How good are electric cars?

– An environmental assessment of the electric car in Sweden from a life cycle perspective

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Master's Thesis 2016
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LUNDS UNIVERSITET
Lunds Tekniska Högskola

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June 2016

ISRN LUTFD2/TFEM-- 16/5110--SE + (1-114)

Dokumentutgivare, Dokumentet kan erhållas från
LUNDS TEKNISKA HÖGSKOLA
vid Lunds universitet
Institutionen för teknik och samhälle
Miljö- och energisystem
Box 118
221 00 Lund
Telefon: 046-222 00 00
Telefax: 046-222 86 44

Dokumentnamn
Examensarbete

Utgivningsdatum
Juni 2016

Författare
Josefin Nilsson

Dokumenttitel och undertitel

Hur bra är elbilar? En miljöstudie av elbilen i Sverige ur ett livscykelperspektiv

Sammandrag

I ett samhälle där bilismen ökar blir en mer hållbar bilism allt viktigare. Sverige har satt upp som mål att ha en fossiloberoende fordonsflotta till 2030 och en helt fossilfri fordonsflotta till 2050. För att kunna uppnå detta spelar elbilen en viktig roll. Genom intervjuer med olika aktörer på den svenska marknaden visas i detta examensarbete att en stor tilltro sätts till elbilen, vid sidan av främst biodrivmedel.

Samtidigt råder det delade meningar och i media figurerar olika uppfattningar om hur bra en elbil är, vilket belyser hur större klarhet i frågan krävs. Elbilen utreds i detta examensarbete både genom litteraturstudier och sedan genom en egen analys där även en jämförelse med andra typer av bilar görs, allt ur ett livscykelperspektiv. Studien har ett Sverige-fokus och syftar till att ta reda på hur stora växthusgasutsläpp och hur stor primärenergianvändning en elbil egentligen ger upphov till, från vagga till grav. I processen definieras också de viktigaste faktorerna i elbilens livscykel.

De huvudsakliga resultaten är att en helt eldriven elbil, en BEV, släpper ut ungefär 72 g CO_2-eq/km och en hybrid, en PHEV, släpper ut ungefär 92 g CO_2-eq/km under en hel livscykel när de körs på en nordisk elmix. Bilarnas respektive primärenergiåtgång för hela livscykeln hamnar på runt 1,8 MJ/km (BEV) och 1,9 MJ/km (PHEV). I en känslighetsanalys visas hur dessa resultat kan variera när olika faktorer ändras. De viktigaste faktorerna avseende totala växthusgasutsläpp samt primärenergianvändning är den elmix som används i laddning av bilen samt vilket sätt bilen körs på (för en PHEV).

I en jämförelse med andra typer av bilar visas att elbilen är överlägsen vad gäller energieffektivitet, detta är då en nordisk elmix används i laddningen. Vad gäller växthusgasutsläpp innebär med gjorda antaganden en bil som körs på 100% HVO (till största del baserad på organiska restprodukter) ännu lägre utsläpp än en BEV, följt av en bil som körs på biogas och därefter en PHEV. Resultaten visar dock att en elbil är ett mycket bättre alternativ än bilar som körs på bensin eller diesel samt bilar som körs på blandningar innehållande bensin eller diesel kombinerat med biodrivmedel.

Nyckelord

Livscykelanalys, elbil, BEV, PHEV, växthusgasemissioner, energianvändning, drivmedel, hållbar utveckling

Sidomfång	Språk	ISRN
114	Engelska	ISRN LUTFD2/TFEM-- 16/5110--SE + (1-114)

Organisation, The document can be obtained through LUND UNIVERSITY Department of Technology and Society Environmental and Energy Systems Studies Box 118 SE - 221 00 Lund, Sweden Telephone: int+46 46-222 00 00 Telefax: int+46 46-222 86 44	Type of document Master's thesis Date of issue June 2016 Author Josefin Nilsson

Title and subtitle

How good are electric cars? An environmental assessment of the electric car in Sweden from a life cycle perspective

Abstract

In a society with growing car mobility, sustainable motorism becomes increasingly important. Sweden has set targets of having a fossil fuel independent vehicle fleet by 2030 and a fossil free vehicle fleet by 2050.In order to reach these targets the electric car plays an important role. Through interviews with different actors on the Swedish market, this thesis shows that much confidence is put in the electric car, in addition to primarily the use of biofuels.

At the same time there are conflicting opinions regarding the benefits of the electric car, sometimes reflected in the headlines in media, and clarity on the subject is needed. The electric car is in this thesis studied both through a literature review and a consequent analysis which includes a comparison to cars with internal combustion engines, all from a life cycle perspective. The study is focused on Sweden and aims to determine the magnitude of the greenhouse gas emissions and primary energy use caused by an electric car from cradle to grave. During this process the most important factors in the life cycle of an electric car are also defined.

The main results are that a completely electric car, a battery electric vehicle (BEV), emits around 72 g CO_2-eq/km and a plug-in hybrid electric vehicle (PHEV), emits around 92 g CO_2-eq/km during a complete life cycle when they are driven on a Nordic electricity mix. The cars' primary energy use for the entire life cycle amounts to approximately 1.8 MJ/km (BEV) and 1.9 MJ/km (PHEV). In a sensitivity analysis it is shown how these results differ when certain factors are changed. The most important factors in determining the total greenhouse gas emissions and primary energy use are the electricity mix used in charging the car and the mode of operation (for the PHEV).

In the comparison with internal combustion engine vehicles (ICEVs) it is shown that the electric car is superior when it comes to energy efficiency when a Nordic electricity mix is used. Under the assumptions made, a car driven on 100% HVO (based mostly on organic waste products) will give rise to lower emissions than a BEV, which in turn results in lower emissions than a car driven on biogas and, in turn, the PHEV. However, the results indicate that an electric car is a much better alternative than a car driven on gasoline or diesel as well as a car driven on a blend containing gasoline or diesel combined with biofuels.

Keywords

Life cycle assessment, electric car, BEV, PHEV, greenhouse gas emissions, energy use, fuel, sustainable development

Number of pages	Language	ISRN
114	English	ISRN LUTFD2/TFEM-- 16/5110--SE + (1-114)

Preface

This study is written as a master's thesis for the program Environmental Engineering at the Faculty of Engineering at Lund University. The work has been carried out in collaboration with the division of Environmental and Energy Systems Studies at Lund Institute of Technology and Trivector Traffic AB, Lund. Examiner for the thesis is Professor Lars J Nilsson at the division of Environmental and Energy Systems Studies.

The idea for this thesis originally came from Christer Ljungberg, CEO at Trivector AB and Trivector Traffic AB and Karin Neergaard, senior consultant at Trivector Traffic AB, with whom the outline for the content of the thesis was initially discussed and determined.

Many thanks to my two very supportive supervisors on this project; Pål Börjesson, professor at the division of Environmental and Energy Systems Studies at Lund Institute of Technology, and Karin Neergaard, senior consultant at Trivector Traffic AB, Lund. Many thanks also to Trivector Traffic AB, Lund for the provision of a work space and for welcoming me and taking good care of me.

I would also like to thank all of the interviewees and people that I have spoken to who have helped me gain a better understanding of the role of the electric car in Sweden.

Lastly, many thanks to my friend Anna Schultze for your support and for the time you have spent correcting my use of English in this thesis.

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Glossary

AER – All Electric Range

BEV – Battery Electric Vehicle

CED – non renewable Cumulated Energy Demand

CNG – Compressed Natural Gas

DICI – Direct Injection Compression Ignition

DISI – Direct Injection Spark Ignition

EOL – End Of Life

EV – Electric Vehicle

FAME – Fatty Acid Methyl Ester

FCEV – Fuel Cell (Hydrogen) Electric Vehicle

GHG – Green House Gas

GI-HEV – Grid-Independent Hybrid Electric Vehicle

GREET – Greenhouse gases, Regulated Emissions, and Energy use in Transportation

HEV – Hybrid Electric Vehicle

HVO – Hydrotreated Vegetable Oil

ICE – Internal Combustion Engine

ICEV– Internal Combustion Engine Vehicle

ILUC – Indirect Land Use Change

ISO – International Organization for Standardisation

LCA – Life Cycle Assessment

N/A – Not Availabe

NEDC – New European Driving Cycle

PHEV – Plug-in Hybrid Electric Vehicle

PISI – Port Injection Spark Ignition

REE – Rare Earth Elements

REEV – Range Extended Electric Vehicle

RME – Rapeseed-Oil Methyl Ester

TTW – Tank To Wheels

WTT – Well To Tank

WTW – Well To Wheels

ZEV – Zero Emission Vehicle

1. Introduction

1.1 Short Introduction

Electric cars seem to be a simple solution to an otherwise difficult question: how can we make car mobility more sustainable? An electric car is associated with less noise than cars with internal combustion engines (ICEs), has no tailpipe emissions and has the potential of having a low climate impact if renewable electricity is used for charging. Electric cars are sometimes said to be ZEVs – zero-emission vehicles, but the use of this expression can be controversial.

However, the claim that the electric car is environmentally beneficial is not always strongly supported by existing research. Several studies report different results, and it can be challenging to distinguish what research is of the greatest relevance and what applies to an electric car driven in Sweden. Interpretations of studies by journalists and laypeople in newspapers and on websites can add to this confusion. A selection of recent headlines found in media are:

“If your all-electric car gets its power from coal, new study says it is dirtier than gasoline” (Borenstein, 2014),

“Green cars have a dirty little secret” (Lomborg, 2013),

“Electric Cars: Not So Environmentally Friendly After All?” (Jackson, 2015),

“Electric cars dirtier than diesel in many countries” (Gustafsson, 2014),

“Electric cars could be worse for the environment than gasoline cars” (Söderholm, 2012).

A point often made is that electric cars have a large environmental impact because of the manufacturing process which differs from conventional cars, especially if the car is produced in a country that uses electricity made from fossil fuels. Another reoccurring argument for electric cars not being as good as people might think is that the electricity mix used to drive the car can actually lead to larger environmental impacts than a diesel or gasoline car.

Studies are rarely done using the same assumptions which adds to the confusion, and it seems hard to grasp what the message about electric cars actually is. As can be seen later in this thesis during interviews with actors on the Swedish market (in section *7.1 Interviews*) the electric car was the single type of car always mentioned as one of the most environmentally beneficial cars.

1.2 Objective

The main objective of this thesis is to investigate the environmental impact of an electric car from a life cycle perspective, specifically studying climate effects (greenhouse gas emissions) and primary energy use and to assess the factors that are most important in determining this impact. This is done with consideration to technology available today and in a near future (until approximately 2030), with a focus on Sweden.

Another objective is to evaluate how well the electric car performs in comparison to ICEVs that run on different types of fuel. This is done with consideration to technology available today and in a near future (until approximately 2030), with a focus on Sweden.

A third objective is to investigate how the electric car is perceived by different actors on the Swedish market.

These objectives are reached by answering the following questions:

- How large are the life cycle greenhouse gas emissions and the primary energy use of an electric car?
- Which parameters are most important in determining the environmental impact of an electric car?
- How well does the electric car perform in comparison to ICEVs run on different types of fuel?
- How do actors on the market perceive the electric car?
- What lack of knowledge is there in the science related to electric cars and sustainable car mobility?

1.3 Scope and Delimitations

When assessing the environmental impact of a vehicle, there are many parameters to take into account. To narrow the scope of this thesis, these analyses focus on the emissions of greenhouse gases (GHG) and the primary energy use of the vehicle seen from a full life cycle perspective. A brief discussion of limited resources such as rare earth elements (REE), for example lithium, will also be carried out. Even though some life cycle assessments (LCA) include and analyse the cost aspect, it will not be taken into consideration in this study. Only passenger/light duty vehicles are studied, all other vehicles such as bikes, buses and trucks are excluded.

The study is limited to the vehicles and their production, use and end of life (EOL) phase. Surrounding systems such as road infrastructure and systems for transportation/distribution of electricity and other fuels are not considered. However, in some LCAs it is impossible to distinguish these from other processes, and in these cases they are included. The ways that human habits and societal structures might have to change in a possible transition from internal combustion engine vehicles (ICEVs) to alternatives are not discussed, and neither is the impact of different types of vehicles on human health. Therefore, no policies or ways of implementing more environmentally beneficial options to cars that run on fossil fuels are included in this thesis.

The vehicle industry, and especially the electric car industry, is under fast development and advancements are made very quickly. This requires a focused time scope, and the review will be limited to LCA from 2008 and onwards.

2. Background

2.1 The car in a sustainable society

2.1.1 Car usage and greenhouse gas emissions

It is very difficult to estimate how many passenger cars exist worldwide today, although it is confirmed that the total number of vehicles have surpassed 1 billion. In mid-2014 the total was estimated to 1.2 billion, and it is projected that 2 billion vehicles will be on the road globally by 2035 (Voelcker, 2014). Between 1990 and 2010 the GHG emissions from road traffic within the EU increased by more than 22% (SOU 2013:84).

It can be argued that transport by car is inherently not a very sustainable mode of transport, and that alternative transport options such as public transport and cycling need to increase. However, considering that the number of vehicles in the world only seems to grow, car mobility does need to be made more sustainable.

Cars today are most commonly run on an internal combustion engine that runs on gasoline or diesel, but options that have lower environmental impact include electric vehicles (EVs) or cars that run on biofuels.

A traditional gasoline or diesel car is associated with the following emissions of GHG gases: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and hydrofluorocarbons (HFCs). The first three are emitted from the tailpipe, and the HFCs are used in the refrigerant in the air condition system (US Environmental Protection Agency, 2014).

An entirely electric car has no tailpipe emissions and during its use it is mostly associated with emissions of the greenhouse gas carbon dioxide that arise in electricity production. However, just like for other vehicles hydrofluorocarbons (HFCs) are used in the air condition and this can leak in small amounts (Centre for climate and energy solutions, 2011; US Environmental Protection Agency, 2014).

Different GHGs will contribute differently towards global heating. The term global warming potential (GWP) is often used to describe the warming potential of a GHG in relation to the GHG carbon dioxide. The GWP of carbon dioxide is always 1, and for a 100-year period of time the GWP of for example methane and nitrous oxide are 25 and 298 respectively (IPCC AR4 WG1, 2007). So even if the tailpipe emissions of methane and nitrous oxide from a traditional car can be very low in comparison to carbon dioxide, they are not to be neglected considering their high GWP (US Environmental Protection Agency, 2014).
GHG emissions are often quantified in carbon dioxide equivalents (CO_2-eq), and for gases that are not carbon dioxide this number is obtained by multiplying the quantity of the gas with the GWP (US Environmental Protection Agency, 2014).

2.1.2 Transport and climate impact in Sweden

The transport sector in Sweden used around 93 TWh of energy in 2014, which corresponds to approximately a fourth of the total energy consumption in Sweden. Out of the fuels used, 88% are fossil fuels. Road traffic is responsible for a vast majority of the 93 TWh, (94%; Energimyndigheten, 2015c).
As can be seen in Figure1, the type of transportation that gives rise to the highest emissions of

GHG in Sweden is passenger cars, making this vehicle type the most important in a shift towards a lower climate impact transportation system.

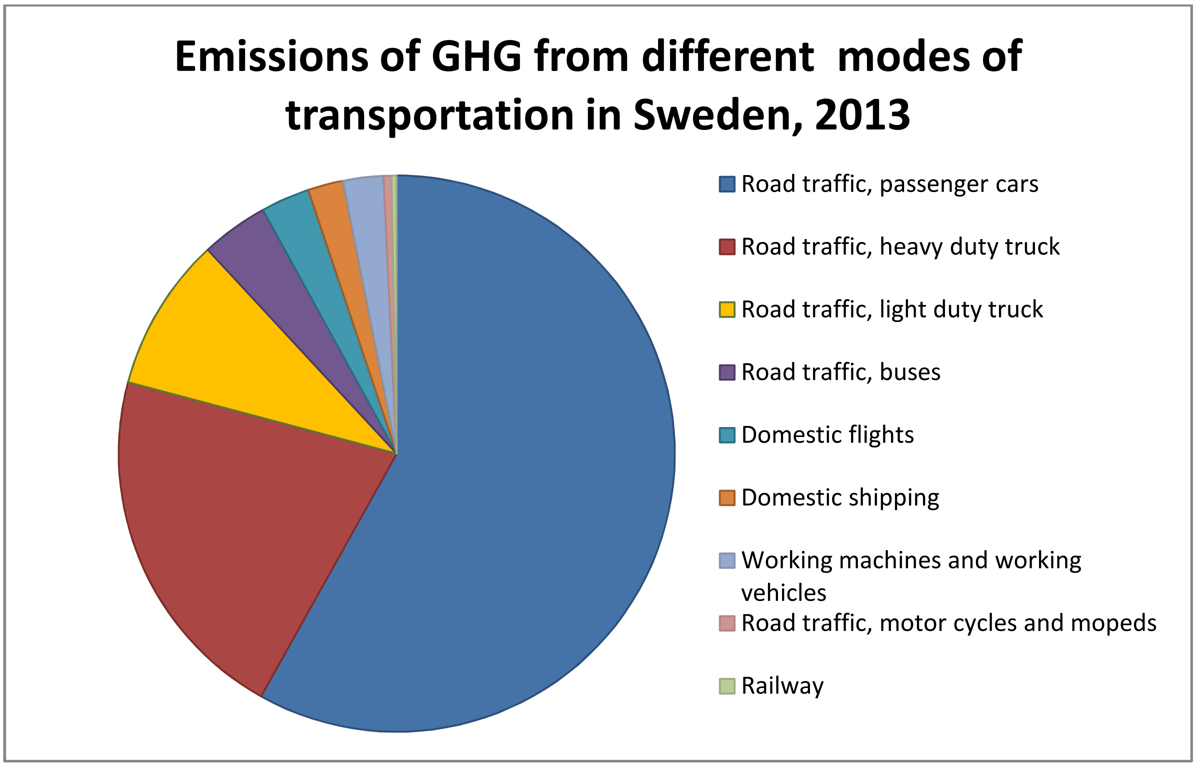

Figure 1. GHG emissions from different types of transportation in Sweden 2013 (Naturvårdsverket, 2015a).

In order to cope with climate change and to make it possible to reach the goal of a maximum of a 2 degree temperature increase, Sweden has set out to have a fossil independent vehicle fleet in 2030 and a fossil fuel free vehicle fleet in 2050. These goals are the most ambitious in the world today (BILSweden and MRF, 2013). Fossil independent vehicles are defined as vehicles that mainly run on biofuels or electricity, and vehicles that can run on a mix with high part of renewable fuel. An example of such a fuel mix is E85 that consists of approximately 85% ethanol and 15% gasoline. All diesel vehicles can theoretically also be classified as belonging to this group (SOU 2013:84).

SOU 2013:84 (2013), also known as [Fossilfrihet på väg], is an extensive public investigation conducted by the Swedish government on the topic of reaching the goal of a fossil free vehicle fleet. However, this investigation only focuses on emissions from the use phase of vehicles and does not describe factors such as vehicle production. SOU 2013:84 (2013) does however state that an analysis from a life cycle perspective is needed as well.

Fuels mentioned as good options to use in the future in SOU 2013:84 (2013) are biofuels and electricity. In a future scenario of passenger car use where Sweden reaches its goal, it is estimated that biofuels will play an important role, representing a major part of the total distance driven in 2040 (60% biofuels, 40% electricity). By 2050, biofuels are depicted to be surpassed by electricity in terms of shares of the total distance driven by passenger cars (60% electricity, 40% biofuels).

2.2 Electric vehicles

There are a range of different versions of EVs, and even though the term ‘electric vehicle’ includes all kinds of vehicles, in this thesis it will most often be used referring to passenger cars.

What differs between different types of cars is most often only the powertrain. The powertrain are the parts of a vehicle that generate mechanical power and deliver it to the surface of the road. Typically, these parts are the ICE or an electrical engine, transmission, drive shaft, differentials and drive wheels (Faria et al., 2012). It is important to note that an EV-battery is usually not counted as part of the powertrain.

2.2.1 Types of electric vehicles

The most common types of electric vehicles are outlined below. This thesis will focus on BEVs and PHEVs that can charge from the grid.

Electric vehicles that charge from the grid

A **Battery Electric Vehicle (BEV)** has an electric engine instead of an ICE, and the powertrain is fully electrified. The engine runs on energy from the battery that is charged from the grid (Hawkins et al., 2012a; Chalmers, 2014).

The **Plug-in Hybrid Electric Vehicle (PHEV)** has an electric motor as well as an ICE, and is sometimes called a ‘power-split hybrid’(Laddaelbilen.se, 2013).The battery in the PHEV can be charged from the electric grid, but can also charge from usage of the ICE and regenerative braking (Hawkins et al., 2012a).The distance that a PHEV can travel using the batteries alone without any assistance from the ICE is called the all electric range (AER) (Nordelöf et al., 2014).

A **Range Extended Electric Vehicle (REEV)**, sometimes also called extended-range electric vehicle (EREV), is a type of PHEV that is connected in series. It often has relatively large batteries and long AER. The REEV differs from a PHEV in the sense that it cannot be propelled by its ICE, instead the ICE is used solely to charge the battery, and propulsion is thus purely electric (Laddaelbilen.se, 2013).

In this thesis REEVs will be labelled PHEVs since there is often no clear distinction between the two in existing LCAs.

Figure 2 shows a simplified schematic view over the powertrains and their main components for different constellations of EVs.

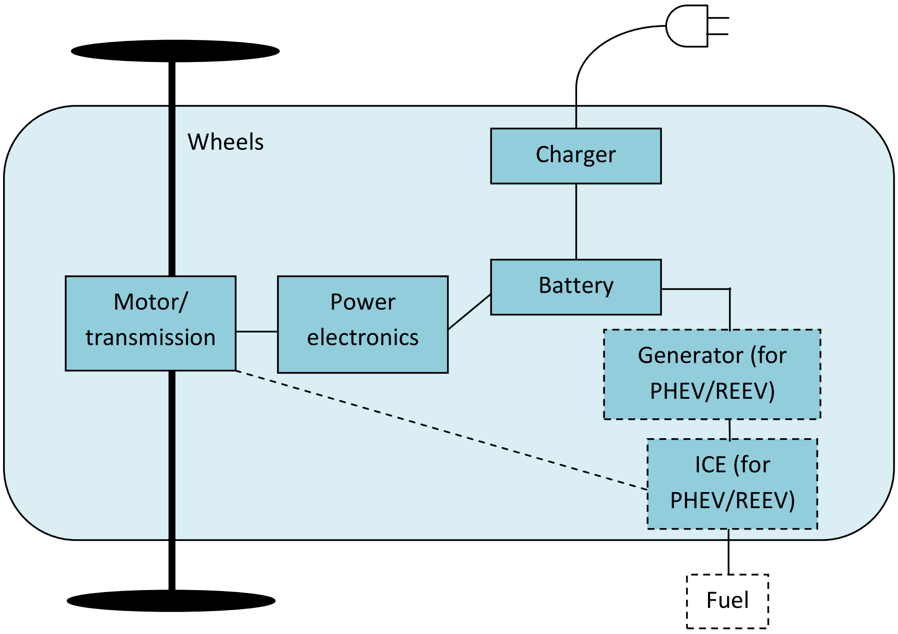

Figure 2. Simplified schematic figure showing the main components for different types of EVs. The generator and the ICE do not exist in a BEV, only in a PHEV or an REEV. The connection between the ICE and the motor (dotted line) only exists in the PHEV, not in the REEV (Edwards et al., 2014a; Del Duce et al., 2013; EVAAP, no date; Laddaelbilen.se, 2013).

Grid-independent electric vehicles

A **Hybrid Electric Vehicle (HEV)** has an electric motor and an ICE, as well as a smaller battery that charges only from the usage of the ICE (Nordelöf et al., 2014; Hawkins et al., 2012a). These vehicles are sometimes referred to as GI-HEV (grid-independent hybrid electric vehicles).

The **Fuel Cell Electric Vehicle (FCEV)** carries hydrogen on board that can be transformed into electricity while driving. The fuel mostly discussed in current research is hydrogen. The vehicle is considered to be electric as the fuel is turned into electricity by fuel cells while driving. The FCEV typically has a small battery as well, making it a type of hybrid. This battery can boost power during accelerations and store energy during regenerative braking amongst other things (Chalmers, 2014).

2.2.2 Batteries

A mature battery technology is the **lead-acid battery (PbA)**, which has been around for 150 years and was used in EVs experimentally during the 1990's. Nowadays it is not considered an option for EVs, except for in micro-hybrid EVs, due to the heavy weight and large volume of the batteries (Chalmers, 2014).

Another type of battery is the **nickel-metal-hydride battery (NiMH)**, which is currently dominating the HEV-market (Chalmers, 2014).

The most common battery technology used in new BEVs and PHEVs is the **lithium-ion battery (Li-ion)** (Chalmers, 2014; Aguirre et al., 2012; Notter et al., 2010). This type of battery has a high energy density, high power density, a long life and low environmental impact compared to many other battery technologies (Lu et al., 2012). Many new EVs today have manganese lithium-ion batteries with blends of nickel, cobalt and manganese, for example popular car models Nissan Leaf, Chevrolet Volt and BMW i3 use these types of batteries (Buchmann, 2016).

2.2.3 Electric vehicle usage

Worldwide

In early 2015 there were more than 740 000 electric cars that can charge from the grid (BEVs, PHEVs and REEVs) on the road worldwide. Most of these are driven in the US, and in early 2015 there was almost 290 000 electric cars in the US vehicle fleet (ZSW, 2015).

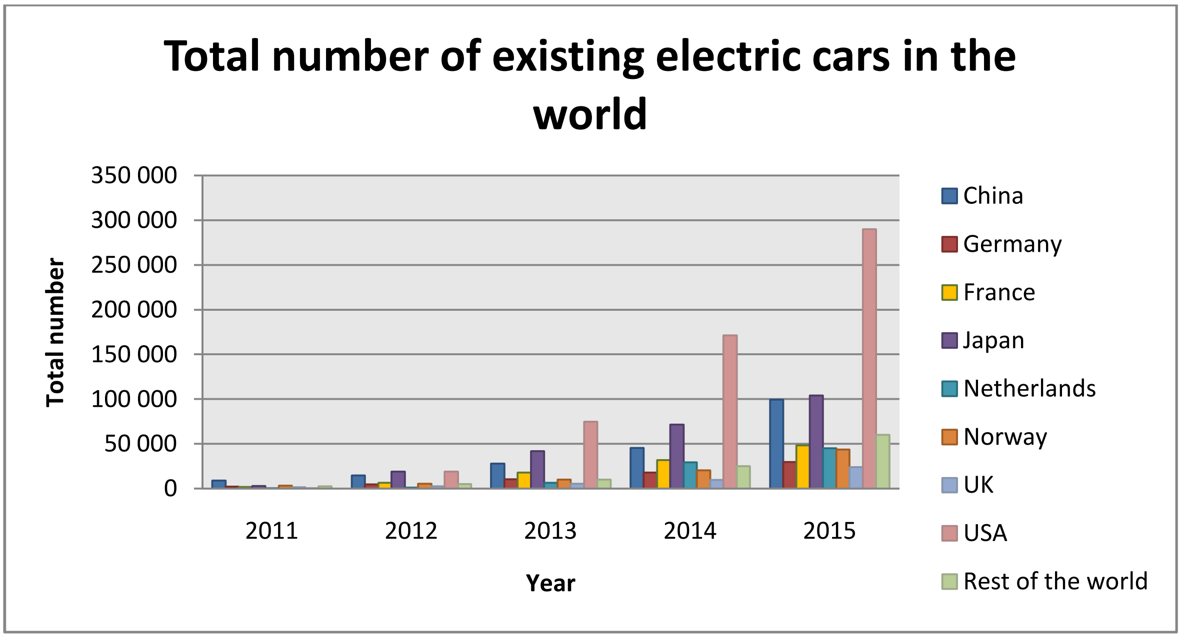

Figure 3. Total number of electric cars that can be charged from the grid, divided by country (ZSW, 2015).

Figure 3 shows the total sales for the most popular models of electric cars worldwide, and some countries with large electric car fleets are listed. As can be seen the number of electric cars are increasing very fast, especially in the US.

In Figure 4 the most common car models are shown, with Nissan Leaf being the market leader (ZSW, 2015). In Europe, the most popular models in 2015 were the Mitsubishi outlander (PHEV) followed by Nissan Leaf (BEV) (Shahan, 2015).

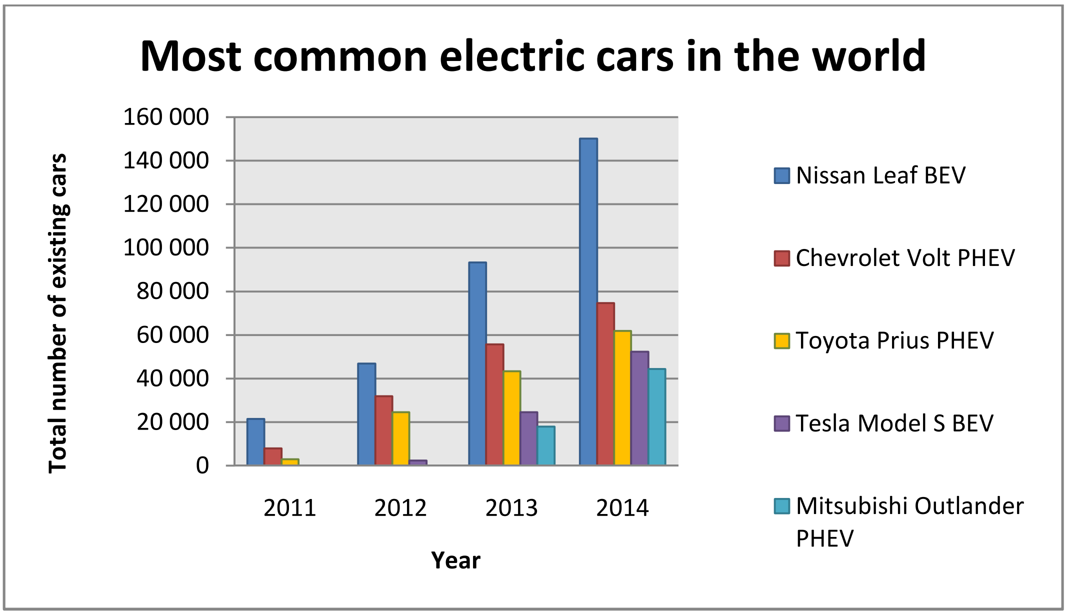

Figure 4. Top 5 electric cars globally, listed by model (ZSW, 2015).

Sweden

The number of electric cars in Sweden is steadily increasing. By the end of 2012 there were 582 passenger car registered BEVs and 654 registered PHEVs, and by the end of 2015 this had increased to a total of 4 756 BEVs (registered as passenger cars) and 9 793 PHEVs (Power Circle, 2016). That corresponds to an increase in the number of vehicles of 8 times for the BEVs and almost 15 times for the PHEVs, during a period of only three years.

It is important to note that even though the absolute number of electric cars is increasing, it remains relatively low when compared to the total number of cars in Sweden. In Figure 5 the total numbers of electric cars are shown, divided into BEVs and PHEVs. The labels over each bar show the share of the Swedish passenger car fleet that both BEVs and PHEVs constitute taken together. Only cars that are in traffic are included in calculations. Even though there is a large increase in the numbers of electric cars, electric cars still only account for 0.31% of the total fleet of passenger cars in 2015 (Power Circle, 2016; Trafikanalys, 2016).

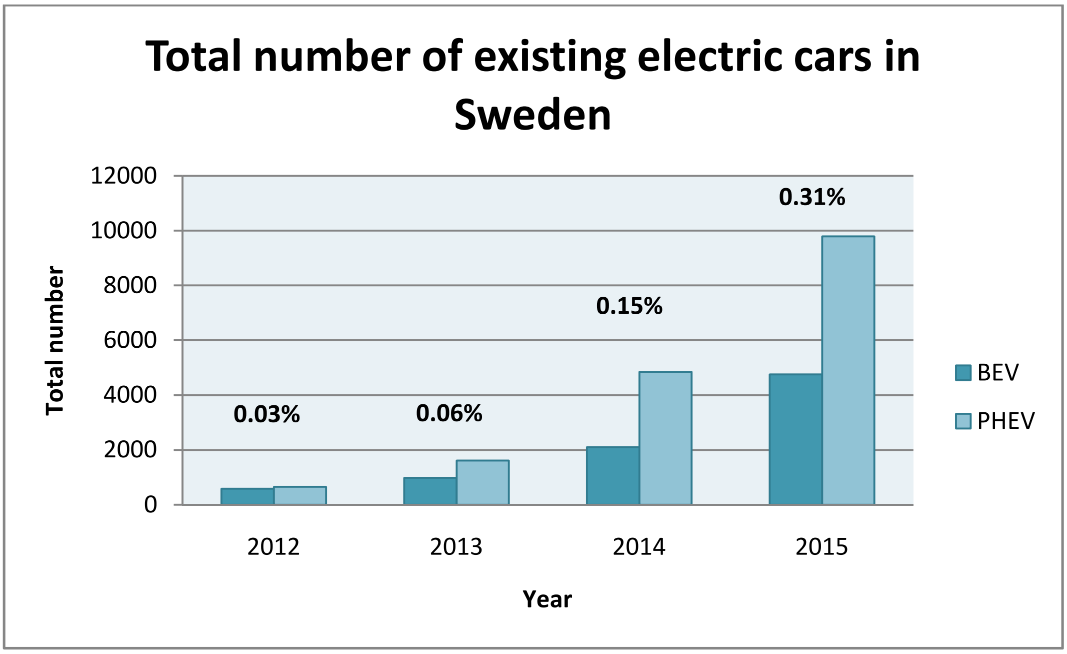

Figure 5. The total number of existing BEVs and PHEVs in Sweden. The percentage above the bars show the share of the total number of passenger cars that electric cars (BEVs and PHEVs) correspond to (Power Circle, 2016; Trafikanalys, 2016).

The most common passenger car BEV model is Nissan Leaf (1 532vehicles registered in early 2016), and the most common PHEV model is Mitsubishi Outlander (5 161 vehicles registered in early 2016). The most popular electric cars in the existing vehicle fleet in Sweden in terms of absolute numbers are shown in Figure 5.

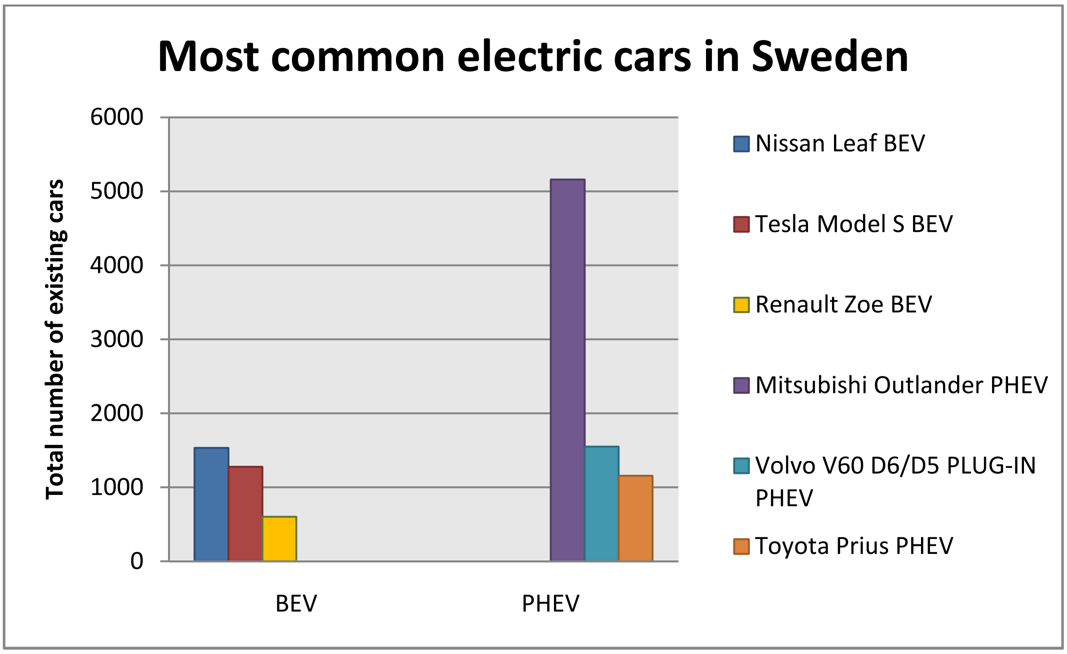

Figure 6. The most common electric car models in Sweden, divided into BEVs and PHEVs (Power Circle, 2016).

2.3 Life cycle assessments (LCA)

An LCA is a tool that allows for systematic evaluation of the environmental aspects of a certain product or service, taking all stages of its life cycle into consideration. How to perform an LCA is described by the International organisation for standardisation (ISO) in their ISO 14040-series (United Nations Environment Programme, 2015).

A complete LCA of a vehicle should include all direct and indirect processes related to both the vehicle and the fuel/electricity, from raw material extraction to the end of life. When data is not available or cannot be accessed, datasets like Greenhouse gases, Regulated Emissions, and Energy use in Transportation (GREET) or EcoInvent can be used to estimate approximate values (Hawkins et al. 2012a).

All stages of the life cycle are not always included in an LCA, and for vehicles it is common to conduct more limited LCAs focusing on the use of the vehicle. The well to wheels (WTW) analysis focuses on the stages of life starting with the production of fuel/electricity used in the vehicle and ending with the energy conversion as the vehicle is being driven. Thus, life stages such as the production and end of life of the vehicle is not studied in a WTW analysis. A WTW analysis in its turn can be divided into two parts: A well to tank (WTT) analysis that focus on the production of fuel/electricity to the storage of the fuel/electricity in tank/battery in the vehicle, and tank to wheels (TTW) analysis that focus on storage in the vehicle to the vehicle being driven.

