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Comparative LCA of Electrified Heavy Vehicles in Urban Use

Master of Science Thesis in the Master's Degree Programme Technology, Society and the Environment

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Cover: Volvo Hybrid Refuse Truck

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Abstract

The Volvo FE Hybrid is one of Volvo's latest trucks and it has been launched as a fuel efficient alternative to the conventional, diesel fueled Volvo FE truck. To be able to determine if the Volvo FE Hybrid is preferable from an environmental point of view, considering the whole life cycle, a life cycle assessment (LCA) has been performed on the drivetrain of the hybrid- and the plug-in hybrid configurations. The analysis has been made for both a distribution truck and a waste collection vehicle.

A dozen components in the hybrid drivetrain have been identified, including a lithium-ion battery and an electric motor. These components were studied throughout their life cycle: raw material extraction, material processing, manufacturing processes, transportation, use phase, maintenance and disposal. In order to quantitatively assess the environmental impact of all lifecycle stages, four different environmental indicators have been used: global warming potential, acidification potential, human toxicity potential and resource depletion potential. In addition, energy use and two weighting methods, EPS and Eco-indicator 99, have been used.

The result shows that for the distribution vehicle it is the step to hybridization that gives the largest environmental gain. Modification to a plug-in hybrid configuration of the same vehicle showed only a little additional environmental benefit. Hybridization of the waste collection vehicle gives environmental benefit for all categories except the EPS weighting system, where no environmental savings are obtained. In this case a shift from hybrid to plug-in hybrid configuration gives a relatively large environmental benefit compared to hybridization only.

Furthermore, it is shown that the use phase, or well-to-wheel, has by far the largest impact of all life cycle stages, for almost all environmental categories (10 to 40 times larger). The exceptions are the human toxicity potential and the EPS system where the well-to-wheel stage has an impact in the same order of magnitude as the cradle to grave lifecycle of the drivetrain for all vehicle types considered (with the use phase excluded).

Looking at the life cycle of the drivetrain, the stage with largest environmental impact is raw material extraction and material transformation. The lithium-ion battery has the largest environmental impact of all components, all categories considered. Second largest impact is shared by the DC/AC converter and electric motor, depending on which indicator that is considered.

The largest uncertainties identified in the study are relating to the plug-in hybrid configuration, due to the fact that it is still a concept. Some uncertainties are fuel consumption, battery life, size and chemistry.

The conclusions from the study are that the plug-in configuration is preferable to the hybrid version for the waste collection vehicle. In the case of the distribution truck, it is hard to justify a shift from hybrid to plug-in hybrid configuration, due to the small additional environmental gain made and the uncertainties mentioned earlier.

Keywords: *LCA, hybrid vehicle, plug-in hybrid, lithium-ion battery, truck, drivetrain, Volvo FE Hybrid*

Sammanfattning

Volvo FE Hybrid är en av Volvos nyare lastbilar, den har lanserats som ett bränslesnålare alternativ till den konventionella, dieseldrivna, Volvo FE. För att ta reda på om Volvo FE Hybrid är mer miljövänlig sett över hela livscykeln har en livscykelanalys (LCA) utförts på drivlinan på hybridlastbilen samt på en laddhybridvariant. Analysen har gjorts både för en distributionslastbil och en sopbil.

Ett tiotal komponenter som tillkommer i hybriddrivlinan har identifierats, bland annat litium-jonbatteriet och elmotorn, och undersökts genom hela livscykeln; råmaterialutvinning, materialbearbetning, tillverkningsprocesser, transporter, användningsfas, underhåll samt avfallshantering. För att kvantitativt kunna avgöra miljöpåverkan har livscykelstegen evaluerats med fyra olika miljöpåverkansindikatorer: klimatpåverkanspotential, försurningspotential, humantoxicitetspotential och resursutarmningspotential. Energianvändning samt två viktningsmetoder, EPS och Eco-indicator 99, har också inkluderats.

Resultatet visar att för distributionslastbilen ger steget att hybridisera den största miljövinsten, medan övergången till laddhybrid endast visar en liten ytterligare miljövinst. För sophanteringsbilen ger hybridisering en miljövinst för alla kategorier utom EPS-viktningen där den inte ger någon miljöbesparing alls. Att gå från hybrid till laddhybrid ger dock en relativt stor miljövinst jämfört med att enbart hybridisera när det gäller sophanteringsbilen.

Vidare visades att användarfasen, eller bränslelivscykeln, har överlägset störst miljöpåverkan av alla livscykelsteg för nästan alla miljökategorier (10 till 40 gånger större), bortsett från humantoxicitetspotentialen och EPS-viktningen där den är av samma storleksordning som hela livscykeln för drivlinorna (användarfasen exkluderad).

Sett till drivlinornas livscykel så är livscykelstegen med störst miljöpåverkan råvaruutvinning tillsammans med materialbearbetning. Av hybridkomponenterna så har litium-jonbatteriet störst miljöpåverkan för alla miljökategorier. Näst störst påverkan har DC/AC-konverteraren eller elmotorn, beroende på vilken indikator som betraktas.

Den största osäkerheten som identifierades i studien rörde laddhybridlastbilen, som på grund av att den inte är en färdig produkt har osäkrare data för bränsleförbrukning, batterilivstid, batteristorlek med mera.

Slutsatsen av studien blir att laddhybridvarianten är att föredra framför hybridvarianten för sophanteringsbilen, men att det för distributionslastbilen är svårt att motivera skiftet till laddhybrid, på grund av den lilla tillkommande miljövinsten i kombination med stor osäkerhet kring detta alternativ.

Nyckelord: *LCA, hybrid, laddhybrid, litium-jonbatteri, lastbil, drivlina, Volvo FE Hybrid*

Acknowledgements

We would like to thank Volvo Group Trucks Technology and the department of Energy and Environment at Chalmers University of Technology for commissioning this study. In particular Maria Wallenius Henriksson, Niklas Thulin and Lisbeth Dahllöf at Volvo have been very helpful. Finally, special thanks to our supervisor at Chalmers, Anders Nordelöf, for being helpful and patient, and showing his commitment to our project.

Confidentiality

Some information used in this project has been declared confidential by Volvo Group Trucks Technology. For this reason, for example detailed flowcharts and specific data for components have been left out this public version of the report. Suppliers are not mentioned by name and manufacturing locations are randomized.

However, all data necessary for the LCA calculations have been available for evaluation by all participating parties. For transparency the agreement is that the data will be a part of a larger data assessment, presented in a generalized format in the Chalmers CPM LCA database and available for scientific research.

