	kg		

Table A.5: Active cathode material (NMC111-cell).

Flow	Amount	Unit	Provider	Ref.
Inputs				
ammonia, liquid	1.14E-01	kg	market for ammonia, liquid|RoW	[89]
Cobalt sulfate	5.50E-01	kg	Cobalt sulfate	Table A.6
electricity, medium voltage	2.30E+01	MJ	market group for electricity, medium voltage|CN	[89]
heat, district or industrial, natural gas	3.90E+01	MJ	heat and power co-generation, natural gas, conventional power plant, 100MW electrical|RoW	[89]
lithium carbonate	3.80E-01	kg	market for lithium carbonate| GLO	[89]
manganese sulfate	5.32E-01	kg	market for manganese sulfate|GLO	[89]
nickel sulfate	5.32E-01	kg	market for nickel sulfate|GLO	[89]
sodium hydroxide, without water, in 50% solution state	8.46E-01	kg	market for sodium hydroxide, without water, in 50% solution state|GLO	[89]
tap water	1.62E+01	kg	market group for tap water|GLO	[89]
Outputs				
Active cathode material	1.00E+00	kg		
Carbon dioxide	2.10E-01	kg		[89]

Table A.6: Cobalt sulfate (NMC111-cell).

Flow	Amount	Unit	Provider	Ref.
Inputs				
Crude $Co(OH)_2$	6.00E-01	kg	Crude $Co(OH)_2$	A.7
electricity, medium voltage	4.20E+00	MJ	market group for electricity, medium voltage|CN	[89]
heat, district or industrial, natural gas	1.10E+01	MJ	heat and power co-generation, natural gas, conventional power plant, 100MW electrical|RoW	[89]
hydrochloric acid, without water, in 30% solution state	5.40E-01	kg	market for hydrochloric acid, without water, in 30% solution state|RoW	[89]
kerosene	1.80E-02	kg	market for kerosene|RoW	[89]
limestone, crushed, for mill	2.10E-02	kg	market for limestone, crushed, for mill|RoW	[89]
quicklime, milled, loose	8.40E-03	kg	market for quicklime, milled, loose|RoW	[89]
soda ash, dense	3.30E-02	kg	market for soda ash, dense|GLO	[89]
sodium hydroxide, without water, in 50% solution state	1.00E+00	kg	market for sodium hydroxide, without water, in 50% solution state|GLO	[89]
sulfuric acid	9.80E-01	kg	market for sulfuric acid|RoW	[89]
tap water	1.30E+00	kg	market group for tap water|GLO	[89]
Outputs				
Cobalt sulfate	1.00E+00	kg		

Table A.7: Crude $Co(OH)_2$ (NMC111-cell).

Flow	Amount	Unit	Provider	Ref.
Inputs				
ammonia, liquid	4.84E-02	kg	market for ammonia, liquid|RoW	[89]
carbon dioxide, liquid	1.23E-01	kg	market for carbon dioxide, liquid|RoW	[89]
cobalt	6.11E-01	kg	market for cobalt|GLO	[89]
diesel, burned in building machine	4.55E+01	MJ	market for diesel, burned in building machine|GLO	[89]
electricity, medium voltage	2.00E+01	MJ	market group for electricity, medium voltage|CN	[89]
heat, district or industrial, natural gas	4.20E-01	MJ	heat and power co-generation, natural gas, conventional power plant, 100MW electrical|RoW	[89]
heat, district or industrial, other than natural gas	1.84E-01	MJ	heat and power co-generation, hard coal|RoW	[89]
limestone, crushed, for mill	2.60E+00	kg	market for limestone, crushed, for mill|RoW	[89]
magnesium oxide	7.50E-01	kg	market for magnesium oxide|GLO	[89]
quicklime, milled, loose	9.50E-01	kg	market for quicklime, milled, loose|RoW	[89]
sodium hydroxide, without water, in 50% solution state	1.10E-01	kg	market for sodium hydroxide, without water, in 50% solution state|GLO	[89]
sodium hydroxide, without water, in 50% solution state	1.26E-02	kg	market for sodium hydroxide, without water, in 50% solution state|GLO	[89]
sulfur dioxide, liquid	4.00E+00	kg	market for sulfur dioxide, liquid| RoW	[89]
sulfur dioxide, liquid	2.01E-02	kg	market for sulfur dioxide, liquid|RoW	[89]
tap water	6.60E+00	kg	market group for tap water| GLO	[89]
tap water	9.36E-01	kg	market group for tap water|GLO	[89]
tap water	9.40E-02	kg	market group for tap water|GLO	[89]
tap water	3.08E-03	kg	market group for tap water|GLO	[89]
Outputs				
Crude $Co(OH)_2$	1.00E+00	kg		Table A.7
Particulates, < 10 um	1.12E-01	kg		[89]
Particulates, < 2.5 um	1.16E-02	kg		[89]
Sulfur dioxide	1.80E-02	kg		[89]

Table A.8: Cell container (NMC111-cell).

Flow	Amount	Unit	Provider	Ref.
Inputs				
aluminium, primary, ingot	3.10E-01	kg	market for aluminium, primary, ingot|RoW	[89]
aluminium, primary, ingot	1.40E-01	kg	market for aluminium, primary, ingot|RoW	[89]
copper	4.80E-01	kg	market for copper|GLO	[89]
injection moulding	4.80E-02	kg	market for injection moulding|GLO	[89]
injection moulding	2.10E-02	kg	market for injection moulding|GLO	[89]
polyethylene terephthalate, granulate, bottle grade	4.80E-02	kg	market for polyethylene terephthalate, granulate, bottle grade|GLO	[89]
polypropylene, granulate	2.10E-02	kg	market for polypropylene, granulate|GLO	[89]
sheet rolling, aluminium	3.10E-01	kg	market for sheet rolling, aluminium|GLO	[89]
sheet rolling, copper	4.80E-01	kg	market for sheet rolling, copper|GLO	[89]
Outputs				
Cell container	1.00E+00	kg		

Table A.9: Electrolyte (NMC111-cell).