It is in the TTW phase that tail pipe emissions from cars with ICEs traditionally occur, and for BEVs this phase does not cause any emissions (Nordelöf et al., 2014).

In Figure 7 a simplified view over the different steps of a vehicle LCA are shown, including a description of which steps are included in which types of LCAs. The horizontal boxes show the stages of the WTW life cycle that concerns the fuel or electricity raw material extraction, production, distribution and energy conversion. The vertical boxes show the stages in a vehicle life cycle, with material production (this stage also includes extraction of raw materials), vehicle manufacturing, maintenance required in the use phase, and vehicle EOL including recycling. A complete LCA of a vehicle involves studying all the life stages illustrated in Figure 7 (vehicle life cycle together with the WTW life cycle).

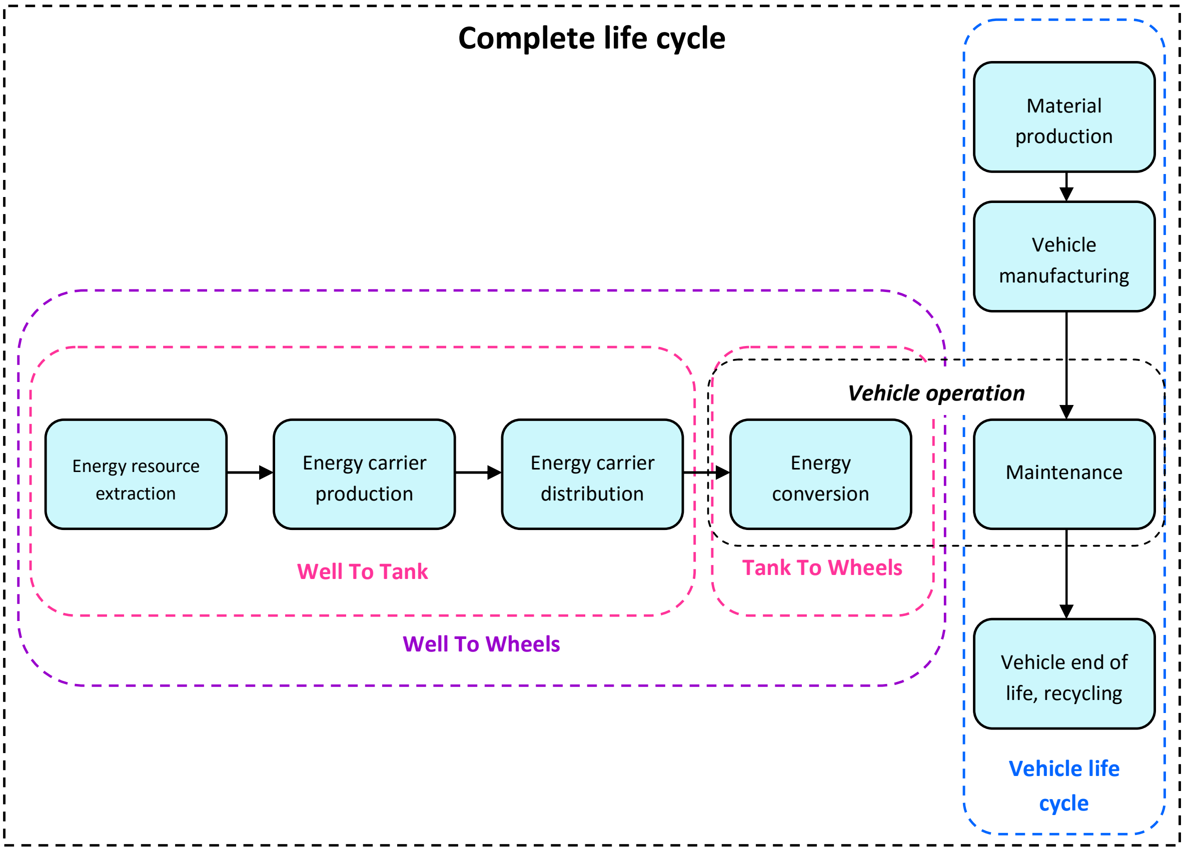

Figure 7. All included processes represent a complete life cycle of a vehicle. The WTW life cycle is circled in purple colour, and the two subdivisions of a WTW life cycle; WTT and TTW are circled in pink. The vehicle life cycle is circled in blue colour. Figure based on Nordelöf et al. (2014).

Both complete LCAs and WTW studies are recurring concepts in this thesis and it is important to highlight the difference between the two. Complete LCAs most often include all of the stages listed in Figure 7 (with some modification) and assess the vehicle from a full life cycle perspective while a WTW analysis focus on the impacts related to the fuel extraction, production and use in combination with the use of the vehicle.

3. Method

The focus of this thesis is passenger cars of compact to mid-range size with five seats. Only electric cars that can be charged from the grid are assessed. Throughout the thesis both complete LCAs and WTW analyses have been used. The primary difference between these two is described in section *2.3 Life cycle assessments (LCA)* and Figure 7.

3.1 Literature review

To produce a high quality literature review and analysis, published LCAs were studied. The selection of LCAs to study closer and include in a compilation (Table 1) was made partly based on the results from two large literature reviews done on LCAs of EVs, Hawkins et al. (2012a) and Nordelöf et al. (2014), and partly based on my own findings either through literature used in other LCAs or by searching the web. Most of the identified LCAs were either old or did not meet the criteria for further description, and these are not included in the study.

When studying the LCAs, a number of different parameters were taken into consideration. First of all, a focus was put on LCAs treating BEVs or PHEVs from a complete life cycle perspective. If several types of cars were included in a study, only compact cars were studied, and not smart cars or larger cars like SUVs. Another requirement was for the LCA to be thorough and transparent with a clear result of either GWP, primary energy consumption or both. Results expressed as values were preferred, but in cases where no other material was available, graphs with approximate values were used.
Only LCAs done from 2008 and onwards have been included in order to provide a recent and up-to-date summary of the evidence.

The studies included in Table 1 all represent a complete life cycle and describe their methods and results relatively clearly. A few other LCAs and studies are mentioned throughout the thesis, and although these might be very well conducted they may not represent a complete life cycle.

Whenever the large European Commission WTW study by Edwards et al. (2014a) or any of the appendices are referenced,[1] the 2010 scenario (not the 2020+ scenario) has been used, unless this is clearly stated.

3.2 Analysis and functional unit

To assess the electric car and produce an analysis a complete life cycle approach with some simplifications has been used, the details are outlined in section *5.1 Background and method*. In order to thoroughly analyse the electric car a base case scenario was set. Parameters used in the base case scenario were consequently varied in a sensitivity analysis, to produce a best and worst case scenario.
These scenarios were based on a compact car with five seats. For a BEV the car is similar to a Nissan Leaf model 2013, and for the PHEV it is similar to a Chevrolet Volt of model 2011-2012. The cars were assumed to be driven in Sweden.

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[1] The studies that are used in this thesis and constitute part of the European Commission JRC (Joint Research Centre) WTW study are Edwards et al. (2014a), Edwards et al. (2014b), Edwards et al. (2014c), Edwards et al. (2014d) and Huss et al. (2013).

In the sensitivity analysis it is determined how different parameters influence the final result, considering the technology that is available today.

When comparing the results from different LCAs and conducting an analysis it is important to have a functional unit that represents the function of a car well. In this thesis the functional unit is set to be the propulsion of a five seat passenger car one km, as transportation is the main purpose of a car. The location for where the car is driven is set to Sweden, but it is also varied in the sensitivity analysis.

In the base case scenario in the analysis of the electric car, a lifetime of 200 000 km was used. More details regarding lifetimes and variations of the lifetime considered is provided in *5.2.2 Sensitivity analysis*.

This functional unit works well for both a complete LCA and a WTW assessment for EVs and ICEVS.

Comparison between EVs and ICEVs

Many of the LCAs of EVs include a comparison with other types of vehicles; most commonly an ICEV, but these results were not studied in this thesis. Instead, a few larger studies that are considered more reliable have been used (Edwards et al. (2014) and Energimyndigheten (2015b)), in the hope of achieving a more accurate comparison group.

Both of these are WTW studies, and in order to be able to compare different types of cars with the results from the analysis of the electric car, a complete life cycle was created for all types of cars. The methodology used for this is further described in section *6.1 Background and method.*

3.4 Interviews

Two different types of interviews have been conducted in this thesis. The first type of interview aims to investigate the opinions and expectations held by people that are involved in or have professional links to the car industry or sustainability and transport in Sweden. These interviews can be found in summarised versions in Appendix *11.3 Interviews*, and are analysed in section *7.1 Interviews*.

The second type of interview is done with experts in a certain field and aims to clarify aspects of electric car mobility and possible future scenarios. Some information from these interviews are included in the thesis, although in some instances the sole purpose of the interview is to increase the author's understanding of the subject.

The selection of interviewees for the first type of interview was a strategic selection based partly on advice from supervisors or advice from other interviewees, and partly on my own judgement. The selection was made so that a wide variety of people from different backgrounds are represented. If the company/institution has an employee specialised in environmental issues this person was preferably selected for the interview.

No interviews have been conducted in English, meaning that everything included in this thesis has been translated and processed.

4. Literature review

4.1 Background and method

There are quite a lot of studies of EVs that somehow investigate electric cars from a life cycle perspective, even if only parts of the life cycle are considered. Two studies that have gathered information and done extensive literature reviews of existing LCAs and studies related to EVs have been particularly helpful when writing this thesis. These reviews were conducted by Hawkins et al. (2012a) and Nordelöf et al. (2014), with the latter stating that they “intend to complement the work of Hawkins et al. (2012)” (Nordelöf et al., 2014, p.1868). Hawkins et al. (2012a) has evaluated 55 studies related to EVs, the majority of which were conducted between 2000 and 2010. As the authors state, the use of results from relatively ‘outdated’ studies can be problematic considering the fast development of new battery techniques (Hawkins et al., 2012a). A discussion of this issue is provided in *4.1 Background and method* and *Timeline for LCAs related to EVs.*

Nordelöf et al. (2014) extend their review to include a total of 79 LCAs. The primary criterion for a study to be included was that it should include an electric vehicle assessed from a life cycle analysis perspective. “To the authors’ best knowledge and access, all peer reviewed papers found in established scientific journals are included” (Nordelöf et al., 2014 p.1868).

Life cycle delimitations and functional unit

How different LCAs choose to treat different parts of the life cycle can be problematic. If cars are only studied from a WTW perspective, electric cars can appear to have a very low climate impact (depending on the electricity mix used). However, it has been shown that battery manufacturing can be a major contributor the environmental impact, and removing this factor from the assessment could be misleading (Faria et al., 2013). On the other hand, it has also been shown that for electricity produced using fossil fuels, the WTW stage will be the dominating life cycle stage in emitting GHG (Nordelöf et al., 2014).

Of the 79 studies that Nordelöf et al. (2014) assessed, 24 are WTW studies, 39 are full LCA, and 14 are EV battery LCA. It is mentioned in Nordelöf et al. (2014) that Notter et al. (2010) and Samaras and Meisterling (2008) are among the most frequently cited studies, and these two studies have also been consulted frequently in this thesis.

In addition to looking at different parts of the life cycle, different studies use different methods and parameters to come to a conclusion regarding emissions and energy efficiency. In many cases it is not evident what assumptions have been made. The use of different parameters or parameter values can cause very different results. A more detailed explanation of how different parameters can affect the results is included in section *4.8 Important parameters*.

In most studies regarding EVs from a life cycle perspective the functional unit is one kilometre or one mile to propel a vehicle; this is especially common in WTW studies. In complete LCAs the most common functional unit used is one vehicle life. The vehicle lifetime is most commonly expressed as a distance in kilometres or miles (sometimes years instead), even though the length of life varies (Nordelöf et al., 2014).

Environmental impacts studied

Of the 73 studies included in Nordelöf et al. (2014) that focus on passenger cars and batteries, a majority have studied GHG emissions and global warming (Figure 8). All types of LCAs study GHG, but it seems to be more common to study energy use in battery LCAs. A WTW analysis was also found more likely to include the energy use than a complete LCA. The category marked 'Energy' is described as 'some type of cumulative energy demand' (Nordelöf et al., 2014, pp. 5) and is most likely referring to primary energy use in the majority of included studies.

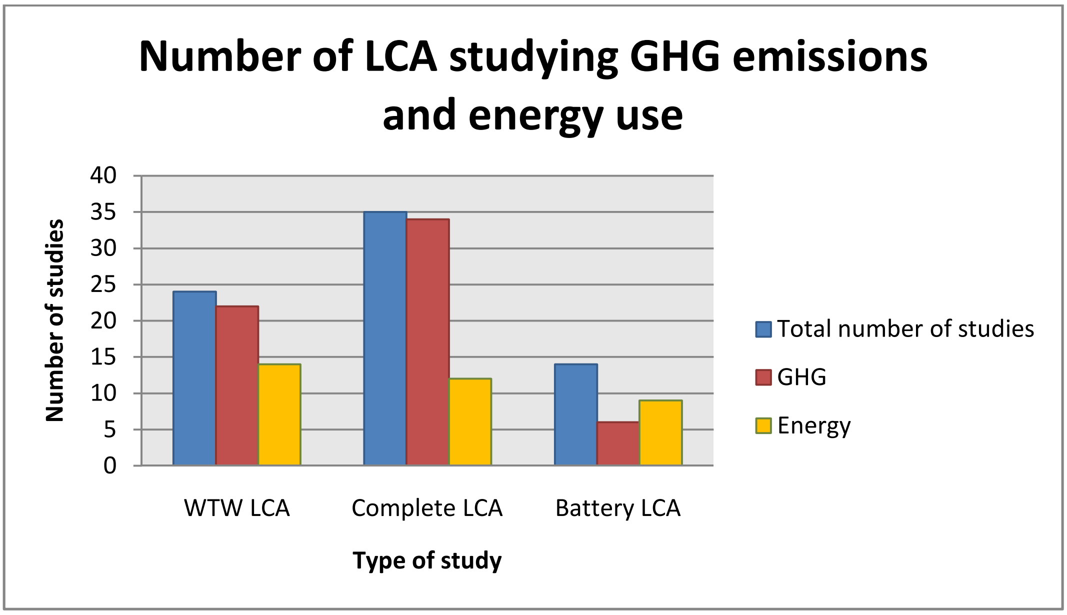

Figure 8. The total number of LCAs studying energy use and GHG emissions between 1998 and early 2013, divided into type of study (Nordelöf et al., 2014).

A focus is put on GHG and energy use as these are the categories considered in this thesis. Other environmental impacts are also studied in LCAs, but not as frequently as GHG emissions and energy use.

Types of EVs studied

In general, more LCAs are done on BEVs and PHEVs than GI-HEVs (Nordelöf et al., 2014). This contradicts Hawkins et al. (2012b) where most studies were done on GI-HEVs, followed by PHEVs and then BEVs. This is probably due to the fact that newer studies tend to focus more on vehicles with a higher degree of electrification. In many LCAs the specific car model studied is not mentioned, but the size and sometimes weight of the car is normally defined.

In the LCAs considered here the BEV Nissan Leaf has commonly been studied, and often data has been based on Nissan Leaf or cars similar to a Nissan Leaf. This could be due to the time frame of the LCAs studied and the fact that Nissan Leaf has been an obvious EV market leader worldwide in recent years (Figure 4) (ZSW, 2015). As stated in one LCA, Nissan Leaf was chosen as it is the first and only mass-produced EV in the world (Gao and Winfield, 2012). To use this car model as a base could be said to be both representative and well-founded, but the risk is that the diversity and variation that exist in other car models are lost, and that the environmental standard of a BEV is judged with too much emphasis put on just one model. Other BEVs mentioned with model name in LCAs have not been found.

For PHEVs specific car models studied in the literature include the Toyota Prius Plug-In and Chevrolet Volt. This could also be explained by the fact that these two car models are the second and third most common EVs worldwide (Figure 4) (ZSW, 2015).

Classification of the vehicles sometimes differs between studies. What is said to be a PHEV in one study could be categorised as a REEV in another. For example, this is the case when the Chevrolet Volt is studied. In Faria et al. (2013) the Chevrolet Volt is referred to as a PHEV, while it is classified as a REEV in Gao and Winfield (2012). In other studies cars are referred to as a PHEV but have several different lengths of range defined, for example in Samaras and Meisterling (2008).

Timeline for LCAs related to EVs

Fast evolving techniques can be problematic when trying to accurately assess electric cars. For example, Hawkins et al. (2012a) has included studies that date back to the 1990s. The same issue occurs in many recent LCAs: even if the study is relatively new, the assumptions and data used are often based on older studies. Although this can be problematic it is an issue that is difficult to overcome without making assumptions about the future, which increases the uncertainty in an analysis.

In the review done by Nordelöf et al. (2014) focus was put on the time scope of studies done on EVs. One of the conclusions from this review is that a majority of LCAs on EVs either do not specify the time scope or focus on previous and existing technology.

Nordelöf et al. (2014) included studies done between 1998 and early 2013, and Figure 9 shows the number of studies divided by year of publication. LCAs of larger vehicles such as buses have been excluded in the figure and only LCAs of light duty or passenger vehicles and battery LCAs are shown. Studies done in early 2013 are not shown in the figure, as this would visually make it seem like there is a drop in the number of studies that year.

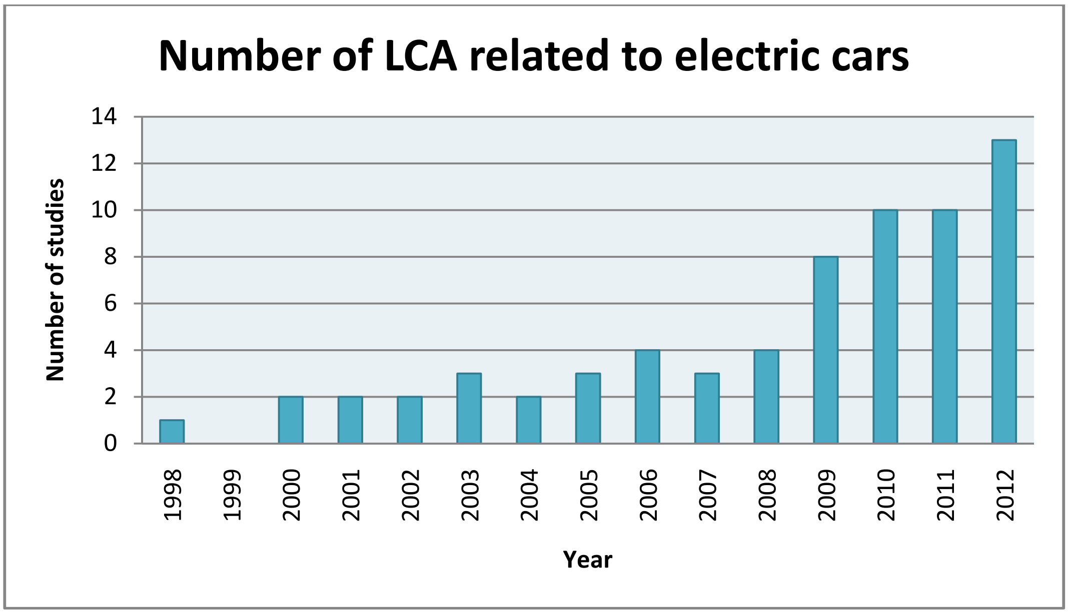

Figure 9. Number of LCAs related to EVs divided by year of publication (Nordelöf et al., 2014).

One of the conclusions that can be drawn from this is that the number of LCAs related to EVs are increasing over time, as indicated by numbers from Nordelöf et al. (2014) and shown in Figure 9. In this thesis an attempt to supplement the work of Nordelöf et al. (2014) in order to continue the timeline showing number of studies related to EVs up until 2015 was made. However, as the exact methods used in Nordelöf et al. (2014) were not described, the findings could not be replicated. The author's judgement is that there are an increasing number of studies, with newer studies tending to focus more on the batteries of electric vehicles. This is partially confirmed in Nordelöf et al. (2014) as many of the newer studies treat only the batteries of EVs.

4.2 An overview of published LCA results on EVs

An aim of this thesis was to determine the size of the environmental impact an electric car produces throughout its life cycle. This would be an easier task if LCAs did not use a number of different variables that all need to be taken into consideration. An attempt to compare the findings from different LCAs has been made in this chapter, in order to estimate the magnitude of GHG emissions and primary energy consumption associated with an electric car. Even though many LCAs study GHG emissions and energy use from a life cycle perspective it is difficult to obtain exact values on the results. Sometimes an LCA study has supporting information attached to provide more detailed information, but in most cases studies are not that transparent.

As mentioned earlier, Notter et al. (2010) and Samaras and Meisterling (2008) are among the most frequently cited studies in existing literature, and these two studies have also been consulted frequently in this thesis. They were found to be two of the most thorough and transparent studies available, and both provide supporting information on details, which is otherwise hard to find among LCAs.

4.2.1 GHG emissions and energy use in a complete life cycle

In Table 1 the results from a number of studies are shown. If a study has a base case, this and not results from sensitivity analyses is shown. If the study does not have a base case, usually one scenario could be considered to be somewhat mid-range and was selected. In some cases results for different scenarios are shown with a short description of each scenario. Parameters and scenarios included are kept brief, to allow for a simpler overview.

The results depend on how the analysis has been performed, and for this reason some of the most important parameters have also been listed in Table 1. These parameters have been selected based on identification of the most important parameters in different LCAs. Some of the main drivers of environmental impacts are the weight of the car, battery production, battery performance and the electricity mix used to charge the battery (Frischknecht and Fury, 2011). How the studies included in Table 1 have been selected is further described in section *3.1 Literature review*.

Not all parameters are described. For example, how PHEVs are treated in terms of the extent to which they run on the electric vs. the internal combustion engine or if the vehicles are tested with or without auxiliary load is not described in detail. Car size is considered in terms of vehicle weight, but the actual size of the cars may vary.

Most studies that account for GWP present this result in g CO_2-eq/km, and it is presented in this way throughout this thesis as well. The results were shown as g CO_2 instead of g CO_2-equivalents in just one study (Table 1). Primary energy use is often shown per kilometre driven, and is shown in MJ/km here. In general it is more common to study GHG emissions than energy use, which is why there is more data on GHG emissions than energy use in the table. It was also slightly easier to find good quality studies on BEVs than PHEVs.

In some cases calculations have been made to convert parameters or results from different studies into the same units. All PHEVs have an ICE that runs on gasoline, and the batteries used in all cars are lithium-ion batteries. When information is left out in the table it was left out or not clearly presented in the original study.

Conclusions that can be drawn from the results in Table 1 are that the GHG emissions and energy use vary largely between studies. For a BEV, life cycle emissions range between 80 and 231 g CO_2-eq/km, and for a PHEV they range between 80 and 245 g CO_2-eq/km. In general, a PHEV emits more GHG than a BEV, this becomes clearer when looking at studies that have studied both BEVs and PHEVs. The life cycle energy use for a BEV ranges from 2.9-4.5 MJ/km and for a PHEV from 2.2-3 MJ/km. No apparent conclusions can be drawn from these results, but it is possible that BEVs have a slightly higher energy use than PHEVs throughout a complete life cycle.

Frischknecht and Flury (2011) has performed a small comparison of 6 different LCA on BEVs, and conclude that the emissions vary between 95 and 240 g CO_2-eq/km. This is very similar to the findings presented here. Reasons that could explain the discrepancies include differences in the electricity mix used for charging and differences in lithium-ion batteries (Frischknecht and Flury, 2011).

Another comparison between EVs has been made in Freire and Marques (2012). Freire and Marques (2012) conclude that there is a wide range of results when it comes to life cycle GHG emissions, and state that in some cases these differences stem from the number of batteries used during a vehicle lifetime.

In the following section, important parameters will be studied and reasons for the variation are discussed.

Table 1. Compilation of parameters and results on GHG emissions and primary energy use on EVs from different studies.

	BEV				PHEV		BEV and PHEV			
LCA	**Aguirre et al.(2012)**	**Ma et al.(2012)**	**Hawkins et al. (2012b)**	**Notter et al. (2010)**	**Samaras and Meisterling(2008)**	**Hearron et al. (2011)**	**Odeh et al. (2013)**	**Gao and Winfield (2012)**	**Helms et al. (2010)**	**Faria et al. (2013)**
Parts of life cycle considered	All	All	All	All	All, but excluding EOL	All	All	All	Probably all	All
Length of life (km)	290 000	180 000	150 000	150 000	240 000	257 000	182 000	256 000	120 000	-
Weight of vehicle (kg)	1575	-	-	1173	-	1715	1561	1528 (BEV), 1437 and 1716 (PHEVs)	1600 (BEV), 1500 (PHEV)	1521 (BEV), 1715 (PHEV)
Number of batteries during life	1.5	-	1	1	1	-	1	>1 (Battery life is 160 000 km)	-	-
Location for battery production	China	-	-	Chile, China, Europe	US	-	UK/ Europe	-	-	-
Battery performance (kWh)	24	-	24	34.2	5.4 - 16.1*	-	44.1	24 (BEV), 4.4 and 16 (PHEV)	25 (BEV), 12.5 (PHEV)	24 (BEV), 16 (PHEV)
Recycling of battery	Yes	-	Yes	Yes	Yes	Yes (66%)	Yes	Most likely	-	Yes
Electricity mix in vehicle use	Californian	UK	European	European	US	US	-	US	German	Portuguese, French and Polish
Drive cycle	-	ECE/EUDC	NEDC	NEDC	US adapted	-	-	-	”70 % urban driving”	"Real world driving profiles"
Life cycle GHG emissions (g CO2-eq/km)										
BEV	110	109 - 148*	197-206*	155	-	-	141	231*	188*	80 (French el. mix) - 210 (Polish el. mix)*
PHEV	-	-	-	-	181-183*	206 g CO2/km*	186	194 and 231*	196*	80 (French el. mix)- 245 Polish el. mix)*
Life cycle energy demands (MJ/km)										
BEV	4.5	-	-	3.0	-	-	-	2.9*	-	-
PHEV	-	-	-	-	2.2-2.3*	2.9	-	2.6 and 3.0*	-	-
Comments		*Average electricity, two scenarios.	*Two different types of batteries.	Infrastructure excluded.	*Three different PHEVs.	*Unit is in g CO2/km.	Infrastructure excluded.	*Values from Freire and Marques (2012). Two different PHEVs.	*Values are appreciated from graph.	*Values are appreciated from graph.

4.2.2 Important parameters and stages of the life cycle

Depending on which parameters that are varied, the electric car can have very different environmental impact. In this chapter different aspects of the EV life cycle will be highlighted and discussed, and the different approaches and results for separate life stages seen in LCAs will be presented.

Which factors that are identified as important will depend on the key assumptions made in each specific study. Nonetheless, there are a number of similarities between many studies, which allows for some conclusions to be drawn. The operational phase or use phase of the vehicle life cycle is often said to be responsible for most of the environmental impact (for example Messagie et al., 2010; Notter et al., 2010).

The two major parameters considered for the use phase in LCAs are the electricity mix used to charge the vehicle and the drive patterns. Most studies seem to agree on the fact that the electricity mix used for charging the car will have a major impact on the environmental performance in the form of GHG emissions of the car. Nordelöf et al. (2014) report that 87% of studies that describe this issue have confirmed that the electricity mix is a key factor. For studies including mode of operation, 100% of the studies identify this as being a key factor (Nordelöf et al., 2014). This could indicate that drive patterns are of an even larger importance than the electricity mix, although this is not necessarily the case.

The use phase is of great importance both for BEVs and PHEVs, although it has a larger impact for a PHEV where the degree of battery use versus combustion engine use has an impact on the environmental performance. The battery production has a larger impact in a BEV than in a PHEV, and the opposite can be true for the vehicle body production including the powertrain (for example Faria et al., 2013; Notter et al., 2010; Samaras and Meisterling, 2008; Odeh et al., 2013).This is probably due to the fact that a PHEV has a smaller battery, and an ICE in the powertrain which marginally adds to the impact of the vehicle body production. Some studies will separate the vehicle glider production from the powertrain and the battery, but in this thesis the term ’vehicle body production’ will refer to the production of glider and powertrain, excluding the batteries.

The importance of different stages of the vehicle life cycle depends on a number of different parameters, including assumptions regarding the manufacturing processes and raw material extraction, mode of operation, the electricity mix used and how the end of life phase is treated. According to results in LCAs the three most important phases are identified as the vehicle body production, battery production and the use phase. Their contribution towards life cycle GHG emissions and energy use can be seen in Table 2, which shows the results from five different studies.[2]

As can be seen in Table 2 there is a variation in the contribution from different life stages, and there is also a variation within single studies. In Samaras and Meisterling (2008), this is due to the use of three different PHEVs with different AER (30, 60 and 90 km).

In Faria et al. (2013) the climate impact resulting from different stages of the life cycle are

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[2] Some of the results are approximate values read from graphs.

different depending on which electricity mix is used during the operational phase. When a low carbon intense electricity mix like the French is used, the use phase impact are kept relatively low while the production of the vehicle body and the battery constitutes a larger share of the climate impact. When a French electricity mix is used, the battery production can be as much as 45% of the GWP of a BEV (Faria et al., 2013).The opposite is true for a high carbon intense electricity mix like the Polish, which explains the low parameter values for the production and high parameter values for the use phase in Faria et al. (2013) in Table 2.

The reason percentages do not add up to 100% in many cases in Table 2 is that the original study included steps such as maintenance, recycling and EOL which had little impact on the full life cycle. These have been excluded in Table 2 and in order to create easily comparable results.

Table 2. Share of total life cycle GHG emissions and energy use expressed in percentages for different stages of life according to a number of studies. The percentages don't always add up because other minor life cycle steps might have been included in the original LCA.

	BEV				**PHEV**		
LCA	**Faria et al. (2013)**	**Aguirre et al. (2012)**	**Notter et al.(2010)**	**Gao and Winfield, (2012)**	**Faria et al. (2013)**	**Gao and Winfield(2012)**	**Samaras and Meisterling (2008)**
Life length (km)	**≈200 000[3]**	**290 000**	**150 000**	**256 000**	**≈200 000[4]**	**256 000**	**240 000**
GHG							
Vehicle body production	12-30%	≈5%	22%	≈11%	13-38 %	≈10%	≈19%
Battery production	20-45%	24%	8%	≈11%	10-30%	≈10%	2-5%
Use phase	20-70%	69%	65%	78%	25-75%	80%	≈76-79%
Energy							
Vehicle body production	N/A	≈5%	20%	≈10%	N/A	≈10%	N/A
Battery production	N/A	19%	7%	≈10%	N/A	≈10%	2-6%
Use phase	N/A	74%	68%	80%	N/A	80%	N/A

*The electricity mix used in charging of the vehicles in each of the studies can be found in Table 1.

The assumed life length in each study will also have a large influence on the distribution of environmental impact. With a relatively low vehicle life length the impact from vehicle body and battery production should become more important in relation to the vehicle use phase. However, when studying the relation between life lengths and impact (Table 2), this correlation was not evident. Assumptions regarding production methods, electricity mix and other factors made in the different studies are probably of greater importance.

The importance of the different life stages in a few studies are illustrated in more detail in Figure 10 and Figure 11. Where percentages varied in the original study, the mean values are shown. Life stages with little impact on the full life cycle such as maintenance, recycling and EOL have been compiled into a category called 'other'.

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[3] No life length accounted for, but an assumption of 200 000 km seems reasonable. More information can be found in *4.2.2 Important parameters and stages of the life cycle* and *Life length of an electric car.*

[4] No life length accounted for, but an assumption of 200 000 km seems reasonable. More information can be found in *4.2.2 Important parameters and stages of the life cycle* and *Life length of an electric car.*

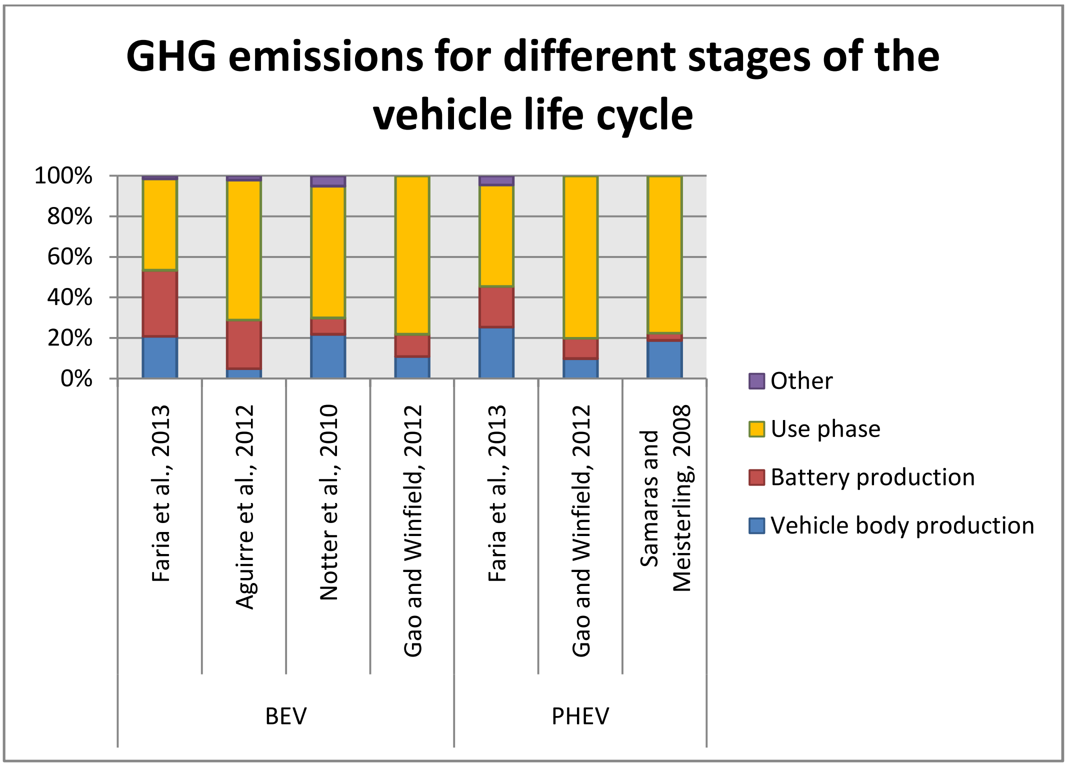

Figure 10. The contribution to life cycle GHG emissions from different stages of life shown for different LCAs. An average is used for studies that present a range of parameter values for a single life stage.

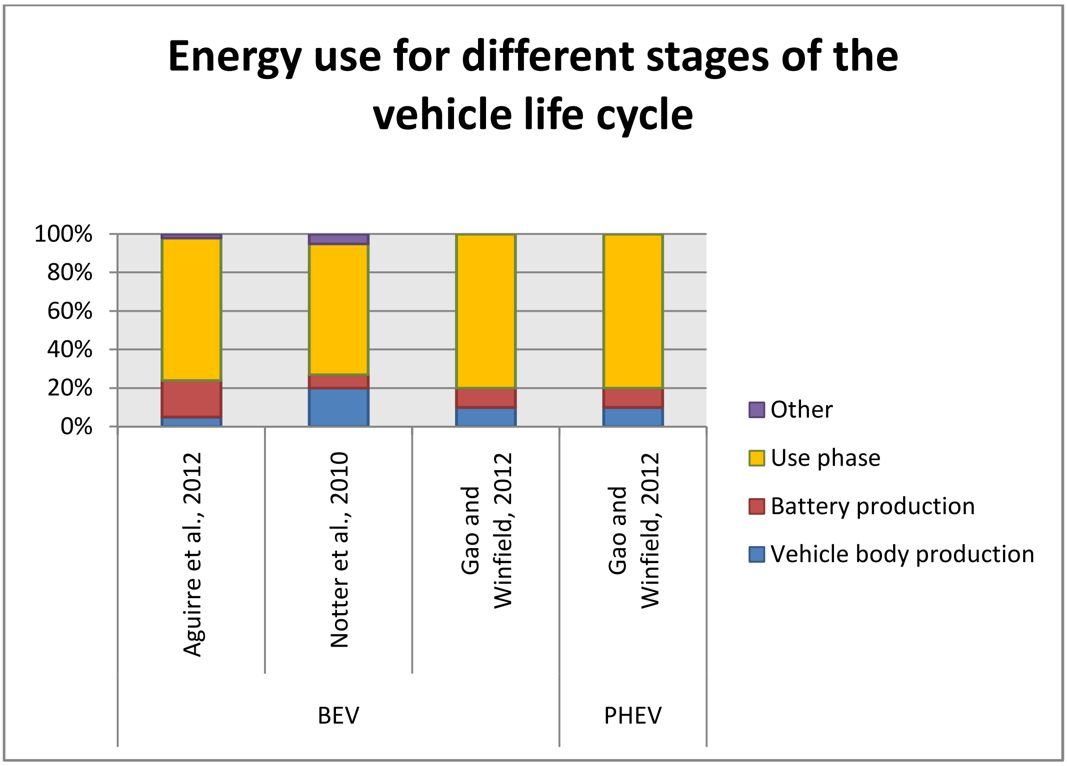

Figure 11. The contribution to life cycle energy use from different stages of life shown for different LCAs. An average is used for studies that present a range of parameter values for a single life stage.

Life length of an electric car

The three most common lengths of life assumed in the studies that Hawkins et al. (2012a) looked at were 150 000 km, 200 000 km and 250 000 km. In Nordelöf et al. (2014) the shortest length of life is 100 000 km and the longest as long as 1 270 000 km, with the most common length of life being somewhere around 200 000 km.

The length of life used for electric cars in most LCAs is relatively low and it is often not discussed, but in some cases life length will be varied in a sensitivity analysis. The reason that many LCA set this relatively low life length is probably due to the low life expectancy of the batteries, or the life expectancy that can be guaranteed by manufacturers. If the vehicle length of life is set to be low, no assumptions about battery replacement need to be done.