Table of Contents

List of Abbreviations

AC	Alternating Current
ADP	Abiotic resource Depletion Potential (RDP)
Ah	Ampere hours
AP	Acidification Potential
BOD	Biochemical Oxygen Demand
BOM	Bill Of Material
CCPP	Coal Condensing Power Plant
CML	Institute of Environmental Sciences (Leiden University, The Netherlands)
COD	Chemical Oxygen Demand
CPM	Center for environmental assessment of Product and Material systems
DC	Direct Current
DSP	Digital Signal Processor
DV	Distribution Vehicle
EAA	European Aluminium Association
EI	Eco Indicator
ELCD	European Life Cycle Database
ELU	Environmental Load Units
EoL	End of Life
EPD	Environmental Product Declaration
EPDM	Ethylene Propylene Diene Monomer
EPS	Environmental Priority Strategies
ES	Electric System
ESS	Energy System Storage
FU	Functional Unit
GWP100	Global Warming Potential 100 years
HDPE	High Density Ploy Ethylene
HEV	Hybrid Electric Vehicle
HEV JB	High Voltage Junction Box (Hybrid Electric Vehicle Junction Box)
HHV	Hybrid Heavy Vehicle
hp	horse power
HPCU	Hybrid Powertrain Control Unit
HTP	Human Toxicity Potential
HVC	High Voltage Cables
IARC	International Agency for Research on Cancer
ICE	Internal Combustion Engine
IMDS	International Material Data System
IPCC	International Panel of Climate Change
I-SAM	Integrated Starter Alternator Motor
ISSF	International Stainless Steel Federation
KOLA	KOnstruktion LAstbil "Construction Truck" (Volvo’s product data management system)
kWh	kilo Watt hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low Density PolyEthylene
LFP	LiFePO4
MDS	Material Data System
ng	natural gas
NiCd	Nickel- Cadmium

NiMH	Nickel Metal Hydrid
PBT	Polybuthylene Terephthalate
PCB	Printed Circuit Board
PCB	Printed Circuit Board
PE	Poly Ethylene
PEC	Power Electronic Converter
PET	Polyethylene Terephthalate
PMSM	Permanent Magnet Synchronous Motor
PMU	Powertrain Management Unit
PP	PolyPropylene
PS	PolyStyrene
PUR	PolyURethane
PVC	PolyVinyl Chloride
RDP	Resource Depletion Potential (ADP)
SBR	Styrene Butadiene Rubber
TPE	ThermoPlastic Elastomer
VAC	Volt Alternating Current
WCV	Waste Collection Vehicle
VGTT	Volvo Group Trucks Technology
VSI	Voltage Source Inverter

1. Introduction

1.1 Background

The hybrid technology, which is a combination of electric and internal combustion engine (ICE) propulsion, is emerging fast within the round bound transport sector. Both passenger cars and heavy vehicles have reached the market and are being series produced (Lake 2001; Volvo Buses 2012). Especially in urban use the hybrid technology is promising with lower energy use, emissions and noise.

Volvo has since 1985 been working on hybrid solutions for the transport sector. Both the Volvo 7700 and the 7900 are hybrid city buses that are now established products. With this success, Volvo is now producing hybrid trucks for distribution and waste handling duties. Test driving of the Volvo FE Hybrid distribution truck shows 15-20% fuel savings, and for the waste handling truck the savings are 15-30%. In addition, there is an equal reduction in emissions and a 50% reduction in noise in acceleration and idling (Volvo Trucks 2011). This indicates that a hybrid truck is environmentally superior to a conventional truck in the use phase. However, it is not known if this is true for the entire life cycle. To find out, Volvo Group Trucks Technology (VGTT) has requested this comparative Life Cycle Assessment (LCA) of their Volvo FE Hybrid waste collection and distribution trucks.

1.2 Technical Background

The Volvo FE Hybrid is propelled by a 7 liter diesel engine and a powerful AC permanent magnet electric motor in parallel. The advantage of this system setup is high reliability as the two power sources can be used separately and with higher efficiency. The idea is that the vehicle always is driven in optimal mode combining the diesel and electric motor.(Volvo Trucks 2008)

Usually the electric motor is used in the beginning when accelerating from zero to 20 km/h to improve power and efficiency. Figure 1-1 shows the motor speed-torque relationship, showing the higher efficiency of the electric motor at low speed. The electric motor is also used during shorter trips, motor idling, traffic jams, loading and unloading of the vehicle. The diesel engine is thus completely shut down to save fuel and to reduce emissions. During braking, the electric motor can work as a generator and convert mechanical energy received from the wheels to electrical energy to charge the battery. This utility is called regenerative braking, explained in section 2.2.4.

The major components of the Volvo FE Hybrid drivetrain include: diesel engine, clutch, gearbox and I-SAM (Integrated Starter Alternator Motor), see Figure 1-2. The I-SAM is an alternating current (AC) permanent magnet (PM) motor which also serves as a generator. Additionally, the electric system consists of a Fe-Li-ion battery pack and electric converters. The HPCU (Hybrid Powertrain Control Unit) is the brain of the system and regulates the operation of the two power sources, gear strategies and battery charging.

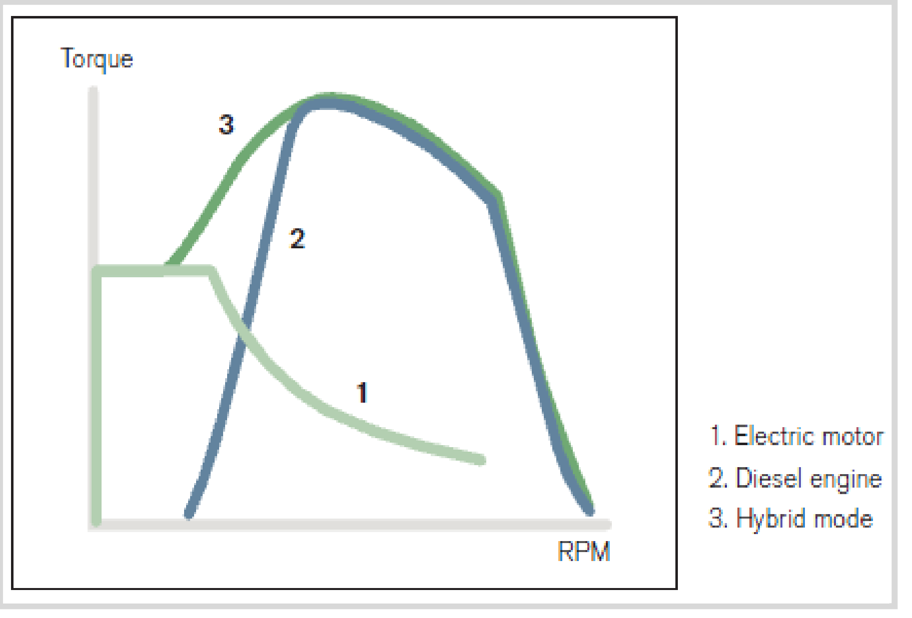


Figure 1-1: Efficiency curve of the different power source configurations (Volvo Trucks 2008).