Flow	**Amount**	**Unit**	**Provider**	**Ref.**
Inputs				
dimethyl carbonate	4.20E-01	kg	market for dimethyl carbonate|GLO	[89]
ethylene carbonate	4.20E-01	kg	market for ethylene carbonate|GLO	[89]
lithium hexafluorophosphate	1.50E-01	kg	market for lithium hexafluorophosphate|GLO	[89]
Outputs				
Electrolyte	1.00E+00	kg		

A.1.1.2 FCEV

The production phase of the FCEV includes the assembly of the vehicle, as well as more detailed modelling of the MS-100 system, Ni-MH battery and the hydrogen tank. Furthermore, along with the modelling of the MS-100 system the modelling of the activation of the system as well as the energy and waste for PowerCell's production facility are presented.

A.1.1.2.1 Modelling of the assembly of FCEV

The assembly of the FCEV is modelled as the production and assembly of glider and FCE powertrain as well as a hydrogen tank. The MS-100 system, the Ni-MH battery and the hydrogen tank in the FCE powertrain are modelled more detailed in later sections. The transmission is approximated by 160 kg of low-alloyed steel. The weight of the fuel receptacle is assumed to be the same as for the electric charger. Thereby it is approximated by 6.2 kg of chromium steel [95]. The full modelling is presented in Table A.10.

Table A.10: Assembly of FCEV.

Flow	**Amount**	**Unit**	**Provider**	**Ref.**
Inputs				
glider, passenger car	1.67E+03	kg	market for glider, passenger car|GLO	[88]
Hydrogen tank	1.00E+00	Item(s)	Hydrogen tank	Table A.15
metal working, average for steel product manufacturing	6.20E+00	kg	market for metal working, average for steel product manufacturing|GLO	[88]
steel, chromium steel 18/8, hot rolled	6.20E+00	kg	market for steel, chromium steel 18/8, hot rolled|GLO	[88]
FCE powertrain				
Assembly of MS-100 system	1.00E+00	Item(s)	Assembly of MS-100 system	Table A.11
Assembly of Ni-MH battery	5.40E+01	kg	Assembly of Ni-MH battery	Table A.14
Inverter unit, IGBT PE motor controller, 10.9 kg	1.00E+00	Item(s)	Production of inverter unit, IGBT PE motor controller, 10.9 kg|RER	[71]
metal working, average for steel product manufacturing	1.60E+02	kg	market for metal working, average for steel product manufacturing|GLO	[88]
Nd(Dy)FeB PMSM 44.9 kg	1.00E+00	Item(s)	Production of Nd(Dy)FeB PMSM 44.9 kg - RER	[70]
steel, low alloyed	1.60E+02	kg	market for steel, low alloyed |GLO	[88]
transport, freight, lorry, 16-32 metric ton, EURO4	2.79E+05	kg·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RER	[88]
transport, freight, sea, container ship	1.36E+06	kg·km	market for transport, freight, sea, container ship|GLO	[88]
Outputs				
Assembly of FCEV	1.00E+00	Item(s)		

A.1.1.2.2 Modelling of MS-100 system

In Table A.11 an aggregated assembly of the MS-100 system is presented. Due to confidentiality the full modelling is presented in Appendix B.

Table A.11: Assembly of MS-100 system.

Flow	**Amount**	**Unit**	**Provider**	**Ref.**
Inputs				
acrylonitrile-butadiene-styrene copolymer	2.82E+01	kg	market for acrylonitrile-butadiene-styrene copolymer |GLO	[88]
aluminium, cast alloy	1.99E+01	kg	market for aluminium, cast alloy|GLO	[88]
cable, unspecified	2.1E+00	kg	market for cable, unspecified|GLO	[88]
copper	1.00E-01	kg	market for copper|GLO	[88]
metal working, average for copper product manufacturing	1.00E-01	kg	market for metal working, average for copper product manufacturing|GLO	[88]
electronics, for control units	2.06E+01	kg	market for electronics, for control units|GLO	[88]
injection molding	2.82E+01	kg	market for injection moulding|GLO	[88]
metal working, average for aluminium product manufacturing	1.99E+01	kg	market for metal working, average for aluminium product manufacturing|GLO product manufacturing|GLO	[88]
metal working, average for chromium steel product manufacturing	1.12E+02	kg	market for metal working, average for chromium steel product manufacturing|GLO	[88]
steel, chromium steel 18/8, hot rolled	1.12E+02	kg	market for steel, chromium steel 18/8, hot rolled|GLO	[88]
Outputs				
Assembly of MS-100 system	1.00E+00	Item(s)		

Table A.12 presents the energy and resource requirements for activation of the FCS and the MS-100 system. The amounts are not disclosed in this Appendix, however they are presented in Appendix B.

Table A.12: Activation of the FCS and the MS-100 system. The process flows in italics belong to the self-created process "Hydrogen from electrolyser for activation of the FCS" which was based on the operation of an electrolyser according to [48].