Needless to say the life cycle length of a vehicle will be of great importance when determining the environmental impact from that vehicle. A longer vehicle life will spread the environmental impact and energy use from production over a larger number of kilometres and thus reduce the environmental impact per kilometre. An electric car with a relatively high impact in the production phase will benefit even more when the life length is assumed to be longer. Hawkins et al. (2012b) found that increasing the vehicle life from 150 000 km to 250 000 km decreases the life cycle GWP by 40 g CO_2-eq/km.[5]

Of the LCAs presented in Table 1, the life length varies between 120 000 and 290 000 km. Faria et al. (2013) do not state a length of life, but for the cost calculations in their paper they assume a distance of 20 000 km/year, and specify 9-10 years as a lifetime. This seems to indicate that the length of life in the LCA was around 200 000 km, and that has been assumed in this thesis.

Vehicle body production

The term ‘vehicle body production’ in this thesis includes the production of the vehicle glider and the powertrain. To illustrate the possible energy use and GHG emissions linked to vehicle body production, studies that clearly separated vehicle body production were consulted. Notter et al. (2010) base BEV data on a Golf A4. Samaras and Meisterling (2008) use a car similar to Toyota Corolla when studying a PHEV.

In Table 3 parameter values from four different studies are shown. The values are of a similar magnitude both for GHG emissions and energy demands, and the differences that exist could be due to different methods used in production.

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[5] The original result on GHG emission was just above 200 g CO_2-eq/km.

Table 3. GHG emissions and energy use associated with vehicle body production. The parameter values are shown per vehicle and expressed in 10^3 kg CO_2-equivalents and 10^3 MJ.

Vehicle body production	BEV		PHEV	
	GHG (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)	**GHG** (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)
Notter et al. (2010)	5.1	88.4[6]		
Samaras and Meisterling (2008)			8.5	102
Odeh et al. (2013)	5.6*			
Faria et al. (2013)	5*		6*	

*Values have been appreciated from a graph.

Battery production

The lithium-ion battery is the predominant technology on the market, and there is no other technology available today that can compete when it comes to use in large vehicles (Chalmers, 2014). This is why the emphasis has been put on LCAs that discuss this kind of battery. For example, the Huss et al. (2013) analysis that constitutes an important part of the large WTW study ordered by the European Commission makes the assumption that lithium-ion batteries are used for all different types of EVs.

Most LCAs seem to agree that lithium-ion batteries will remain the dominating technology in future electric vehicles. Sometimes older techniques are used in vehicles that require smaller batteries, for example nickel batteries in an HEV (Faria et al., 2012), but these will not be discussed here.

Even though there are different kinds of lithium-ion batteries, they are mostly just referred to as ‘lithium-ion’ in the existing studies. The same will be done throughout this thesis as it is sometimes not possible to distinguish the specific type of lithium-ion battery. In addition, the difference between the different types of lithium-ion batteries is not very large (Hawkins et al., 2012b).To investigate the difference that does exist in lithium-ion batteries; Hawkins et al. (2012b) performed an LCA of BEVs with different lithium-ion batteries. They found that EVs with the two most common types of lithium-ion batteries, LiNCM and $LiFePO_4$ emit 197 and 206 g CO_2-eq/km during a lifetime, respectively. This is a relatively small difference, but it could still be of importance in a country like Sweden where the electricity mix used in charging is low in GHG emissions.

Notter et al. (2010) identifies the GWP of different components of a lithium-ion battery, and points out that the components of the cathode, followed by the battery pack and the anode have the biggest impact on GHG emissions. The material causing the high impact of the cathode is aluminium. The conclusion that the battery has a minor impact on the total GWP of a BEV is explained in part by the fact that the lithium content in a battery is relatively low, typically around 7 g lithium/kg lithium-ion battery. As mentioned previous, the battery is not considered a key factor in some LCAs, but rather the use phase and the electricity mix is pointed out as the most important parameter (Notter et al., 2010).

In older LCAs (from around 2005) it was more common to assume a shorter battery life and to include calculations for one or even two battery replacements during the vehicle lifetime. In

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[6] Numbers for energy use are expressed in CED (non renewable cumulated energy demand) in the original study.

recent LCAs it is mostly assumed that the battery has the same lifetime as the vehicle (Chalmers, 2014). It has been shown that assuming a long vehicle lifetime (of 240 000 km) with one battery replacement still lowers the life cycle GHG emissions for a BEV (Notter et al., 2010). However, it should be noted that Notter et al. (2010) have made assumptions about GHG emissions from battery production that appear relatively low in comparison to other LCAs (Hawkins et al., 2012b). This can also be seen in Table 4.

The energy intensity of the production method used and electricity mix used in the production will have a major impact on the environmental performance of the battery. The country of battery production is often not specified. Countries of production that have been mentioned in some studies are China, Chile, the US and somewhere in Europe (country not defined, but this probably refers to the UK as production is said to be regional). Table 1 contains more detailed information. When studying the average electricity mixes in these countries, the GHG emissions linked to the electricity production is as follows; China: 921 g CO_2-eq/kWh, Latin America: 243 g CO_2-eq/kWh, the US: 658 g CO_2-eq/kWh and the UK: 597 g CO_2-eq/kWh (DEFRA, 2012).[7] These rather diverse, and in some cases very high emissions indicate the importance of production method and production country.

In the production phase an increase in battery size corresponds to an increase in GWP, with the largest battery in a BEV having the largest GWP, followed by a PHEV and then an HEV (Hawkins et al., 2012). This is also illustrated in Samaras and Meisterling (2008) where the environmental impact become larger with larger battery size used in PHEVs. Aguirre et al. (2012) states that the manufacturing of the battery alone is responsible for 19% of the life cycle energy use and 24% of the life cycle GHG emissions for a BEV. Faria et al. (2013) also show high parameter values of GHG emissions for battery production; 20-45% for a BEV and 10-30% for a PHEV. This is contradictory to findings in other LCAs, for example Notter et al. (2010) who found that the battery for a BEV represents 7% of the energy use and 8% of GWP (road infrastructure excluded). Thus, the method of production and electricity use in production is likely to have a great impact on both emissions and energy use. However, it is important to note that a large difference on a percentage scale doesn’t necessarily correspond to a large difference in absolute numbers.

To estimate the possible energy demand and GHG emissions linked to battery production, Notter et al. (2010) and Samaras and Meisterling (2008) are consulted again. Other studies (Faria et al., 2013 and Odeh et al., 2013) show higher parameter values for GHG emissions linked to the production of the battery, even though the energy use linked to battery production is not explicitly stated in these studies. In Table 4 the estimated energy use and GHG emissions linked to battery production from four different studies are shown.

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[7] The emission factors used are the grand total GHG emissions for consumed electricity (generated+losses), and for all countries numbers are based on year 2009.

Table 4.GHG emissions and energy use associated with battery production. The parameter values are shown per battery and expressed in 10^3 kg CO_2-equivalentsand 10^3 MJ. The batteries are a 24 kWh battery for the BEV and a 16 kWh battery for the PHEV, except for Odeh et al. (2013) that use a 44kWh battery for the BEV.

	BEV 24 kWh battery		PHEV 16 kWh battery	
Battery production	**GHG** (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)	**GHG** (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)
Notter et al. (2010)	1.8	31.2[8]		
Samaras and Meisterling (2008)			1.9	27.2
Odeh et al. (2013) (**44 kWh battery**)	6.2*			
Faria et al. (2013)	9*		5*	

* Values have been appreciated from a graph.

This difference in GHG emissions could be due to different manufacturing procedures, and in the case of Odeh et al. (2013) it is most likely also related to the larger battery capacity. The energy density in Notter et al. (2010) is 0.08 kWh/kg battery, while the one used in Samaras and Meisterling (2008) is 0.1 kWh/kg battery. Both assumptions are reasonable, lithium-ion batteries often range between 0.8 and 0.12 kWh/kg battery (Del Duce et al., 2013; Chalmers, 2014).

The location for battery production is probably one of the most important factors when looking at GHG emissions. It is worth mentioning that Odeh et al. (2013) assume a regional production of the battery (UK/European) in order to try to maintain low GHG emissions. This could explain why the estimated emissions from this study are lower than the emissions in Faria et al. (2013) despite the larger battery capacity. Unfortunately the country of production in Faria et al. (2013) is not explicitly stated, and it is difficult to find an explain to why emissions in Faria et al. (2013) appear to be much larger than those in Notter et al. (2010) and Samaras et al. (2008). Dunn et al. (2012) estimate energy and GHG emissions of 75 MJ/kg battery and 5.1 kg CO_2-eq/kg battery. Using these numbers for a 300 kg and a 200 kg battery, end results are close to the estimated values in Notter et al. (2010) and Samaras and Meisterling (2008). Dunn et al. (2012) explain the differences to other studies by differences in approaching material and energy streams.

Steen et al. (2013) studies the GWP of vehicle and battery manufacturing in EVs in a few different LCAs. They explain variations in GHG emissions linked to the production of batteries partly by different assumptions about energy requirements in the production process. Another explanation given for the variation is the use of different solvents and binding agents in the batteries (Steen et al., 2013).

Use Phase

Many LCAs identify the user phase as a very important factor for the environmental impact of an electric car (Table 2) (Notter et al., 2010; Aguirre et al., 2012). Estimates from this phase contain a lot of uncertainty, as this part of the life cycle is highly related to the user and may vary a lot (Helmers et al., 2015). Geographical conditions will be a major factor in deciding how large an environmental impact the EV will have. The electricity mix used in the country of car usage plays a key role, but how the car is used and the climate in which it is driven also has

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[8] Numbers for energy use are expressed in CED (non renewable cumulated energy demand) in the original study.

an effect. If an EV is driven in a city or for long distances on a motorway, this will influence its environmental impact considerably.

Drive cycles, drive patterns & load

User-dependent factors such as drive patterns, load and acceleration patterns are very important factors to consider in an LCA of EVs (Hawkins et al., 2012a). The way in which a vehicle is driven will impact the fuel/electricity consumption and the environmental impact of the vehicle. It has been shown that an electric car has a more sustainable effect in urban areas. The many starts and stops and the low speed benefit the EVs regenerative braking system (Nordelöf et al., 2014; Ma et al., 2012).

EVs have their highest energy consumption when driving on motorway-like conditions (Helms et al., 2010). Estimates of how a BEV and a PHEV perform while driving in urban areas, extra urban areas and on a motorway in terms of electricity consumption can be found in Table 12, section *5.1.1 Life cycle stages*. A BEV has higher electricity consumption when driving in extra urban areas or on a motorway than in urban areas. A PHEV will instead shift and use less electricity on a motorway compared to in an urban environment as the decrease in electricity is compensated by an increase in fuel use (Helms et al., 2010; Raykin et al., 2012).

Several LCAs use what is called the New European Driving Cycle (NEDC). The NEDC is approximately 11 km of driving for almost 20 minutes (DieselNet, 2013), and includes four phases of urban driving and one phase of extra urban driving (TTW, 2013). Figure 12 illustrates the drive patterns, speed and acceleration used in the NEDC.

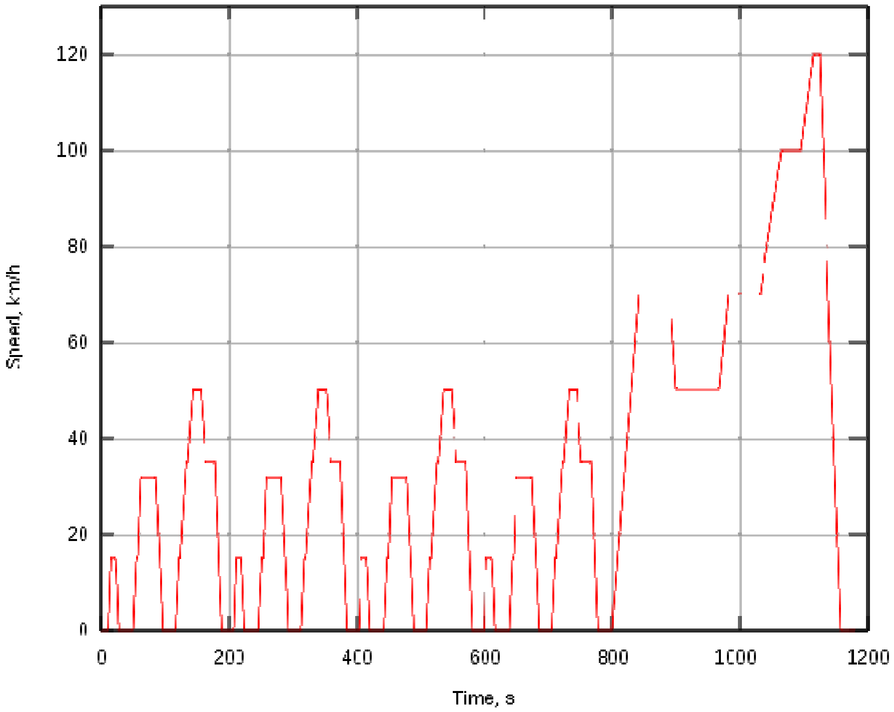

Figure 12. The speed profile for the NEDC (Orzetto, 2006).

There are several reasons to why the NEDC might not be an accurate reflection of how well a vehicle performs in real life. For example, the NEDC does not include any auxiliary load

(Stansfield, 2012) which means that the fuel/electricity consumption might be underestimated. Even when the auxiliary load is added to the NEDC, it has a low electricity consumption compared to average urban, extra urban and motorway driving (Helms et al., 2010).

Out of the 11 studies that were studied in detail (in Table 1), four were conducted using a standardised drive cycle, and in all of these a European drive cycle was used (NEDC in three cases). Four of the studies do not mention how the car is driven. In another three studies, driving is mentioned but the specifics are not stated or clarified. The large European Commission WTW study (Edwards et al., 2014a) uses the NEDC, but adds electrification of auxiliaries (Huss et al., 2013).

Ma et al. (2012) specifies a drive cycle, but vary the components of the drive cycle and study how different driving conditions affect the outcome when it comes to GHG emissions from a mid-size BEV. The two scenarios examined are: 1) Urban driving, only driver and no auxiliary load (use of for example air conditioning, ventilation, fluid pumps etc.) and 2) Extra-urban driving, driver +cargo and auxiliary load. Both scenarios are studied for the two electricity mixes; average UK electricity with GHG emissions of 450 g CO_2-eq/kWh and UK marginal electricity with emissions of 799 g CO_2-eq/kWh.[9] A brief discussion of marginal electricity is found in this section, under *Marginal electricity*.

The results show that the first scenario gives significantly less lifetime GHG emissions for a BEV, 109 g CO_2-eq/km as compared to 148 g CO_2-eq/km (with average grid intensity) and are illustrated in Figure 13. It should be noted that this study was done for a slightly futuristic scenario set in 2015 while the study was written in 2012.

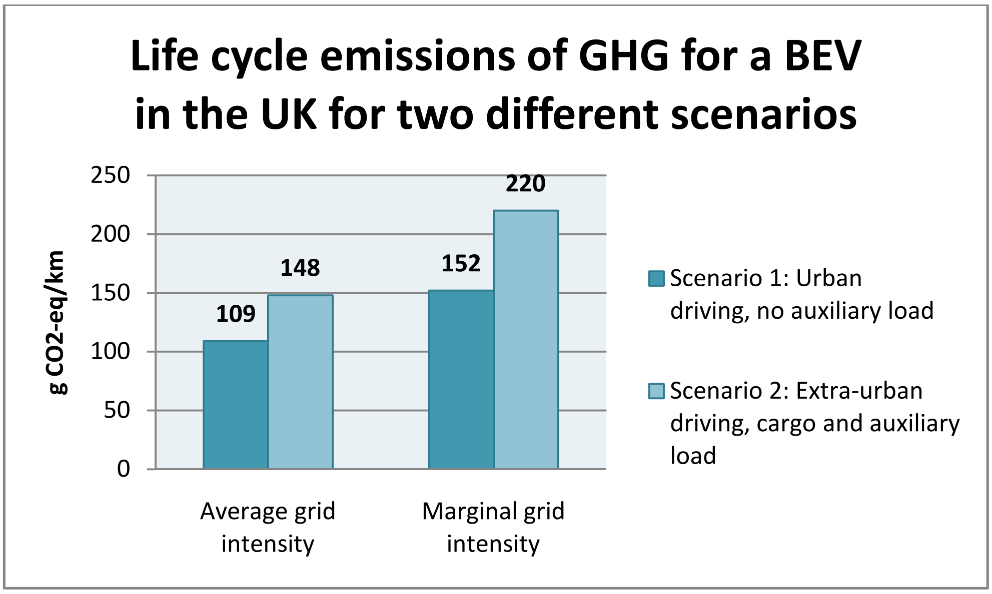

Figure 13. Life cycle emissions of GHG for a BEV in the UK. In scenario 1 the BEV is driven with low speed and load and in scenario 2 it is driven with higher speed and load (Ma et al., 2012).

The importance of drive patterns are highly related to the electricity mix used. If an aggressive drive pattern with sudden acceleration and brakes is applied in combination with the use of

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[9] Originally 125 g CO_2-eq/MJ and 222 g CO_2-eq/MJ.

auxiliaries, this will have a much larger effect on the total GHG emissions in countries with GHG intense electricity mixes (Faria et al., 2013).

In conclusion, the differences in life cycle GHG emissions depend greatly on which drive pattern is used. It should also be noted that standardised drive cycles used to test vehicles are artificial tests and cannot always accurately represent the different circumstances for different geographical areas.

Electricity mix

Nowadays it is relatively common to be able to choose what type of electricity mix you use in your home, which gives the owner of an EV the potential to decide how large the environmental impact due to the electricity used for charging the car will be. Many studies look at different electricity mixes for charging an EV and include this in alternative scenarios. To vary the electricity mix used for charging was very common in the LCAs considered in this thesis, and this variation could be either for country specific electricity mixes or for different electricity production methods.

An example of how electricity mixes are varied is found in Faria et al. (2013) who compare GHG emissions from BEVs and PHEVs when used in three different European countries: Portugal, France and Poland. Another example is found in Nordelöf et al. (2014), who present scenarios on WTW GHG emissions for a BEV, a REEV and a PHEV for different electricity mixes. In Figure 14 below, GHG emissions associated only with the use phase (WTW only) from three different studies are shown. Emissions linked to the production of the vehicle, the production of the battery or EOL are therefore not shown in the figure, which is why some emissions are very low. For example, the BEV run on electricity generated from wind power only emits 1-2 g CO_2-eq/km during the use phase.

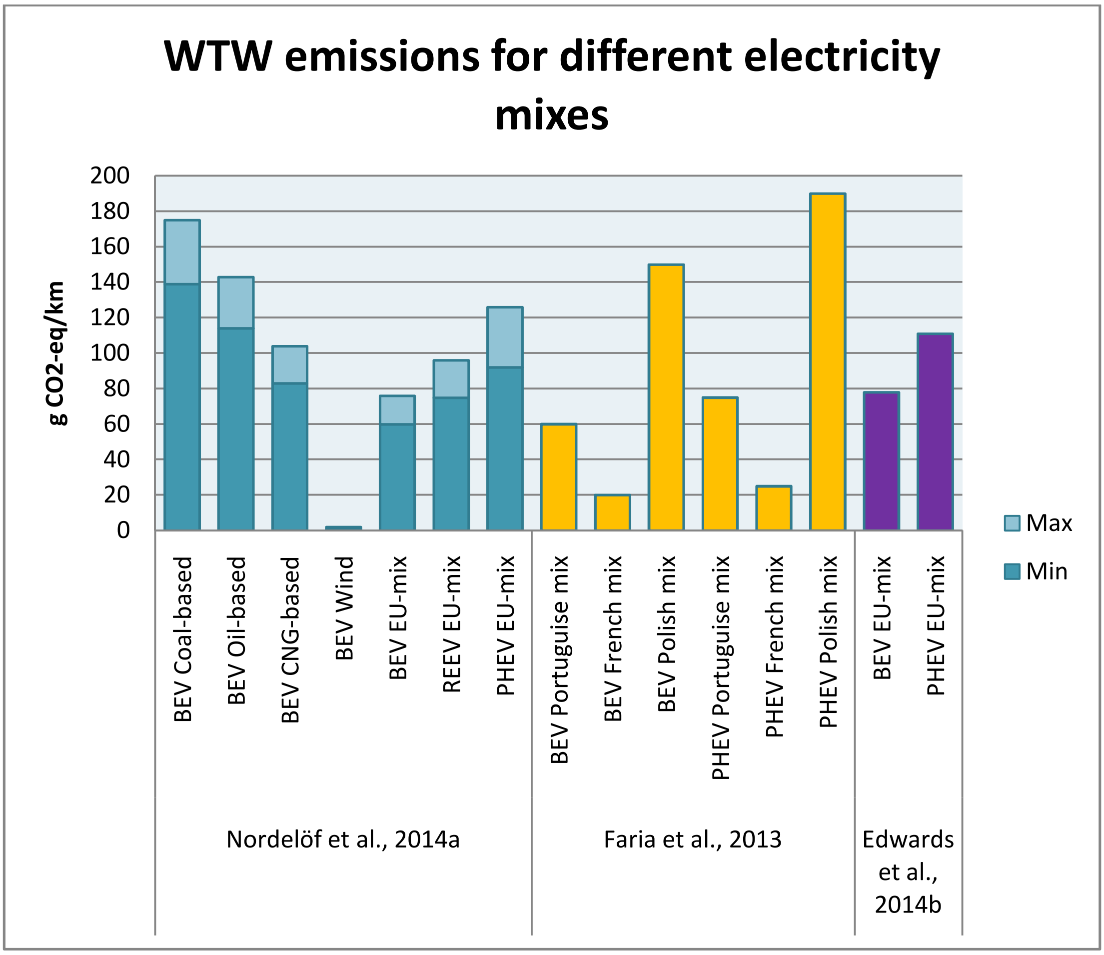

Figure 14. GHG emissions from a WTW perspective using different electricity mixes according to three different studies. Results from Nordelöf et al. (2014) are given both as minimum and maximum values. The results from Faria at al. (2013) are approximate values.

One explanation for the differences between Edwards et al. (2014b) and Nordelöf et al. (2014) even though EU electricity mix is assumed in both could be the different assumptions about electric energy consumption or battery capacity that were made in the two studies. However, the most likely explanation is differences in the assumption of GHG emissions linked to the electricity production. The EU electricity mix used in Edwards et al. (2014b) emits approximately 540 g CO_2-eq /kWh (Edwards et al., 2014c), and the EU electricity mix used in Nordelöf et al. (2014) emits 467 g CO_2-eq/kWh (Nordelöf et al., 2014). The GHG emissions in Nordelöf et al. (2014) are based on an older edition of Edwards et al. (2014c) from 2011. This highlights another aspect of the electric car: the same car can have different environmental impact in different years, even if it is driven in the same region, depending on how the electricity mix changes.

Marginal electricity

Marginal electricity is generally defined as the most expensive electricity produced in a power plant for use at a certain point of time. This electricity is generally associated with high GHG emissions, but this is not always the case.

Out of the studies included in Table 1 only one mentions marginal electricity, Ma et al. (2012). Most studies will assume an average country specific electricity mix, and possibly conduct alternative scenarios where coal intensive electricity is used. The life cycle emissions of GHG from Ma et al. (2012) are shown in Figure 13 for two scenarios. Both scenarios are studied for two UK electricity mixes; one average electricity mix with GHG emissions of 450 g CO_2-eq/kWh and one marginal electricity mix with emissions of 799 g CO_2-eq/kWh.[10]

If the same type of drive pattern is used the difference between life cycle emissions of GHG in scenario one is 43 g CO_2-eq/km and in scenario two it is 72 g CO_2-eq/km (Ma et al., 2012). This is a rather large difference, and it might be worth considering if the electric car is charged with marginal electricity or not. A short discussion on this is included in section *5.1.1 Life cycle stages* and *Use phase.*

Degree of electrification for PHEVs

The extent to which the battery is charged and used in PHEVs will affect the total environmental impact of the car. The assumed percentage battery use for the PHEV varies across studies, and as it is not always described it has not been included in the Table 1. Odeh et al. (2013) has encountered degrees of electrification of 31%, 40%, 47% and 49% in four different studies of PHEVs. However it is somewhat unclear what types of PHEVs all of these numbers refer to. The 47% degree of electrification is referring to Samaras and Meisterling (2008), but this would be for a PHEV with an AER of 30 km, which is relatively low. Samaras and Meisterling (2008) assume a 76% degree of electrification for a PHEV with an AER of 90 km. To what degree the electric motor is used will depend on in what areas the PHEV is driven. Generally, electric drive is more common in urban areas, and using the ICE is more common for country side and motorway driving. Helms et al. (2010) who study a PHEV with a battery capacity of 12.5 kWh and an AER of 50 km state that mixed driving implies 49% electric drive, while driving in urban areas correspond to 74% electric drive.

End of life and recycling

In some LCAs the EOL phase is not included as it is deemed to not have any great influence on the life cycle GHG emissions and energy use (for example Samaras and Meisterling (2008)). Even though Samaras and Meisterling (2008) do not include the EOL, they assume recycling of the battery, implying that this might be of significance.

Aguirre et al. (2012), Bartolozzi et al. (2012), Faria et al. (2013) and Odeh et al. (2013) all assess the influence of different life stages of EVs on GWP (Aguirre et al. (2012) and Bartolozzi et al. (2012) also assess energy use). Only Aguirre et al. (2012) provide exact parameter values on the EOL phase. In the other studies, the impact of the EOL phase is difficult to determine in absolute numbers as the EOL phase is too small to distinguish on a scale in graphs showing life cycle GWP and energy use. These studies show that vehicle and battery disposal only have a marginal influence on life cycle environmental impact, indicating that the vehicle and battery EOL is not of great importance.

For a BEV, which has larger batteries, the EOL phase could be of greater importance than for a PHEV. However results from Faria et al. (2013) who investigate GWP for vehicle disposal and battery disposal for both a BEV and a PHEV found that there was hardly a distinguishable difference. Effects of disposal are marginally larger for a BEV than a PHEV.

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[10] Originally 125 g CO_2-eq/MJ and 222 g CO_2-eq/MJ.

Ma et al. (2012) state that “almost all studies to date conclude or assume that this phase [the EOL phase] makes a small contribution to the whole life cycle” (Ma et al., 2012, p.172). The study where the EOL phase seems to have the largest impact is in Notter et al.;s study of a BEV, (2010) where it is clearly distinguishable. It is worth noting that Notter et al. (2010) present the vehicle disposal and maintenance as one and the same, and maintenance can be assumed to be contributing around 50% to this category (based on findings in Faria et al. (2013) where maintenance and disposal are shown separately).

It has been pointed out in a previous literature study of LCAs on EVs (Nordelöf et al. (2014)) that many LCA assume an EOL phase with efficient recycling, but whether this is the case or not remains to be seen. Most studies assume at least partial recycling of the batteries, and the only conclusion that can be drawn from this is that the EOL for the vehicle in most cases has a very small impact on GHG emissions and energy use, and that the impact of the battery unless recycled is not clearly stated.

Odeh et al. (2013) assume 100% recycling of lithium-ion batteries, but say that no GHG savings are made because of this for their 2010-scenario.They go on to say that GHG savings due to battery recycling will be possible in the future. However, there are large uncertainties as to whether or not recycling does have a high impact on the GHG emissions of an EV from a life cycle perspective. Dunn et al. (2012) who study the recycling of lithium-ion batteries in detail state that recycling could mean that emissions and energy use related to the production of batteries could be reduced if recycled materials are used instead of virgin materials. They estimate that a reduction of as much as 50% in energy use and GHG emissions could be achieved for a lithium manganese oxide battery (Dunn et al., 2012; Dunn et al., 2015).

Even though many LCA assume recycling of the battery, it is not guaranteed that recycling will occur. The batteries in cars that enter the market today are still young and it is not yet possible to say to what extent recycling will be carried out. The EU has set targets that require at least 50% of the weight of a battery to be recycled (Eurostat, 2016). Batteries that contain nickel and cobalt will most likely be recycled at a high rate, but it might not be the case with many batteries in EVs that are sold today according to Christer Forsgren, head of Technology and Environmental Science at Stena Metall (Personal communication, 2015). It is not always economically justified to have a 50% or higher recycling rate, and it will depend on the composition of the battery. Materials like graphite and manganese often used in batteries are not very expensive or rare. In order for these materials to get recycled the product needs to be sold at a higher price to cover the costs of a future recycling (Forsgren, Personal communication, 2015).

In Table 5 the impact from the EOL stage from five different LCAs is shown.

Table 5. EOL including vehicle and battery disposal and recycling, shown per vehicle.

End Of Life	**BEV**		**PHEV**	
	GHG (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)	**GHG** (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)
Notter et al. (2010)[11]	1.1	23.7		
Aguirre et al. (2012)	0.7	15.2		
Faria et al. (2013)	1*		1*	
Samaras and Meisterling (2008)			N/A*	N/A*
Bartolozzi et al. (2012)	N/A*	N/A*		

*Values have been appreciated from a graph. N/A means that the impact was not included or indistinguishable.

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[11] Vehicle disposal and maintenance during the vehicle life are both included in the EOL phase.

5. Life cycle analysis of an electric car in Sweden

5.1 Background and method

In this chapter a BEV and a PHEV will be analysed from a life cycle perspective and GHG emissions and primary energy use linked to different life stages will be examined. Based on knowledge acquired from the literature review presented in the previous chapter a base case scenario is created and some of the uncertain factors are varied and investigated in a sensitivity analysis. Which parameters to vary, and how, is also decided based on findings from the LCAs included in the literature review.

At the end of this chapter (*5.2.3 Best and worst case scenarios*) a best and a worst case scenario are created with regards to length of life, electricity mix, drive patterns, battery recycling and battery replacement.

The parameter values that will be used for obtaining a base case result are labelled "best estimate" in tables, and when a factor is varied in a sensitivity analysis this will be clearly expressed.

Life cycle stages studied

The life cycle of the electric car is divided into different categories to facilitate the identification and variation of key parameters. Stages of the car's life cycle are divided into: vehicle body production (glider and powertrain excluding battery), battery production, use phase and the EOL phase including recycling (shown in Figure 15). The model used to illustrate the vehicle life cycle is a simplified version of the more detailed schematic figure of a complete LCA seen in Figure 7 earlier in the thesis (section *2.3 Life cycle assessments (LCA)*). An emphasis will be put on the battery production and the use phase as these stages are believed to contain the greatest amount of uncertainty and variability. The EOL stage and recycling is only examined in the sensitivity analysis, and in the base case this stage of life is considered to have a marginal impact and is disregarded.

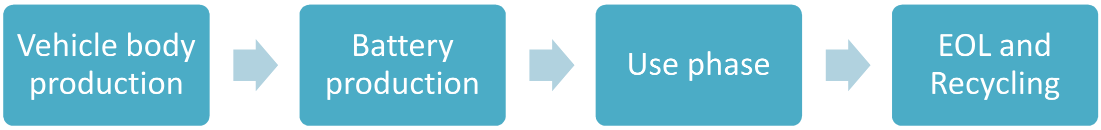

Figure 15. The different life stages of an electric car. All of the four stages are included in the investigated scenarios in this analysis, and efficient recycling of the battery specifically is investigated in an alternative scenario in the sensitivity analysis.

These specific categories are used as they are the ones that are easily distinguishable in LCAs. The extraction of raw materials will in most LCAs be included in the vehicle body production and the battery production. The energy use and emissions linked to extraction and production of electricity or fuel here falls on the use phase, making the use phase a representation of a WTW analysis.

It could be argued that the vehicle body production should be separated into glider and powertrain production, but this is not done in many studies (only in Notter et al. (2010)). The ideal would be to base decisions on a study that transparently accounts for GHG emissions and energy use linked to different stages of the vehicle life for both a BEV and a PHEV.

Unfortunately, no such study was identified. Gao and Winfield (2012) come close, but like many other studies they do not separate production of vehicle from production of battery, and instead show them as one.

In general, many LCAs will only show parameter values for GHG emissions, and not include energy use. To perform this analysis, results from a number of different LCAs will be used in order to create a complete life cycle. There are risks with using this strategy, as different LCAs have used different methods. However, an attempt is made to take this into account by using an average parameter value, assuming a similar GHG intensity of energy used in production and by performing a sensitivity analysis.

Types of electric cars studied

The BEV is assumed to have the energy characteristics of a Nissan Leaf in the use phase, and the same size and weight of battery (24kWh and 300 kg). The PHEV is assumed to have the energy characteristics similar to a Chevrolet Volt, with a battery capacity of 16 kWh and a battery weight of 200 kg. The PHEV should have a range of around 80 km (Faria et al. 2013). These cars are of similar size and well represent cars and battery capacities that are often studied in LCAs.

Life length of an electric car

Based on the life lengths often figuring in LCAs (*4.2.2 Important parameters and stages of the life cycle* and *Life length of an electric car*) the base case life length of a vehicle is set to be 200 000 km in this analysis.

Alternative life lengths, 150 000, 300 000 and 400 000 km are examined in the sensitivity analysis. A life length of 200 000 km can be regarded as relatively low for a car and it is possible that lithium-ion batteries could soon have even longer life lengths, which justifies examining two longer life lengths. As there is a relative fast turn-over in cars, a shorter life length (150 000 km) could also be justified. The 400 000 km life length scenario is examined in combination with a battery replacement as lithium-ion batteries might not last and stay efficient for a life length of 400 000 km.

5.1.1 Life cycle stages

Vehicle body production

Vehicle body production includes production of the glider and the powertrain, and is based on Notter et al. (2010) and Samaras and Meisterling (2008). These two studies clearly show parameter values for energy use and GHG emissions for different stages of the life cycle. The original value from Samaras and Meisterling (2008) for GHG emissions linked to PHEV vehicle body production is changed to better match the GHG intensity of energy used in BEV production in Notter et al. (2010).[12] The BEV data from Notter et al. (2010) is believed to have a GHG intensity of the production process more relevant to Europe (as production is stated to be regional and the study is from the UK) than the PHEV data from Samaras and Meisterling (2008), which is a study conducted in the US. It is also believed to be more representative to use the lower GHG intense scenario in Notter et al. (2010) because this study is more recent

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[12] For calculations please refer to Appendix *11.1.1 PHEV production.*

than Samaras and Meisterling (2008). In Table 6 the energy use and GHG emissions linked to vehicle body production are shown in total numbers per vehicle. Note that the vehicle body for the BEV is slightly different to that of the PHEV, based on findings in studies.

Table 6. Total GHG emissions and energy use linked to vehicle body production shown per vehicle. Best estimate represents the parameter values used in this analysis.

Vehicle body production	BEV		PHEV	
	GHG (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)	**GHG** (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)
Notter et al. (2010)	5.1	88.4[13]		
Samaras and Meisterling (2008)			5.9*	102
Best estimate	**5.1**	**88.4**	**5.9**	**102**

*Value has been changed to match the GHG intensity of energy used in BEV production in Notter et al. (2010).

In the sensitivity analysis the parameter values for vehicle body production will not change as they are similar in other studies (for example Faria et al., 2013; Hawkins et al., 2012a), in addition to the fact that there is not a lot of detailed information on alternative estimates available (Table 3).[14]

Battery production

Lithium-ion batteries are the only battery technology considered, as this is seen as most likely to dominate the market for the near future (Chalmers, 2014).

The estimated values on energy use and emissions from battery production found in the literature review are shown in Table 4. These are diverse, and many LCA do not account for energy use but only GHG emissions linked to battery production.

In order to determine the energy use in battery production, references cited in some LCAs are consulted: Sullivan and Gaines (2012) and Dunn et al. (2012). These studies do not provide information on the electricity requirements for battery production and therefore no calculations for country specific production will be performed in this analysis. It might be of interest to study considering the rather large differences in GHG emissions linked to electricity production in some battery producing countries (more information can be found in *4.2.2 Important parameters and stages of the life cycle* and *Battery production*).

Sullivan and Gaines (2012) present an average energy consumption for battery production of 180 MJ/kg lithium-ion battery. Possible GHG emissions could be similar to those of Faria et al. (2013) as this study bases battery production partially on Sullivan and Gaines (2012). Sullivan and Gaines (2012) include material production, battery manufacturing and assembly and have considered results from several different studies of lithium-ion batteries. Dunn et al. (2012) present parameter values of energy requirements of 75MJ/kg and GHG emissions of 5.1 kg CO_2-eq/kg battery.

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[13] In CED (non renewable cumulated energy demand).

[14] However, in chapter *6. Electric cars in comparison to other types of cars* a small alteration is made to the vehicle body of the PHEV to match the vehicle body of the BEV. These results are presented later in section *6.2 Results.*

The results of using the values from Sullivan and Gaines (2012) and Dunn et al. (2012) on batteries weighing 300 and 200 kg and results from the literature review, battery production energy and GHG emissions are compiled in Table 7. Once again, the original parameter value for GHG emissions linked to PHEV battery production in Samaras and Meisterling (2008) (marked with a star in Table 7) has been changed to better match the GHG intensity of energy used in BEV production in Notter et al. (2010).[15]

Table 7. Total GHG emissions and energy use linked to battery production shown per battery. Best estimate represents the parameter values used in this analysis.

Battery production	**BEV 24kWh battery**		**PHEV 16 kWh battery**	
	GHG (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)	**GHG** (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)
Notter et al. (2010)	1.8	31.2[16]		
Samaras and Meisterling (2008)			1.6*	27.2
Dunn et al. (2012)	1.5	22.5	1.0	15.0
Faria et al. (2013)	9		5	
Sullivan and Gaines (2012)		54.0		36.0
Best estimate	**4.1**	**35.9**	**2.5**	**26.0**

*Value has been changed to match the GHG intensity of energy used in BEV production in Notter et al. (2010).

No alternative scenarios for the method of battery production are examined in the sensitivity analysis. However, battery capacity will drop with the number of charging cycles the batteries go through, and the older they get (for example Faria et al., 2012). Therefore, in one scenario a battery replacement during the vehicle life is examined in combination with a longer life length of 400 000 km. This is done simply by doubling the impact from battery production in the base case scenario.