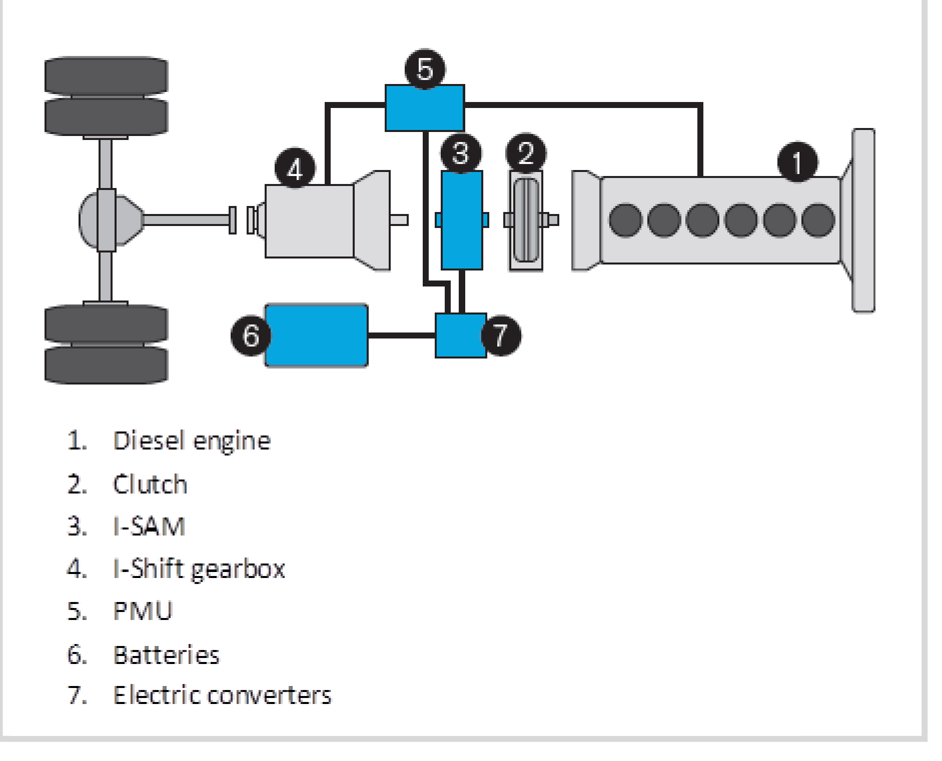


Figure 1-2: Basic overview of the Volvo FE Hybrid drivetrain (Volvo Trucks 2008).

1.3 Life Cycle Assessment

Life Cycle Assessment (LCA) is a standardized tool to assess the environmental impact in the different stages of the lifecycle of a product (or service). Activities usually included are raw material extraction, transports, material processing, manufacturing, use, maintenance, recycling and disposal. When the whole lifecycle is included, it is referred to as a cradle-to-grave assessment. However, sometimes just a part of the lifecycle is in focus, for example an assessment from manufacture to disposal, and this is referred to as a gate-to-grave assessment. The LCA procedure consists of a few major steps; Goal and Scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation see Figure 1-3. It is an iterative process, so all parts can be adjusted during all phases of the LCA. (ISO 2006)

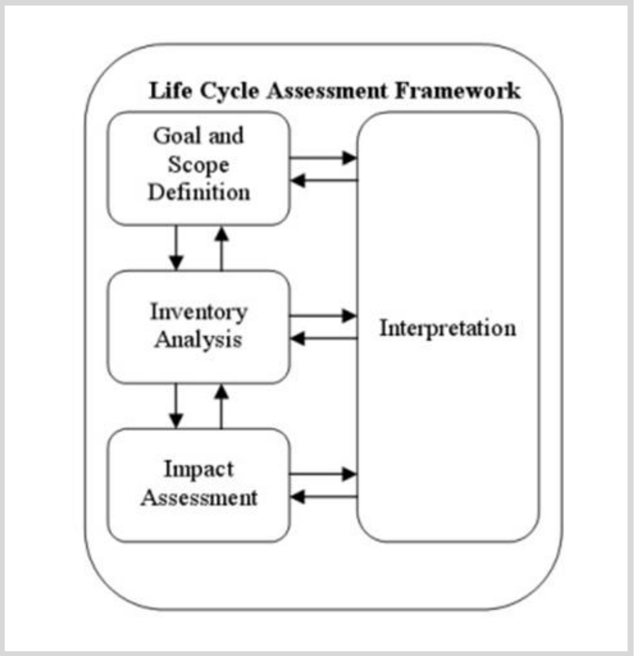


Figure 1-3: Standard procedure in an LCA (Pavement Interactive 2011).

In the Goal and Scope definition, the aim of the study and which questions to be answered are determined, as well as what will be included in the study. A functional unit (FU) is set, which is a quantified performance of the product system, to which all flows are compared and normalized. System boundaries are defined, determining which processes to include in the LCA, following the goal of the study. Usually a flow diagram of the processes is set up for the system. Also impact categories, category indicators and characterization models used in the LCIA shall be determined, and assumptions and limitations are stated.

In the subsequent Inventory Analysis a detailed flowchart over all activities is set up. The aim is to determine the energy flows, material flows and emissions for each activity in relation to the functional unit. To achieve this, data for each activity needs to be collected, followed by calculations to relate it to the functional unit. Data collection is often the most time consuming part of an LCA (Baumann and Tillman 2009), and whether it is measured, calculated or estimated the quality should be checked. In multi-input or multi-output processes there might be allocation problems, when it is unclear how much of the environmental burden that should be associated with each material. There are several ways to deal with this; for example division into sub processes, system expansion, partitioning or allocation based on weight or economic value.

In the Impact Assessment the inventory data is classified into different impact categories, to determine what kind of and how large impact each emitted substance yield. The choice of impact categories is done in the Goal and Scope definition. The assignment of LCI results to each impact category is called classification, and the subsequent calculation of category results is called characterization. For each category a characterization model is used, for example IPCC 100 years model for global warming, and a category indicator like radiative forcing (W/m^2).

After characterization some optional elements can be carried out with the results, for example normalization and weighting, i.e. creating an aggregated impact indicator by valuing the different impacts.

In the interpretation phase important issues in the LCA like certain emissions or waste are identified. The results of the LCA are then evaluated and completeness is checked by making sure that all relevant data and information are available. A sensitivity analysis is done testing the model to determine the importance of certain parameters and a consistency check is done to make sure that methods and assumptions are in accordance with the Goal and Scope of the study. Finally the results are used to draw conclusions, identify limitations and make recommendations to the LCA constituent and other stakeholders. (ISO 2006; Baumann and Tillman 2009)

1.4 Volvo Group Trucks Technology

This study was commissioned by Volvo Group Trucks Technology (former Volvo Technology), which is the center for innovation, research and development within the Volvo Group. Its customers include all Volvo Group companies, and some selected suppliers. Fields of research include logistics, telematics, ergonomics, electronics, combustion and mechanics. (Press release - AB Volvo 2011; Persson 2012)

1.5 GaBi LCA Software

GaBi is a market leading LCA software (PE International AG 2012). It can be coupled to databases detailing with the energy and the environmental impact of sourcing and refining every raw or processed element of a manufactured item. Examples of databases are Ecoinvent, Plastics Europe, PE, ELCD and Worldsteel.