Flow	Amount	Unit	Provider	Ref.
Inputs				
Air	-	kg		[88]
electricity, medium voltage, label-certified	-	kWh	market for electricity, medium voltage, label-certified|CH	[88]
ethylene glycol	-	kg	market for ethylene glycol|GLO	[88]
Hydrogen, gaseous			Hydrogen from electrolyser for activation of the FCS	
electricity, medium voltage	-	kWh	market for electricity, medium voltage|SE	[88]
tap water	-	kg	market group for tap water|RER	[88]
nitrogen, liquid	-	kg	Air separation, cryogenic |nitrogen,liquid|RER	[88]
water, deionised	-	kg	market for water, deionised |EUR-w-CH	[88]
water, deionised	-	kg	market for water, deionised|EUR-w-CH	[88]
Outputs				
Activation of MS-100 system	1,00E+00	Item(s)		

Table A.13 presents the heat and waste for the facility that is related to the production of the MS-100 system.

Table A.13: Energy and waste for PowerCell's production facility.

Flow	Amount	Unit	Provider	Ref.
Inputs				
Heat, district or industrial, other than natural gas	1.73E+01	MWh	Heat, from municipal waste incineration to generic market for heat district or industrial, other than natural gas|SE	[88]
Outputs				
Cardboard waste	5.59E+01	kg		[88]
Iron waste	7.32E+00	kg		[88]
Metal waste	4.70E+00	kg		[88]
PowerCell facility	1.00E+00	Item(s)		
Propylene glycol waste	1.51E+01	kg		[88]
Waste, industrial	1.37E+02	kg		[88]

A.1.1.2.3 Modelling of Ni-MH battery

The modelling of the Ni-MH battery is presented in Table A.14.

Table A.14: Ni-MH battery.

Flow	Amount	Unit	Provider	Ref.
Inputs				
Electrode, negative, Ni				
carbon black	1.00E-02	kg	market for carbon black|GLO	[91]
carboxymethyl cellulose, powder	1.00E-02	kg	market for carboxymethyl cellulose, powder|GLO	[91]
chemical factory, organics	1.00E+00	Item(s)	market for chemical, factory, organics|GLO	[91]
electricity, medium voltage	2.70E-01	MJ	market for electricity, medium voltage|JP	[91]
hydrogen, liquid	3.30E-01	kg	market for hydrogen, liquid|RoW	[91]
mischmetal	1.10E-01	kg	market for mischmetal|GLO	[91]
nickel, 99.5%	2.20E-01	kg	market for nickel, 99.5%|GLO	[91]
tetrafluoroethylene	1.00E-02	kg	market for tetrafluoroethylene|GLO	[91]
transport, freight train	2.20E-01	t·km	market group for transport, freight train|GLO	[91]
transport, freight, lorry 16-32 metric ton, EURO4	4.00E-02	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RoW	[91]
Electrode, positive LaNi5				
carbon black	3.35E-02	kg	market for carbon black|GLO	[91]
carboxymethyl cellulose, powder	8.38E-03	kg	market for carboxymethyl cellulose, powder|GLO	[91]
tetrafluoroethylene	8.38E-03	kg	market for tetrafluoroethylene|GLO	[91]
transport, freight train	2.01E-01	t·km	market group for transport, freight train|GLO	[91]
transport, freight, lorry 16-32 metric ton, EURO4	3.35E-02	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RoW	[91]
Electrolyte, KOH, LiOH additive				
lithium hydroxide	1.60E-03	kg	market for lithium hydroxide|GLO	[91]
potassium hydroxide	2.14E-02	kg	market for potassium hydroxide|GLO	[91]
transport, freight train	1.40E-02	t·km	market group for transport, freight train|GLO	[91]
transport, freight, lorry 16-32 metric ton, EURO4	2.50E-03	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4 |RoW	[91]
water, deionised	5.92E-02	kg	water production, deionised|RoW	[91]
Nickel hydroxide				
nickel sulfate	4.76E-01	kg	market for nickel sulfate|GLO	[91]
sodium hydroxide, without water, in 50% solution state	2.45E-01	kg	market for sodium hydroxide, without water, in 50% solution state|GLO	[91]
transport, freight train	4.27E-01	t·km	market group for transport, freight train|GLO	[91]
transport, freight, lorry 16-32 metric ton, EURO4	6.10E-02	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RoW	[91]
Other components				
acrylic acid	1.34E-03	kg	market for acrylic acid|RoW	[90]
copper	3.62E-06	kg	market for copper|GLO	[90]
electricity, medium voltage	5.44E-01	kWh	market for electricity, medium voltage|JP	[90]
heat, district or industrial,natural gas	8.35E+00	MJ	market group for heat, district or industrial,natural gas|GLO	[90]
injection moulding	1.18E-01	kg	market for injection moulding|GLO	[90]
nickel, 99.5%	5.83E-02	kg	market for nickel, 99.5%|GLO	[90]
polycarbonate	8.12E-02	kg	market for polycarbonate|GLO	[90]
polyethylene, low density, granulate [90]	1.83E-02	kg	market for polyethylene, low density, granulate|GLO	
polypropylene, granulate	1.85E-02	kg	market for polypropylene, granulate|GLO	[90]
precious, metal refinery	1.65E-19	Item(s)	market for precious metal refinery|GLO	[90]
sheet rolling, copper	3.62E-06	kg	market for sheet rolling, copper|GLO	[90]
sheet rolling, steel	1.05E-01	kg	market for sheet rolling, steel|GLO	[90]
steel, low-alloyed	4.63E-02	kg	market for steel, low-alloyed|GLO	[90]
transport, freight train	9.47E-02	t·km	market group for transport, freight train|GLO	[90]
transport, freight, lorry 16-32 metric ton, EURO4	3.06E-02	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RoW	[90]
water, decarbonised	1.83E+02	kg	water production, decarbonised|RoW	[90]
zinc	3.62E-08	kg	market for zinc|GLO	[90]
zinc coat, pieces	4.81E-05	m2	market for zinc coat, pieces|GLO	[90]
Outputs				
Assembly of Ni-MH battery	1.00E+00	kg		
hazardous waste, for incineration	8.84E-01	kg	market for hazardous waste, for incineration|RoW	[90]
Heat, waste	7.73E+01	MJ		[90]
Heat, waste	2.70E-01	MJ		[91]
hydrogen, gaseous	3.30E-01	kg		[91]
sodium sulfate, anhydrite	4.27E-01	kg		[91]

A.1.1.2.4 Modelling of fuel tank

Table A.15: Hydrogen tank. EUR-w-CH is an abbreviation for Europe without Switzerland.