Use phase

During use, the BEV is presumed to have an average electricity consumption of 18 kWh/100 km[17][18] in this thesis (same as a Nissan Leaf, 2013 model) (US Department of Energy, 2015). The PHEV has an electricity consumption of 16 kWh/100 km and a fuel consumption of 4.5 l/100 km. These numbers are a based on Faria et al. (2013) and Samaras and Meisterling (2008) who both use a PHEV with a battery capacity of 16 kWh. Faria et al. (2013) state that they are using a Chevrolet Volt, Samaras and Meisterling (2008) do not specify a car model, but provide parameter values that makes it possible to do calculations for any size of battery.

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[15] For calculations please refer to Appendix *11.1.1 PHEV production.*

[16] In CED (non renewable cumulated energy demand).

[17] Originally 29 kWh/mile.

[18] Electricity use related to the use phase is most often referred to in kWh instead of MJ which is why kWh is used here.

Table 8. Electricity and gasoline consumption for a BEV and a PHEV. Best estimate represents the parameter values used in this analysis to create a base case scenario.

Use phase	**BEV 24kWh battery**	**PHEV 16 kWh battery**	
	Electricity consumption (kWh/100 km)	**Electricity consumption** (kWh/100 km)	**Gasoline consumption** (l/100 km)
US Department of Energy (2015)	18		
Faria et al. (2013)		14	3.9
Samaras and Meisterling (2008)		18	5
Best estimate	**18**	**16***	**4.5***
Degree of electricity/fuel use	**100 %**	**75 %**	**25 %**

*Mean value of the numbers above.

A PHEV with an AER of 90 km has an electric drive of 76% and a combustion engine drive of 24%, for driving in the US with a US adapted drive cycle in Samaras and Meisterling (2008). Roughly the same parameter values are applied to the PHEV in this analysis as the electric drive is set to be 75% and the ICE drive 25%. Parameter values on the degree of electrification mentioned in the literature review can often be lower (*4.2.2 Important parameters and stages of the life cycle* and *Use Phase)*, but for a newer model of PHEV with a relatively powerful battery a higher degree of electrification is probably justified. Therefore the best estimate is a 75 % degree of electrification, and this will be used in the base case scenario (Table 8 presents an overview).

As discussed in previous chapter during the literature review it has been shown that the electricity mix chosen is one of the most important factors when it comes to deciding the environmental impact of an EV. The electric car is in this thesis assumed to be used in Sweden, with a Nordic electricity mix. The reason as to why a Nordic electricity mix is the best choice for the base case scenario is that Nordic electricity is what is traded on the Swedish market. The EU Renewable Energy Directive, which sets up policies for the production and promotion of energy from renewable sources in Europe (European Commission, 2016) also states that contracted electricity should not be used when calculating GHG performance in relation to renewable fuels (Energimyndigheten, 2015a).

The electricity consumption shown in Table 8 only accounts for the actual energy use by the car, and not the energy use linked to the life cycle of the electricity. Therefore extra calculations are done in order to include all energy use related to electricity production. GHG emissions and primary energy use linked to the use of gasoline in the PHEV are based on fuel properties from Edwards et al. (2014c) and Huss et al. (2013). The fuel cycle is as in the case of electricity considered from a full life cycle perspective and factors such as extraction, production and distribution are taken into account.[19]

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[19] Calculations can be found in Appendix *11.1.2 Emission factors for different fuels* and *Gasoline,* and Appendix *12.1.3 Fuel consumptions* and *Electricity and gasoline consumption of the EVs.*

Table 9. Life cycle GHG emissions and primary energy use linked to Nordic electricity mix and gasoline used in the base case scenario (Naturvårdsverket, 2015c; Gode et al., 2011; Huss et al., 2013; Edwards et al., 2014c).

	Nordic electricity mix	Gasoline
GHG emissions	125 g CO_2-eq/kWh *(34.7 g CO_2-eq/MJ)*	2800 g CO_2-eq/l *(87.2 g CO_2-eq/MJ)*
Primary energy use	1.7 kWh/kWh electricity	38 MJ/l *(1,2 MJ/MJ final fuel)*

The base case scenario estimates on electricity and gasoline consumption are not necessarily representative, and therefore alternatives are explored in the sensitivity analysis. Uncertainty linked to assumptions about the use phase is represented through varying the values, as stated in the following sub-sections; *Electricity mix*, *Drive patterns* and *Use of auxiliaries*.

Electricity mix

In alternative scenarios a high and low voltage European, a low emission Nordic, a Swedish and a renewable (hydropower) electricity mix are examined. Estimated parameter values on electricity mixes vary in different sources, (Table 10), but the emissions and primary energy use from different electricity mixes are set according to the values in Table 11. These values take the entire electricity life cycle into account and include factors like primary fuel extraction and distribution losses.

The estimated values for GHG emissions linked to electricity are in some cases (the first two sources in Table 10) given in g CO_2/kWh and not g CO_2-eq/kWh. The last four sources cited in Table 10 have all considered the entire life cycle of electricity, and in the first two sources it is unclear if a life cycle perspective was used and if distribution losses were included.

Table 10. GHG emissions from different electricity mixes in g CO_2/kWh or g CO_2-eq/kWh according to different sources of literature.

	European high voltage	European low voltage	Nordic	Swedish	Renewable (hydropower)
Svensk Energi, 2010	415		100	20	
Ecotraffic, 2015	450		75-100	20-25	
Martinsson et al., 2012			125-131		
Naturvårdsverket, 2015c			125		
Gode et al., 2011			97	36	6
Edwards et al., 2014c	490	540			

Table 11. GHG emissions and primary energy use electricity linked to electricity production for a few different electricity mixes (Naturvårdsverket, 2015c; Gode et al., 2011; Edwards et al., 2014d).

	Nordic (Base case)	European, high voltage	European, low voltage	Nordic, low emission scenario	Swedish	Renewable (hydropower)
GHG emissions (g CO2-eq/kWh)	125	490	540	97	36	6
Primary energy use (kWh/kWh electricity)	1.7	2.0	2.3	1.7	2.1	1.2

* The parameter values in Table 11 are used to assess the electric car in this thesis. The Nordic electricity mix is used in the base case, and the other five electricity mixes are used in a sensitivity analysis.

Marginal electricity will not be taken into account in this analysis as this might give an unfair disadvantage to the electric car, and it is also not representative of the environmental performance of an electric car. If marginal electricity were to be studied, it would be fair to argue that marginal gasoline and marginal diesel should be given equal focus when assessing conventional cars.

Drive patterns

The influence of drive patterns is difficult to estimate, but it is still interesting to include in some form in a sensitivity analysis. Therefore, information found in Helms et al. (2010) is used to illustrate the energy requirements for driving in different types of environments for BEVs and PHEVs (Table 12). In Helms et al. (2010) a PHEV with AER of 50 km and a battery capacity of 12.5 kWh and a BEV with a battery capacity of 25 kWh are studied for three different drive scenarios. These scenarios are; urban areas (cities), extra urban areas (outside of cities, similar to countryside) and motorway. In Table 12 the base case scenario is also included to allow for comparison.

Table 12. Energy consumption of a BEV with a battery capacity of 25 kWh and a PHEV with a battery capacity of 12.5 kWh for different drive profiles according to Helms et al. (2010). The base case scenario used in this analysis is also presented to allow for comparison.

	Energy consumption BEV				Energy consumption PHEV			
	Base case	**Urban areas**	**Extra urban areas***	**Motorway**	**Base case**	**Urban areas**	**Extra urban areas***	**Motorway**
Electric drive	100%	100%	100%	100%	75%	90%	50%	10%
Electricity consumption (kWh/100km)	18.0	20.4	20.8	24.9	16.0	17.8	10.6	3.3
Fuel consumption (l/100 km)	-	-	-	-	4.5	0.6	2.6	6.0

* The term ‘extra urban areas’ used by Helms et al. (2010) equate to countryside or similar (author’s interpretation).
These parameter values are used in the sensitivity analysis when assessing the impact of different drive patterns.

There is likely not a large difference in battery weight for the differences in battery capacities between 24 and 25 kWh and 12.5 and 16 kWh, and to facilitate the calculations the battery production energy use and GHG emissions for the BEV and PHEV are kept at the same levels in this sensitivity analysis as in the base case scenario. This also applies to the vehicle body production and EOL treatment.

The parameter values on electricity consumption in different environments for the BEV (Table 12) are slightly higher than those in the base case scenario for all three drive conditions. For the PHEV, the electricity consumption is roughly the same while the fuel consumption is a bit lower than in the base case. This difference in electricity and fuel consumption between the base case scenario and the sensitivity analysis illustrate how assumptions about fuel economy and drive patterns can change the outcome of the results, and for the BEV it shows how the use phase might look with a slightly less efficient battery.

One might argue like Helmers et al. (2015) that the electric car, especially the BEV, will mostly be used in urban areas due to its relatively low AER. If this is the case, an urban drive cycle is of greater relevance to study. However, in a future society where the car is used less and less in urban areas, longer travels in extra urban areas and motorway conditions are also of interest.

Use of auxiliaries

In a country like Sweden the use of auxiliaries is of interest as we need to heat up the inside of the vehicle for a large period of the year, and for this purpose parameter values on electricity consumption from Faria et al. (2013) are used. However, this information was only available for a BEV. The estimates on energy consumptions are based on an older Nissan Leaf and might differ a bit to the base case scenario where a Nissan Leaf model 2013 is used. As can be seen in Table 13 the overall electricity consumption is a bit lower than in the base case scenario.

Table 13. Energy consumption of a Nissan Leaf with 24 kWh battery capacity for different drive profiles according to Faria et al. (2013). The base case scenario used in this analysis is also presented to allow for comparison.

	Energy consumption BEV (kWh/100km)		
	Base case	**AC off**	**AC on heat**
Eco	-	10.5	16.7
Normal	18.0	13.1	18.3
Aggressive	-	15.5	21.3

The energy and fuel consumption linked to different drive patterns and use of auxiliaries might not be representative of the battery capacity used in the base case scenario. However, it is still within a probable range and can therefore be useful for illustrative purposes in possible scenarios.

End of life and recycling

Even though literature reviews show a marginal effect of the EOL phase, it might still be of interest to investigate this as it possibly is of higher importance in a country with a low GHG intense electricity mix, like Sweden. Most studies did not present results on energy use or GHG emissions linked to vehicle EOL, rather they would only show a graph where the EOL/disposal phase is hardly distinguishable (for example Bartolozzi et al., 2012; Faria et al., 2013; Odeh et al., 2013).

Estimated values on energy use and GHG emissions for disposal of the entire vehicle for a BEV are found in Notter et al. (2010) and Aguirre et al. (2012). It should be noted that maintenance is also included in the EOL from Notter et al. (2010) and that these values are probably too high to represent only disposal of the vehicle. As stated in the included studies, the battery is often assumed to be recycled. Today this most likely happens with no energy savings or GHG savings (Odeh et al., 2013). The vehicle EOL will include some sort of recycling in most studies, often of both of the vehicle body and the battery. However, it is difficult to understand to what extent this represents recycling as it is not always clearly stated, and it is not evident if energy or GHG savings are made as a consequence of this recycling.

Due to great uncertainty and different indications in LCAs, the estimated value from Aguirre et al. (2012) will be used both for a BEV and a PHEV. This is deemed a good estimate as it is rather low, which could explain why many LCA would simply exclude the EOL and why it is difficult to distinguish in the graphs published in certain studies. Notter et al. (2010) also include maintenance in the EOL phase, and maintenance is believed to correspond to a large portion (around 50%) of GHG emissions when maintenance and vehicle disposal are bundled together (seen in graphs in Faria et al. (2013)).

In Table 14 impact from the EOL phase from five different LCAs are presented, along with the best estimate used to create a base case scenario.

Table 14. Total GHG emissions and energy use linked to EOL including vehicle and battery disposal and recycling.

End Of Life	BEV		PHEV	
	GHG (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)	**GHG** (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)
Notter et al. (2010)	1.1	23.7		
Aguirre et al. (2012)	0.7	15.2		
Faria et al. (2013)	1*		1*	
Samaras and Meisterling (2008)			N/A*	N/A*
Bartolozzi et al. (2012)	N/A*	N/A*		
Best estimate	**0.7**	**15.2**	**0.7**	**15.2**

*Values have been appreciated from graphs. N/A means that the impact was not distinguishable in graphs.

As discussed in *4.2.2 Important parameters and stages of the life cycle* and *End of life and recycling*, assuming an efficient recycling of batteries does not necessarily equal savings in energy or emissions of GHG (Odeh et al. 2013). Therefore it is assumed that even though the parameter value on EOL in the base case might include some form of battery recycling, a separate scenario with efficient battery recycling that results in energy and GHG savings is appropriate to include in the sensitivity analysis.

Recycling of aluminium, copper and lithium manganese oxide in particular could mean energy and GHG savings of up to 50% in the production of a new EV battery as compared to using virgin materials (Dunn et al. 2012). In the sensitivity analysis, the assumption of 50% savings in energy use and GHG emissions through the use of recycled material for the production of a new battery is investigated, (Table 15). This scenario might be optimistic and should be viewed as a best case scenario in terms of battery recycling, illustrating potential maximum savings.

Table 15. Total GHG emissions and energy use linked to battery production with efficient recycling shown per battery used in the sensitivity analysis.

Battery production	BEV		PHEV	
	GHG (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)	**GHG** (10^3 kg CO_2-eq)	**Energy** (10^3 MJ)
Efficient recycling	2.1	18.0	1.3	13.0

*The original parameter values on battery production are twice as high as in Table 15 (found in Table 7), and have here been reduced by 50% due to the efficient battery recycling.

5.2 Results

An outline of the scenarios that were examined in the base case and sensitivity analysis is provided in Table 16.

Table 16. Summary of the different parameters used in the base case scenario and the sensitivity analysis.

	Base case	Sensitivity analysis
Vehicle life length	200 000 km	•150 000 km •300 000 km •400 000 km (including battery exchange)
Vehicle body production	Found in Table 17	Same as base case
Battery production	Found in Table 17	Same as base case
Use Phase - Electricity used in charging	Nordic electricity mix	•European, high voltage •European, low voltage •Nordic, low emissions •Swedish •Renewable (hydropower)
Use Phase - Drive pattern	Found in Table 17	**3 different types of environment:** •Urban •Extra urban •Motorway **Use of auxiliaries (only for BEV):** •Eco •Normal •Aggressive
End of life	Found in Table 17. No particular recycling of battery*	Efficient recycling with 50 % reduction in GHG and energy use in the manufacturing of new batteries

*Recycling of battery is partially included, but is not believed to result in any reduction of GHG emissions and energy use.

5.2.1 Base case

Total emissions and total primary energy use assuming a life length of 200 000 km and a Nordic electricity mix used for charging the vehicles, are shown in Table 17. For detailed calculations used for the use phase, please refer to Appendix *11.1.2 Emission factors for different fuels* and *11.1.3 Fuel consumptions*.

Table 17. Total GHG emissions and energy use for different life stages of the cars.

	BEV		PHEV	
	GHG (10^3 kg CO_2-eq)	Energy (10^3 MJ)	GHG (10^3 kg CO_2-eq)	Energy (10^3 MJ)
Vehicle body production	5.1	88.4	5.9	102
Battery production	4.1	35.9	2.5	26.0
Use phase	4.5	225	9.3	235
EOL	0.7	15.2	0.7	15.2
Total	**14.4**	**365**	**18.4**	**379**

The life cycle GHG emissions and primary energy use per km with a life length of 200 000 km are shown in Figure 16 and Figure 17, according to the different stages of the vehicle life.

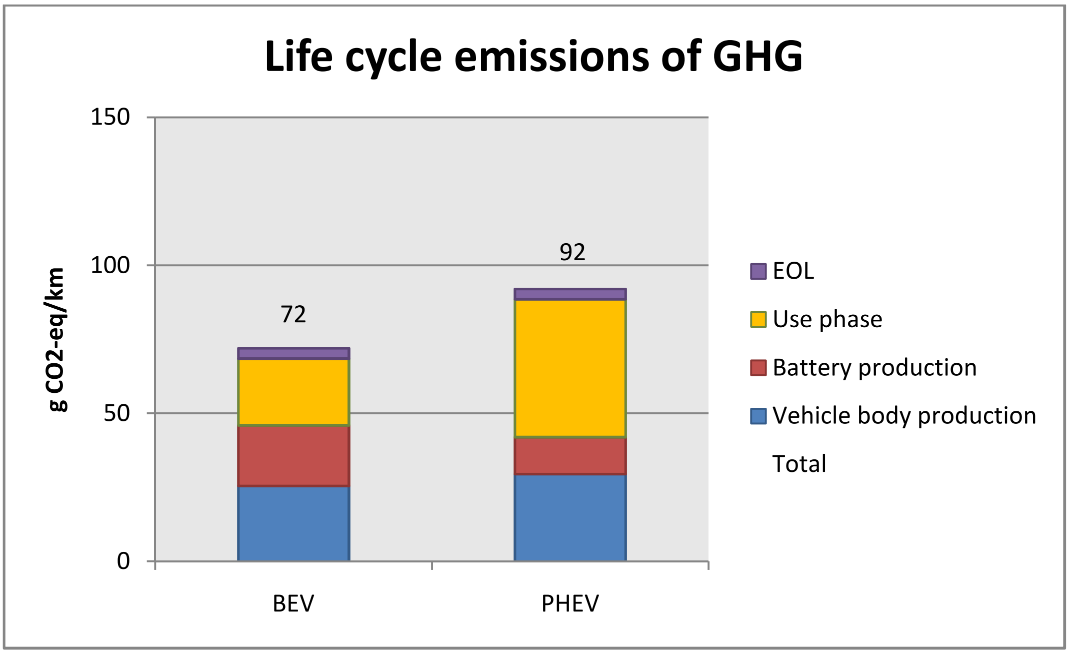

Figure 16. Base case life cycle GHG emissions divided on the different stages of life shown in g CO_2-eq/km.

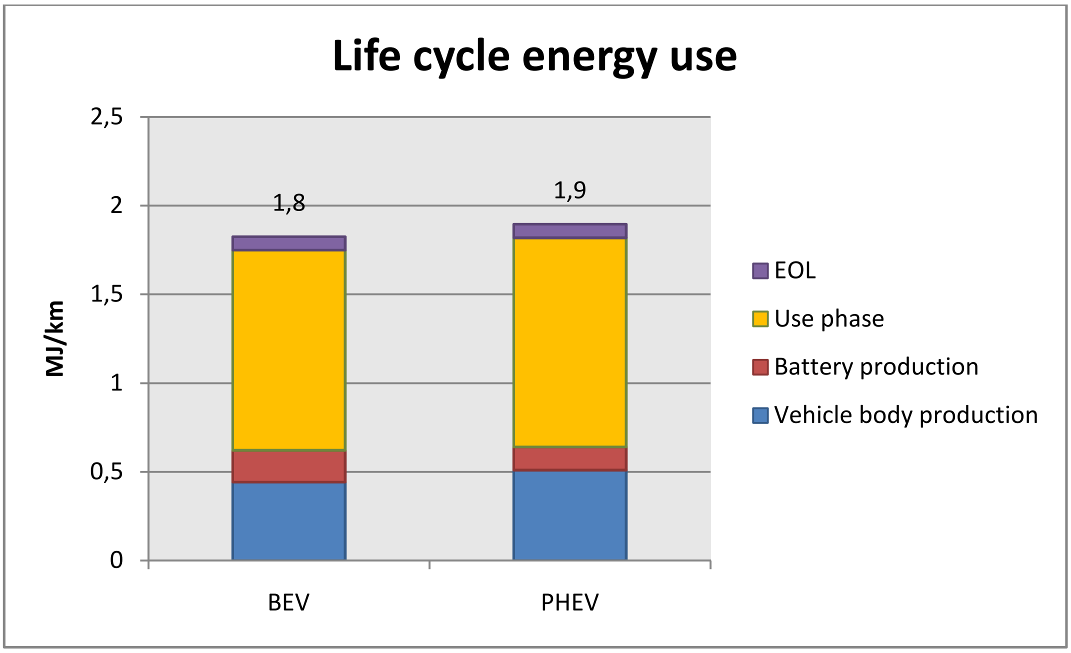

Figure 17. Base case life cycle energy use divided on the different stages of life shown in MJ/km.

The results in this analysis show that the PHEV has higher life cycle emissions of GHG and slightly higher energy use compared to the BEV. The GHG emissions in the base case scenario are 72 and 92 g CO_2-eq/km for the BEV and the PHEV respectively and the energy use is 1.8 and 1.9 MJ/km for the BEV and the PHEV respectively. Both results are relatively low compared to results in the literature review, found in *4.2.1 GHG emissions and energy use in a complete life cycle* where estimates of GHG emissions lie between 80 and 245 g CO_2-eq/km and energy use between 2.2 and 4.5 MJ/km. The BEV and the PHEV in this thesis were set to have relatively low electricity demands, 18 and 16 kWh/100 km respectively, which could partly explain this discrepancy. Another possible explanation is that the Nordic electricity mix causes relatively low GHG emissions, and that the primary energy use per kWh is also relatively low (1.74 kWh/kWh$_{electricity}$).

For the base case scenario the impact from different life stages for both the BEV and the PHEV were calculated. The raw numbers that allowed for the calculation of the percentages in Table 18 can be found in Table 17.

Table 18. The percentual contribution towards life cycle GHG emissions and energy use from different stages of the life cycle in the base case.

	BEV		**PHEV**	
% of total life cycle impact	**GHG**	**Energy**	**GHG**	**Energy**
Vehicle body production	35%	24%	32%	27%
Battery production	28%	10%	14%	7%
Use phase	31%	62%	51%	62%
EOL	5%	4%	4%	4%

The most important life cycle stage for both the BEV and the PHEV was found to be the use phase, except in the case of GHG emissions for a BEV where the vehicle body production is of greater importance. This is in general agreement with what previous studies have shown, as can be seen in Table 2 which shows the use phase as the dominating phase when it comes to GHG emissions and energy use. Percentages found in Table 18 are however lower than in most other studies, especially for GHG emissions during the use phase for the BEV. The main reason for this is probably that the GHG emissions linked to Nordic electricity are relatively low compared to other electricity mixes in Europe and worldwide.

5.2.2 Sensitivity analysis

In this subchapter results from all of the alternative scenarios are discussed. Detailed results are found in Appendix *11.2.1 Detailed results of the sensitivity analysis of EVs*. The base case scenario has been added in all of the graphs to facilitate comparisons.

Length of life

The lengths of life of the EVs were varied for; 150 000 km, 300 000 km, and 400 000 km with a battery exchange. All other parameters were kept the same as in the base case scenario. The battery exchange was added to the 400 000 km life length because the batteries are believed to have a very limited capacity otherwise. In addition, a battery replacement is probably needed in order to maintain the assumption of 75% degree of electrification.

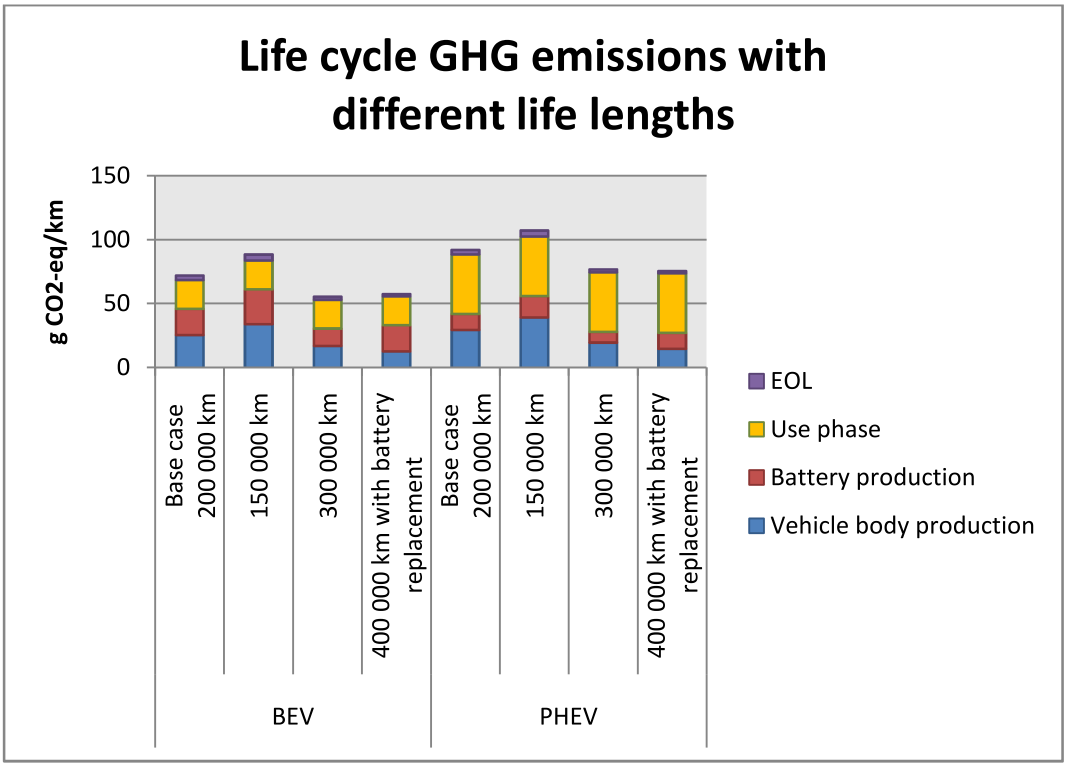

Figure 18. Life cycle GHG emissions divided on the different stages of life shown in g CO_2-eq/km.

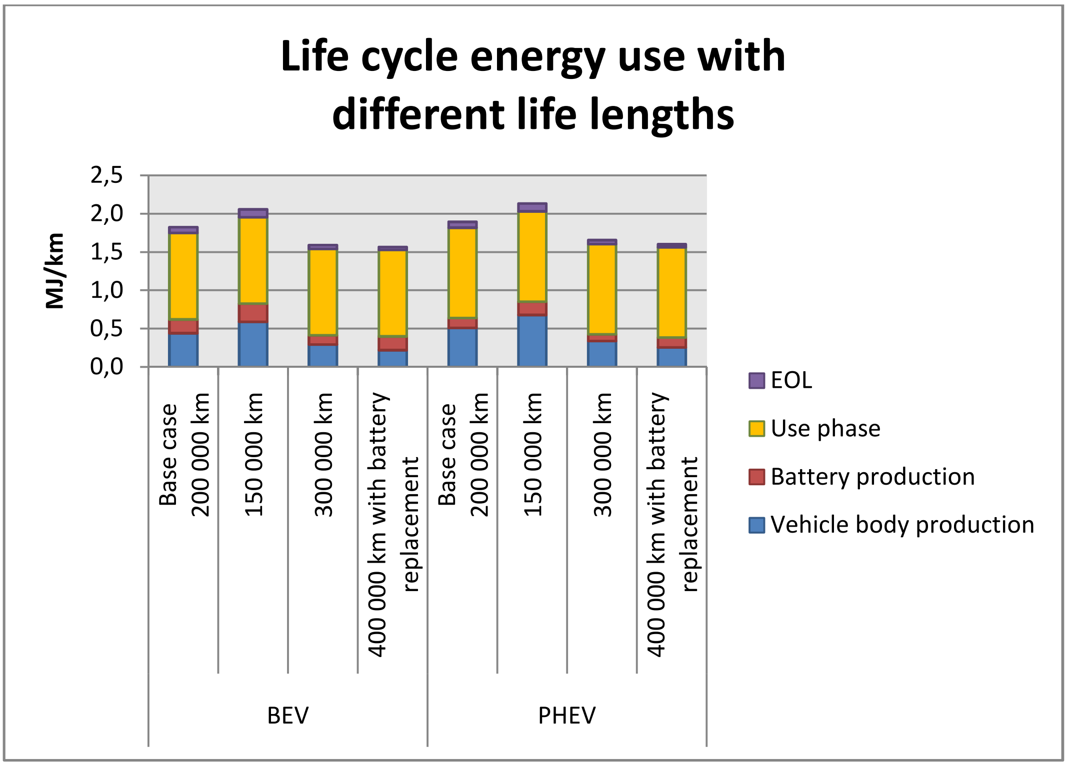

Figure 19. Life cycle energy use divided on the different stages of life shown in MJ/km.

As shown in Figure 18 and Figure 19 the scenario with a life length of 150 000 km stands out both in terms of GHG emissions and energy use, and it has the highest impact for both of these. There is not a large difference between the life lengths of 300 000 km and 400 000 km with a battery replacement. The scenario of a 400 000 km life length causes slightly lower impact, but this does not include any EOL handling of the extra battery. Parameter values on this were hard to find, but even if they had been included it is likely that the impact would have remained below the scenario with a 300 000 km life length.

Use phase

Electricity mix

All parameters were kept the same as in the base case scenario, except for the electricity mix used for charging.

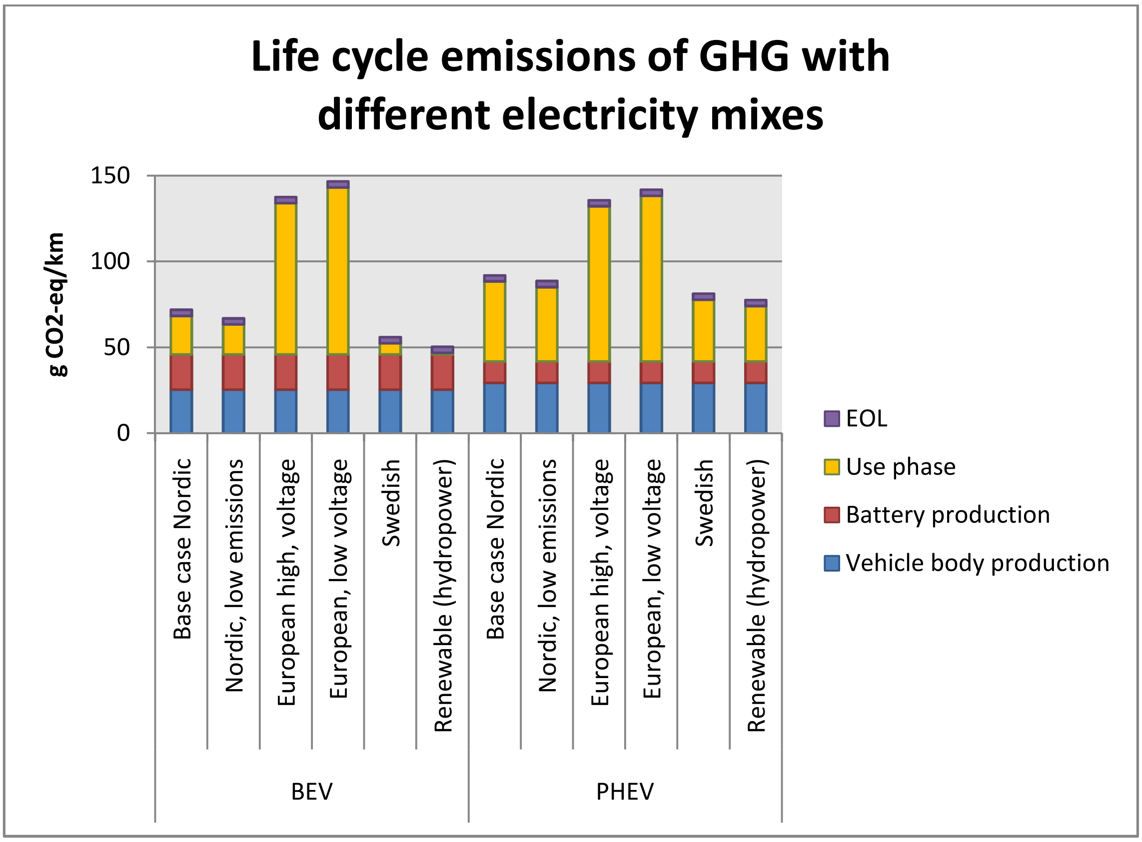

Figure 20. Life cycle GHG emissions divided on the different stages of life shown in g CO_2-eq/km.

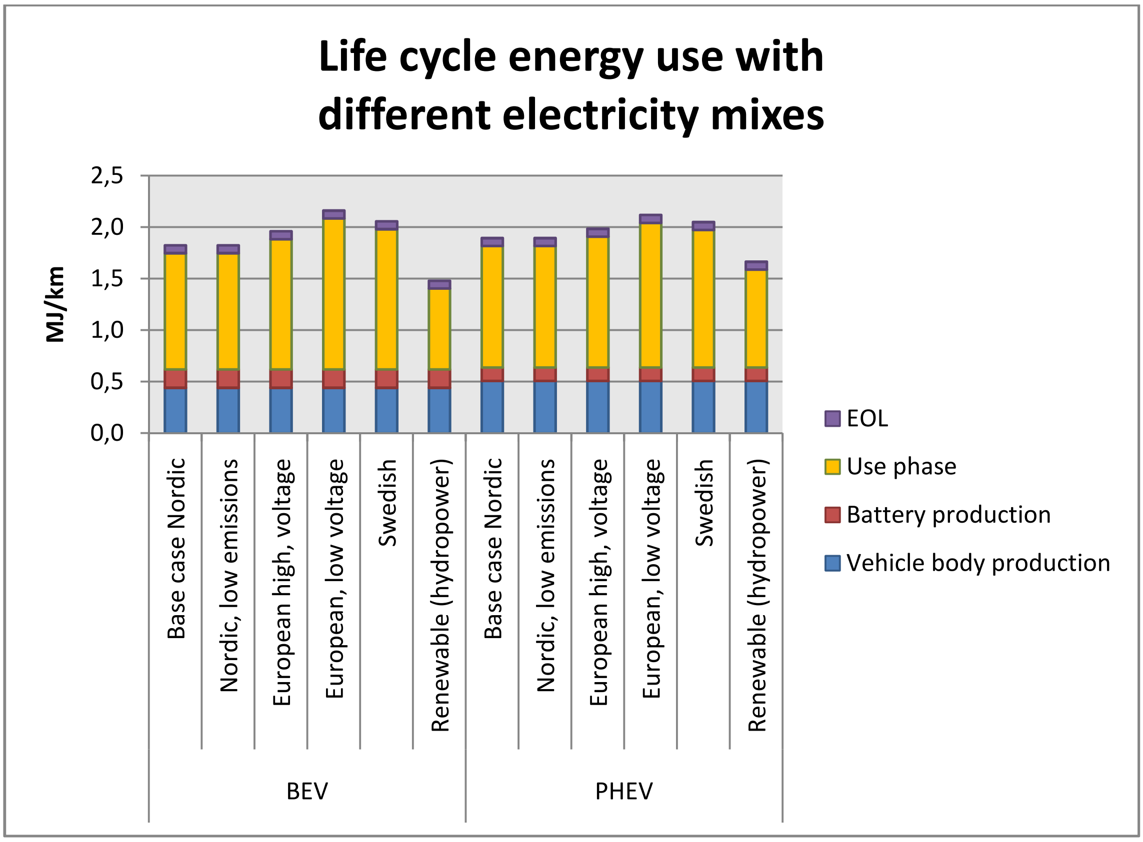

Figure 21. Life cycle energy use divided on the different stages of life shown in MJ/km.

In Figure 20 the large importance of which electricity mix used for charging the EVs is shown. For the BEV, there is a difference in GHG emissions of almost 100 g CO2-eq/km between driving on a renewable (hydropower) electricity mix and a European (low voltage) electricity mix.

In the base case scenario the relatively low life cycle energy use as compared to other studies was discussed. Part of the explanation to the lower energy use of the EVs in this study was that the electricity demands of the BEV and PHEV might be relatively low. However, when studying Figure 21 it can be seen that with different electricity mixes used in charging the vehicles life cycle energy use increases to estimates more similar to those found in other studies.

Drive patterns

All parameters were kept the same as in the base case scenario, except for the drive patterns in the use phase. Parameter values on electricity and fuel consumption are found in Table 12. Life cycle energy use and GHG emissions for driving in different areas are shown in Figure 22 and Figure 23.

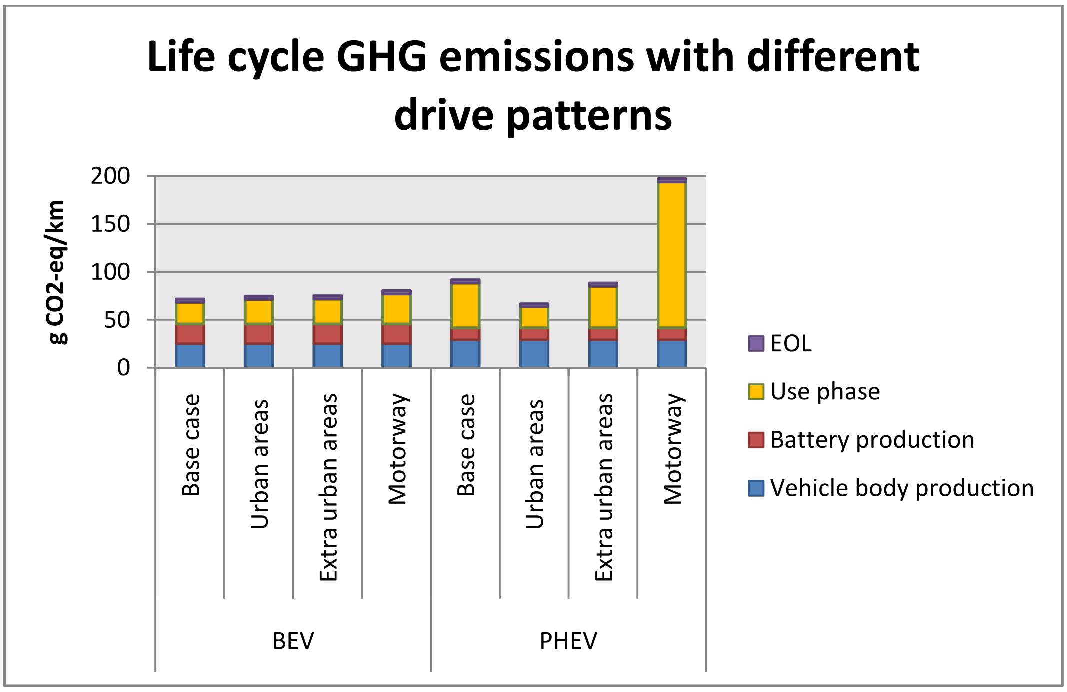

Figure 22. Life cycle GHG emissions divided on the different stages of life shown in g CO_2-eq/km.