GaBi version 4.4.139.1 has been used for this study together with database version 4.131.

2. Description of the Technical System

This chapter describes the technical system relevant for the study. First there are general descriptions of hybrid technology, electrical propulsion systems and battery technology, followed by specific descriptions of the systems included in the Volvo FE and Volvo FE Hybrid vehicles.

2.1 Hybrid Technology

A vehicle that has more than one power source is called a hybrid. In the case of electric hybrid technology, the combination consists of an electric propulsion system and an internal combustion engine (ICE). By combining these two power sources it is possible to avoid each technology's disadvantages, while utilizing their advantages. Looking at each technology separately, the major disadvantages are that ICEs suffer from poor energy efficiency and high environmental pollution, while electric vehicles have much shorter operating range. The poor energy efficiency of ICEs is due to several factors, like loss of kinetic energy from braking, bad correlation between engine fuel efficiency and operation requirements, and low efficiency of hydraulic transmissions. Relatively low energy content in the battery compared to liquid fuels is the reason for the low operating range of electric vehicles. The long recharging time of the battery module is another problem for the plug-in hybrid technology. (Ehsani, Gao et al. 2010)

Efficient utilization of a hybrid electric vehicle (HEV) provides a significant energy saving potential in comparison with conventional vehicles. Volvo has shown that in urban driving the fuel saving potential for distribution vehicles (DV) and waste collection vehicles (WCV) is 15-30% (Volvo Trucks 2011). For city buses it can be as high as 35% (Volvo Buses 2012).

Several different types of hybrid electric drive trains have been developed; the most well-known ones being parallel hybrid and series hybrid, two other configurations are called series-parallel hybrid and complex hybrid. In addition there is a subtype of plug-in hybrid vehicles that have a battery with larger capacity. These vehicles have the possibility to be charged with electricity from the grid, to decrease the use of the ICE.

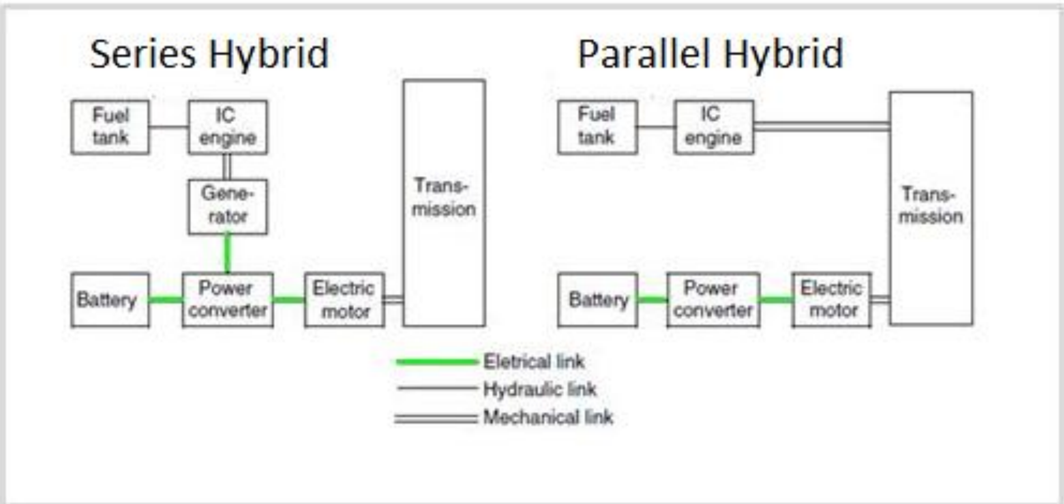


Figure 2-1: Different hybrid vehicle configurations.(Ehsani, Gao et al. 2010)

2.1.1 Parallel Hybrid Technology

The basic concept of a parallel hybrid vehicle is seen in Figure 2-1. Both an ICE and an electric motor are mechanically coupled to the transmission. At low speed, when the ICE is inefficient, the electric motor can power the vehicle alone. At higher speed, or when the battery state of charge is low, the ICE provides power both to the wheels and to charge the battery through the electric motor which then works as a generator. Since the engine and motor is sharing the traction power, neither need to be very powerful.

2.1.2 Series Hybrid Technology

In a series hybrid vehicle, only the electric motor is mechanically connected to the wheels, see Figure 2-1. An ICE is driving a generator which is powering the electric motor and charging a battery. Advantages with a series hybrid configuration are that the ICE can run independently from the vehicle's speed and torque requirements, thus it can potentially always run at an optimal engine speed. In turn, this makes it possible to develop an engine optimized for a narrow operating range. Disadvantages include the need for a powerful electrical motor since it must provide all output power, and that there are two energy conversions from the engine, mechanical to electrical in the generator and electrical to mechanical in the motor. These system aspects can lead to significant energy losses which partially outweighs the savings.

2.1.3 Plug-In Hybrid Technology

Unlike other hybrid vehicles, the plug-in has the possibility to be charged with electricity from the grid, thus it is one step closer to a pure electric vehicle. With a plug-in vehicle it is possible to drive short distances solely on the electric motor supplied with energy from the battery, often with a range less than 50 km (Siler 2010; Volvo Cars 2012). Due to this the battery requirements are much higher, since the battery needs to be able to store a larger amount of energy compared to that of a hybrid vehicle. The advantage is increased fuel efficiency, how large fuel savings depends on how frequently the vehicle is charged. (Ehsani, Gao et al. 2010)

2.2 Electric Propulsion Systems

The purpose of an electric motor is to convert electrical energy to mechanical energy, usually by letting a current flow through a wire which is positioned in a magnetic field. This gives rise to a Lorentz force on the wire, and by aligning the field and current to each other the force will put the motor into rotation. The magnetic field is created by magnets or coils. Several types of electric motors exist, some are described below. (Westbrook 2001)

2.2.1 DC Motors

One of the most basic DC motor setups is seen in Figure 2-2, where a rotating coil with electric current is wound in between two magnets or coils. Permanent magnets can be used to create the magnetic fields, however DC motors used for propulsion usually use electromagnets. For the force to always point in the same direction the current in the coil needs to switch direction every half revolution. This can be accomplished by having a segmented fixed commutator with brushes connected to the rotor (the rotating part of the motor). A commutator is a device that switches the current in the rotor by alternating which pole that is connected to the outside. The connectors are called brushes. A disadvantage with this kind of motor is the mechanical wear out of the brushes due to friction between the brushes and the commutator.