Flow	Amount	Unit	Provider	Ref.
Inputs				
Carbon fibre production				
ammonia, liquid	1.93E+01	kg	market for ammonia liquid|RER	[92]
electricity, low voltage	3.68E+02	kWh	market group for electricity, low voltage|EUR-w-CH	[92]
polypropylene, granulate	4.81E+01	kg	market for polypropylene, granulate|GLO	[92]
Other components				
chromium steel pipe	2.86E+00	kg	market for chromium steel pipe|GLO	[92]
glass fibre reinforced plastic, polyester resin, hand lay-up	3.29E+00	kg	market for glass fibre reinforced plastic, polyester resin, hand lay-up|GLO	[92]
polyethylene, high density, granulate	5.71E+00	kg	market for polyethylene, high density granulate|GLO	[92]
polymer foaming	2.86E+00	kg	market for polymer foaming|GLO	[92]
silicon, electronics grade	7.10E-01	kg	market for silicon, electronics grade |GLO	[92]
steel, low-alloyed	9.79E+00	kg	market for steel, low-alloyed|GLO	[92]
transport, freight, lorry 16-32 metric ton, EURO4	5.17E+03	kg·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RER	[92]
Outputs				
Type IV hydrogen tank	1.00E+00	Item(s)		

A.1.2 Use phase

In this section the modelling of the use phases for the BEV and FCEV are presented. In the use phase both the operation of the vehicle and the electricity and hydrogen production is included.

A.1.2.1 Modelling of the use phase for BEV

The use phases for BEV-RER Mix and BEV-SE Mix are presented in Table A.16 and A.17. The "Assembly of BEV" and "BEV to EoL-treatment" are included in order to correctly link the phases in openLCA.

Table A.16: Use phase for BEV-RER Mix.

Flow	Amount	Unit	Provider	Ref.
Inputs				
Assembly of BEV	1.00E+00	Item(s)	Assembly of electric vehicle	Table A.1
electricity, low voltage	7.98E+04	kWh	market for electricity, low voltage|RER	[88]
maintenance, passenger car, electric, without battery	1.00E+00	Item(s)	maintenance, passenger car, electric, without battery|GLO	[88]
Outputs				
BEV to EoL-treatment	1.00E+00	Item(s)	BEV manual disassembly EoL-treatment	Table A.25
Use phase for BEV-RER Mix	2.50E+05	v·km		

Table A.17: Use phase for BEV-SE Mix.

Flow	Amount	Unit	Provider	Ref.
Inputs				
Assembly of BEV	1.00E+00	Item(s)	Assembly of electric vehicle	Table A.1
electricity, low voltage	7.98E+04	kWh	market for electricity, low voltage|SE	[88]
maintenance, passenger car, electric, without battery	1.00E+00	Item(s)	maintenance, passenger car, electric, without battery|GLO	[88]
Outputs				
BEV to EoL-treatment	1.00E+00	Item(s)	BEV manual disassembly EoL-treatment	Table A.25
Use phase for BEV-SE Mix	2.50E+05	v·km		

A.1.2.2 Modelling of the use phase for FCEV

The use phases for FCEV-SMR and FCEV-WP Electrolysis are presented in Table A.18 and A.19. The "Assembly of BEV" and "BEV to EoL-treatment" are included in order to correctly link the phases in openLCA.

Table A.18: Use phase for FCEV-SMR.

Flow	Amount	Unit	Provider	Ref.
Inputs				
Assembly of FCEV	1.00E+00	Item(s)	Assembly of FCEV	Table A.10
Hydrogen from fuelling station, SMR production	3.60E+03	kg	Fuelling station, hydrogen produced by SMR	Table A.22
maintenance, passenger car, electric, without battery	1.00E+00	Item(s)	maintenance, passenger car, electric, without battery|GLO	[88]
Outputs				
FCEV to EoL-treatment	1.00E+00	Item(s)	FCEV manual disassembly EoL-treatment	Table A.27
Use phase for FCEV-SMR	2.50E+05	v·km		

Table A.19: Use phase for FCEV-WP Electrolysis.

Flow	Amount	Unit	Provider	Ref.
Inputs				
Assembly of FCEV	1.00E+00	Item(s)	Assembly of FCEV	Table A.10
Hydrogen from fuelling station, wind powered production	3.60E+03	kg	Fuelling station, hydrogen produced by wind power	Table A.23
maintenance, passenger car, electric, without battery	1.00E+00	Item(s)	maintenance, passenger car, electric, without battery|GLO	[88]
Outputs				
FCEV to EoL-treatment	1.00E+00	Item(s)	FCEV manual disassembly EoL-treatment	Table A.27
Use phase for the FCEV-WP Electrolysis	2.50E+05	v·km		

A.1.2.2.1 Hydrogen production from SMR

The hydrogen production by SMR of natural gas is presented in Table A.20. The transport of hydrogen in pipelines to the fuelling station is presented in Table A.21 and the fuelling station is presented in A.22.

Table A.20: Hydrogen production from SMR.