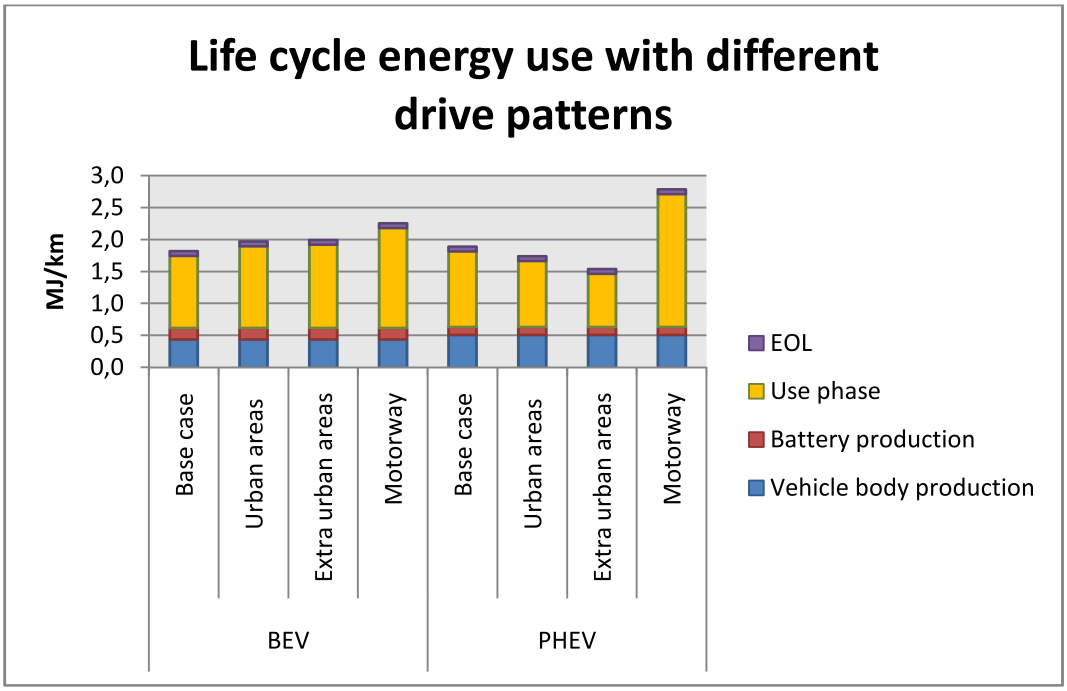

Figure 23. Life cycle energy use divided on the different stages of life shown in MJ/km.

When driving on a Nordic electricity mix, the impact of changing the electricity consumption in the use phase is rather small, both in terms of GHG emissions and energy use. The result that really stands out is the PHEV driving in motorway conditions, which increases a lot both in terms of GHG emissions and energy use. This is probably due to the high use of the ICE on motorway conditions, the use of electric drive on the motorway only amounts to 10%. Motorway driving increases the environmental impact of the BEV as well, but not nearly as much.

The base case scenario of driving a BEV is almost identical to driving a BEV in urban areas and extra urban areas, which means that an electricity consumption of 20.4 and 20.8 kWh/100 km instead of 18 kWh/100 km has very little impact on the final result. As highlighted before, the results in the BEV's case are used mostly to illustrate how driving in different environments can affect the end result. If the base case scenario was to be adapted to driving under specific conditions the electricity consumption in especially the urban areas would naturally be lower than the base case electricity consumption, but this is not the case here since such information has not been found.

Use of auxiliaries

All parameters were kept the same as in the base case scenario, except for the use of auxiliaries. This was done only for the BEV. Parameter values on electricity consumption are shown in Table 13. In Figure 24 and Figure 25 the GHG emissions and energy use for a BEV with a battery capacity of 24 kWh is shown when the car is driven with the AC off and with the AC on heat. The electricity consumption is relatively low compared to the base case, and the base case parameter values correspond very well to normal driving with the AC on heat. This scenario serves mostly to illustrate how energy use and GHG emissions are influenced by the use of AC, and since the electricity consumption is set to be lower than in the base case the GHG emissions and energy use when the AC is off are all lower than in the base case scenario. As can be seen in Figure 24 and Figure 25 there are some minor variation depending on auxiliary use which leads to the conclusion that GHG and energy savings, albeit rather small, can be made from driving eco friendly with the AC off.

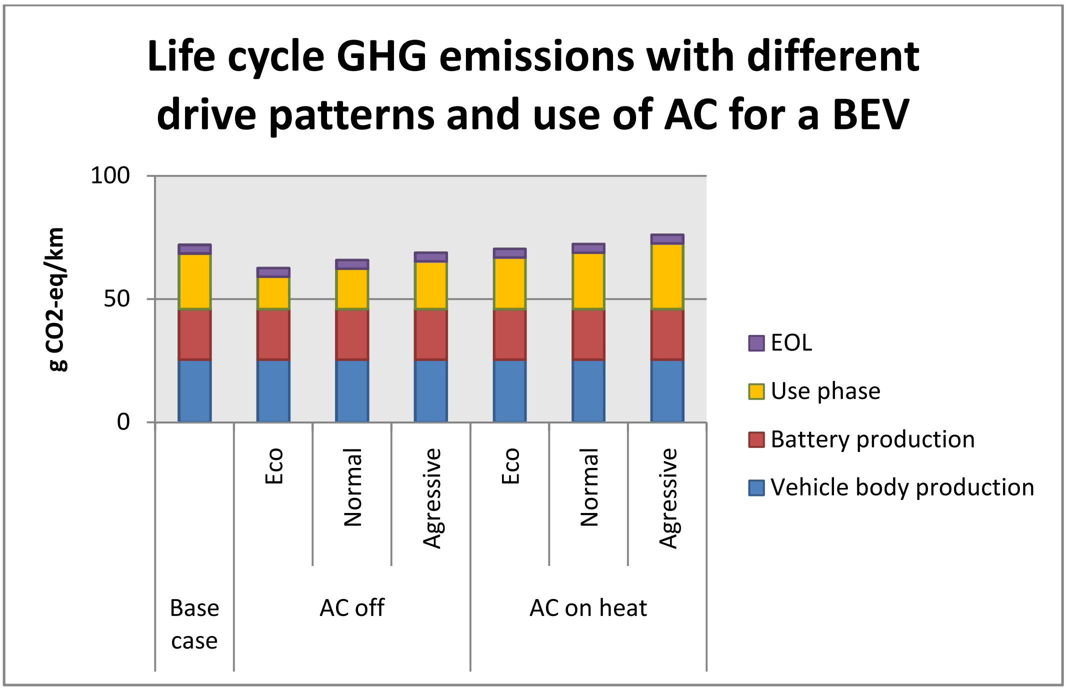

Figure 24. Life cycle GHG emissions divided on the different stages of life shown in g CO_2-eq/km.

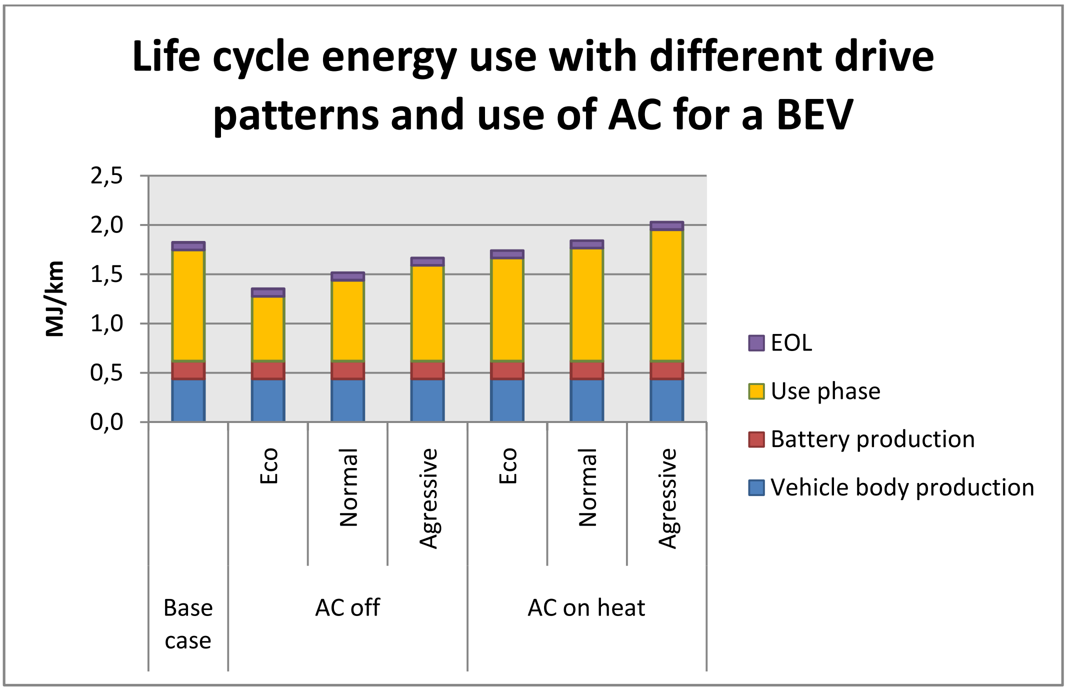

Figure 25. Life cycle energy use divided on the different stages of life shown in MJ/km.

Recycling of battery

This alternative scenario should be seen as a best case situation for battery recycling, as the recycling of lithium-ion batteries is currently not well documented (as hardly any have reached their EOL). The GHG emissions and energy use with efficient battery recycling are shown in Figure 26 and Figure 27.

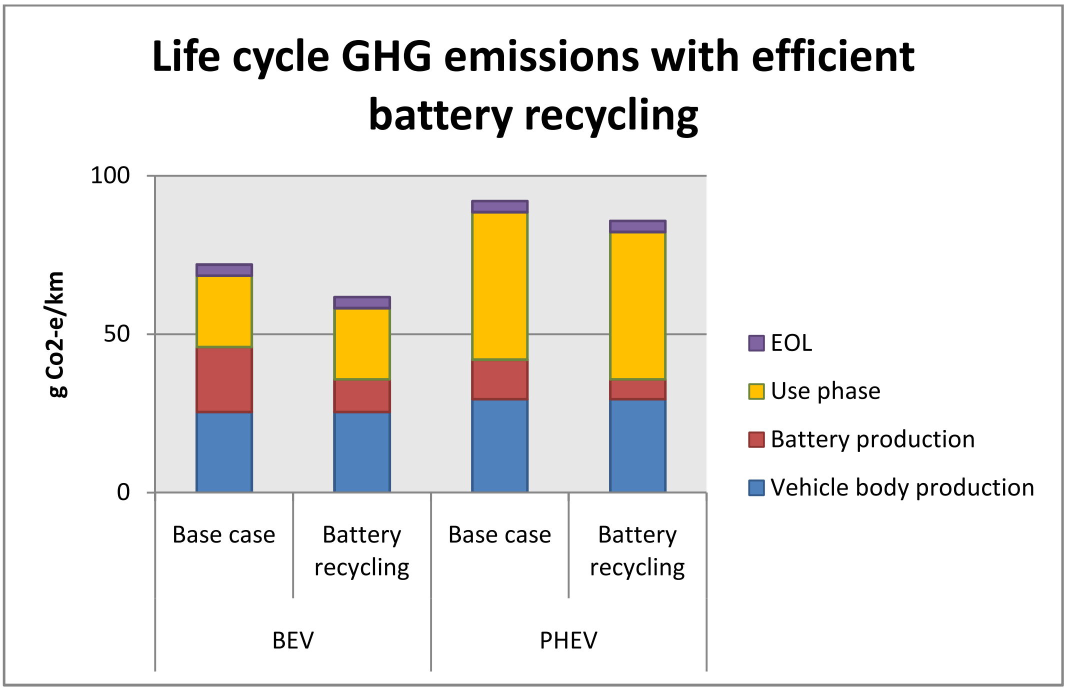

Figure 26. Life cycle GHG emissions divided on the different stages of life shown in g CO_2-eq/km.

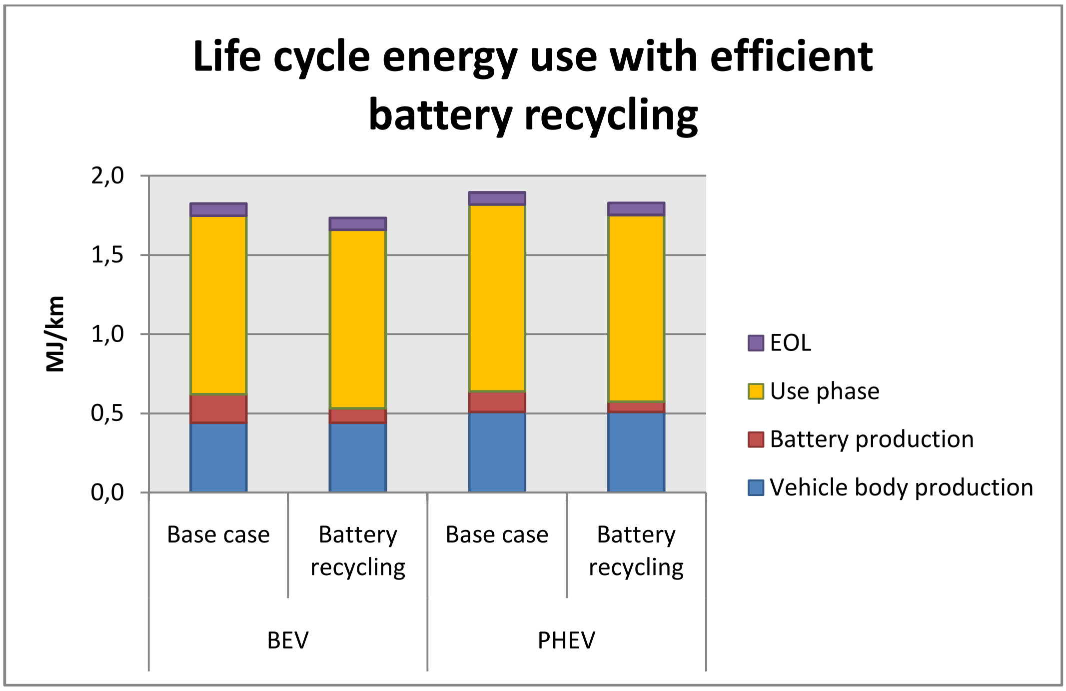

Figure 27. Life cycle energy use divided on the different stages of life shown in MJ/km.

Efficient battery recycling does make a minor difference, and it is has a greater impact in the case of GHG emission reductions for the BEV with a larger battery. A 50% reduction in GHG emissions due to efficient battery recycling corresponds to a 14% reduction in life cycle GHG emissions for the BEV.

5.2.3 Best and worst case scenarios

All factors evaluated in the analysis above were taken into account when creating a best and a worst case scenario with the exception of the use of the AC, as these parameter values were only available for a BEV and not a PHEV. Two generic best and worst case scenarios were created for the BEV and the PHEV.[20]

In the best case scenario for the PHEV, driving in urban areas was the most beneficial in terms of GHG emissions, but when it comes to energy use driving in extra urban areas (similar to countryside) consumed less energy. To be able to use one and the same scenario, results that showed lower GHG emissions were prioritised above results showing lower energy use, and therefore only driving in urban areas are shown in the best case scenario.

The best case and the worst case scenarios meet the criteria listed in Table 19. The base case scenario is also included to facilitate comparisons.

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[20] The best case scenario was also varied in alternative best case scenario for the BEV as there was a slightly more advantageous result using the base case electricity consumption than driving in urban areas which was used in the generic best case scenario. The results were very similar to the generic best case scenario and the alternative best case scenario is therefore not included in Figure 28 and 29.

Table 19. Summary of the different parameters used in the base, best and worst case scenarios.

	Base case	**Best case**	**Worst case**
Vehicle life length	200 000 km	400 000 km (including battery exchange)	150 000 km
Vehicle body production	Found in Table 17	Same as base case	Same as base case
Battery production	Found in Table 17	Same as base case	Same as base case
Use Phase - Electricity used in charging	Nordic electricity mix	Renewable (hydropower)	European, low voltage
Use Phase - Drive pattern	Average, found in Table 8	Urban*	Motorway
End of life	Found in Table 17. No particular recycling of battery**	Efficient recycling with 50 % reduction in GHG and energy use in the manufacturing of new batteries	Same as base case

*An alternative base case drive pattern for the BEV was also assessed, but found to only result in marginal differences to the best case

**Recycling of battery is partially included, but is not believed to result in any reduction of GHG emissions and energy use.

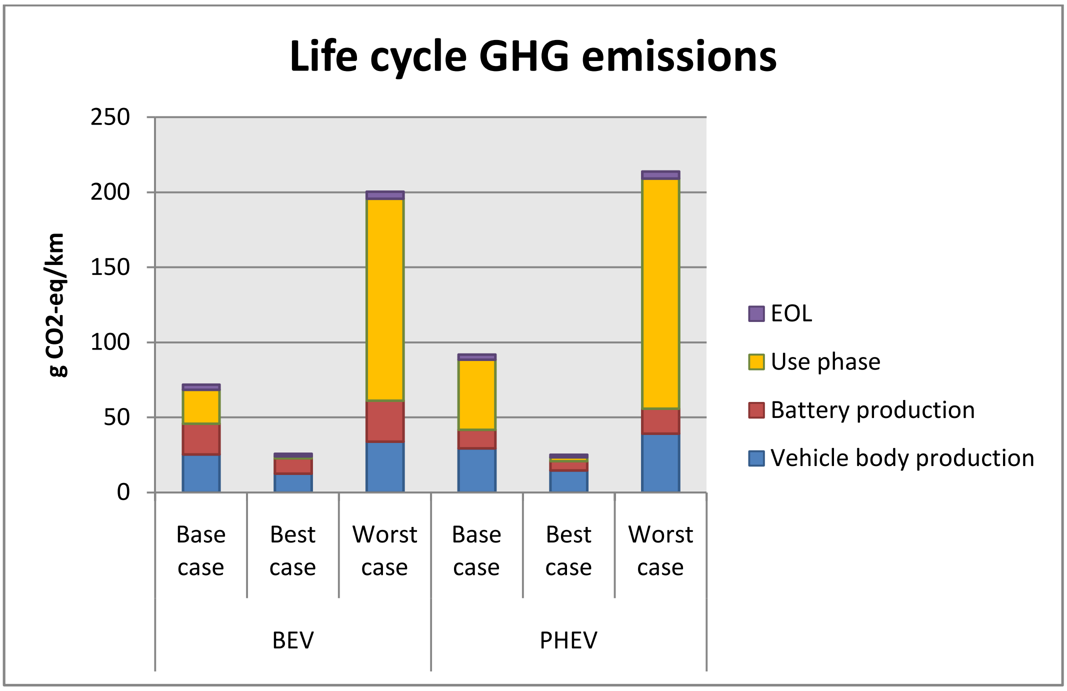

Figure 28. Life cycle GHG emissions divided on the different stages of life shown in g CO_2-eq/km.

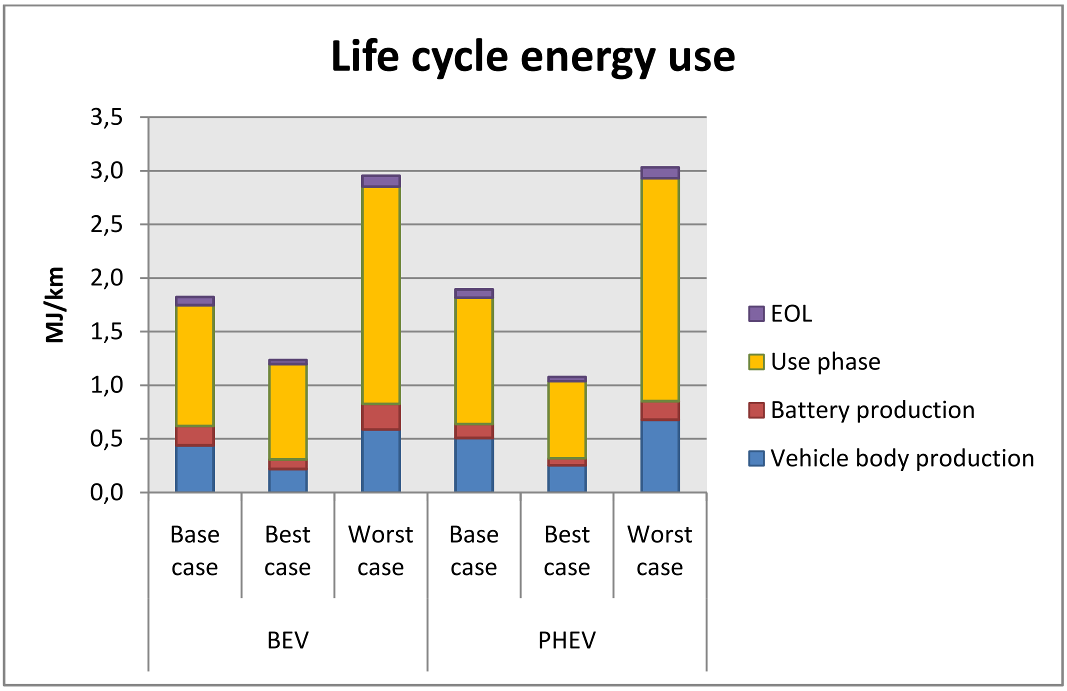

Figure 29. Life cycle energy use divided on the different stages of life shown in MJ/km.

The results show that the environmental impact of an EV varies between approximately 25 and 215 g CO_2-eq/km and 1 and 3 MJ/km depending on the length of life, user related factors and recycling. There is a large difference between the best and the worst case scenarios, and the use phase is the most important phase for determining the environmental impact. An efficient battery recycling has a large impact in the best case scenario where renewable electricity is used in charging and the use phase is more or less non-existent, especially when looking at GHG emissions.

It is of interest that there does not seem to be a large difference between the environmental performance (GHG emissions and energy use) of a BEV and a PHEV in any of the scenarios. This could be due to partly optimistic assumptions regarding the electric drive for the PHEV or the slightly higher electricity consumption of the BEV that represent the urban driving scenario. Even though this shows that a PHEV can consume less energy and emit less GHG than a BEV under specific conditions, it is important to remember that this assumes a relatively high use of the battery (90% electric drive) in the PHEV. When a motorway drive pattern is used in the worst case scenario the BEV and PHEV are still relatively equal in terms of GHG emissions and energy use, but it should be noted that this is if a European electricity mix is used in charging, and that the results would look quite different if a Nordic electricity mix had been used instead.

In Appendix Table 35 and Table 37, the relative contribution towards life cycle GHG emissions and energy use are shown for different stages of the life cycle for the best and the worst case scenarios. Interestingly, the use phase contribution towards the life cycle emissions of GHG varies between 3 and 67% for a BEV and 10 and 72% for a PHEV. The factors that have the highest impact on the use phase GHG contribution are the drive pattern for the PHEV and the electricity mix used in charging for the BEV. The energy use does not fluctuate in the same way and stays similar for all life stages (around 65% for the use phase) in the best and worst case scenarios both for the BEV and the PHEV.

6. Electric cars in comparison to cars with combustion engines

6.1 Background and method

There are many LCA and similar studies that compare EVs to ICEVs. Most of the LCAs found on EVs (section *4. Literature review*) also included a comparison with an ICEV run on gasoline or diesel, but they might not always clearly separate all of the life cycle phases and account for both primary energy use and GHG emissions. The results for ICEVs from these LCAs will not be thoroughly analysed in this thesis, but some of the information is used later in this chapter. However, a conclusion reached in the vast majority of the LCAs consulted for this thesis is that electric cars are superior to conventional cars. This is independent of the electricity mix used in the charging of EVs, but with even larger benefits when the electricity mix is renewable. In some cases electric cars do cause a larger climate impact than diesel cars, depending on assumptions made (if for example a German average or a coal based electricity mix is used) (Helms et al., 2010).

Studies comparing EVs to other types of cars than ICEV are relatively rare, but lately there has been a number of LCAs looking at BEVs compared to FCEVs, for example Bartolozzi et al. (2012) and Edwards et al. (2014a) (although the latter is only a WTW analysis).

One way that many LCA handle comparison between different types of cars is to produce a common glider, and then vary the powertrains and add a battery and for EVs. The parameters responsible for the main differences between the different types of cars are typically the manufacturing (and possibly recycling) of the battery, the powertrain and the vehicle use phase (for example Notter et al., 2010; Helmers and Marx, 2012; Aguirre et al., 2012). Aguirre et al. (2012) assume a common glider and vary only the battery or the combustion engine, with only marginal impact on GHG emissions and energy use from the combustion engine. The same is seen in Faria et al. (2013) for GHG emissions.

Hawkins et al. (2012a) is one of the studies that has compared a conventional car to EVs, and they state that the comparison might not be fair as an EV is typically of a smaller size than an ICEV. Faria et al. (2013) also compared ICEVs to BEVs and PHEVs, and account for the curb weights of all vehicles. They compared a conventional Golf of 1240-1290 kg to a Nissan Leaf (BEV) of 1520 kg and a Chevrolet Volt (PHEV) of 1720 kg. This means that even if an ICEV happens to be larger in size it is not likely to be heavier than an EV, which should be kept in mind.

To be able to compare between different types of cars in this chapter, a focus will be put on cars in the golf-size class, similar to a Nissan Leaf and a Chevrolet Volt which are the models that the results in section *5. Life cycle analysis of an electric car in Sweden* of a BEV and a PHEV are based on. This is also the vehicle type that was studied in the large WTW analysis by the European commission (Edwards et al., 2011; Huss et al., 2013).

Types of fuels studied and their emission factors

The different types of fuels studied are conventional gasoline, conventional diesel, ethanol, biodiesel/ fatty acid methyl esters (FAME) (in the form of rapeseed-oil methyl ester (RME)), biogas and hydrotreated vegetable oil (HVO).

Biofuels can originate from many different sources, and their environmental impact may differ. A brief comparison of the GHG emissions and primary energy use found in different reports was made, and the result is shown in Table 20.

Table 20. GHG emissions and primary energy use linked to different kinds of biofuels (Edwards et al., 2014c; Edwards et al., 2014d; Gode et al., 2011; Energimyndigheten, 2015b).

Study	**Fuel**	**GHG emissions** (g CO2-eq/MJ)	**Primary energy**(MJ/MJ final fuel)	**Primary energy** (MJ/l)	**Primary energy** (MJ/Nm3)	**GHG emissions** (g CO2-eq/l)
Edwards et al. (2014c); Edwards et al. (2014d)	**Ethanol**	9.2 - 86.0	0.92 - 2.09	-		-
	Biogas	-69.9 - 40.8	0.99 - 2.17	-	35.7 (50 MJ/kg)*	-
	FAME	13.8 - 62.6	0.28 - 2.69	-	-	-
	HVO	8.1 - 57.1	0.16 - 2.51	-	-	-
Gode et al.(2011)	**Ethanol**	11 - 29	1.28 - 1.48	-	-	-
	E85	35	1.09	-	-	-
	Biogas**	3.1 - 23	0.15 - 1.46	-	-	-
	RME	18	1.27	-	-	-
	Crude tall oil***	0.2	-	-	-	-
Energimyndigheten (2015b)	**Ethanol**	35.7	-	21.1	-	753
	Biogas	23.6	-	-	35.0 (49.0 MJ/kg)	-
	FAME	45.6	-	34.4	-	1 569
	HVO	15.6	-	34.3	-	537

*Values are for methane in the form of gas.

**Energy content in fuel is sometimes not included, which explains the lower values.

***Production not included.

There are quite large differences in both the GHG emissions and the primary energy use within each category of fuel. Lower GHG emissions from biofuels often arise when co-products are used for energy production, or the biofuel is produced from waste products (Edwards et al., 2014a). For example, in Edwards et al. (2014c) the lowest climate impact FAME and HVO are based on waste cooking oil (the highest are based on meal), and the lowest climate impact biogas is based on manure (the highest is based on maize).

A reason for large variation between the studies is that they use different methods and/or different system design. As can be seen in Table 20, the climate impact sometimes drops below zero. This is because Edwards et al. (2014c and d) use system expansion in their calculation methods. Gode et al. (2011) state that they try to avoid using system expansion, but on the other hand they might not always include the energy content in the fuel as seen in the case of biogas.

Factors that are not taken into account regarding biofuels are impacts from indirect land use change (ILUC) and direct land use change (DLUC) associated with the crop that is used to produce the biofuel (Edwards et al. 2014a). Gode et al. (2011) and Energimyndigheten (2015b) do not mention ILUC and DLUC at all, and it is assumed that these have not been considered.

If they had been, the effects on GHG emissions would most likely appear larger. In some studies the energy content in the biofuel might not be included in the total energy. This is the case for fuels based on for example waste and manure in Gode et al. (2011).

System expansion is not allowed according to the EU Renewable Energy Directive[21], and this is why the parameter values on GHG emissions from biofuels are slightly higher in Energimyndigheten (2015b) who calculate the GHG emissions according to the rules in the Renewable Energy Directive. This is also the method that is preferred in this thesis.

Biofuels are often used in different blends with conventional gasoline and diesel, and the different blends studied are based on fuels that are available in Sweden. The blends that are studied in this thesis are gasoline with 5% ethanol, diesel with 5% FAME, E85 (85% ethanol with 15% gasoline) and diesel with 35% HVO and 5% FAME.[22]

The GHG emissions and primary energy use linked to gasoline and diesel are based on Huss et al. (2013) and Edwards et al. (2014c). The GHG emissions and primary energy use linked to the different biofuels are based on Energimyndigheten (2015b), as they use calculation methods allowed in the Renewable Energy Directive, and present estimated values that are representative to Sweden during the year of 2014. The ethanol is mostly based on wheat and corn, the biogas and the HVO are mostly based on organic waste products and the FAME is solely produced from rapeseed (therefore it could also be called RME).

The primary energy use of biogas will however be based solely on fuel consumption from Huss et al. (2013) (Table 22).

In Table 21 the GHG emissions and primary energy use for different fuels are shown in g CO_2-eq/l and MJ/l respectively. Appendix *11.1.2 Emission factors for different fuels* contains more information on the calculations and methods.

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[21] The Renewable Energy Directive contains policies for the production and promotion of energy from renewable sources in Europe. For example it requires the EU to by 2020 meet its total energy needs with at least 20% renewable energy and 10% of fuels for transport to come from renewable sources (European Commission, 2016).

[22] Fuel distributors OKQ8 and Statoil have diesel blends with up to 40% biodiesel in Sweden, and Statoil specify the content as 35% HVO and 5% RME (Statoil Fuel and Retail, 2013; OK-Q8 AB, 2015).

Table 21. Life cycle GHG emissions and primary energy use linked to different fuels used in the analysis (Energimyndigheten, 2015b; Huss et al., 2013; Edwards et al., 2014c).

Fuel	**GHG emissions** (g CO2-eq/l)	**Primary Energy use**(MJ/l)
Conventional gasoline	2806	38
Conventional diesel	3177	43
Biogas	24 (g CO2-eq/MJ)	-
Ethanol	753	21
FAME	1 569	34
HVO	537	34
Gasoline with 5% ethanol	2703	37
E85 (85% ethanol and 15% gasoline)	1061	24
Diesel with 5% FAME	3097	43
Diesel with 35% HVO and 5% FAME	2173	39

Life length of an ICE car

As discussed previously the life length of an electric car is relatively low. Some LCA will manage a comparison between different types of cars by setting the life length of other cars to the lower life length of an electric car. In this thesis, the life lengths of the ICEVs are set to be 200 000 km just as in the base case for the EVs (*5.2.1 Base case)*. Because this might be a too short life length for cars that are not limited by a battery life length, longer life lengths of 300 000 and 400 000 km are also tried in a sensitivity analysis.

6. 1.1 Life cycle stages

Vehicle body production

Vehicle body production is highly dependent on what type of car is assumed. Based on results regarding GHG emissions and primary energy use related to vehicle body production, the powertrain used does not seem to influence this, rather the car model and vehicle size is of importance. Some studies will consider battery and vehicle body production together, and these studies have not been consulted for this thesis. Studies that show similar or even identical parameter values on GHG emissions and energy use for vehicle body production for similar car models for BEVs, PHEVs and ICEVs include Faria et al. (2013), Notter et al. (2010), Aguirre et al. (2012) and Samaras and Meisterling (2008). However, there is a slight difference in the powertrains in Notter et al. (2010).

To make the different types of cars easier to compare, all of the ICEVs are assumed to have the same vehicle glider as the BEV in section *5.1.1 Life cycle* stages and *Vehicle body production* (Table 6). The BEV is manufactured in Europe, and this is deemed to be of greater interest here as the cars will be driven in Europe.

Because the PHEV in the earlier chapter (section *5.1.1 Life cycle* stages and *Vehicle body production)* is based on vehicle body production estimates from other studies, these figures will be altered in this section to match the BEV and ICEV production, which will facilitate a fairer comparison. This is the only alteration made to the results from the earlier chapter. Therefore, all of the cars will have an identical vehicle body.

Powertrains and batteries

In a comparative LCA between an ICEV and a BEV it has been shown that the GHG emissions and energy use is larger for the powertrain of an ICEV than a BEV, excluding the battery for the BEV (Notter et al., 2010). If the battery is added to the equation, the opposite is true. However, this is not apparent in studies like Samaras and Meisterling (2008) and Faria et al. (2013), where there is no distinguishable difference between vehicle productions for different cars. A common approach to handling differences in the powertrain is seemingly to discount any differences and instead add the impacts related to the battery, and this is the methodology that will be used in this thesis. This means that the effects of the battery from the BEV and the PHEV are added, but otherwise differences in powertrains are ignored.

Use phase

Fuel consumptions are based on Huss et al. (2013), which is a part of the large WTW study made by the European Commission. Huss et al. (2013) list the fuel consumption for gasoline, diesel, biogas, FAME, HVO and E85 for both a 2010 and a 2020+ scenario.

In this thesis, pure ethanol and different gasoline and diesel blends with renewable fuels are also analysed. The fuel consumptions of these fuels are obtained by weighting the contents of the components, based on fuel consumptions in Huss et al. (2013). Huss et al. (2013) and Edwards et al. (2014) assess three types of motors for ICEVs, port injection spark ignition (PISI) and direct injection spark ignition (DISI) for gasoline powered vehicles and direct injection compression ignition (DICI) for diesel powered vehicles. All of the motor types are studied in this thesis, but in the results section there will be an emphasis on DISI motors for gasoline powered vehicles as this is a newer technology and therefore more comparable with new EVs (Kerr, 2011). The DISI motor consumes slightly less fuel compared to the PISI motor (Table 22).

In Table 22 the fuel consumptions for different types of engines are shown for different fuels for the two scenarios, 2010 and 2020+. The decrease in fuel consumption for the 2020+ scenario compared to the 2010 scenario varies between 27-34% depending on motor and fuel type. E85 here contains 85% ethanol and not 80% like in Huss et al. (2013).[23]

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[23] For an explanation on how fuel consumption is calculated, please refer to Appendix *11.1.3 Fuel consumptions* and *Fuel consumption for blends of different fuels.*

Table 22. Fuel consumption for Golf sized vehicles driving on the NEDC (based on Huss et al. (2013)).

		2010		2020+	
Fuel consumption		**l/100 km**	**MJ/100 km**	**l/100 km**	**MJ/100 km**
PISI	**Gasoline**	6,6	*211,3*	4,7	*150,1*
	E85	9,2	206,8	6,5	145,2
	Biogas*	-	232,3	-	152,5
	Gasoline with 5% ethanol	6,7	211,0	4,8	149,8
	Ethanol	9,9	205,7	6,9	144,0
DISI	**Gasoline**	6,3	*203,8*	4,4	*142,5*
	E85	8,8	198,3	6,2	138,4
	Biogas*	-	211,8	-	145,1
	Gasoline with 5% ethanol	6,5	203,5	4,5	142,2
	Ethanol	9,4	196,9	6,6	137,3
DICI	**Diesel**	4,5	*162,5*	3,3	*118,5*
	FAME	4,9	*162,5*	3,6	*118,5*
	HVO	4,7	*162,5*	3,5	*118,5*
	Diesel with 5% FAME	4,5	*162,5*	3,3	*118,5*
	60% diesel, 35 % HVO, 5% FAME	4,6	*162,5*	3,4	*118,5*

*The parameter values for biogas consumption are based on CNG consumption in Edwards et al. (2014a) as these are said to be equivalent (Edwards et al., 2014a).

The drive cycle used in Huss et al. (2013) is the NEDC (Edwards et al., 2014a). A standardized drive cycle is still very useful when comparing different vehicles to each other, but it is important to highlight the fact that the real life performances can be very different to those in a lab.

It has been showed that a majority of ICE cars consume around 25% more fuel in real life performance as compared to tests (with a European test scheme). A few cars show an increase in fuel consumption as high as 70% in real life driving as compared to the standardized drive cycle (Helmers and Marx, 2012). According to Wedberg (2015) the NEDC is not an accurate measure of the actual fuel consumption of ICEVs. When compared to real fuel consumption in Sweden all of the cars tested in Golf- and middle-range car size the car will consume at least 25% more.

To include this factor in the analysis, a 25% extra fuel consumption is added to all of the ICEVs, but only for the 2010 scenario. This is done in a sensitivity analysis to model a worst case scenario. The fuel consumptions for the 2020+ scenario are also used in a sensitivity analysis to model a best case scenario.