DC motors were earlier often used for propulsion, thanks to accurate control of speed and torque, but due to their high weight and short lifetime they have gradually been replaced by AC motors. (Wallmark 2001; AB Volvo 2011)

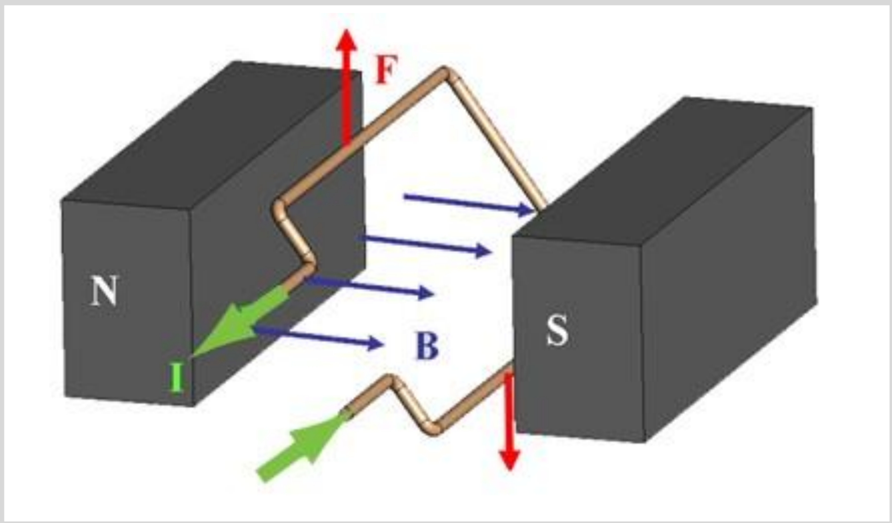


Figure 2-2: Basic DC motor setup. (LIMS 2011)

2.2.2 AC Motors

Two important categories of AC motors for vehicle applications are inductance motors and synchronous motors. In the inductance motor, the current in the rotor winding is not created by an external power source like in the DC motor, instead the magnetic field from the stator magnets give rise to the current through induction. The stator itself is also different compared to that of the DC motor. It consists of a steel frame with a hollow cylindrical core made of stacked laminations with slots evenly distributed, in which the field coils are wound. Within the stator the rotor is positioned, it usually has the form of a squirrel cage, with bare copper bars connected at the ends. In operation a three-phase supply is applied to the stator coil which gives rise to a rotating magnetic field in the core. Currents are created in the rotor windings and a rotating force acts on the rotor. For the rotating force to arise the rotor has to turn slower than the stator field during operation, therefore this motor type is often referred to as an asynchronous motor.

The synchronous motor is another variation of the AC motor. The stator field is here similar to an induction motor, but the rotor windings are either fed by a direct current via slip rings or a set of permanent magnets which creates an air gap field that matches the number of poles and sinusoidal distribution of the stator field. During operation the rotor and stator field patterns will be aligned with North poles facing South poles, so that the rotor turns with the rotation of the stator field. The stator field is created by a three phase voltage supply. A relative displacement in the fields will be adjusted by a torque trying to align the rotor with the stator field. When a load is put on the rotor, the angle between the poles will increase until the torque balances the load. Thus it can also be used as an alternator, which produces electrical energy from mechanical energy (which is also possible for an asynchronous motor).

A permanent magnet synchronous motor (PMSM) is used in the Volvo FE Hybrid truck. It uses permanent magnets attached to the rotor to produce the rotating magnetic field. More specifically Neodymium-Iron-Boron (NdFeB) magnets are used, which provide useful properties like high flux density and high resistance to being demagnetized (coersivity). In a PMSM the stator windings are fed by a sinusoidal current. A convention is that if it is fed by a trapezoidal current it is referred to as a brushless DC motor, but this is not the case with the motor in the FE Hybrid.[1]

Controlling a PMSM is complicated and requires a voltage source inverter (VSI), a digital signal processor (DSP) and feedback devices. The combination of the VSI and DSP controls the three phases of the motor accurately, together with the feedback device that detects the rotor position and measures currents. The PMSM provides long lifetime, high torque-to-volume ratio and high efficiency, but it is expensive due to the price of the magnets (Wallmark 2001). In general, AC motors are smaller and more efficient than DC motors, and are more suited to be used for vehicle propulsion. (Westbrook 2001)

2.2.3 Power Electronics and Accessories

In an electric propulsion system several components managing the power are needed. An inverter is a device that converts the DC voltage to AC voltage by using oscillator circuits. This is useful if the vehicle uses an AC motor and if there are other machines operating on AC, for example compressors. A junction box has the purpose to distribute power to different parts of the system, as well as concealing electrical wirings and components.

A DC/DC converter can be used to adjust the power supply to auxiliary systems like fans and speakers. Usually the voltage supplied by the battery is too high, and it needs to be converted to a lower voltage that's suitable for these systems (most often 12/24 V).

An onboard charger is needed in a plug-in hybrid vehicle. It is connected to a power supply, a standard wall-socket or a high voltage supply for fast charging. It is basically an AC/DC converter.

A hybrid power control unit controls power distribution between the engine and the electric motor, gearing and charging strategies (Volvo Trucks - Great Britain & Ireland 2011).

High voltage cables are needed in vehicles with electric propulsion to conduct power between different systems in the drivetrain. They need to prevent leakage currents, protect people and objects from contact and provide sufficient insulation.

2.2.4 Regenerative Braking

In urban area driving a large amount of the traction energy is lost during braking. Often more than 25% and even up to as much as 70% can be lost in large cities (Westbrook 2001). Effective regenerative braking can retrieve a large part of this energy. In hybrid vehicles a regenerative

[1] Johan Hellsing (Alternative drivetrains, Volvo) e-mail conversation Spring 2012

braking system is working together with the mechanical braking system. Usually at gentle braking only the regenerative system is used, at moderate braking both of the systems work together and during emergency braking the mechanical system does most of the braking. In vehicles, three main categories of systems exist; series brake with optimal feel, series brake with optimal energy recovery and parallel brake. In the series brake systems, only the regenerative brake is used at low braking. At moderate braking the mechanical system kicks in, but a bit later in the energy recovery optimized system. During emergency the mechanical system does most of the braking.

In the parallel system the two brakes work together at all times, except at low deceleration when the regenerative system works alone. Instead of an electronically controlled mechanical brake system it uses a pressure sensor to determine the deceleration requirement. Depending on the pressure in the hydraulic brakes (for a private vehicle) the regenerative braking is applied. The parallel system is a simpler construction and needs less control systems, but at the same time less efficient than the series system. (Westbrook 2001)

2.3 Lithium-Ion Batteries

Li-ion battery technology was first discovered in 1912 and the first non-rechargeable battery was commercialized in 1970. Sony was the first company to launch the rechargeable Li-ion battery in 1991 and since then the technology has been further developed.

Some advantages over other battery technologies are:

- Compared to NiCd, it avoids cadmium which is an extremely toxic substance compared to lithium (Buchmann 2012; US Department of Labor 2012).
- Low maintenance and relatively low discharge.
- No memory effect and no scheduled cycling is required for prolonging the battery life.
- High electrochemical potential and high energy density per unit weight compared to other technologies, such as NiCd and NiMH batteries (Buchmann 2012).

A disadvantage is that it is fragile and requires a protection circuit to maintain safe operation. This limits current and voltage which allows a maximum discharge current of 1C-2C (see chapter 2.3.1 for an explanation).