Flow	Amount	Unit	Provider	Ref.
Inputs				
Facility				
aluminium, cast alloy	2.47E-06	kg	market for aluminium, cast alloy|GLO	[53]
diesel, burned in building machine	5.09E-02	MJ	diesel, burned in building machine|GLO	[53]
concrete, normal	4.16E-07	m3	market group for concrete, normal|GLO	[53]
iron ore, crude ore, 46% Fe	3.65E-06	kg	market for iron ore, crude ore, 46% Fe|GLO	[53]
reinforcing steel	2.99E-04	kg	market for reinforcing steel|GLO	[53]
Operation				
electricity, medium voltage	1.02E-01	MJ	market for electricity, medium voltage|SE	[53]
natural gas, high pressure	4.05E-01	m^3	market for natural gas, high pressure|SE	[53]
tap water	1.69E+00	kg	market group for tap water|RER	[53]
Outputs				
benzene	1.26E-04	kg		[53]
carbon dioxide	9.55E-01	kg		[53]
carbon monoxide	5.12E-04	kg		[53]
dinitrogen monoxide	3.60E-06	kg		[53]
Hydrogen from SMR hydrogen production	1.00E+00	m^3H_2		[53]
methane	5.37E-03	kg		[53]
nitrogen dioxide	1.11E-03	kg		[53]
NMVOC, non-methane volatile organic compounds, unspecified origin	1.51E-03	kg		[53]
particulates, unspecified	1.80E-04	kg		[53]
steam, in chemical industry	3.77E-01	kg		[53]
sulfur dioxide	8.54E-04	kg		[53]
waste bulk iron, excluding reinforcement	9.55E-01	kg		[53]

Table A.21: Transport of hydrogen gas from SMR to fuelling station, high pressure. Modified from an existing dataset in Ecoinvent 3.6 named *market for natural gas, high pressure/Cutoff U, SE* [88]. Only changed flows are reported and X_1 is a coefficient that cannot be disclosed.

Flow	Amount	Unit	Provider	Ref.
Inputs - added				
heat, district or industrial, natural gas	X_1	MJ	market for heat, district or industrial, natural gas|RER	[88]
Hydrogen from SMR hydrogen production	1.22E+01	m^3	SMR hydrogen production	Table A.20
transport, pipeline, long distance, natural gas	X_2·5.00E+01	kg·km	market for transport, pipeline, long distance, natural gas|RER	[88]
Inputs - removed				
natural gas, high pressure transport, pipeline, long distance, natural gas				
Outputs - added				
Transport of hydrogen gas from SMR to fuelling station, high pressure	1.00E+00	m^3H_2		
Outputs - removed				
natural gas, high pressure				
heat, district or industrial, natural gas				[88]
transport, pipeline, long distance, natural gas				[88]

Table A.22: Fuelling station for hydrogen produced by SMR.

Flow	Amount	Unit	Provider	Ref.
Inputs				
Compressor				
aluminium, cast alloy	4.23E-05	kg	market for aluminium, cast alloy| GLO	[48]
cast iron	4.23E-04	kg	market for cast iron|GLO	[48]
steel, chromium steel 18/8	1.34E-03	kg	market for steel, chromium steel 18/8|GLO	[48]
copper	3.17E-05	kg	market for copper|GLO	[48]
electricity, medium voltage	8.00E+00	kWh	market for electricity, medium voltage|SE	[48]
electricity, medium voltage	7.05E-04	kWh	market for electricity, medium voltage|SE	[48]
ethylene glycol	4.94E-06	kg	market for ethylene glycol| GLO	[48]
heat, district or industrial, other than natural gas	2.54E-03	MJ	heat, from municipal waste incineration to generic market for heat, district or industrial, other than natural gas|SE	[48]
lubricating oil	1.27E-05	kg	market for lubricating oil|RER	[48]
reinforcing steel	1.75E-03	kg	market for reinforcing steel|GLO	[48]
transport, freight, lorry 16-32 metric ton, EURO4	3.62E-04	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RER	[48]
tube insulation, elastomere	1.06E-05	kg	market for tube insulation, elastomere|GLO	[48]
Hydrogen gas				
Transport of hydrogen gas from SMR to fuelling station, high pressure	1.11E+01			Table A.21
Maintenance				
cast iron	2.54E-02	kg	market for cast iron|GLO	[48]
electricity, medium voltage	4.23E-02	kWh	market for electricity, medium voltage|SE	[48]
ethylene glycol	2.96E-04	kg	market for ethylene glycol|GLO	[48]
heat, district or industrial, other than natural gas	1.52E-01	MJ	heat, from municipal waste incineration to generic market for heat, district or industrial, other than natural gas|SE	[48]
lubricating oil	7.62E-04	kg	market for lubricating oil|RER	[48]
reinforcing steel	5.50E-02	kg	market for reinforcing steel|GLO	[48]
steel, chromium steel 18/8	3.69E-02	kg	market for steel, chromium steel 18/8|GLO	[48]
transport, freight, lorry 16-32 metric ton, EURO4	2.20E-01	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RER	[48]
Other components				
nitrogen, liquid	1.01E-04	kg	market for nitrogen, liquid|RER	[48]
reinforcing steel	1.16E-03	kg	market for reinforcing steel|GLO	[48]
polypropylene, granulate	7.05E-06	kg	market for polypropylene, granulate|GLO	[48]
steel, chromium steel 18/8	2.85E-04	kg	market for steel, chromium steel 18/8|GLO	[48]
transport, freight, lorry 16-32 metric ton, EURO4	6.90E-02	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4 |RER	[48]
Storage module				
diesel, burned in building machine	6.04E-04	MJ	market for diesel, burned in building machine|GLO	[48]
electricity, medium voltage	6.77E-04	kWh	market for electricity, medium voltage|SE	[48]
steel, chromium steel 18/8	5.93E-02	kg	market for steel, chromium steel 18/8|GLO	[48]
transport, freight, lorry 16-32 metric ton, EURO4	5.93E-03	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4 |RER	[48]
Walls and foundation				
Concrete, normal	7.05E-06	m^3	market group for concrete, normal|GLO	[48]
Concrete, high exacting requirements	9.17E-05	m^3	market for concrete, high exacting requirements |CH	
diesel, burned in building machine	3.02E-02	MJ	market for diesel, burned in building machine|GLO	[48]
electricity, medium voltage	3.53E-04	kWh	market for electricity, medium voltage|SE	[48]
flat glass, coated	2.29E-03	kg	market for flat glass, coated|RER	[48]
gravel, crushed	1.27E+00	kg	market for gravel, crushed|CH	[48]
gypsum fibreboard	7.05E-05	kg	market for gypsym fibreboard|GLO	[48]
lubricating oil	1.41E-05	kg	market for lubricating oil|RER	[48]
occupation, industrial area	6.44E-03	$m^2 \cdot a$		[48]
reinforcing steel	6,35E-03	kg	market for reinforcing steel|GLO	[48]
silica, sand	4.06E-02	kg	market for silica sand|GLO	[48]
transport, freight, lorry 16-32 metric ton, EURO4	1.56E-01	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4 |RER	[48]
Outputs				
Hydrogen from fuelling station, SMR production	1.00E+00	kgH_2		