End of life and recycling

Just like in the case of vehicle body production, studies tend to show similar or even identical parameter values on GHG emissions and energy use linked to the vehicle EOL for both EVs and ICEVs (for example Aguirre et al. (2012); Faria et al. (2013)). Since there is uncertainty around the EOL phase (with it sometimes being omitted in studies) and if and how the batteries in EVs are recycled, the EOL phase is assumed to be identical for all types of vehicles. The effects of EOL treatment is found in Table 14 and is the same both for EVs and ICEVs.

6.2 Results

First of all, a WTW analysis was performed. The results are shown in Figure 30 and Figure 31. These results from the WTW analysis form part of the base case scenario in the following section and were used to build a complete life cycle for the different types of cars. As a reference to which scenarios that were being examined in the base case analysis and in the sensitivity analysis, please refer to Table 23. The only change made to the EVs from previous chapter is the slightly altered vehicle body production of the PHEV to match that of the BEV and thereby all of the ICEVs. Otherwise no changes were made to the EVs from the previous chapter (*5. Life cycle analysis of an electric car in Sweden*). That means that the fuel consumption was only altered for the ICEVs in this chapter.

To simplify the presentation of the results, not all combinations of motor types and fuels are included in all of the graphs. The WTW life cycle analysis used in the base case is the only representation of all fuel mixes and motor types that is included in this chapter. For the complete results including all motor and fuel types, please refer to Appendix *11.2.2 Detailed results of the analysis of cars with combustion engines*.

A best and worst case scenario has been created based on the results; these are found in section *6.2.4 Best and worst case scenarios*. This best and worst case scenario was then compared to the best and worst case scenario for the EVs from *5.2 Results* and *5.2.3 Best and worst case scenarios*.

Table 23. Summary of the different parameters used for the EVs and ICEVs in the base case scenario and the sensitivity analysis.

	Base case	**Sensitivity analysis**
Vehicle life length	200 000 km	•300 000 km •400 000 km (including battery exchange for the EVs)
Vehicle body production	Same as BEV, found in Table 17	Same as base case
Battery production (EV only)	Found in Table 17	Same as base case
Use phase – Fuel consumption (ICEVs only)	Found in Table 22, 2010 scenario	•25% higher fuel consumption •2020+ scenario
End of life	Found in Table 17. No particular recycling of EV battery*	Same as base case

*Recycling of battery is partially included, but is not believed to result in any reduction of GHG emissions and energy use.

6.2.1 WTW

The WTW analysis includes only the GHG emissions and energy use linked to the fuel and the use phase of the car, and not the vehicle body production, battery production or EOL. The WTW analysis is of interest as it a fair way to compare the impact of the car connected to the use phase, and it is a common way of comparing different types of cars to each other. When other steps of the vehicle life cycle are added, as is done in the following section of this analysis, more uncertainty is also added.

For the EVs, these WTW results were obtained from the previous chapter, and the base case scenario with a life length of 200 000 km was used. For the other fuels, the 2010 scenario based on Huss et al. (2013) has been used, this can be found in Table 22. It should be noted that the assumptions made for driving conditions might differ between the EVs and the ICEVs, for example all the ICEVs are driven according to the NEDC while the EVs are driven according to facts from LCAs and car manufacturers.

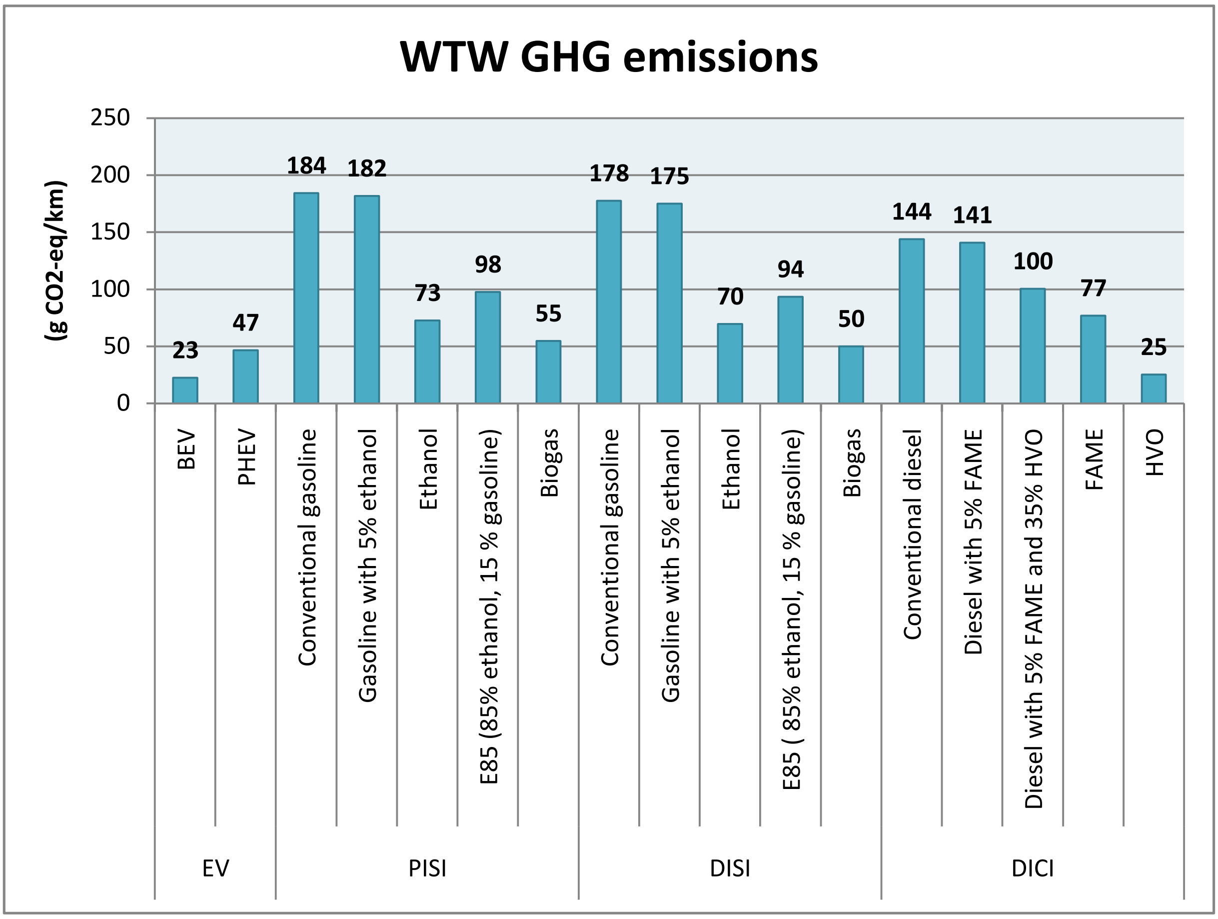

Figure 30. WTW GHG emissions for different types of motors and fuels for a life length of 200 000 km, using a 2010 scenario for the ICEVs. The WTW GHG emissions are only linked to the use phase, including the fuel and its production, no vehicle body production, battery production or EOL is included here.

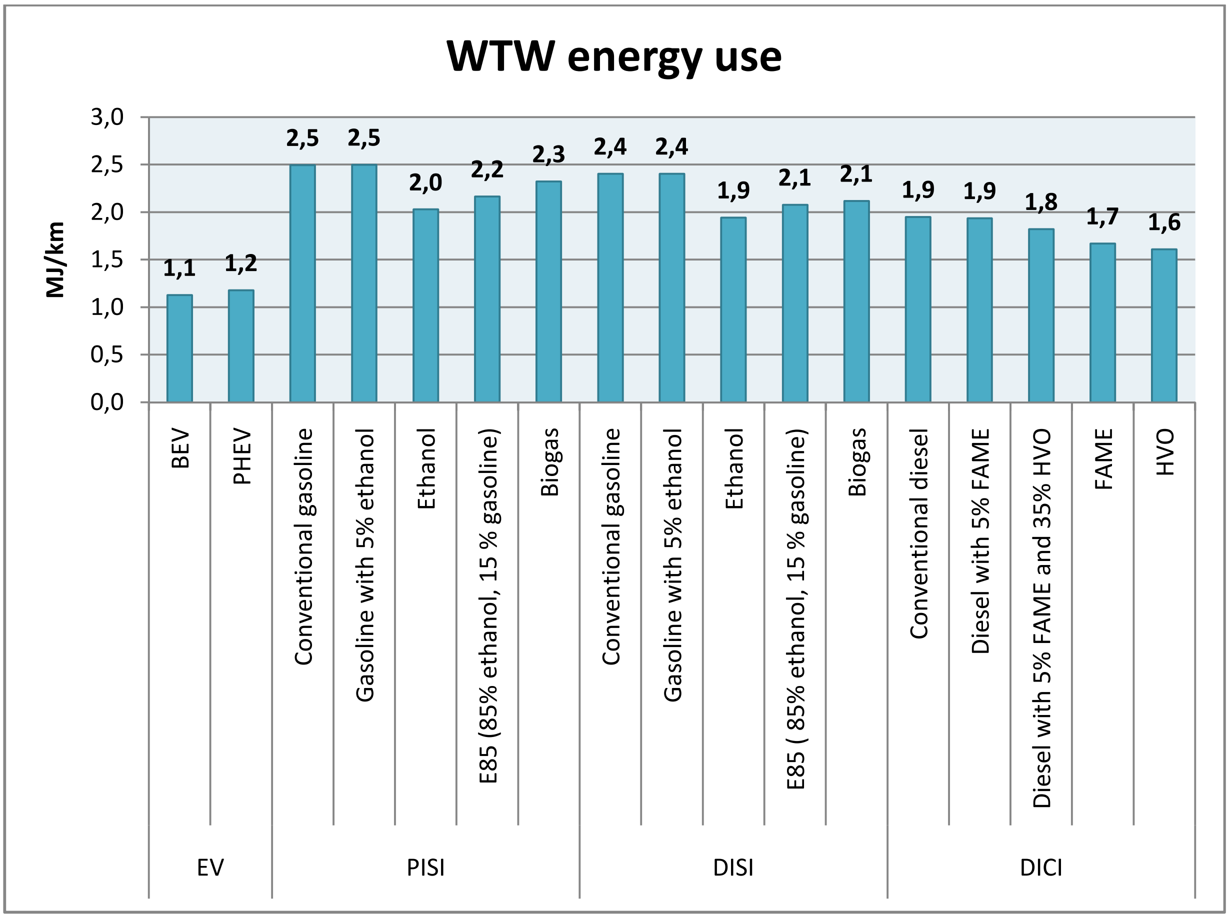

Figure 31. WTW primary energy use for different types of motors and fuels for a life length of 200 000 km, using a 2010 scenario for the ICEVs. The WTW energy use is only linked to the use phase, including the fuel and its production, no vehicle body production, battery production or EOL is included here.

As can be seen in Figure 30 and Figure 31 there are no major differences between the PISI and the DISI motor, but the DISI consumes slightly less fuel. As for the differences between the ICEVs and the EVs they vary greatly depending on the fuel. The BEV analysed in a WTW perspective is superior to all other options both in terms of GHG and energy use, and the PHEV also performs well in comparison. HVO has very low emissions of GHG, but it should be noted that this HVO is based mostly on organic residues and by-products explaining its relatively low climate impact.

6.2.2 Base case

In the complete life cycle analysis base case scenario a vehicle life length of 200 000 km was examined, just as in the WTW analysis in the previous section. However, in this section the vehicle body production, battery production and EOL have been added in order to create a complete description of the life cycle of the vehicles. The fuel economy refers to a 2010 scenario; Table 22. This was compared to the base case of the BEV and the PHEV, with the slightly altered vehicle body production of the PHEV to match that of the BEV. Only the DISI motor is shown for gasoline powered vehicles, and the results in Figure 32 and Figure 33 are compilations, for full results please refer to Appendix *11.2.2 Detailed results of the analysis of cars with combustion engines.*

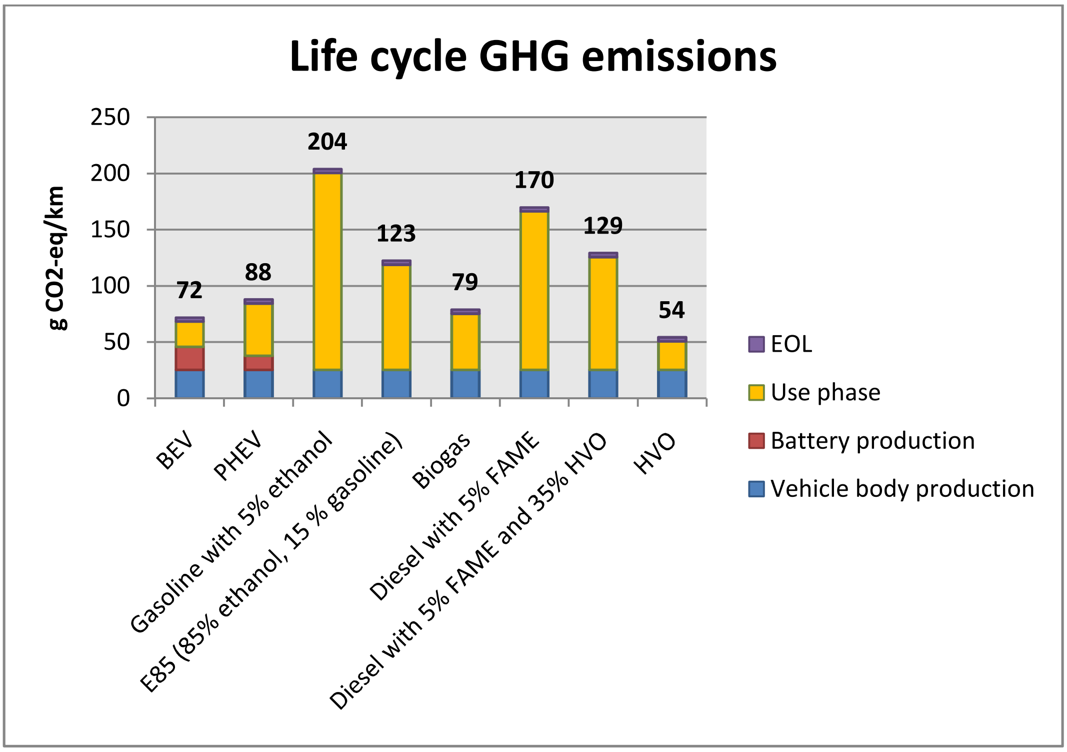

Figure 32. Base case life cycle GHG emissions divided on the different stages of life shown in g CO_2-eq/km for different types of cars.

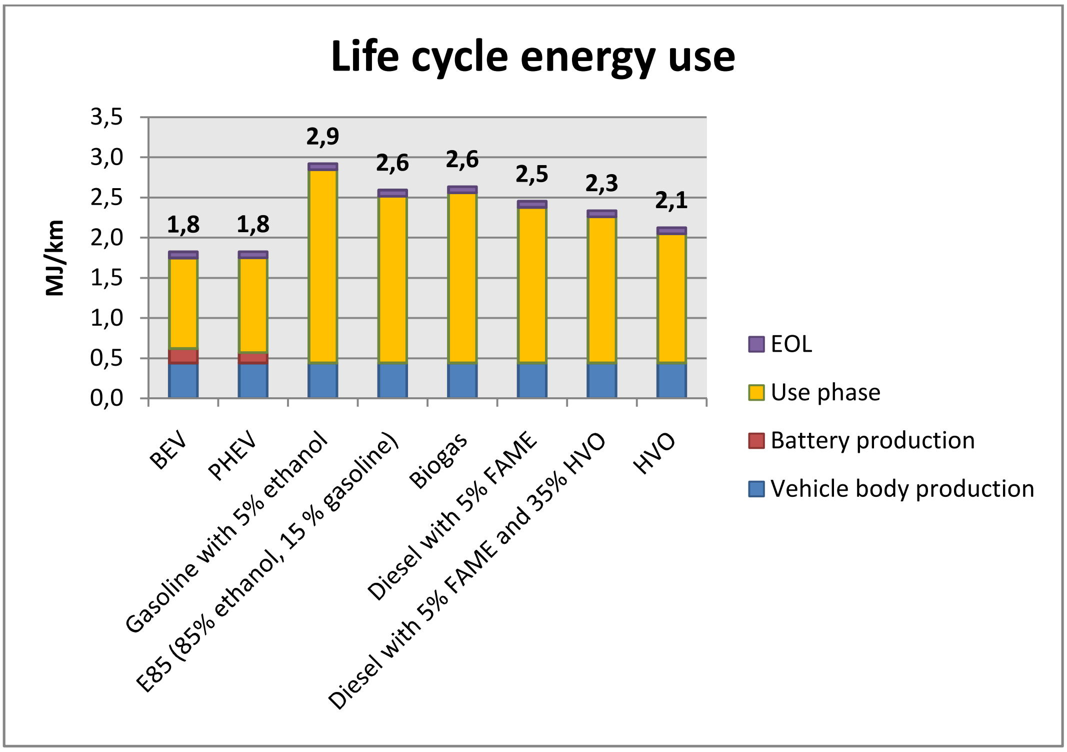

Figure 33. Base case life cycle energy use divided on the different stages of life shown in MJ/km for different types of cars.

The results show that driving a car on pure HVO (based mostly on waste products) has the lowest GWP, followed by the BEV, biogas and then the PHEV. Driving on gasoline mixed with 5% ethanol has the highest environmental impact followed by diesel with 5% FAME.

The life cycle energy use for different vehicles is lower for the EVs than for the ICEVs, making these cars a more energy efficient option from a life cycle perspective. They are followed by driving on 100% HVO, and HVO thus seems to be a strong competitor to the electric car.

6.2.3 Sensitivity analysis

A sensitivity analysis was performed for other types of cars, but it was not as extensive as the sensitivity analysis performed on the EVs in section *5. Life cycle analysis of an electric car in Sweden*. This sensitivity analysis only examined longer life lengths of the ICEVs (as these cars are not limited by battery life) and different fuel consumptions, including a future lower fuel consumption and a current higher fuel consumption in case the NEDC is not a realistic drive cycle. Further discussion about the background to these sensitivity analyses are found in section *6.1 Background and method* and *Life length of an ICE* car and *6. 1.1 Life cycle stages* and *Use phase*.

Length of life

In a sensitivity analysis the life lengths of 300 000 km and 400 000 km were examined. This was done using the 2010 scenario for all types of cars except the EVs where scenarios of longer lengths of life from previous chapter (section *5.2 Results* and *5.2.2 Sensitivity analysis*) were used as a reference with the slight adjustment that the PHEV now had the same vehicle body production as the BEV and all of the ICEVs. Note that the life length of 400 000 km includes a battery replacement for the EVs.

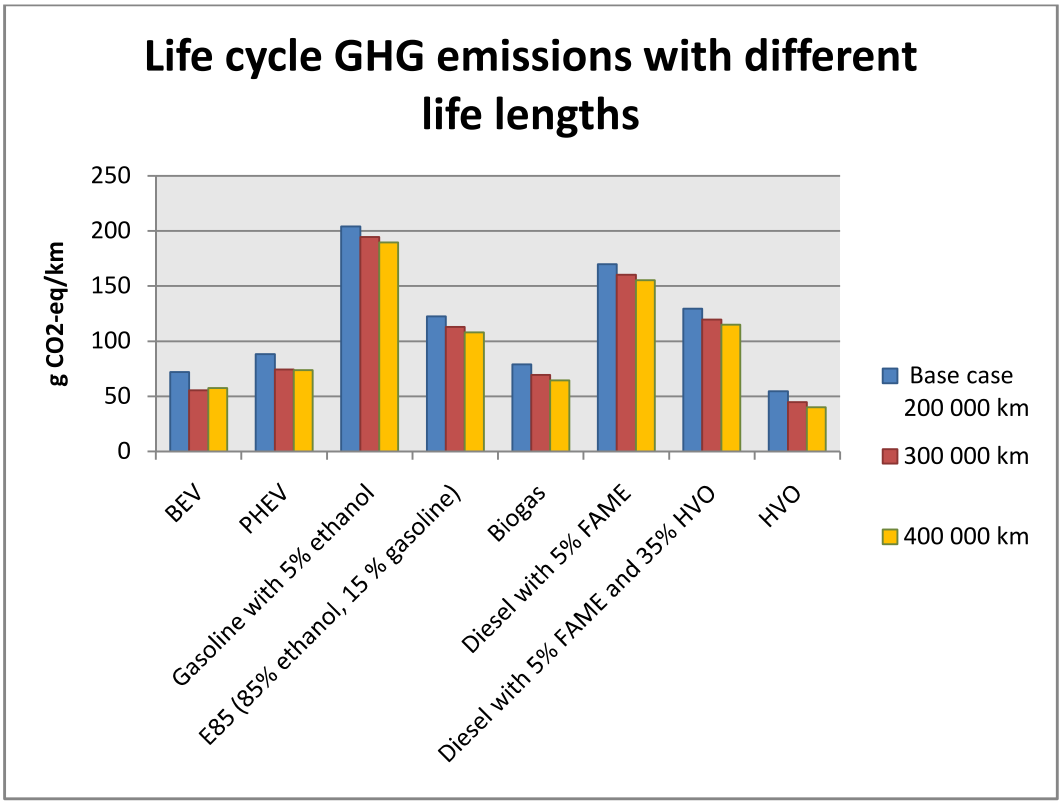

Figure 34. Life cycle GHG emissions for different life lengths shown in g CO_2-eq/km for different types of cars.

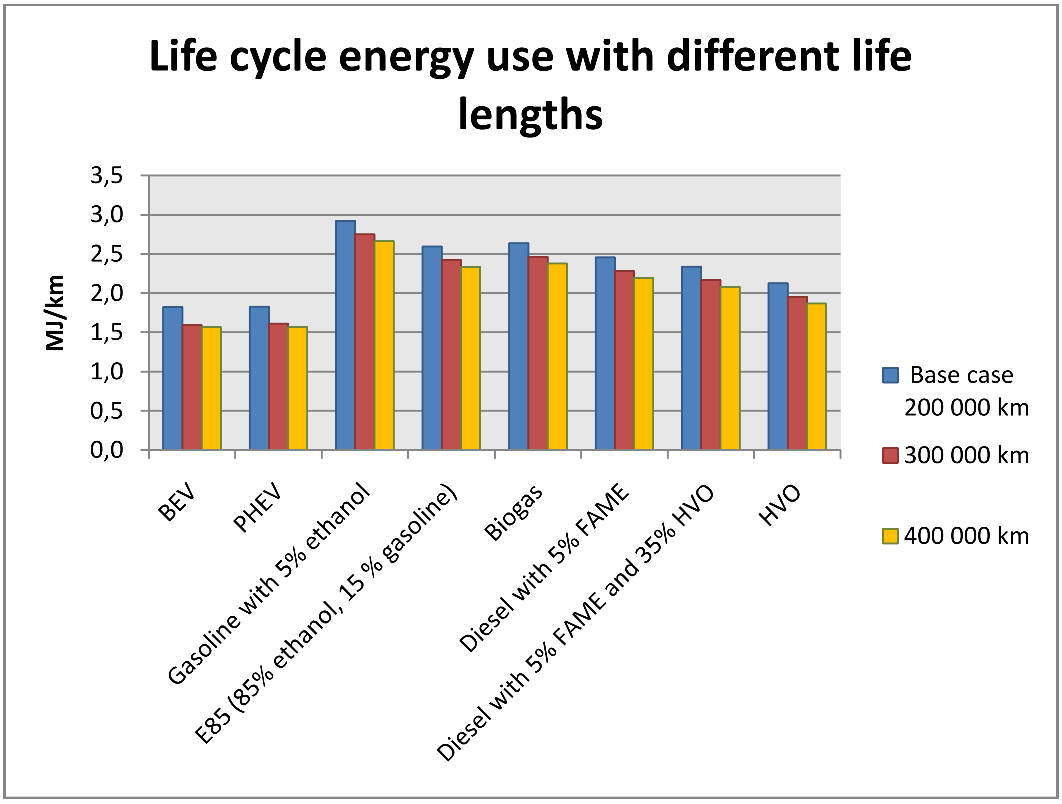

Figure 35. Life cycle energy use for different life lengths shown in MJ/km for different types of cars.

The results in Figure 34 and Figure 35 show that there are rather small differences to the environmental impacts of all of the cars if life length is prolonged. In the case that batteries are not replaced in the EVs and electric cars only have a 200 000 km life length, as in the base case, while the ICEVs are assumed to have a longer life length of 400 000 km there is not a large difference to the base case scenario (section *6.2.2 Base case*) but it is still notable. A 400 000 km life length for the ICEVs and a 200 000 km life length for the EVs would for example render the ICEV that run on biogas a more favourable option than the BEV in terms of GHG. However, that is the largest difference to the case where the EVs and the ICEVs have an equally long life length (Figure 34).

Even in the case of assuming a shorter life length for the EVs of 200 000 km and a longer life length of 400 000 km for the ICEVs, the EVs are more energy efficient than all of the ICEVs (Figure 35).

Fuel consumption

The life length of 200 000 km combined with the 2010 scenario was examined again, but with an increase in fuel consumption with 25% for all types of cars except the EVs. A 2020+ scenario with lower fuel consumption (Table 22) for all types of cars except the EVs was also explored. In these two cases the base case for EVs from previous chapter (section *5.2 Results* and *5.2.1 Base case)* was used as a reference with the slight adjustment that the PHEV now had the same vehicle body production as the BEV and all of the ICEVs. The results are shown in Figure 36 and 37.

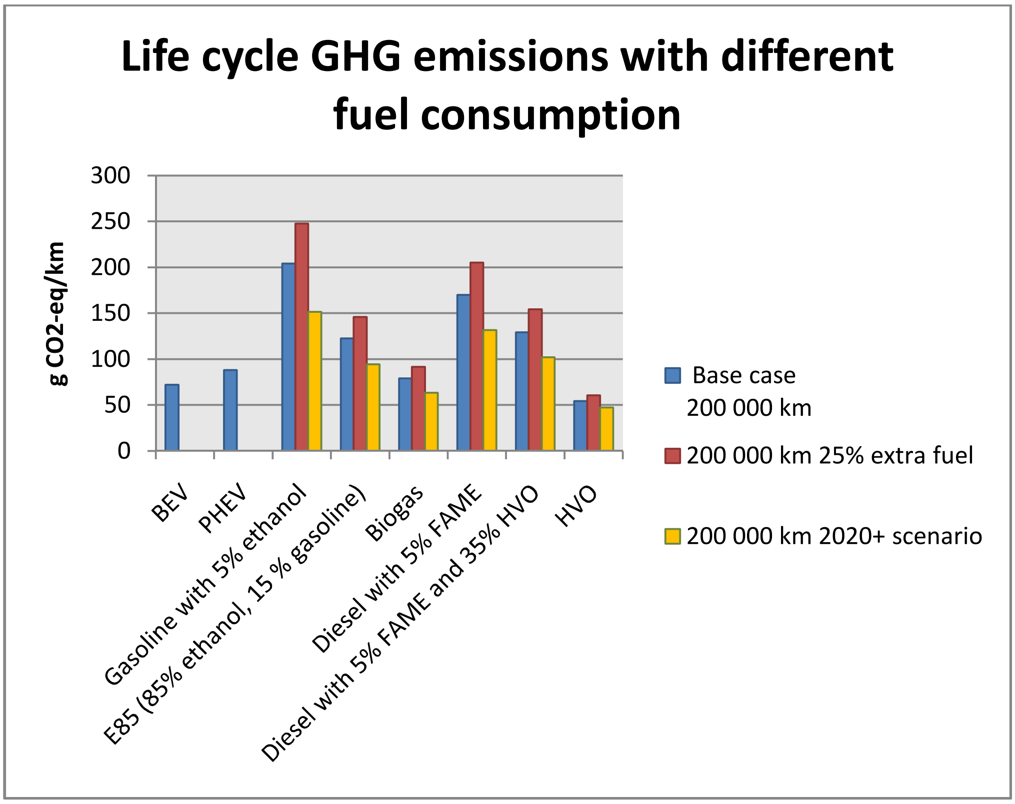

Figure 36. Life cycle GHG emissions for different fuel consumptions (for the ICEVs) shown in g CO_2-eq/km for different types of cars.

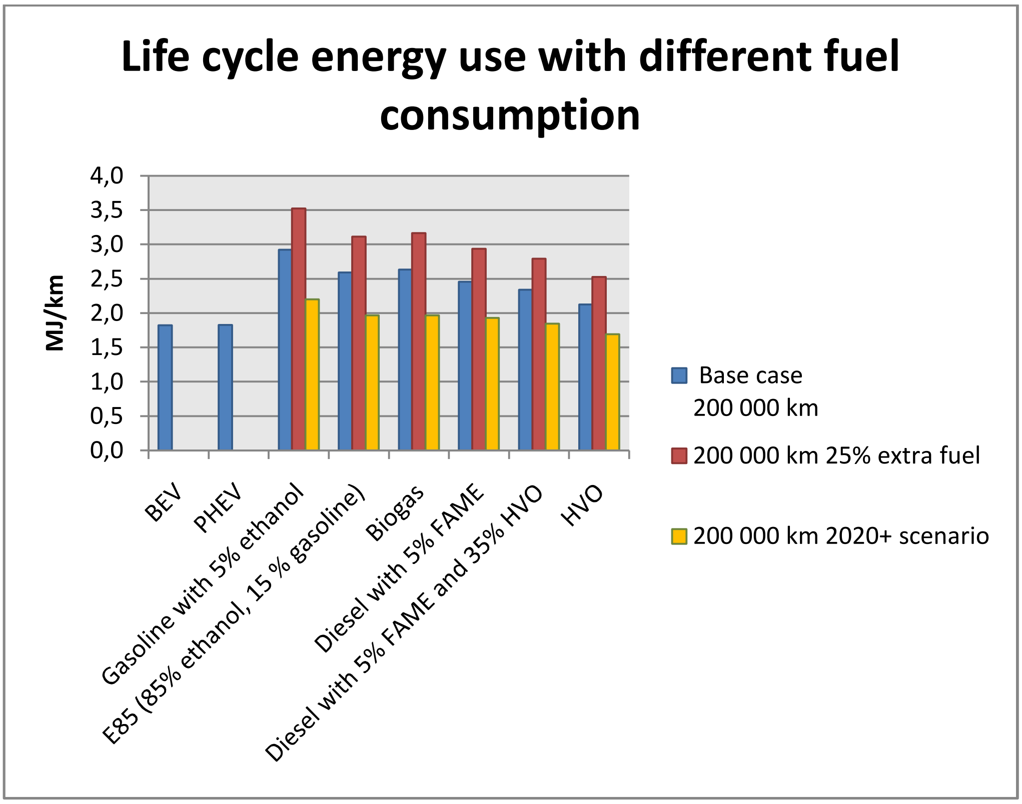

Figure 37. Life cycle energy use for different fuel consumptions (for the ICEVs) shown in MJ/km for different types of cars.

In the case that it is more correct to assume a 25% higher fuel consumption both the GHG emissions and energy use increase notably. This renders the EVs even more favourable in many cases; however an increase in fuel consumption does not highly affect the GHG emissions of HVO and biogas. In a 2020+ scenario the ICEVs are approaching today's EVs in terms of energy efficiency, and many of the ICEVs have lowered their GHG emissions but the ICEVs running on some form of fossil fuel are still not superior to today's EVs.

6.2.4 Best and worst case scenarios

The best and the worst case for the ICEVs were compared to the best and the worst cases for the EVs from the previous chapter (section *5.2 Results* and *5.2.3 Best and worst case scenarios)*, with the slight adjustment that the PHEV now had the same vehicle body production as the BEV and all of the ICEVs.

For the ICEVs the best case scenario was the 2020+ scenario for all types of motors and fuels except for the DICI running on pure HVO. Here, the best case was instead the life length of 400 000 km, using a fuel consumption of 2010.
For all ICEVs, the worst case scenario was the 2010 scenario adding an extra 25% fuel consumption.

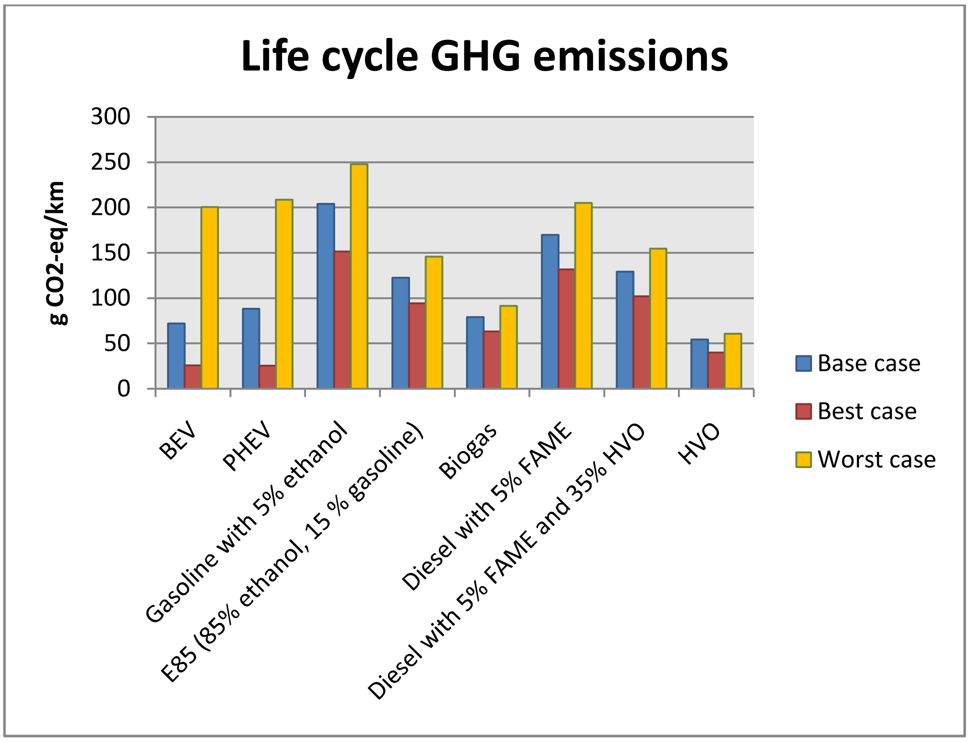

Figure 38. Life cycle GHG emissions for different fuel consumptions (for the ICEVs) shown in g CO_2-eq/km for different types of cars.

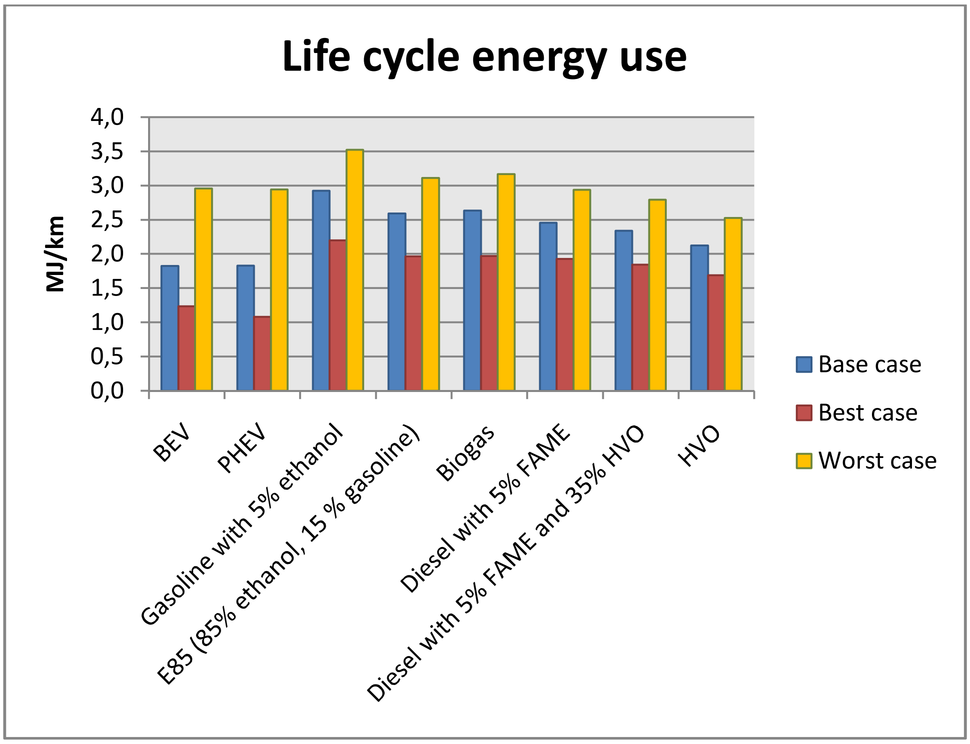

Figure 39. Life cycle energy use for different fuel consumptions (for the ICEVs) shown in MJ/km for different types of cars.

This might not be a fair comparison of best and worst cases as the EVs were assessed for many more parameters than the ICEVs, for example for different electricity mixes. For all biofuels only ‘average’ emission factors have been examined. The results might have been different if the lowest and highest emission factors for the biofuels had been examined as well. For example, the GHG emissions linked to HVO can vary between 8.1 - 57.1 g CO_2-eq/MJ and the parameter value that is used in this thesis corresponds to 35.7 g CO_2-eq/MJ (Table 20).

As the electric car was tried for a higher number of parameters in its best and worst case scenario, the GHG effects and the energy use vary more for the BEV and the PHEV than for any of the ICEVs.

In their best cases the EVs were superior to all other cars both in terms of GHG emissions and energy use. In their worst case scenario, using a high electricity consumption, lifetime of only 150 000 km and charging with a European electricity mix the EVs are still not the worst option in the combined worst case scenarios. This makes the EVs quite competitive, as parameters have been tried for more extreme values in the worst case scenario of the EVs. For example a longer lifetime of 200 000 km is used for the ICEVs in their worst case scenario, while a 150 000 km lifetime is used for the EVs.