2.3.1 LFP-Battery

The Volvo FE hybrid and plug-in hybrid uses a LFP-battery ($LiFePO_4$) in their vehicle. The electrochemical potential of a Li-ion cell is in the range of 2-4 V depending on cathode and anode material compositions. In the case of LFP the nominal cell voltage is around 3.4 V. The battery operates at a very flat voltage yielding a capacity from $75 - 170\ \mathrm{mAh \cdot g^{-1}}$ depending on the C-rate, the latter being the theoretical capacity. (Yuan, Liu et al. 2012)

A C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1 C-rate means that a discharge current will discharge the entire battery in 1 hour. A battery with a capacity of 100 A-h will have a discharge current of 100 A during one hour. A 5 C-rate for the same battery equals 500 A and a C/2-rate would be 50 A. Note that by changing the current to 500 A and 50 A respectively also the discharge time is shortened in the former case and prolonged in the latter (same amount of electric energy delivered). (MIT Electric Vehicle Team 2008)

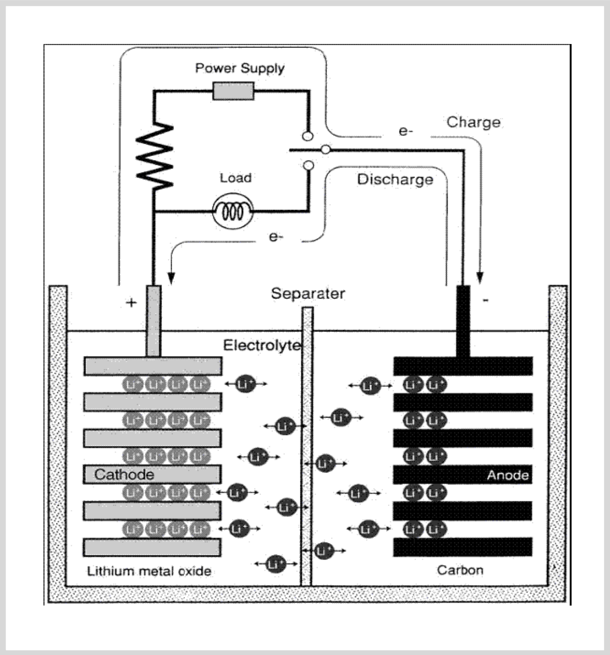


Figure 2-3: Schematic overview of an LFP-battery (Yuan, Liu et al. 2012).

The net reaction of the LFP-battery is:

$$FePO_4 + LiC_6 \leftrightarrow LiFePO_4 + C_6$$

The cathode reaction is:

$$FePO_4 + Li^+ + e^- \rightarrow LiFePO_4$$

The anode reaction is:

$$LiC_6 \rightarrow C_6 + Li^+ + e^-$$

$FePO_4$ is the transition metal oxide (Majeau-Bettez et.al 2011).

Advantages over other Li-ion compositions are:

- Strong covalent bonds, stabilizes the structure of the phospho-olivine compared to layered oxides e.g. $LiCoO_2$.
- The entire 3-D framework is stabilized leading to improved stability and extreme safety under abusive conditions.
- Stable up to 400^{o}C, compared to 250^{o}C for $LiCoO_2$.
- Slow decline of capacity loss compared to other Li-ion alternatives (low discharge rate)(Yuan, Liu et al. 2012).

Disadvantages are:

- The strong covalent bond of the oxygen atoms gives an insulation effect and restricts the electrochemical reaction kinetics. This leads to a very low Li-ion diffusivity and a very low electronic conductivity, about 10^{-9}S/cm at room temperature.
- Lithium diffusion occurs in 1-D. This along with the above mentioned low conductivity results in poor performance of LFP cathode.

Other general properties affecting performance:

- The electrochemical properties of the cathode materials are determined by the crystal structure, particle size/morphology, and stoichiometry of the active materials, and these are directly influenced by the chosen synthesis or production method.
- The performance of cathode materials depends on the arrangement of the active particles with the carbon additive, polymeric binder, and current collector. This is critical because it must form an efficient pathway for electron and lithium-ion transportation within the electrode.
- In an actual production process, cathode material composition, structure, particle size, and morphology are optimized for maximum electrochemical reactivity but minimum side reactions with electrolyte. This means faster delivery of electric energy, increased power, and lowers the parasitic consumption of the electrolyte. The side reaction of the electrolyte in the Li-ion battery can be compared to the lead-acid battery where continuous refilling of deionized water (electrolyte carrier) is needed due to the electrolysis of water (battery overcharge) (Department of Electrical-Computer and Energy Engineering n.d.).
- Particle size reduction will increase the active surface area of the electrode material leading to improved electrochemical kinetics.

The battery used in the Volvo FE Hybrid truck is a 120kW Li-ion ($LiFePO_4$) battery.

2.4 Volvo FE and Volvo FE Hybrid

The Volvo FE truck is developed primarily for regional distribution, waste collection duties, light construction duties and refrigerated haulage. Its gross weight ranges from 18 to 26 tonnes, it has a 7 liter engine (D7F) with power output ranging from 240 – 340 hp, and is certified to Euro 5 emission standards (Volvo Trucks 2012). See Figure 2-4 and Figure 2-5.

Figure 2-4: Volvo FE Hybrid distribution truck (Volvo Trucks 2012).

Figure 2-5: Volvo FE Hybrid waste collection vehicle (Volvo Trucks 2012).

2.4.1 Volvo FE Drivetrain

The main components of the drivetrain in the conventional FE truck comprise a diesel engine (D), clutch and automatic gearbox (I). The system also contains lead-acid batteries (B) and a solo axle with hub reduction (C), see Figure 2-6.