A.1.2.2.2 Hydrogen production from wind powered electrolysis

The wind powered production of hydrogen is presented in Table A.23. The transport of hydrogen in pipelines is neglected since it was assumed to be produced in conjunction with the fuelling station. The fuelling station is presented in Table A.24.

Table A.23: The wind powered production of hydrogen.

Flow	Amount	Unit	Provider	Ref.
Inputs				
Electrolyser				
acrylonitrile-butadiene-styrene copolymer	5.64E-05	kg	market for acrylonitrile-butadiene-styrene copolymer|GLO	[48]
aluminium, cast alloy	1.55E-04	kg	market for aluminium, cast alloy|GLO	[48]
cast iron	4.80E-05	kg	market for cast iron|GLO	[48]
copper	5.40E-04	kg	market for copper|GLO	[48]
glass fibre	1.41E-04	kg	market for glass fibre|GLO	[48]
nickel, 99.5%	2.82E-03	kg	market for nickel, 99.5%|GLO	[48]
nickel, 99.5%	7.05E-04	kg	market for nickel, 99.5%|GLO	[48]
nylon 6-6, glass-filled	1.76E-05	kg	market for nylon 6-6, glass-filled|RER	[48]
polyethylene, low density, granulate	1.41E-04	kg	market for polyethylene, low density, granulate|GLO	[48]
reinforcing steel	1.87E-03	kg	market for reinforcing steel|GLO	[48]
steel, chromium steel 18/8	5.99E-03	kg	market for steel, chromium steel 18/8|GLO	[48]
synthetic rubber	1.41E-04	kg	market for synthetic rubber|GLO	[48]
synthetic rubber	3.53E-05	kg	market for synthetic rubber|GLO	[48]
transport, freight, lorry 16-32 metric ton, EURO4	9.91E-04	t·km	market for transport, freight, lorry 16-32 metric ton,EURO4|RER	[48]
tube insulation, elastomere	2.40E-04	kg	market for tube insulation, elastomere|GLO	[48]
Operation				
electricity, high voltage	5.30E+01	kWh	electricity production, wind, 1-3MW turbine, onshore|SE	[48]
tap water	9.97E+00	kg	market group for tap water|tap water|RER	[48]
Outputs				
carbon dioxide, fossil	2.84E+01	kg		[48]
carbon monoxide, fossil	1.36E-02	kg		[48]
dinitrogen monoxide	5.19E-02	kg		[48]
methane, fossil	4.53E-02	kg		[48]
NMVOC	4.82E-03	kg		[48]
Hydrogen from wind powered hydrogen production	1.00E+00	kgH_2		[48]
sulfur dioxide	1.17E-01	kg		[48]

Table A.24: Fuelling station for hydrogen produced by wind powered electrolysis.