7. Perceptions of the electric car and a future outlook

In this chapter the views on the electric car in Sweden today and in the near future are investigated through interviews with actors on the Swedish market. Following the interviews, a short analysis of the answers and a discussion about car mobility and the role of the electric car in the future are included. The methods used in regards to the interviews are described in section *3.4 Interviews.*

7.1 Interviews

To understand the electric car's role in Sweden and to get insight in how people think about sustainability and cars, a series of interviews were made. The questions posed were the same for all interviewees, and the aim was to figure out which type of car that is perceived as the more sustainable option from an environmental perspective both currently and in the future, why, and whether the entire vehicle life cycle is considered while answering or if focus is on the use phase.

Here, the overall results from these interviews are presented and discussed.[24] For more detailed information on interviewees and their answers please refer to Appendix *11.3 Interviews.*

The questions asked were the following:[25]

- **Which type of car available on the market today do you perceive as the most sustainable option from an environmental perspective?**

- ***Which type of electric car? (This question was asked in case the previous answer was 'electric car' and the question is meant to clarify if it is BEV, PHEV etc.).The answer to this question is integrated in the answer to the question above.***

- **Are you considering the vehicle use phase or the entire life cycle?**

- **Why do you think this is the most sustainable option?**

- **Do you consider this type of car the best option in the future as well?**

A total of 9 people representing key actors on the market or specialists connected to sustainable transport were interviewed and during the interviews I took care not to mention the focus on electric cars in this thesis, in order to avoid bias in the answers. The persons interviewed were: Britt Karlsson-Green; strategist at Sustainable Mobility Skåne, Eva Sunnerstedt; working with clean vehicles at the Environment and Health Administration, City of Stockholm, Jakob Lagercrantz; founder of the '2030 secretariat', Johanna Grant; chairperson of the Swedish Association of Green Motorists, Lasse Swärd; reporter at DN specialised in the car industry, Peter Kasche; Swedish Energy Agency, Åsa Kastensson; Researcher within Energy Engineering at Luleå University of Technology, Anna Henstedt;

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[24] It should be highlighted that the answers are personal opinions, and might not coincide with the views and opinions of the companies, organisations or institutions connected with the interviewed person.

[25] The questions were originally in Swedish and have been translated here.

responsible for environmental issues at BIL Sweden and Håkan Johansson; coordinator for climate mitigation at the Swedish Transport Administration.[26] In the summary of answers below there is a slight focus on the parts of answers that covers electric vehicles because that was considered more relevant for this thesis.

All in all the questions were open to different interpretation which could lead to greater variability in the answers. In some cases when no specific technology could be pointed out as superior in the first question, the follow-up questions were not always applicable. In these instances the interviewed person would instead clarify why many different technologies were good and what they had in common, and the last question would become an open speculation about what good technology could look like in the future.

For some of the interviews, answers from one question might be presented under another question in the summary below; this was done in order to give an easy overview of the answers and to allow for a homogenous presentation of all the answers.

7.1.1 Answers

- **Which type of car available on the market today do you perceive as the most sustainable option from an environmental perspective?**

Only Swedish people were interviewed, which means that there is a focus on Sweden and Swedish conditions in all answers. Five of the interviewed people would clarify that geographical conditions such as country where the car is used is of importance and talk around that when discussing the best option of car type today. Other conditions such as infrastructure, personal needs and personal budget were sometimes also mentioned.

The most obvious theme seen in the answers is that the electric car is the single type of car that is always mentioned as a sustainable option; even though some of the interviewees pointed out that they did not like to label any car as ‘sustainable’. The electric car is also the only type of car that is mentioned as the single best option in answers (this happens in three out of nine interviews), no other type of car is mentioned as a possible single best option. When biofuels or fuel cell electric vehicles (FCEVs) are mentioned it is always in a combination with EVs.

For EVs, all nine interviewees specify that an electric car is only a good option if the electricity mix used in charging is good. Different words are used to describe what is considered to be a good electricity mix, such as ‘sustainable’, ‘green’, ‘renewable’ and ‘low in carbon dioxide emissions’. All interviewees seem to be considering the climate impact of vehicles.

Five of the interviewees state that a mix of electric cars and cars run on biofuels is the most sustainable option. Biofuels mentioned are most frequently biogas and ethanol, and in some cases biodiesel. Two people name FCEVs as a sustainable option and one of them thinks that this is probably the best option, if FCEVs are considered part of the market today.

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[26] More information on the interviewees can be found in *11.3 Interviews* in the appendix.

- ***Which type of electric car?***

  When clarified which type of EV people had in mind, the answer would in most cases be a BEV. Many of the interviewed people were also open to the use of PHEVs when a longer range is needed, but there seems to be a consensus that a higher degree of electrification should be a better option. Two of the interviewees expressed concern for how PHEVs are used, and said that there is always a risk of becoming 'lazy' and not charging the battery but relying too heavily on the combustion engine.

- **Are you considering the vehicle use phase or the entire life cycle?**

  Six of the interviewees said that they consider the entire vehicle life cycle, and three people stated that they were considering the use phase. Three people also mentioned that the use phase is the dominating phase when it comes to environmental impacts. Three people touched on the subject of how the production of an electric car has a higher impact than production of a conventional car.

  Five people highlighted the batteries used in EVs here, and mentioned how resources used in these are of importance (two also use the term 'rare metals').

- **Why do you think this is the most sustainable option?**

  All of the interviewees said that the electric car is sustainable in the sense that it has low climate impact or low emissions (depending on electricity mix used). Four people also mentioned how there are no local emissions/tailpipe emissions with a BEV. Five of the interviewees talked about the noise reduction benefits of a BEV compared to combustion engine cars, and this was often linked to being extra beneficial in cities. One of the interviewed people mentioned the high efficiency of electric cars as a plus, and another one mentioned the decreased need for maintenance.

  In most cases the interviewees also pointed out the problems with the electric car, including the high price and the low range. Four of the interviewed people mentioned high costs of EVs as a problem and eight out of nine talked about the low range of EVs. In general it is believed that for the electric car to have a breakthrough it needs to become cheaper and the range will need to be increased.

  Five people also favoured different types of biofuels, and the positive effects of these that were mentioned include a longer range than EVs and the possibility to use with the existing vehicle fleet. Three of the interviewees talked about how biofuels can be produced from decay products, like for example biogas that is produced from waste. This was in two cases also highlighted as a limitation, as it is not possible for all cars to be run on biofuels produced from waste.

  The two interviewees that mentioned the FCEV as a sustainable option highlighted how hydrogen needs to be produced in a sustainable way in order for the FCEV to have a low environmental impact.

- **Do you consider this type of car the best option in the future as well?**

  Generally, the interviewees perceived this a very difficult question. The most obvious theme here was that the FCEVs or some kind of electrofuels seem to be a popular option (five people mentioned this). One of the interviewees who mentioned the FCEV was sceptical as to when this technology might actually become a reality, and emphasised that it might still be a distant future. Another interviewee believed that FCEVs will need to be complemented by BEVs.

  Three people stated that the BEV is probably the best option for sustainable car mobility, at least for a near future. Three of the interviewees believed in some sort of mix between EVs and biofuels, and two of these talked about the great potentials for producing biofuels in a country like Sweden.

  Possible other technologies mentioned were biodiesel produced from algae and inductive roads making EVs more desirable.

  Three people also addressed the issue of the number of cars existing today, and they believe that the car will have to play a smaller role in the future, particularly in cities.

7.1.2 Discussion of the answers

To summarise the results of the interviews; an electrification of the vehicle fleet is seen as the most likely solution for making car mobility more sustainable. A higher degree of electrification is considered to be better, and therefore the BEV is preferred to hybrid options, especially when range is not a limitation, like in cities. Fuel cells combined with hydrogen or some kind of electrofuels were often mentioned. If not perceived as the best option today, it is seen as a sustainable future technology, although concerns about the production of hydrogen were expressed.

There is an obvious focus on the use phase in vehicle life cycles in the answers, but this seems to be justified as the use phase is normally the most influencing phase in the vehicle life cycle. This is particularly the case when studying LCAs from other countries that often have a more carbon dioxide intense electricity mix than Sweden. This was also observed by the interviewees in this chapter. All nine interviewees specified that an electric car only is a good option if the electricity mix used in charging is renewable or connected to low GHG emissions. However, the use phase might not necessarily deserve equal attention in a country like Sweden, as shown in chapter 5. The GHG emissions linked to the use phase of a BEV only correspond to around 30% of the total life cycle GHG emissions when the car is driven on a Nordic electricity mix (Table 18). Vehicle and battery production are of similar importance in the case of the BEV. If the electricity used was renewable as in the case of hydropower the use phase would contribute to only 2% of the life cycle GHG emissions of a BEV (under the same conditions as in the base case). Given this, the focus should instead be on improving vehicle and battery manufacturing to lower the BEV life cycle GHG emissions.

7.2 Future outlook

A great challenge for the electric car today is the limited range of distance, and this has been identified as a reason for why many people will avoid buying an electric car. However, society and infrastructure in the future will probably not look the way it does today and neither will

technology. The electric car has been proved most beneficial in urban areas with a lot of stopping and lower speeds due to regenerative braking. This is also where other advantages like no tailpipe emissions and noise reduction are of high importance. By the year 2050 two-thirds of the global population will be living in urban areas, and in 2014 this percentage was already 54 % (United Nations Department of Economic and Social Affairs, 2015).
This might increase the importance of EVs and make them an even more competitive option. In Sweden the average travel length for a commute to work is 21 kilometres, 42 kilometres round trip (Trafikanalys, 2015). This is a distance that could easily be driven by a BEV and many PHEVs just using electricity.

7.2.1 Projections for the car market in Sweden

As mentioned in section *2.1.2 Transport and climate impact in Sweden* both electricity and biofuels will play important roles in making transportation in Sweden fossil free. It is highlighted in SOU 2013:84 (2013) how an electrification of the vehicle fleet would increase the efficiency of vehicles and increase flexibility as electricity can be produced from a range of different energy sources.

According to Håkan Johansson, coordinator for climate mitigation at the Swedish Transport Administration [Trafikverket], the share of electric miles[27] by 2030 will represent 20% for all types of cars, but 40% for new cars. By 2050 the share of electric miles will instead be 60%, for all existing cars (Johansson, Personal communication, 2015; SOU 2013:84, 2013).This is in a modelled scenario where Sweden reaches its goal of becoming fossil free by 2050.

In order to reach these targets, society and car mobility need to evolve according to three principles: 1) a more aware society with fewer transports and more energy efficient solutions, such as public transport, cycling and walking, 2) improvements in technology in the form of energy efficiency and 3) a transit to renewable fuels (such as renewable electricity/hydrogen gas and biofuels) (Johansson, Personal communication, 2015; SOU 2013:84, 2013).

The GHG emissions from transportation have been decreasing in recent years, and in 2013 the emission levels were 1% below 1990-levels (Trafikverket, 2015). For cars the decrease in emissions for the same period was 16%. The main cause of this reduction was an increased efficiency level in cars and an increased use of biofuels (Naturvårdsverket, 2015b).
Even though emissions from car traffic have been experiencing a dip lately, car traffic is expected to increase 26% from 2010 to 2030 (Trafikverket, 2015).

Håkan Johansson is optimistic about Sweden being able to reach the goal of having a vehicle fleet that is free from fossil fuels, something he believes that all OECD countries are capable of doing. Improvements in regards to energy efficiency in vehicles are advancing, and technology is improving. However, traffic in Sweden is increasing today and this will have to change if Sweden is going to reach the targets. Håkan Johansson emphasizes that besides a transit to cars that run on renewable fuels, journeys made by car need to become shorter and fewer (Personal communication, 2015).

The electric car is mostly associated with driving in cities today, but this could possibly change in

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[27] Miles that are travelled with electricity as fuel.

the future. As there is an increasing amount of options and different varieties of fuels but in lower volumes, the business concept of fuel stations in the countryside will probably become less profitable. The distribution of electricity already exists and the electric car might thus become more important in the countryside (Johansson, Personal communication, 2015).

With regards to biofuels, the total share of biofuels in the transport sector in Sweden is increasing, mostly driven by an increase in biodiesel. Ethanol-use is decreasing, even though the technology to use ethanol is already present in the existing vehicle fleet (Johansson, Personal communication, 2015).

According to Anna Henstedt, responsible for Environmental Issues at BIL Sweden, ethanol reached peak sales numbers in 2008 and cars that run on gas, for example biogas, reached peak sales in 2010 (Personal communication, 2015). In the Swedish Energy Agency's [Energimyndighetens] prognosis for the transport sector in Sweden until 2030, both FAME and biogas will contribute most to the increase in biofuels in the close future (Energimyndigheten, 2013a).

Further, Anna Henstedt notices an increase in the sales of electric cars in Sweden, both BEVs and PHEVs. It is a slow increase, but she believes that it will speed up. She says that besides the lower range of BEVs, an obstacle is the high cost of electric cars. Anna Henstedt hopes that the Swedish government will increase their support in order to 'help' the customer choose the 'right' car, for example with bonus systems like the one that have been used in Norway (Personal communication, 2015).

7.2.2 Future electricity supply and natural resources

The electric car can be perceived as a solution to problems with fuel scarcity, and the argument that electricity can be produced from many different sources is often brought up. A relevant question could be: Is there an issue with how much electricity electric cars consume, and can everybody drive an electric car? Greger Ledung, expert at the Swedish Energy Agency [Energimyndigheten], says that an all electric Swedish car fleet would consume around 20 TWh of electricity per year in the charging of the cars.[28] This is a relatively small number compared to the total electricity consumption per year in Sweden, and the energy requirements of these EVs would not be an issue even though nuclear plants could be shut down in the future. The total electricity consumption in Sweden today is around 126 TWh (Energimyndigheten, 2013b).

The availability of other fuels will not be discussed in this thesis, as it can be rather complex. It should be noted that all fuels might not exist in abundance. As mentioned in the background, the future scenario for a fossil fuel vehicle fleet presented by the Swedish government implies using a mix of biofuels and electricity.

As seen in the interviews, section *7.1.1 Answers* there are also some concerns regarding the use of rare metals and resources used in the electric car's batteries among the interviewees. Examples of resources used in batteries are lithium, cobalt, nickel, REE (for example

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[28] Based on that today's Swedish car fleet consume around 50 TWh and that electric cars are presumed to be roughly 2.5 times more energy efficient than the ICEVs that constitute most of today's car fleet.

neodymium, dysprosium and terbium) and manganese. Lithium is currently the most constraining resource used in EV batteries (Chalmers, 2014). Lithium is especially interesting to study as it is and will most likely remain the leading future battery technology.
There is a future generation of lithium batteries called lithium-air, and these batteries that are currently under development are projected to have an energy density of around 10 times the energy density in today's lithium-ion batteries. The lithium-air technology is not likely to be available for commercial use for another 20-30 years (Chalmers, 2014).

Whether there is enough lithium to cover the needs for future demands is going to be highly dependent on how recycling is carried out (Chalmers 2014). However, the lithium content in a car battery is mostly below 2%, and today it is not economically viable to recycle this, as virgin lithium is sold at a much lower cost than the cost of recycling lithium. Either this has to change, or legislations about recycling of lithium needs to be established in order to make the use of lithium in batteries sustainable from a long term perspective (Forsgren, Personal communication, 2015).

As mentioned, lithium is the primary constraining resource used in EVs, followed by dysprosium and terbium. In a scenario looking at large-scale production of PHEVs worldwide, it is these three resources that could possibly restrict production, although this does not seem particularly likely. This is the conclusion in Chalmers (2014) that study a future scenario with no material losses, which is why recycling will be necessary. However, no lithium is currently recycled with a high-enough quality to allow it to be reused in new batteries (Chalmers, 2014). In another study, a scenario that involves large-scale EV usage all over the world was modelled. The lithium supplies in this study were estimated to be large enough to support that development, but it is unclear what assumptions of recycling that were made by the authors (Dunn et al. 2015).

Based on this, there seems to be no reason for concern regarding the abundance on resources, even in a high demand scenario, as long as recycling is carried out. But as pointed out by Chalmers (2014) it is possible that the increased demand for some of these resources could create bottle-necks, and there might be some increases in price.

8. Discussion

8.1 The electric car

A theme that emerged during the writing of this thesis was that it is surprisingly difficult to find good quality LCA on EVs that are easy to read and interpret. One of the aims with this thesis was to create an overview of results on emissions and energy use of EVs from existing LCAs, as well as identifying important steps of the life cycle from these. This proved difficult as many LCAs do not present any details of their calculations or assumptions, but instead rely on a single graph or a general discussion to present their findings. In many cases the results from the same LCAs will figure in many other LCAs, meaning that many studies are probably based on the same (sometimes undeclared) underlying parameter assumptions.

Another important finding was that there is a gap in the literature regarding recent LCAs of newer electric cars. These LCAs will need to be more transparent than existing studies, and it should be easier to follow energy use and emissions linked to different stages of life. This would allow for a single LCA to be of use to a wider range of readers, as it could more easily be adapted to specific conditions.

When selecting which literature to include there is always a risk that the presented results are somewhat biased, and that information has been lost in the literature selection process. It is also sometimes hard to assess where published studies have gathered all of their information from, and to evaluate if these sources are reliable and well-founded. This could be researched further, but lay outside the scope of this thesis. Looking at the studies represented in this thesis there is a predominance of European studies. This was a conscious choice as it was deemed more relevant for the consequent analysis of the electric car, which assumed that the car was driven in Sweden or Europe. In addition, a number of otherwise good quality studies could not be used as they did not clearly separate the different life stages of the EVs.

The results obtained in the analysis of the EVs that was made in this thesis (in chapter *5. Life cycle analysis of an electric car in Sweden*) indicate lower GHG emissions and energy use than what has been found in other LCAs. This is made clear when comparing the base case results (in the analysis in Figure 16 Figure 17) to those obtained in the literature review (Table 1). This difference is probably due to the fact that a Nordic electricity mix was assumed in the analysis of the electric car in this thesis, while other studies have assumed more carbon dioxide intense electricity mixes.

In the sensitivity analysis, where different electricity mixes were assessed among other factors, it was estimated that for a BEV the GHG emissions range from between around 26-201 g CO_2-eq/km, and the energy use between 1.1-3 MJ/km. For a PHEV these values were 25-214 g CO_2-eq/km and 1-3 MJ/km. The upper limits of the estimates based on a European electricity mix (among other factors changed) are more similar to the results found in other studies, and even higher than some. Under these assumptions, the PHEV might appear to be superior or at least very similar to the BEV, but it is important to remember that this is under very specific conditions and that the electricity consumption for the BEV was set relatively high in the sensitivity analysis. In the base case scenario, a PHEV emitted more life cycle GHG and had higher life cycle energy consumption than a BEV. However, the results suggest that if driven in the electrical mode, a PHEV can be superior to a BEV in terms of environmental performance under specific conditions.

More detailed results may have been obtained if more focus had been put on the type of lithium ion batteries used in the EVs. This was deemed difficult as different studies used different batteries, and it was sometimes hard to distinguish specific battery types. The exact components of the batteries change over time, and sometimes even between different model years of the same car model. However, all batteries examined are lithium-ion. The difference between different types of lithium-ion batteries is discussed briefly in *4.2.2 Important parameters and stages of the life cycle* and *Battery production.*

As for the importance of different life stages of the electric car, the use phase was the phase where the highest variation was noted, and it is also this phase that was in focus for the sensitivity analyses in this thesis. This corresponds well to what has been found in other LCAs. However, in this thesis, other phases such as vehicle body production and battery production were found to be contributing highly towards the life cycle GHG emissions and energy use. The contribution was relatively higher for BEVs than for PHEVs. That is why these stages of life are of greater interest to study when the electricity mix used in charging is relatively sustainable and low in GHG emissions, like the Nordic electricity mix. In the base case, vehicle body production and battery production corresponded to 35% and 28% respectively of the total life cycle GHG emissions. For a PHEV these percentages were 32% and 14%.

Both in previous studies found during the literature review and in some of the interviews (Appendix *11.3 Interviews*) it is common to quote impacts of different life phases such as battery production and use phase as a percentage of total life cycle impacts. However, it is crucial to emphasise that a percentage is not an absolute number, and that the same battery with an impact of 5% on the total life cycle GHG emissions using a certain electricity mix might correspond to 40% in a different setting since electricity mix used to charge the car will have a larger impact. This is particularly important to bear in mind when studying LCAs from countries that use different electricity mixes.

To further improve the electric car in a country like Sweden, the largest potential decrease in life cycle GHG emissions might not always be achieved by improving the electricity used in charging. Judging from results in this thesis, more focus should be given to manufacturing methods in particular. As has been discussed briefly, the electricity mix used for producing the batteries could possibly make a large difference, but this has not been investigated further in this thesis.

In the analysis restricted to EVs (*5. Life cycle analysis of an electric car in Sweden*) and in the analysis of EVs and ICEVs (*6. Electric cars in comparison to cars with combustion engines*), two different estimated values of vehicle body production were used for the PHEV. In the EV analysis in this thesis (*5. Life cycle analysis of an electric car in Sweden*) a parameter value representative of PHEV specific studies was used, but the production of a vehicle body is really more dependent on the model of car chosen and the method of production than the type of powertrain the vehicle body is constructed for.

In the comparison of EVs and ICEVs a uniform vehicle body was used; that of the BEV. This in itself can be seen as a sort of sensitivity analysis when it comes to small changes to the vehicle body. In the base case of the PHEV, changing the vehicle body resulted in a total change of 4 g CO_2-eq/km and 0.1 MJ/km. These are not very large differences, but it still shows how changing the vehicle body does make a small difference.

Another factor that could influence the final results on GHG emissions and energy use for the PHEV in the analysis is the fact that conventional gasoline was used and not a mix with 5% ethanol. This is the case both in chapter *5. Life cycle analysis of an electric car in Sweden* and in chapter *6. Electric cars in comparison to cars with combustion engines.* Had the gasoline mix with 5% ethanol been used instead the base case scenario would have resulted in lowering the GHG emissions with 2 g CO_2-eq/km, but it would have almost no effect on the primary energy use.

It is also of interest to discuss the assumed electricity consumption, as this is a key factor that could influence the results. An electricity consumption of 18 kWh/100 km was used in the base case scenario for the BEV, and because this is based on information from the manufacturer (Nissan) it could be an underestimate. When studying different drive patterns in chapter 5, the BEV was investigated for higher electricity consumptions of up to 24.9 kWh/100 km for driving in motorway conditions only (*5.1.1 Life cycle* stages and *Use phase)*. Differences in the electricity consumption were found to produce an increase of 9 g CO_2-eq/km and 0.4 MJ/km on the total life cycle GHG emissions and energy use as compared to the base case scenario (Appendix *11.2.1 Detailed results of the sensitivity analysis of EVs* and *Drive patterns*). This corresponds to an increase of 12.5% in GHG emissions and 23.5% in primary energy use as compared to the base case, which represents a significant increase. However, an electricity consumption as high as 24.9 kWh/100 km is not likely to occur during average driving conditions with the battery technology used today.

On the other hand, Gröna Bilister (2015) have reported an electricity consumption of 15 kWh/100 km for a Nissan Leaf, which is lower than the parameter value used in the base case analysis in this thesis. In Huss et al. (2013), the electricity consumption of a 2020+ scenario for a BEV battery that has a battery capacity of 22 kWh (the BEV battery in this thesis has 24 kWh) is 11 kWh/100 km, which is even lower. However, it should be noted that this is for a slightly futuristic scenario of 2020+ where battery efficiency is even further improved.
Considering these factors an electricity consumption of 18 kWh/100 km is probably a realistic assumption.

In this thesis many of the changes in the sensitivity analyses were tested in combination with using a Nordic electricity mix. This should be highlighted as the impact on GHG emissions and energy use presented in the sensitivity analysis could be very different had another electricity mix, with a more GHG intense production and primary energy use, been used instead. For example, small changes to the GHG emissions when driving in motorway conditions may have corresponded to larger changes in GHG emissions if a European electricity mix had been the focus of study instead. This has to some extent been modelled in the best and worst case scenario for the EVs.

Although it has not been the focus of this study, a number of aspects of driving an EV in addition to the climate benefits could have been brought to attention and discussed. EVs will not pollute an urban environment in the same way an ICEV does by spreading particle matter that can have a negative impact on human health. The same is true for noise, which does not occur with an electric motor to the same extent as an ICE. This is highlighted while doing interviews with actors on the Swedish market (*7.1.1 Answers*).

The EOL stage does imply a certain degree of uncertainty, but this stage was found to not be a major contributor to either life cycle GHG emissions or energy use. It is debated whether or not there are GHG emission and energy savings to be made if recycling is carried out.
In this thesis a reduction of 50% to both GHG emissions and energy use in new battery production was tested in the sensitivity analysis. This did result in noticeable changes for the entire life cycle of EVs, a 10 g CO_2-eq/km and a 0.1 MJ/km reduction for the BEV and a 6 g CO_2-eq/km and a 0.1 MJ/km reduction for the PHEV. Whether recycling will be carried out to this extent and using methods that allow for this degree of efficiency remains to be seen.

To touch briefly on the limitations of electric cars, ones that are often mentioned in the interviews (*7.1.1 Answers*) include the price and the range. These are also highly connected as it is the batteries that make electric cars so expensive and it is also the batteries that determine the range. An example is given in Thomas (2011), who states that to double the range of a BEV from 161 km to 322 km an extra 800 kg of batteries (lithium-ion) is needed. To put this number in perspective, the most common BEV in the world and in Sweden, Nissan Leaf has a battery of 300 kg. This remains a limitation for EVs.

8.2 The electric car in comparison to cars with combustion engines

When doing a comparison between different types of vehicles there is always going to be a number of difficulties concerning the method. In this thesis, the EV has been examined and looked at closely while more generalised assumptions have been made for other types of cars. Therefore, the outcome and results related to an EV were scrutinised at a more detailed level, giving more depth to that part of the analysis. This could mean that the results in the comparison with ICEVs were affected in either direction, as not as many studies were used for input for these vehicles. Nor was the sensitivity analysis as extensive for the ICEVs and that has to be kept in mind when studying the results in *6.2.4 Best and worst case scenarios*. The comparison still does give a broad idea of the possible range of GHG emissions and energy use the cars may have, particularly when only studying the base case scenarios.

Chalmers (2014) concluded that electric cars are more energy efficient than ICE cars. Efficiency in the electric motor varies between 85-95 %, which is superior to an ICE. ICEVs typically have motor efficiencies of 28-30% (Faria et al., 2012). This is reflected in the results in the comparison between EVs and ICEVs in this thesis. Both the BEV and the PHEV used less life cycle energy/km than all of the other types of cars and fuels (Figure 33). Even in the worst case scenario where the EVs were evaluated for many more factors, the EVs still used less life cycle energy than the worst case scenario of many of the ICEVs. The exceptions were the HVO and the diesel blend with 5% FAME and 35% HVO, and the EVs were on a similar level to the energy use of diesel with 5% FAME (Figure 39).

The EVs also gave rise to lower GHG emissions per km than other types of cars (in the base case scenario) with the exception of a car run on low carbon intense HVO based mostly on organic residues and by-products, shown in Figure 32. Seemingly, the electric car is a very strong candidate to sustainable car mobility. This becomes even clearer if a renewable electricity mix is used, and the life cycle emissions of GHG and energy use was found to be lower for a BEV run on hydropower electricity than an ICEV run on 100% low carbon intense HVO, which can be seen when comparing results in Figure 20 and Figure 21 to Figure 32 and Figure 33.

As mentioned previously, the sensitivity analysis in this thesis is not as extensive for ICEVs as for EVs. A factor that might have been interesting to study in greater detail is the effect of different drive patterns. While electric cars benefit from driving in an urban area, the opposite has been found to be true for ICEVs (Raykin et al., 2012; Helms et al., 2010). Other factors that could have been interesting to include in a sensitivity analysis for ICEVs are the effects of different GHG emission factors depending on feedstock for biofuels and DLUC and ILUC effects related to biofuels. LUC effects were not studied in this thesis as they can be rather complex. The large European commission WTW study acknowledges that “both DLUC and ILUC can be important in understanding the impact of biofuels, but they are difficult to estimate” (Edwards et al., 2014a, p21).

When it comes to production of fossil vehicle fuels, there is not likely room for improvement unless we move towards using some sort of CCS technique on tailpipe emissions. In the near future, emissions from these fuels will most likely remain unaltered or possibly increase due to new more demanding extraction methods. The emissions connected to electricity production do not have the same limitations, and this is possibly the main reason that the electric car is seen as the solution to more sustainable mobility. If electricity production is made more sustainable, electric cars could theoretically have very close to zero GHG emissions in the use phase, as was shown in this thesis in the case of using hydropower in charging a BEV (Figure 20).

8.3 Suggestions for continued work

- Similar studies looking at different types of vehicles. During the work for this thesis, requests for a similar study focusing on larger vehicles, especially buses, were put forward by various people.
- Batteries: An analysis of methods used in battery production, through a literature inventory and interviews. Estimates of energy requirements related to battery production and the effects of battery production in different countries with different electricity mixes. Where are most EV batteries manufactured and where is future production headed?
- How much further can battery and vehicle body manufacturing processes be improved?
- Behavioural patterns in relation to driving PHEVs. How are PHEVs used and charged in a country like Sweden? What is reasonable to assume in terms of electric drive?
- As seen in the comparison to other fuels in section *6.2 Results*, low carbon intense HVO (if based mostly on residues and by-products) is a competitive option to the electric car and results in low emissions of GHG. What are the potentials for low carbon intense HVO as a

fuel? Is it realistic for a larger proportion of for example the Swedish vehicle fleet to be run on low carbon intense HVO?

- An even more extensive sensitivity analysis for other types of fuel would be interesting to conduct. Additional factors analysed could include different drive patterns and different feedstock for biofuels.

9. Conclusion

In this thesis, estimates of life cycle GHG emissions and life cycle energy use of electric cars driven in Sweden were compiled. The results indicate that a BEV driven in Sweden emits approximately 72 g CO_2-eq/km, and uses around 1.8 MJ/km of energy. A PHEV driven in Sweden emits approximately 92 g CO_2-eq/km, and uses around 1.9 MJ/km of energy. In a sensitivity analysis of the EVs these parameters range between around 26-201 g CO_2-eq/km and 1.1-3 MJ/km for the BEV, and 25-214 g CO_2-eq/km and 1-3 MJ/km for the PHEV.

The electricity mix used in charging was identified to have the largest impact on the life cycle GHG emissions and energy use of the EVs, and the chosen life length of the vehicle was found to be the second most important factor. However, for the PHEV alone, the drive pattern had the largest impact. This is due to the fact that when the PHEV is not driven in a highly electric mode (as is the case when driving in motorway conditions) the GHG emissions and energy use increase drastically.

The results also showed that the relative impacts related to the use phase of an EV, especially a BEV, are most likely lower in Sweden than what is often quoted in studies done in other countries. If the production of the electricity mix used for charging the vehicle results in low GHG emissions and has a low primary energy use, more focus should instead be given to improvement of vehicle and battery production.

When compared to ICEVs, in particular those that run on fossil fuels, the electric car has emerged as a very good option in terms of reducing the environmental impact. The BEV is the second best option when it comes to GHG emissions, only driving on a 100% low carbon intense HVO based mostly on residues and by-products is a better option. The third best option is driving on biogas, and this is followed by the PHEV.
Both of the EVs have a lower primary energy use than all of the ICEVs, rendering the electric car superior in terms of energy.

The results from the interviews with different actors on the Swedish market showed that the electric car is perceived to be a very competitive option. It is the only type of car that is always mentioned as an answer to the question '*Which type of car available on the market today do you perceive as the most sustainable option from an environmental perspective?'* The electric car is also the only type of car that is pointed out as a single best option in answers.

When it comes to electric cars and sustainable mobility, there were a number of uncertainties considering the battery manufacturing and the recycling in particular. These processes are not described in a transparent manner in existing LCAs of electric vehicles. Additionally, almost all EV batteries that are currently being introduced on the market are still in use, which makes it hard to determine how batteries will be recycled.

To conclude where this thesis first started, it is fitting to address the allegations made in the articles quoted in the introduction. While there may be doubts regarding the performance of an electric car, the research presented here shows that an EV driven in Sweden is always better than a gasoline car or a diesel car, and in many cases also better than cars that run on biofuels in terms of environmental impact. This is the case for all electricity mixes similar or more sustainable than the Nordic electricity mix.

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11. Appendix

11.1 Calculations

11.1.1 PHEV production

The original parameter values for GHG emissions linked to PHEV vehicle body production and battery production in Samaras and Meisterling (2008) have been changed to better match the GHG intensity of energy used in BEV production in Notter et al. (2010). This is done keeping while the original energy used in production in Samaras and Meisterling (2008). Calculations as follows:

GHG emissions linked to vehicle body production:

$$\frac{102 \cdot 10^3 MJ}{\left({88.4 \cdot 10^3 MJ}\Big/{5.1 \cdot 10^3\ kg\ CO_2 - eq} \right)} = 5.9 \cdot 10^3\ kg\ CO_2 - eq$$

GHG emissions linked to vehicle battery production:

$$\frac{27.2 \cdot 10^3 MJ}{\left({31.2 \cdot 10^3 MJ}\Big/{1.8 \cdot 10^3\ kg\ CO_2 - eq} \right)} = 1.6 \cdot 10^3\ kg\ CO_2 - eq$$

11.1.2 Emission factors for different fuels

Gasoline

The WTT gasoline life cycle emits 13.8 g CO_2-eq/MJ final fuel and has a primary energy use of 0.18 MJ/MJ final fuel (Edwards et al., 2014c). Gasoline emits 73.4 g CO_2-eq/MJ, the energy content is 43.2 MJ/kg fuel (low heating value) and the density is 745 kg/m^3 (Huss et al., 2013). Both of these studies constitute the foundation of the large WTW study ordered by the European Commission.

The GHG emissions and primary energy use linked to gasoline is calculated as follows:

$$(73.4 + 13.8)\text{g } \mathrm{CO_2 - eq/MJ} = 87.2 \text{ g } \mathrm{CO_2 - eq/MJ}$$

$$(73.4 + 13.8)\text{g } \mathrm{CO_2 - eq/MJ} \cdot 43.2\ \mathrm{MJ/kg} \cdot 745\ \mathrm{kg/m^3} \cdot 0.001\mathrm{m^3/l} = 2\,806\ \mathrm{CO_2 - eq/l}$$

$$43.2\ \mathrm{MJ/kg} \cdot 745\ \mathrm{kg/m^3} \cdot 0.001\mathrm{m^3/l} \cdot (1 + 0.18\ \mathrm{MJ/MJ_{final\ fuel}}) = 37.98\ \mathrm{MJ/l}$$

Diesel

The WTT diesel life cycle emits 15.4 g CO_2-eq/MJ final fuel and has a primary energy use of 0.20 MJ/MJ final fuel (Edwards et al., 2014c). Diesel emits 73.2 g CO_2-eq/MJ, the energy content is 43.1 MJ/kg fuel (low heating value) and the density is 832 kg/m^3 (Huss et al., 2013).

Both of these studies constitute the foundation of the large WTW study ordered by the European Commission.

The GHG emissions and primary energy use linked to diesel is calculated as follows:

$$(73.2 + 15.4)\text{g CO}_2 - \text{eq/MJ} = 88.6 \text{ g CO}_2 - \text{eq/MJ}$$

$$(73.2 + 15.4)\text{g CO}_2 - \text{eq/MJ} \cdot 43.1 \text{ MJ/kg} \cdot 832 \text{ kg/m}^3 \cdot 0.001\text{m}^3/\text{l} = 3\,177 \text{ CO}_2 - \text{eq/l}$$

$$43.1 \text{ MJ/kg} \cdot 832 \text{ kg/m}^3 \cdot 0.001\text{m}^3/\text{l} \cdot (1 + 0.20 \text{ MJ/MJ}_{\text{final fuel}}) = 43.03 \text{ MJ/l}$$

Biofuels in blends

For all pure biofuels, GHG emission factors (in g CO_2-eq/l) from Energimyndigheten (2015b) are used. For biofuels in blends with gasoline and diesel, a new emission factor for that blend is calculated. This is done using the GHG emission factors on gasoline and diesel (also in g CO_2-eq/l)obtained from Huss et al. (2013) and Edwards et al. (2014c) shown in the sections above.

For a mix of 95% gasoline and 5% ethanol the fuel consumption is calculated as follows:

$$0.95 \cdot \text{emission factor of gasoline} + 0.05 \cdot \text{emission factor of ethanol}$$

The same principle applies to all other mixed fuels.

11.1.3 Fuel consumptions

Electricity and gasoline consumption of the EVs

For a BEV only electricity is of interest, but for a PHEV the GHG emissions and energy use from both electricity and gasoline is of interest. Below is accounted for how GHG emissions and primary energy use has been calculated for both electricity and gasoline.

In the sensitivity analysis where different drive patterns and use of auxiliaries are applied the same calculations have been made, but the electricity consumption in kWh/km has been altered. For the PHEV the fuel consumption in l/km and the degree of electrification/fuel use have also been altered. In the base case scenario this was kept at 0.75 (electricity use) and 0.25 (fuel use).

The total GHG emissions given in g CO_2-eq for electricity used in a BEVs is calculated as follows for a Nordic electricity mix:

$$0.18 \text{ kWh/km} \cdot \text{distance driven } \cdot 125 \text{ g CO}_2 - \text{eq/kWh}$$

Distance driven corresponds to the vehicle length of life.