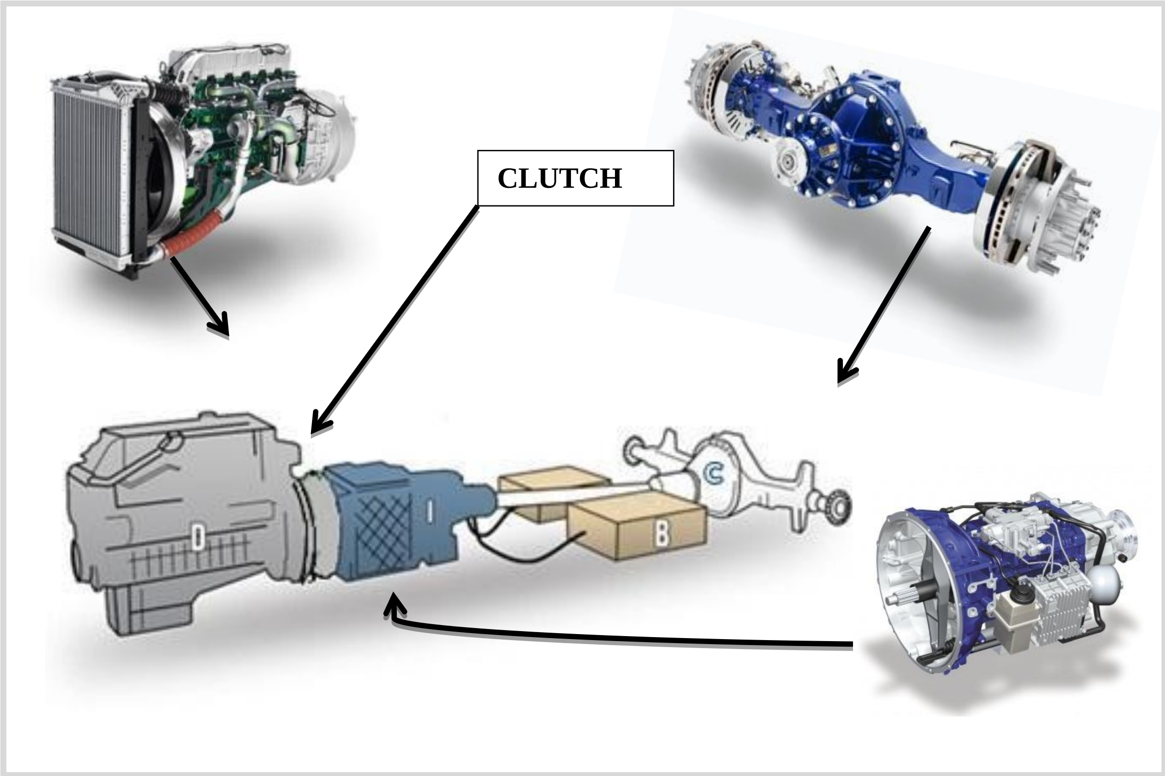


Figure 2-6: Conventional heavy vehicle drivetrain. (Volvo Trucks 2012)

2.4.2 Volvo FE Hybrid Drivetrain

In the FE Hybrid the main components of the drivetrain comprise a diesel engine (D), clutch, I-Shift gearbox (I) and the motor drive system (E/G), see Figure 2-7. The motor drive system consists of a permanent magnet motor that also functions as a generator and a power electronic converter (PEC). Li-ion battery module (B) and a solo axle with hub reduction (C) are also included. The heart of the system is the Hybrid Powertrain Control Unit (HPCU) or Power Management Control Unit (PMU). It controls the in- and out- connection of electrical power and diesel engine, gear change strategies and charging. Not seen in the picture are the other power converters, also part of the drivetrain (Volvo Trucks 2011). Important to note is that, unlike most hybrid vehicles, Volvo has chosen not to downsize the diesel engine in their FE Hybrid truck. Thus it is the same 7 liter engine in the conventional, hybrid and plug-in hybrid trucks.

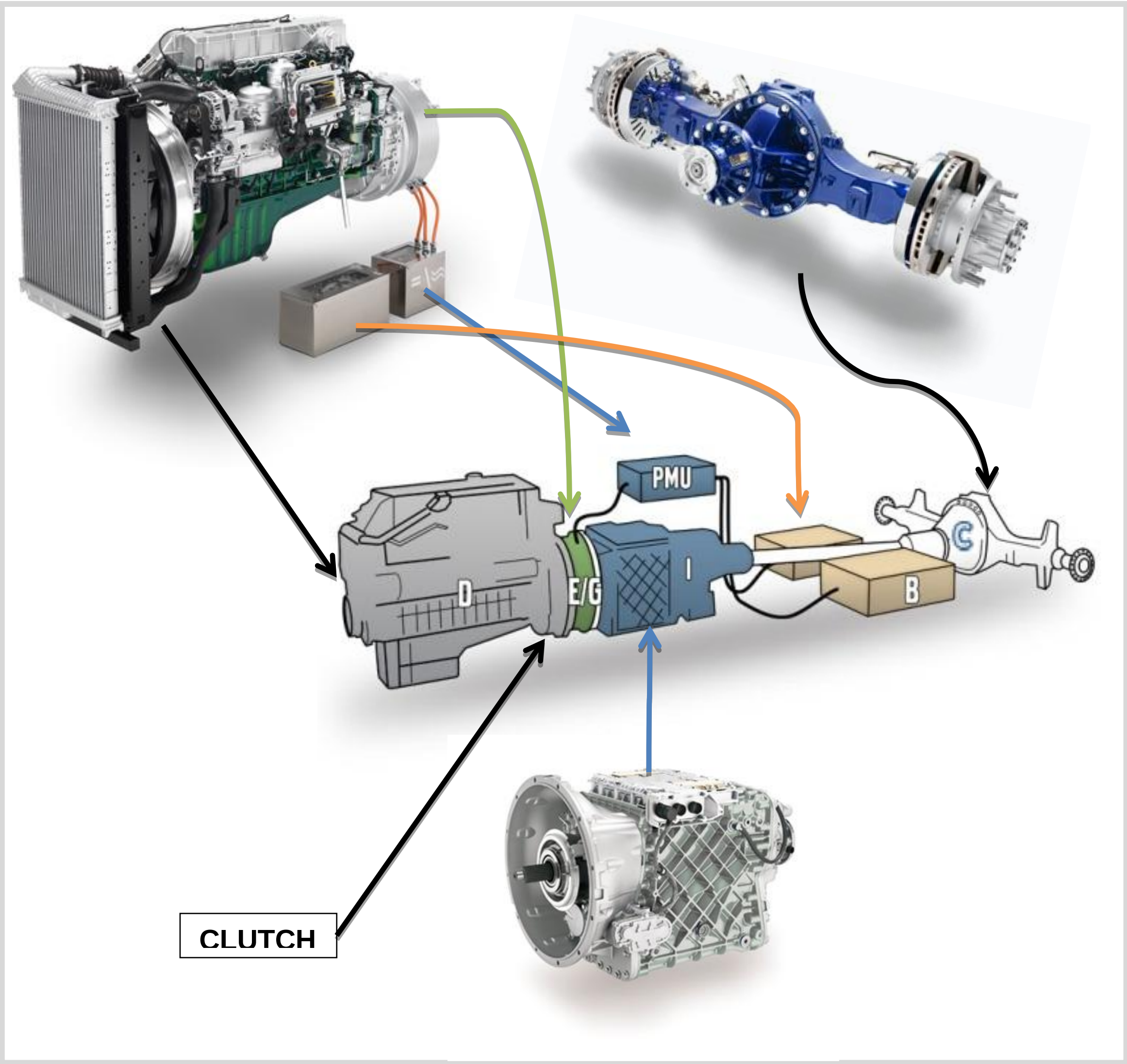


Figure 2-7: Hybrid heavy vehicle drivetrain. (Volvo Trucks 2011)

2.4.3 Drivetrain Components Included in the LCA

Many parts of the drivetrain are kept unchanged in the hybrid vehicle compared to the conventional, for example the internal combustion engine. Also, not all of the components in the drivetrain of the hybrid truck were considered to be relevant by Volvo to include in the LCA study. On the basis of weight and estimated environmental impact a number of components were chosen, indicated in Figure 2-8with green dots, and in Table 2-1with short descriptions.