Flow	**Amount**	**Unit**	**Provider**	**Ref.**
Inputs				
Compressor				
aluminium, cast alloy	4.23E-05	kg	market for aluminium, cast alloy|GLO	[48]
cast iron	4,23E-04	kg	market for cast iron|GLO	[48]
steel, chromium steel 18/8	1.34E-03	kg	market for steel, chromium steel 18/8|GLO	[48]
copper	3.17E-05	kg	market for copper|GLO	[48]
electricity, high voltage	8.00E+00	kWh	electricity production, wind, 1-3MW turbine, onshore|SE open ground installation, multi-Si|SE	[48]
electricity, medium voltage	7.05E-04	kWh	market for electricity, medium voltage|SE	[48]
ethylene glycol	4.94E-06	kg	market for ethylene glycol|GLO	[48]
heat, district or industrial, other than natural gas	2.54E-03	MJ	heat, from municipal waste incineration to generic market for heat, district or industrial, other than natural gas|SE	[48]
lubricating oil	1.27E-05	kg	market for lubricating oil|RER	[48]
reinforcing steel	1.75E-03	kg	market for reinforcing steel|GLO	[48]
transport, freight, lorry 16-32 metric ton, EURO4	3.62E-04	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RER	[48]
tube insulation, elastomere	1.06E-05	kg	market for tube insulation, elastomere|GLO	[48]
Hydrogen				
Hydrogen from wind powered hydrogen production	1.00E+00	kg		Table A.23
Maintenance				
cast iron	2.54E-02	kg	market for cast iron|GLO	[48]
electricity, medium voltage	4.23E-02	kWh	market for electricity, medium voltage| SE	[48]
ethylene glycol	2.96E-04	kg	market for ethylene glycol|GLO	[48]
heat, district or industrial, other than natural gas	1.52E-01	MJ	heat, from municipal waste incineration to generic market for heat, district or industrial, other than natural gas|SE	[48]
lubricating oil	7.62E-04	kg	market for lubricating oil|RER	[48]
reinforcing steel	5.50E-02	kg	market for reinforcing steel|GLO	[48]
steel, chromium steel 18/8	3.69E-02	kg	market for steel, chromium steel 18/8|GLO	[48]
transport, freight, lorry 16-32 metric ton, EURO4	2.20E-01	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RER	[48]
Other components				
nitrogen, liquid	1.01E-04	kg	market for nitrogen, liquid|RER	[48]
reinforcing steel	1.16E-03	kg	market for reinforcing steel|GLO	[48]
polypropylene, granulate	7.05E-06	kg	market for polypropylene, granulate|GLO	[48]
steel, chromium steel 18/8	2.85E-04	kg	market for steel, chromium steel 18/8|GLO	[48]
transport, freight, lorry 16-32 metric ton, EURO4	6.90E-02	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RER	[48]
Storage module				
diesel, burned in building machine	6.04E-04	MJ	market for diesel, burned in building machine|GLO	[48]
electricity, medium voltage	6.77E-04	kWh	market for electricity, medium voltage|SE	[48]
steel, chromium steel 18/8	5.93E-02	kg	market for steel, chromium steel 18/8|GLO	[48]
transport, freight, lorry 16-32 metric ton, EURO4	5.93E-03	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RER	[48]
Walls and foundation				
Concrete, normal	7.05E-06	m^3	market group for concrete, normal|GLO	[48]
Concrete, high exacting requirements	9.17E-05	m^3	market for concrete, high exacting requirements |CH	
diesel, burned in building machine	3.02E-02	MJ	market for diesel, burned in building machine|GLO	[48]
electricity, medium voltage	3.53E-04	kWh	market for electricity, medium voltage|SE	[48]
flat glass, coated	2.29E-03	kg	market for flat glass, coated|RER	[48]
gravel, crushed	1.27E+00	kg	market for gravel, crushed|CH	[48]
gypsum fibreboard	7.05E-05	kg	market for gypsym fibreboard|GLO	[48]
lubricating oil	1.41E-05	kg	market for lubricating oil|RER	[48]
occupation, industrial area	6.44E-03	$m2 \cdot a$		[48]
reinforcing steel	6.35E-03	kg	market for reinforcing steel|GLO	[48]
silica, sand	4.06E-02	kg	market for silica sand | GLO	[48]
transport, freight, lorry 16-32 metric ton, EURO4	1.56E-01	t·km	market for transport, freight, lorry 16-32 metric ton, EURO4|RER	[48]
Outputs				
Hydrogen from fuelling station, wind powered production	1.00E+00	kgH_2		

A.1.3 EoL phase

Within this section the EoL phases of the BEV and FCEV are presented. The FCEV is modelled more thoroughly since the FCS is assumed to be manually dismantled, which requires further modelling steps.

A.1.3.1 BEV

The EoL for the BEV consists of two separate processes: manual disassembly of BEV and treatment of BE powertrain. The manual disassembly of the BEV is presented in Table A.25 and the treatment of BE powertrain is presented in Table A.26.

A.1.3.1.1 Manual disassembly of BEV

The manual disassembly of the BEV is presented in Table A.25.

Table A.25: BEV manual disassembly EoL-treatment. Modified from an existing dataset in Ecoinvent 3.6 named *manual dismantling of used electric passenger car | Cutoff U, GLO* [88]. Only changed flows are reported and X_3 is a coefficient that cannot be disclosed.

Flow	**Amount**	**Unit**	**Provider**	**Ref.**
Inputs - added				
BEV to EoL-treatment	1.00E+00	Item(s)		
manual treatment facility, waste electric and electronic equipment	X_3·2.29E+03	Item(s)	market for manual treatment facility, waste electric and electronic equipment|GLO	[88]
transport, freight, lorry 16-32 metric ton, EURO4	2.29E+03·1.50E+02	$kg \cdot km$	market for transport, freight, lorry 16-32 metric ton, EURO4|RER	[88]
Inputs - removed				
manual treatment facility, waste electric and electronic equipment				[88]
Outputs - added				
BE powertrain without battery to shredding	2.26E+02	kg	Treatment of used BE powertrain, without battery,shredding|RER	Table A.26
used glider, passenger car	1.66E+03	kg	treatment of used glider, passenger car, shredding|GLO	[88]
used Li-ion battery	2.02E+02	kg	treatment of used Li-ion battery, hydrometallurgical treatment|GLO	[88]
used Li-ion battery	2.02E+02	kg	treatment of used Li-ion battery, pyrometallurgical treatment|GLO	[88]
Outputs - removed				
manual dismantling of used passenger car				[88]

A.1.3.1.2 Treatment of BE powertrain

The treatment of the BE powertrain is presented in Table A.26.

Table A.26: Treatment of used BE powertrain without battery, shredding. Modified from an existing dataset in Ecoinvent 3.6 named *treatment of used glider, passenger car, shredding | Cutoff U, GLO* [88]. Only changed flows are reported.