The total primary energy use given in MJ for electricity used in a BEV is calculated as follows for a Nordic electricity mix:

$$0.18 \text{ kWh}_{\text{electricity}}/\text{km} \cdot \text{distance driven } \cdot 1.74 \text{ kWh/kWh}_{\text{electricity}} \cdot 3.6 \text{ MJ/kWh}$$

The total GHG emissions given in g CO_2-eq for electricity used in a PHEV is calculated as follows for a Nordic electricity mix:

$$0.16 \text{ kWh/km} \cdot \text{distance driven } \cdot 0.75 \cdot 125 \text{ g CO}_2 - \text{eq/kWh}$$

The total primary energy use given in MJ for electricity used in a PHEV is calculated as follows for a Nordic electricity mix:

$$0.16\ \mathrm{kWh_{electricity}/km} \cdot \text{distance driven } \cdot 0.75 \cdot 1.74\ \mathrm{kWh/kWh_{electricity}} \cdot 3.6\ \mathrm{MJ/kWh}$$

The same calculations are done in the sensitivity analysis. Parameters that will change for electricity are distance driven, degree of electrification (in the examples above electricity use is 0.75), GHG emissions linked to electricity production (in the examples above it is 125 g CO_2-eq/kWh) and primary energy use in electricity production (in the examples above it is 1.74 kWh/$kWh_{electricity}$).

The total GHG emissions given in g CO_2-eq for gasoline used in a PHEV is calculated as

$$0.045\ \mathrm{l/km} \cdot \text{distance driven } \cdot 0.25 \cdot 2\,806\ \mathrm{g\ CO_2 - eq/l}$$

The total primary energy use given in MJ for gasoline used in a PHEV is calculated as

$$0.045\ \mathrm{l/km} \cdot \text{distance driven } \cdot 0.25 \cdot 37.98\ \mathrm{MJ/l}$$

The same calculations are done in the sensitivity analysis. Parameters that will change for gasoline are distance driven and degree of electrification (in the examples above fuel use is 0.25).

Fuel consumption for blends of different fuels

The fuel consumptions in *6. Electric cars in comparison to cars with combustion engines* are based on Huss et al. (2013) that present parameter values on the fuel consumption of gasoline, diesel, E85, biogas, FAME and HVO. Calculations are made to obtain fuel consumptions for all blends (including a new mix of E85) and pure ethanol. Huss et al. (2013) use a mix of E85 that contains 80% ethanol and 20% gasoline. This is used to obtain the fuel consumption of pure ethanol to use in blends, and to create a new blend of E85 containing 85% ethanol and 15% gasoline.

For a mix of 95% gasoline and 5% ethanol the fuel consumption is calculated as follows:

$$0.95 \cdot \text{fuel consumption of gasoline} + 0.05 \cdot \text{fuel consumption of ethanol}$$

The same principle applies to all other mixed fuels.

11.2 Results

11.2.1 Detailed results of the sensitivity analysis of EVs

In Tables 24-33 the total life cycle GHG emissions and primary energy use are shown for a BEV and a PHEV for different life lengths, electricity mixes, drive patterns and battery recycling. In Tables 34-37 the total life cycle GHG emissions and primary energy use and percentual contributions of each life cycle stage towards the total life cycle GHG emissions and primary energy are shown for a BEV and a PHEV in the best and worst case scenario.

Length of life

In the battery replacement scenario with a life length of 400 000 km the GHG emissions and the energy use linked to battery production have been doubled. No changes have been made to the EOL phase, but it is probable EOL would increase slightly because of the extra battery.

Table 24.Life cycle GHG emissions divided on the different stages of life shown in g CO_2-eq/km.

GHG (g CO_2-eq/km)	BEV				PHEV			
	Base case 200 000 km	**150 000 km**	**300 000 km**	**400 000 km with battery replacement**	**Base case 200 000 km**	**150 000 km**	**300 000 km**	**400 000 km with battery replacement**
Vehicle body production	26	34	17	13	30	39	20	15
Battery production	21	27	14	21	13	17	8	13
Use phase	23	23	23	23	47	47	47	47
EOL	4	5	2	2	4	5	2	2
Total	**72**	**89**	**56**	**58**	**92**	**107**	**77**	**76**

Table 25. Life cycle energy use divided on the different stages of life shown in MJ/km.

Energy (MJ/km)	BEV				PHEV			
	Base case 200 000 km	**150 000 km**	**300 000 km**	**400 000 km with battery replacement**	**Base case 200 000 km**	**150 000 km**	**300 000 km**	**400 000 km with battery replacement**
Vehicle body production	0.44	0.59	0.29	0.22	0.51	0.68	0.34	0.26
Battery production	0.18	0.24	0.12	0.18	0.13	0.17	0.09	0.13
Use phase	1.13	1.13	1.13	1.13	1.18	1.18	1.18	1.18
EOL	0.08	0.10	0.05	0.04	0.08	0.10	0.05	0.04
Total	**1.83**	**2.06**	**1.59**	**1.57**	**1.89**	**2.13**	**1.66**	**1.60**

Electricity mix

Table 26. Life cycle GHG emissions divided on the different stages of life shown in g CO_2-eq/km.

GHG (g CO_2-eq/km)	BEV						PHEV					
	Base case Nordic	**Nordic, low emissions**	**European high, voltage**	**European, low voltage**	**Swedish**	**Renewable (hydropower)**	**Base case Nordic**	**Nordic, low emissions**	**European high, voltage**	**European, low voltage**	**Swedish**	**Renewable (hydropower)**
Vehicle body production	26	26	26	26	26	26	30	30	30	30	30	30
Battery production	21	21	21	21	21	21	13	13	13	13	13	13
Use phase	23	18	88	97	7	1	47	**43**	90	96	36	32
EOL	4	4	4	4	4	4	4	4	4	4	4	4
Total	**72**	**67**	**138**	**147**	**56**	**51**	**92**	**89**	**136**	**142**	**81**	**78**

Table 27. Life cycle energy use divided on the different stages of life shown in MJ/km.

Energy (MJ/km)	BEV						PHEV					
	Base case Nordic	**Nordic, low emissions**	**European high, voltage**	**European, low voltage**	**Swedish**	**Renewable (hydropower)**	**Base case Nordic**	**Nordic, low emissions**	**European high, voltage**	**European, low voltage**	**Swedish**	**Renewable (hydropower)**
Vehicle body production	0.44	0.44	0.44	0.44	0.44	0.44	0.51	0.51	0.51	0.51	0.51	0.51
Battery production	0.18	0.18	0.18	0.18	0.18	0.18	0.13	0.13	0.13	0.13	0.13	0.13
Use phase	1.13	1.13	1.26	1.46	1.36	0.78	1.18	1.18	1.27	1.40	1.33	0.95
EOL	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Total	**1.83**	**1.83**	**1.96**	**2.16**	**2.06**	**1.48**	**1.89**	**1.89**	**1.99**	**2.12**	**2.05**	**1.67**

Drive patterns

Table 28. Life cycle GHG emissions divided on the different stages of life shown in g CO_2-eq/km.

GHG (g CO_2-eq/km)	BEV				PHEV			
	Base case	**Urban areas**	**Extra urban areas**	**Motorway**	**Base case**	**Urban areas**	**Extra urban areas**	**Motorway**
Vehicle body production	26	26	26	26	30	30	30	30
Battery production	21	21	21	21	13	13	13	13
Use phase	23	26	26	31	47	22	43	152
EOL	4	4	4	4	4	4	4	4
Total	**72**	**75**	**76**	**81**	**92**	**67**	**89**	**197**

Table 29. Life cycle energy use divided on the different stages of life shown in MJ/km.

Energy (MJ/km)	BEV				PHEV			
	Base case	**Urban areas**	**Extra urban areas**	**Motorway**	**Base case**	**Urban areas**	**Extra urban areas**	**Motorway**
Vehicle body production	0.44	0.44	0.44	0.44	0.51	0.51	0.51	0.51
Battery production	0.18	0.18	0.18	0.18	0.13	0.13	0.13	0.13
Use phase	1.13	1.28	1.30	1.56	1.18	1.03	0.83	2.07
EOL	0.08	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Total	**1.83**	**1.98**	**2.00**	**2.26**	**1.89**	**1.74**	**1.54**	**2.79**

Table 30. Life cycle GHG emissions divided on the different stages of life of a BEV shown in g CO_2-eq/km.

GHG (g CO_2-eq/km)	Base case	AC off			AC on heat		
		Eco	**Normal**	**Aggressive**	**Eco**	**Normal**	**Aggressive**
Vehicle body production	26	26	26	26	26	26	26
Battery production	21	21	21	21	21	21	21
Use phase	23	13	16	19	21	23	27
EOL	4	4	4	4	4	4	4
Total	**72**	**63**	**66**	**69**	**70**	**72**	**76**

Table 31. Life cycle energy use divided on the different stages of life of a BEV shown in MJ/km.

Energy (MJ/km)	Base case	AC off			AC on heat		

		Eco	Normal	Aggressive	Eco	Normal	Aggressive
Vehicle body production	0.44	0.44	0.44	0.44	0.44	0.44	0.44
Battery production	0.18	0.18	0.18	0.18	0.18	0.18	0.18
Use phase	1.13	0.66	0.82	0.97	1.05	1.15	1.33
EOL	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Total	**1.83**	**1.36**	**1.52**	**1.67**	**1.74**	**1.84**	**2.03**

Battery recycling

Table 32. Life cycle GHG emissions divided on the different stages of life shown in g CO_2-eq/km.

GHG (g CO_2-eq/km)	BEV		**PHEV**	
	Base case	**Battery recycling**	**Base case**	**Battery recycling**
Vehicle body production	26	26	30	30
Battery production	21	10	13	6
Use phase	23	23	47	47
EOL	4	4	4	4
Total	**72**	**62**	**92**	**86**

Table 33. Life cycle energy use divided on the different stages of life shown in MJ/km.

Energy (MJ/km)	BEV		**PHEV**	
	Base case	**Battery recycling**	**Base case**	**Battery recycling**
Vehicle body production	0.44	0.44	0.51	0.51
Battery production	0.18	0.09	0.13	0.07
Use phase	1.13	1.13	1.18	1.18
EOL	0.08	0.08	0.08	0.08
Total	**1.83**	**1.74**	**1.89**	**1.83**

Best and worst case scenarios

Table 34. Life cycle GHG emissions divided on the different stages of life shown in g CO_2-eq/km.

GHG (g CO_2-eq/km)	**BEV**				**PHEV**		
	Base case	**Best case**	**Alternative best case**	**Worst case**	**Base case**	**Best case**	**Worst case**
Vehicle body production	25.5	12.8	12.8	34.0	29.5	14.8	39.3
Battery production	20.5	10.3	10.3	27.3	12.5	6.3	16.7
Use phase	22.5	1.2	1.0	134.5	46.6	2.6	153.3
EOL	3.5	1.8	1.8	4.7	3.5	1.8	4.7
Total	**72.0**	**25.9**	**25.8**	**200.5**	**92.1**	**25.3**	**214.0**

Table 35. The percentual contribution towards life cycle GHG emissions from different stages of the life cycle in the best and worst case scenarios.

GHG, % of total life	**BEV**	**PHEV**

cycle impact	Base case	Best case	Alternative best case	Worst case	Base case	Best case	Worst case
Vehicle body production	35%	49%	49%	17%	32%	58%	18%
Battery production	28%	40%	40%	14%	14%	25%	8%
Use phase	31%	4%	4%	67%	51%	10%	72%
EOL	5%	7%	7%	2%	4%	7%	2%

Table 36. Life cycle energy use divided on the different stages of life shown in MJ/km.

	BEV				PHEV		
Energy (MJ/km)	**Base case**	**Best case**	**Alternative best case**	**Worst case**	**Base case**	**Best case**	**Worst case**
Vehicle body production	0.44	0.22	0.22	0.59	0.51	0.26	0.68
Battery production	0.18	0.09	0.09	0.24	0.13	0.07	0.17
Use phase	1.13	0.89	0.78	2.03	1.18	0.72	2.08
EOL	0.08	0.04	0.04	0.10	0.08	0.04	0.10
Total	**1.83**	**1.24**	**1.13**	**2.96**	**1.89**	**1.08**	**3.03**

Table 37. The percentual contribution towards life cycle energy use from different stages of the life cycle in the best and worst case scenarios.

	BEV				PHEV		
Energy, % of total life cycle impact	**Base case**	**Best case**	**Alternative best case**	**Worst case**	**Base case**	**Best case**	**Worst case**
Vehicle body production	24%	18%	20%	20%	27%	24%	22%
Battery production	10%	7%	8%	8%	7%	6%	6%
Use phase	62%	72%	69%	69%	62%	67%	69%
EOL	4%	3%	3%	3%	4%	4%	3%

11.2.2 Detailed results of the analysis of cars with combustion engines

WTW analysis

In Table 38 the WTW GHG emissions and primary energy use linked to different types of vehicles and fuels are shown for three scenarios.

Table 38. WTW GHG emissions and energy use for different motor and fuel types for three scenarios.

		WTW 2010		**WTW 2010, 25% extra fuel consumption**		**WTW 2020+**	
Motor type	**Fuel type**	**GHG** (g CO2-eq/km)	**Primary Energy** (MJ/km)	**GHG** (g CO2-eq/km)	**Primary Energy** (MJ/km)	**GHG** (g CO2-eq/km)	**Primary Energy** (MJ/km)
PISI	**Conventional gasoline**	184.4	2.5	230.4	3.1	131.0	1.8
	Gasoline with 5% ethanol	181.8	2.5	227.2	3.1	129.1	1.8
	Ethanol	72.7	2.0	90.9	2.5	51.0	1.4
	E85 (85%	97.5	2.2	121.9	2.7	68.5	1.5

	ethanol, 15 % gasoline)						
	Biogas	54.8	2.3	68.5	2.9	36.0	1.5
DISI	**Conventional gasoline**	177.6	2.4	222.0	3.0	124.3	1.7
	Gasoline with 5% ethanol	175.1	2.4	218.8	3.0	122.5	1.7
	Ethanol	69.7	1.9	87.1	2.4	48.6	1.4
	E85 (85% ethanol, 15 % gasoline)	93.5	2.1	116.9	2.6	65.3	1.4
	Biogas	50.0	2.1	62.5	2.6	34.2	1.5
DICI	**Conventional diesel**	143.9	1.9	179.9	2.4	104.8	1.4
	Diesel with 5% FAME	140.9	1.9	176.1	2.4	102.6	1.4
	Diesel with 5% FAME and 35% HVO	100.4	1.8	125.4	2.3	73.1	1.3
	FAME	77.0	1.7	96.3	2.1	56.2	1.2
	HVO	25.4	1.6	31.8	2.0	18.5	1.2

Base case

In Table 39 the complete life cycle GHG emissions and primary energy use linked to different types of vehicles and fuels in the base case scenario are shown. The life length is 200 000 km and the 2010 scenario for fuel consumption is used for all types of cars except for the EVs.

Table 39. Complete life cycle GHG emissions and primary energy use linked to different types of vehicles and fuels for a life length of 200 000 km. This is used as the base case scenario in a comparison between the electric car and other types of cars.

GHG (g CO_2-eq/km)		**Vehicle body production**	**Battery production**	**Use phase**	**EOL**	**Total**
EV	**BEV**	25.5	20.5	22.5	3.5	**72.0**
	PHEV	25.5	12.5	46.6	3.5	**88.1**
PISI	**Conventional gasoline**	25.5	-	184.4	3.5	**213.4**
	Gasoline with 5% ethanol	25.5	-	181.8	3.5	**210.8**
	Ethanol	25.5	-	72.7	3.5	**101.7**
	E85 (85% ethanol, 15 % gasoline)	25.5	-	97.5	3.5	**126.5**
	Biogas	25.5	-	54.8	3.5	**83.8**
DISI	**Conventional gasoline**	25.5	-	177.6	3.5	**206.6**
	Gasoline with 5% ethanol	25.5	-	175.1	3.5	**204.1**
	Ethanol	25.5	-	69.7	3.5	**98.7**
	E85 (85% ethanol, 15 % gasoline)	25.5	-	93.5	3.5	**122.5**
	Biogas	25.5	-	50.0	3.5	**79.0**
DICI	**Conventional diesel**	25.5	-	143.9	3.5	**172.9**
	Diesel with 5%	25.5	-	140.9	3.5	**169.9**

	FAME					
	Diesel with 5% FAME and 35% HVO	25.5	-	100.4	3.5	**129.4**
	FAME	25.5	-	77.0	3.5	**106.0**
	HVO	25.5	-	25.4	3.5	**54.4**
Energy (MJ/km)		**Vehicle body production**	**Battery production**	**Use phase**	**EOL**	**Total**
EV	**BEV**	0.4	0.2	1.1	0.1	**1.8**
	PHEV	0.4	0.1	1.2	0.1	**1.8**
PISI	**Conventional gasoline**	0.4	-	2.5	0.1	**3.0**
	Gasoline with 5% ethanol	0.4	-	2.5	0.1	**3.0**
	Ethanol	0.4	-	2.0	0.1	**2.5**
	E85 (85% ethanol, 15 % gasoline)	0.4	-	2.2	0.1	**2.7**
	Biogas	0.4	-	2.3	0.1	**2.8**
DISI	**Conventional gasoline**	0.4	-	2.4	0.1	**2.9**
	Gasoline with 5% ethanol	0.4	-	2.4	0.1	**2.9**
	Ethanol	0.4	-	1.9	0.1	**2.5**
	E85 (85% ethanol, 15 % gasoline)	0.4	-	2.1	0.1	**2.6**
	Biogas	0.4	-	2.1	0.1	**2.6**
DICI	**Conventional diesel**	0.4	-	1.9	0.1	**2.5**
	Diesel with 5% FAME	0.4	-	1.9	0.1	**2.5**
	Diesel with 5% FAME and 35% HVO	0.4	-	1.8	0.1	**2.3**
	FAME	0.4	-	1.7	0.1	**2.2**
	HVO	0.4	-	1.6	0.1	**2.1**

Length of life, fuel economy and best and worst case scenarios

In Table 40 the total life cycle GHG emissions and primary energy use linked to different types of vehicles and fuels for the different conditions that are investigated in a sensitivity analysis are shown. The investigated scenarios are life length of 200 000 km (base case), life length of 200 000 km with 25% extra fuel consumption for all types of cars except for the EVs, life length of 300 000 km, life length of 400 000 km with a battery replacement for the EVs and a 2020+ scenario for all types of cars except for the EVs. The parameter values representative of the best case scenario are in the figure highlighted in green and the worst case in red.

Table 40. Complete life cycle GHG emissions and primary energy use in the scenarios examined in a sensitivity analysis of different types of cars and fuels. The best case results are highlighted in green and the worst case in red. Note that the results obtained for the EVs here are not used as a best and worst case for the EVs in the analysis in *6.2.4 Best and worst case scenarios.*

GHG emissions (g CO2-eq/km)	**2010**				**2020+**
	Base case 200 000	**200 000 km 25%**	**300 000 km**	**400 000 km**	**200 000 km 2020+**

		km	extra fuel			scenario
EV	BEV	72		56	58	
	PHEV	88		74	74	
PISI	Conventional gasoline	213	259	204	199	160
	Gasoline with 5% ethanol	211	256	201	196	158
	Ethanol	102	120	92	87	80
	E85 (85% ethanol, 15 % gasoline)	127	151	117	112	97
	Biogas	84	98	74	69	65
DISI	Conventional gasoline	207	251	197	192	153
	Gasoline with 5% ethanol	204	248	194	190	151
	Ethanol	99	116	89	84	78
	E85 (85% ethanol, 15 % gasoline)	123	146	113	108	94
	Biogas	79	91	69	64	63
DICI	Conventional diesel	173	209	163	158	134
	Diesel with 5% FAME	170	205	160	155	132
	Diesel with 5% FAME and 35% HVO	129	154	120	115	102
	FAME	106	125	96	92	85
	HVO	54	61	45	40	48
Primary energy use (MJ/km)		**Base case 200 000 km**	**200 000 km 25% extra fuel**	**300 000 km**	**400 000 km**	**200 000 km 2020+ scenario**
EV	BEV	1.8		1.6	1.6	
	PHEV	1.8		1.6	1.6	
PISI	Conventional gasoline	3.0	3.6	2.8	2.8	2.3
	Gasoline with 5% ethanol	3.0	3.6	2.8	2.8	2.3
	Ethanol	2.5	3.1	2.4	2.3	1.9
	E85 (85% ethanol, 15 % gasoline)	2.7	3.2	2.5	2.4	2.0
	Biogas	2.8	3.4	2.7	2.6	2.0
DISI	Conventional gasoline	2.9	3.5	2.7	2.7	2.2
	Gasoline with 5% ethanol	2.9	3.5	2.8	2.7	2.2
	Ethanol	2.5	2.9	2.3	2.2	1.9
	E85 (85% ethanol, 15 % gasoline)	2.6	3.1	2.4	2.3	2.0
	Biogas	2.6	3.2	2.5	2.4	2.0
DICI	Conventional diesel	2.5	3.0	2.3	2.2	1.9
	Diesel with 5% FAME	2.5	2.9	2.3	2.2	1.9

	Diesel with 5% FAME and 35% HVO	2.3	2.8	2.2	2.1	1.8
	FAME	2.2	2.6	2.0	1.9	1.7
	HVO	2.1	2.5	2.0	1.9	1.7

11.3 Interviews

The interviews were all made in Swedish, but questions and answers have been translated to English. The answers are not direct citations but summaries of what was said, and the translated versions have all been approved by the person interviewed.

It should be highlighted that the answers are personal opinions, and might not coincide with the views and opinions of the companies, organisations or institutions connected with the interviewed person.

Britt Karlsson-Green

Strategist at Sustainable Mobility Skåne [Hållbar Mobilitet Skåne], Region Skåne.

- **Which type of car available on the market today do you perceive as the most sustainable option from an environmental perspective?**
  Which type of car that is the better option depends on many different things and can vary with geographical placement. But considering existing infrastructure and technology available today my answer would be that the battery electric car is the most sustainable option. This is assuming that the electric car is charged with green electricity. There are of course other parameters to take into consideration when talking about battery electric vehicles, such as its relatively low range and high price.

- **Are you considering the vehicle use phase or the entire life cycle?**
  I am considering the entire life cycle. For an electric car this means considering effects from using batteries that contain certain rare metals, but also how it differs in maintenance from a conventional car.

- **Why do you think this is the most sustainable option?**
  A battery electric car takes care of a lot of aspects that usually are not very pleasant with cars; it reduces noise, and direct emissions such as carbon dioxide and nitric oxides are eliminated. If green electricity is used to charge the car it reduces environmental impacts. A battery electric vehicle also needs less maintenance since it has less mobile parts compared to a conventional car.

- **Do you consider this type of car the best option in the future as well?**
  I would prefer not to choose one option here, the options that we have today may look completely different tomorrow. The most important thing is that the future vehicle technology optimises energy efficiency, minimises the environmental impacts and secures provision of fuel.
  To speculate, I believe that fuel cell cars that run on hydrogen could be a good option in the future, assuming that the hydrogen is produced in an environmentally sustainable way,

demanding less energy than today. If so, a hydrogen fuel cell car would deliver the same benefits as a battery electric vehicle, but adding other benefits in form of a longer range and a smaller battery with less environmental impacts than a large battery.

Eva Sunnerstedt

Working with clean vehicles in Stockholm at the Environment and Health Administration, City of Stockholm. Project manager for the Electric Vehicle Initiative, City of Stockholm.

- **Which type of car available on the market today do you perceive as the most sustainable option from an environmental perspective?**
  I find that question almost impossible to answer. There is not one single type of car that alone manages to deal with all transports by car, and I believe that we need a mix of different options. All cars that run on non-fossil fuels are relatively sustainable from an environmental perspective, talking about climate impacts. There are several options to consider, for example electric cars, hydrogen fuel cell cars, cars that run on biogas, ethanol or biodiesel to mention a few. When I say electric cars I am mostly thinking of battery electric cars, but plug-in hybrids that run on some kind of biodiesel like HVO or other biofuels are also a good alternative.

- **Are you considering the vehicle use phase or the entire life cycle?**
  I am considering the entire vehicle life cycle, including production of the car in itself, industries to manufacture the fuels, transportation, recycling etc. However, it has been shown that the use phase normally stands for around 90% of the environmental impacts of a car.

- **Why do you think this is the most sustainable option?**
  Since I can’t point out one option this question is not really applicable, but I will discuss a bit around the options I mentioned. I want to clarify that I find the cars that run on 100% renewable fuels the most sustainable. Today it is common to mix fossil fuels into biofuels, or use fossil fuels in electricity production, and I do not consider these sustainable options. If 100 % biogas is used, or green electricity is used to run an electric car or produce hydrogen gas, then I consider it a sustainable option. The electricity mix used to run electric cars can be discussed further. Here in Sweden we use a large share of nuclear power, and it can be debated whether that is sustainable or not.
  A positive aspect of electric cars worth mentioning is that they do not cause noise which is especially beneficial in cities, but range and price remain issues with electric cars today. Another aspect of sustainability is that you have to consider the potentials and conflicting interests of use for a fuel. For example, not all cars in Sweden can run on biogas from waste, especially seeing as we simultaneously try to reduce our waste. And it is not an obvious choice to use a certain biofuel for transport when it is also required for heat production.

- **Do you consider this type of car the best option in the future as well?**
  This is also very difficult to answer. I believe that hydrogen fuel cell cars could be a good option, but then again I have heard that hydrogen fuel cell cars is the technology of the future for the last 20 years and this future still seems rather distant. I personally hope that electrification of some kind could be the answer, as long as energy can be stored in a way that

increases the range. If inductive charging on the road becomes possible that might be a solution to the relatively low range of electric cars today.
Yet another option could be biodiesel made from algae, or maybe other new options that could pop up in the future.

Jakob Lagercrantz

Founder of '2030 sekretariatet' (national secretariat for follow-up on the work on fossil fuel independent vehicle fleet 2030).

- **Which type of car available on the market today do you perceive as the most sustainable option from an environmental perspective?**
  Which type of car that is most sustainable depends on a number of things. You always have to study the fuel together with the powertrain, and factors such as geographical location and needs in terms of range can play a major part. If you live in a city, I personally do not think that you should have a car but look to other options such as public transport and car pools. If you do have a car, sustainable options are biogas, ethanol or electricity. If you live on the country side and need a longer range and there are no options for refuelling for example biogas, then a biodiesel like HVO (with no palm oil) is a good option.
  What kind of electric car that is the best option is determined by the needs of the driver, but the longer you can drive on electricity, the better. With plug-in hybrids I thus favour the ones with longer electric range, with a short electric range the risk of not charging the battery and only using the combustion engine is greater.
  To conclude I believe in a mix of different types of cars.

- **Are you considering the vehicle use phase or the entire life cycle?**
  I mostly consider this from a well to wheels perspective, but in general the use phase is the dominating phase when it comes to environmental impacts for cars. For a traditional car the use phase stands for about 70-80 % of the environmental impacts. For electric cars this looks slightly different with a higher impact in the production phase, but this will most likely decrease as we get better at designing electric cars.

- **Why do you think this is the most sustainable option?**
  I am considering data on well to wheel emissions when answering, and the options I mentioned in the first question all result in low climate impacts.
  For electric cars the electricity production will to a large extent determine how sustainable the car is, if you charge the battery with electricity generated from wind power the emissions associated with the car will be significantly lower compared to if you use for example an average European electricity mix.

- **Do you consider this type of car the best option in the future as well?**
  First of all, as mentioned already I believe that cars will play a smaller role in the future, especially in cities, and the cars that exist in the future will need to be lighter as they are too heavy today.
  The way I see it there is no obvious solution for transportation by car in the future, and the development of new techniques and powertrains will determine what the better options will

be. Talking about development, electric cars have been going through a rather fast development lately and are increasing their range; it will be interesting to see what technologies Tesla come up with in the future.
One possibility is that electrofuels could become a good option for future transportation. Especially if we learn how to better use solar power in the process, then maybe we could extract hydrogen from the ocean on a large scale, and produce other fuels from that source.

Johanna Grant

Chairperson of the Swedish Association of Green Motorists [Gröna Bilister].

- **Which type of car available on the market today do you perceive as the most sustainable option from an environmental perspective?**
  I don't favour a specific technology, and I would say that all cars that do not use fossil fuels in any way are preferable from an environmental perspective. Examples of car types that I would consider better alternatives for the environment are electric cars that run on renewable energy, or cars that run on biofuels like biogas or ethanol. When I say electric cars I mostly consider battery electric cars, and not hybrids. Even if a hybrid might get you further in terms of range, I think it is easier to become 'lazy' and run a hybrid car on the combustion engine more than necessary instead of using electricity. To summarise, a variety of sustainable, non-fossil fuels are important.

- **Are you considering the vehicle use phase or the entire life cycle?**
  The entire life cycle, all cars should 'carry' their own climate impact from a life cycle perspective.

- **Why do you think this is the most sustainable option?**
  The options that I mentioned in the first question are all preferable alternatives because they have low climate impacts, and the fuels are non-fossil. The biofuels sometimes can have the extra benefit of taking care of different decay products, making them part of a circular economy as well. I think that ethanol has received undeserved negative attention in land use issues and the competition of land use for food or fuel. You never hear that discussion about growing tobacco for example, which is of course also taking up land areas that could be used for food production instead.
  Electric cars I consider 'as good as it can get' if the electricity used to charge them comes from renewable energy sources. That way you end up being very close to no emissions at all when driving an electric car. Although, electric cars have other challenges when it comes to rare metals used in the batteries.

- **Do you consider this type of car the best option in the future as well?**
  Once again I believe in a variety of different types of cars. I think that we will see a boom in electric cars in about three years or so. For example Tesla is coming out with a more competitive version of an electric car in 2017 that should be able to appeal to a wider audience, including families with children.
  But electric cars will not be our only good option and variety is the solution. For a near future, biodiesel (for example HVO) that has the ability of replacing fossil diesel could be a good

option, to make sure that we reach the Swedish goals of having a fossil fuel independent vehicle fleet in 2030.
Sweden has a great potential of using resources in Sweden and our agricultural sector to produce environmentally sustainable fuels, and this should be made better use of in the future.
It is important to remember that travelling by car comes with a lot of complications (emissions being only one of them). I believe that in the future we will have to make a shift towards using the car less and other means of transportation more, especially in cities.

Lasse Swärd

Reporter at Dagens Nyheter specialised in the car industry.

- **Which type of car available on the market today do you perceive as the most sustainable option from an environmental perspective?**
  Battery electric cars are very good, if you assume that they run on for example a Swedish electricity mix with low carbon dioxide emissions. An electric car might not be as good in Germany, for example, if it runs on electricity produced in a coal power plant.
  If hydrogen fuel cell cars that run on electricity produced from hydrogen is considered part of the market today, I think that these cars are an even better option.
  To summarise you could say that I don't believe that a specific type of electric vehicle in itself is superior, but that an electrification of the vehicle fleet in general is the most sustainable option.

- **Are you considering the vehicle use phase or the entire life cycle?**
  I am mostly considering the use phase of a car and the impact from emissions connected to its use.

- **Why do you think this is the most sustainable option?**
  Assuming that electricity and hydrogen production is done in a sustainable way an electric car or a hydrogen fuel cell car gives low carbon dioxide emissions. A battery electric car is also beneficial in other ways, especially in urban areas since it does not produce any local emissions and causes hardly any noise. One negative aspect of a battery electric car is the low range, which is limiting travel distance today.

- **Do you consider this type of car the best option in the future as well?**
  I believe that hydrogen fuel cell cars will be the best option in the future, assuming that the hydrogen can be produced in a sustainable way with low carbon dioxide emissions. These cars usually have a greater range than battery electric cars, and are possible to refuel in a very short time (3-4 minutes). Battery electric cars could possibly be a good complement to use alongside of hydrogen fuel cell cars.

Peter Kasche

Working at the Swedish Energy Agency [Energimyndigheten], in charge of Energy and Environment at Vehicle strategic Research and Innovation [Fordonsstrategisk Forskning och Innovation].

- **Which type of car available on the market today do you perceive as the most sustainable option from an environmental perspective?**
  It is very difficult to just name one type of car as there are many parameters that play an important role. You have to consider for example geographical placement, what electricity mix is used, what budget you have and how long distances you plan to drive. Even if you set a limitation to consider only Swedish circumstances I still find it difficult.
  If I have to give an answer I would say that it is a combination of electric cars and biogas cars, possibly ethanol as well depending on production method. When I say electric cars I'm referring to battery electric cars, but possibly also plug-in hybrids for long distance driving, and I assume that the electricity mix used is renewable or very low in carbon dioxide emissions.

- **Are you considering the vehicle use phase or the entire life cycle?**
  I'm considering the entire life cycle. Worth mentioning is that the emissions linked to production of an electric car is often a lot higher than those that occur in the production of a conventional car with an internal combustion engine. Unfortunately there are not a lot of studies done regarding the entire life cycle of vehicles.

- **Why do you think this is the most sustainable option?**
  With electric cars you get a very high degree of efficiency, approximately 2.5 times the efficiency of a car with an internal combustion engine. If renewable electricity is used to charge the car this gives very good results.
  Biogas is sustainable in the way that it can be produced from for example waste material that would otherwise contribute to a leakage of methane to the atmosphere. By using this biogas as fuel you reduce the leakage of methane that would have otherwise occurred and thus you limit the emissions of greenhouse gas while you also get the benefit of the biogas as a fuel. This specific type of biogas has its limitations though, as there is a limited amount of waste to produce biogas from.

- **Do you consider this type of car the best option in the future as well?**
  I believe that the battery electric car is the strongest candidate that we have today. However, I must point out that car mobility the way it looks today is not especially sustainable and I think that changed behaviour with a shift towards more public transportation and less car dependency will be necessary.

Åsa Kastensson

Researcher in the area Energy Engineering at Luleå University of Technology. Has been involved in research on ethanol for F3 (The Swedish knowledge centre for renewable transportation fuels).

- **Which type of car available on the market today do you perceive as the most sustainable option from an environmental perspective?**
  That would be electric cars, at least for Sweden with our electricity mix. With electric cars I mean cars that are charged from the grid. In countries where electricity production generates higher emissions of carbon dioxide, biofuels should be a better option. But if you consider the limited driving range of electric cars and the high cost of the batteries making these cars expensive for the users, electric cars are still not the only sustainable solution. This is why

biofuels are a competitive alternative.

- **Are you considering the vehicle use phase or the entire life cycle?**
  I was mostly thinking of the use phase, and how electricity is produced. But if you consider the battery electric car in a life cycle perspective it should be mentioned that the material used in many of the batteries has an environmental impact both when it comes to the mining but also from an end-use perspective.

- **Why do you think this is the most sustainable option?**
  For electric cars, I think that they are a sustainable option if the electricity they run on is produced in a sustainable way, based on renewable energy. The electricity mix in Sweden has low emissions of carbon dioxide, which makes the electric car a good option here.
  With cars that run on biofuels it can be argued that they are sustainable in the same matter. The emissions from vehicles running on biofuels have less climate impact than vehicles run on fossil fuels and major climate benefits depending on how the biofuel is produced. This option is sustainable in another sense as well since the existing, traditional vehicle fleet can run on biofuels, with the so called drop in fuels, thus avoiding a perhaps unnecessary replacement of vehicles.

- **Do you consider this type of car the best option in the future as well?**
  That is a very hard question to answer. It depends on how technology evolves. It could be that the next generation of biofuels is the best option for the future. In Sweden with the large areas of forest, biofuels made of wood waste will be a sustainable option. A big plus is also that any conventional car can be used with the next generation drop-in biofuels, so you don’t have to replace the existing vehicle fleet. It could also be that electric cars are the best option depending on how electricity is produced, but first the problem with their relatively short driving range and expensive and environmental unfriendly battery production has to be overcome.
  I think that a mix of the two is a good option; I don’t think that only electric cars or only cars that run on biofuels would be a solution.

Anna Henstedt

Responsible for Environmental Issues at BIL Sweden.

- **Which type of car available on the market today do you perceive as the most sustainable option from an environmental perspective?**
  The battery electric car, assuming that it is run on green electricity.

- **Are you considering the vehicle use phase or the entire life cycle?**
  The entire life cycle. But it has been shown that the use phase is the phase that will dominate the environmental impacts of the vehicle.

- **Why do you think this is the most sustainable option?**
  If the electric car is run on green electricity, the environmental impacts are heavily reduced. The production of an electric car is associated with higher environmental impacts than other types of cars. This is especially because of the battery and the resources used to produce the

battery, but this is compensated for in the long run as the electric car has so many environmental benefits in the use phase. An electric car has low climate impact, as the emissions of carbon dioxide are very low (if green electricity is used), and there are no tailpipe emissions such as nitric oxides and other particles. In urban areas like cities the electric car has another benefit as well in form of noise reduction followed from having no combustion engine.

- **Do you consider this type of car the best option in the future as well?**
  That is a hard question to answer, but in a relatively long-term perspective I think that the battery electric car is the best option.

Håkan Johansson

Coordinator, climate mitigation at the Swedish Transport Administration [Trafikverket].

- **Which type of car available on the market today do you perceive as the most sustainable option from an environmental perspective?**
  It is a difficult question, but I would have to say the battery electric car. The electric car still has its limits though, in terms of range for example.

- **Are you considering the vehicle use phase or the entire life cycle?**
  The entire vehicle life cycle. It is worth mentioning that the batteries of an electric car have relatively high environmental impacts associated with production and extraction of raw materials.

- **Why do you think this is the most sustainable option?**
  I think that the electric car is a sustainable option if the electricity used to run the car has a low climate impact with low emissions of carbon dioxide linked to it. So to drive an electric car in Sweden with our electricity mix is good, but the same car in Poland might not be very good. But seen from a long term perspective the electricity production in Europe is heading towards lower emissions, so a transit to more electrification of vehicles will probably be justified in all of Europe in the long run.
  Other positive effects with electric cars are lower levels of noise as it doesn't have a combustion engine, this could be especially beneficial in city environments. Also, there are no local emissions from an electric car.

- **Do you consider this type of car the best option in the future as well?**

  I think that the electric car is the best option in a near future (at least until 2030), and the development of batteries is currently going very fast. In a realistic scenario plug-in hybrids probably play a role in the near future as well, since these can overcome the problem of the low range of battery electric cars.
  Battery electric cars are not the only option for the future; in a long term perspective I believe that the hydrogen fuel cell car could be a good option as well.