Flow	Amount	Unit	Provider	Ref.
Inputs - added				
BE powertrain without battery to shredding	1.00E+00	kg		
Inputs - removed				
aluminium scrap, post-consumer				[88]
copper scrap, sorted, pressed				[88]
iron scrap, unsorted				[88]
used glider, passenger car				[88]
Outputs - added				
waste plastic, mixture	1.25E-02	kg	market group for waste plastic, mixture|RER	[88]
Outputs - removed				
waste plastic, mixture				[88]

A.1.3.2 FCEV

The EoL for the FCEV consists of four different processes: manual disassembly of FCEV, treatment of FCE powertrain, treatment of dismantled FCS from vehicle and platinum recovery from FCS. The processes are presented in Tables A.27-A.29.

A.1.3.2.1 Manual disassembly of FCEV

The modelling of the manual disassembly of the vehicle is presented in Table A.27. The abbreviation, W_{FCS}, is defined as the weight of the FCS, which due to confidentiality cannot be disclosed. The modelling of the treatment of the dismantled FCS from vehicle is presented in Appendix B since it contains confidential information.

Table A.27: FCEV manual disassembly EoL-treatment. Modified from an existing dataset in Ecoinvent 3.6 named *manual dismantling of used electric passenger car | Cutoff U, GLO* [88]. Only changed flows are reported and X_3 is a coefficient that cannot be disclosed. W_{MS-100} is defined as the weight of the MS-100 system and W_{FCS}, is defined as the weight of the FCS, which due to confidentiality cannot be disclosed.

Flow	Amount	Unit	Provider	Ref.
Inputs - added				
FCEV to EoL-treatment	1.00E+00	Item(s)		
manual treatment facility, waste electric and electronic equipment	X_3·2.20E+03	Item(s)	market for manual treatment facility, waste electric and electronic equipment|GLO	[88]
manual treatment facility, waste electric and electronic equipment	$X_3 \cdot W_{MS-100}$	Item(s)	market for manual treatment facility, waste electric and electronic equipment|GLO	[88]
transport, freight, lorry 16-32 metric ton, EURO4	2.20E+03·1.50E+02	$kg \cdot km$	market for transport, freight, lorry 16-32 metric ton, EURO4|RER	[88]
Inputs - removed				
manual treatment facility, waste electric and electronic equipment				[88]
Outputs - added				
Dismantled FCS from vehicle	W_{FCS}	kg	Treatment of dismantled FCS from vehicle	Appendix B
FCE powertrain without battery and FCS to shredding	4.45E+02	kg	Treatment of used FC powertrain without battery and FCS, shredding – RER	Table A.28
used glider, passenger car	1.66E+03	kg	treatment of used glider, passenger car, shredding|GLO	[88]
used Ni-metal hydride battery	5.40E+01	kg	treatment of used Ni-metal hydride battery, pyrometallurgical treatment|GLO	[88] [88]
Outputs - removed				
manual dismantling of used passenger car				[88]

A.1.3.2.2 Treatment of FCE powertrain

The treatment of the FCE powertrain is presented in Table A.28.

Table A.28: Treatment of used FCE powertrain without battery and FCS, shredding. Modified from an existing dataset in Ecoinvent 3.6 named *treatment of used glider, passenger car, shredding | Cutoff U, GLO* [88]. Only changed flows are reported.

Flow	Amount	Unit	Provider	Ref.
Inputs - added				
FCE powertrain without battery or FCS to shredding	1.00E+00	kg		
Inputs - removed				
aluminium scrap, post-consumer				[88]
copper scrap, sorted, pressed				[88]
iron scrap, unsorted				[88]
used glider, passenger car				[88]
Outputs - added				
waste plastic, mixture	5.80E-02	kg	market group for waste plastic, mixture|RER	[88]
Outputs - removed				
waste plastic, mixture				[88]

A.1.3.2.2.1 Platinum recovery from FCS

The recovery process of platinum from the FCS is presented in Table A.29. The category denoted as "Avoided w/p" is referring to the option in openLCA called Avoided waste/product.

Table A.29: Platinum recovery from FCS.

Flow	Amount	Unit	Avoided w/p	Provider	Ref.
Inputs					
1-pentanol	6.20E+02	kg		hydroformylation of butene | 1-pentanol|RER	[92]
ammonium chloride	2.66E+01	kg		market for ammonium chloride|GLO	[92]
hydrochloric acid, without water, in 30% solution state	2.84E+02	kg		tetrafluoroethane production | hydrochloric acid, without water,in 30% solution state|GLO	[92]
hydrogen peroxide, without water, in 50% solution state	5.00E+00	kg		hydrogen peroxide production, product in 50% solution state|RER	[92]
phosphorous chloride	3.66E+01	kg		phosphorous chloride production|RER	[92]
Platinum recovery from FCS	1.00E+00	kg		Platinum recovery from FCS	[92]
sodium hydroxide, without water, in 50% solution state	7.40E+01	kg		market for sodium hydroxide, without water, in 50% solution state|GLO	[92]
water, deionised	1.90E+03	kg		water production, deionised|CH	[92]
Outputs					
hazardous waste, for incineration	1.40E+00	kg		treatment of hazardous waste, hazardous waste incineration|CH	[92]
platinum	7.00E-01	kg	x	market for platinum|GLO	[92]
spent solvent mixture	7.37E+02	kg		market for spent solvent mixture|CH	[92]
wastewater, average	1.90E+00	m3		treatment of wastewater, average, capacity 4.7E10l/year|CH	[92]

B

Appendix B - Confidential

This Appendix is excluded in this version of the Master's thesis due to confidentiality and has been reviewed by the Chalmers supervisor.

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
DIVISION OF ENVIRONMENTAL SYSTEMS ANALYSIS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

CHALMERS
UNIVERSITY OF TECHNOLOGY