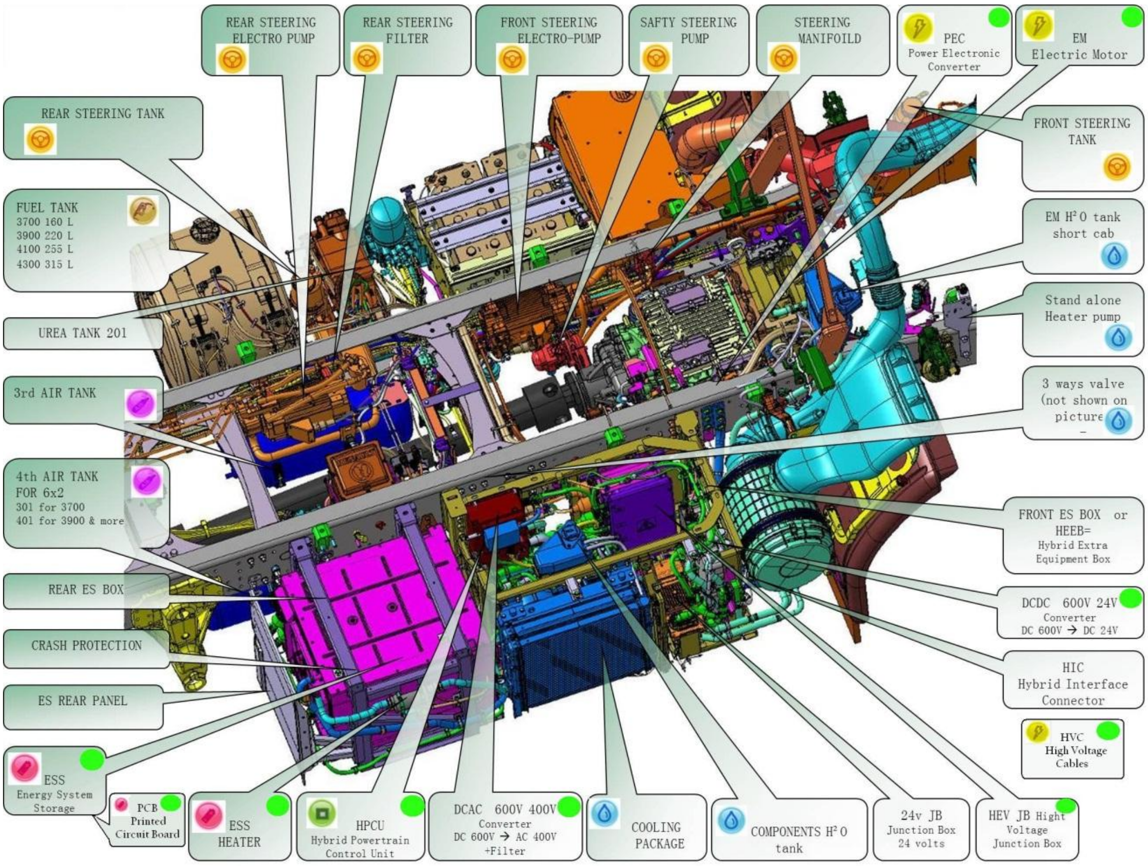
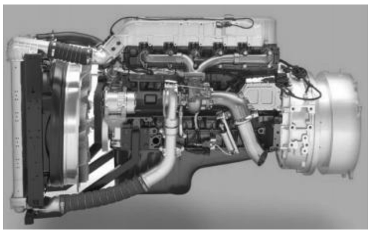


Figure 2-8: A representation of some of the hybrid vehicle components. Boxes with green dots are components included in the study.

Table 2-1: Major parts of the hybrid electric drivetrain.

Component	Specifications	Description	Representative picture
Energy System Storage(ESS) Li-ion battery with printed circuit board	120kW, 600V battery. Total energy capacity is 5 kWh, 1.2 kWh used before recharging (75% SOC). **Weight:** 217.6 kg	Deliver and store energy to and from the drivetrain.	 (Heidebauer 2007)
ESS Heater	24 V, 2.5 kW. **Weight:**1.835 kg	Used to heat up the Li-ion battery to increase performance and life.	 (Lulusoso 2012)
Hybrid Powertrain Control Unit (HPCU) / Power Management Unit (PMU)	**Weight:**1.9 kg	This unit controls the interplay between the diesel engine and the electrical motor to optimize energy consumption.	 (Keihin Corporation n.d.)
Inverter(DC/AC converter)	600 V DC to 400V AC.High voltage cable is integrated. **Weight:** 14 kg	Converts direct current, 600V, to alternating current, 400V. The inverted current is used to power air tanks and hydraulic systems in the vehicle auxiliary systems.	 (LED Lights World)

High Voltage Junction Box (HEV JB)	**Weight:** 22.625 kg	A container for high voltage electrical equipment. The box is intended to provide circuit integrity, function as a junction for cables and distribute power to different parts of the vehicle.	 (Pollak 2012)
DC/DC converter	600V DC to 24V DC **Weight:** 21 kg	Can convert to different voltages depending on the requirement. This particular converts to 24 V for auxiliary systems like speakers etc. Other applications like the lift in the distribution truck needs a different voltage, 340 V.	 (Brusa Elektronik AG 2012)
Electric Motor(EM)	Permanent magnet synchronous Integrated Starter Alternator Motor (I-SAM). **Weight:** 152 kg	It serves both as a motor and a generator during braking.	 EM attached to the engine. (Volvo Trucks 2008)
Power Electronic Converter(PEC) / Inverter	**Weight:**28 kg	A unit used to convert DC/AC or AC/DC currents between battery pack and the electric motor. Maximum power 120 kW.	 (Bourne Electronics 2012)

High Voltage Cables **HEV JB-PEC** **HEV JB-ESS** **HEV JB-DC/DC** **HEV JB-DC/AC**	**Weight:**8.1 kg total 3.032 kg 4.685 kg (2 cables) 0.38 kg Integrated in DC/AC converter	Used for conducting high voltage from the HEV JB to all high voltage components listed to the left. The difference from low voltage cables is the amount of insulation used to control the electrical field of the cable to prevent insulation breakdown and current leakage.	 (Essex 2012)

Table 2-2: Major components of the plug-in electric drivetrain.

Modified ESS (plug-in hybrid battery system)	Total energy 14 kWh, discharges up to 60% of total energy. **Weight:** 239.5 kg	Increased amount of active material in order to increase total energy storage to 14 kWh.	 (Heidebauer 2007)
Onboard charger	Converts 230 VAC to 600 VDC,maximum power 2.1 kW. **Weight:** 6.2 kg	An AC/DC converter designed to be connected to the power grid to charge the battery in maximum 4 hours.	 (Brusa Elektronik AG 2012)

The weight of included components in the hybrid configuration is about 466 kg. In the plug-in hybrid the total weight is 494 kg. Included are also assembly parts related to each component such as screws, terminals, sensors, fuses, etc. The only major component removed from the conventional vehicle is the lead-acid starter battery, see Table 2-3.

Table 2-3: Major part from the conventional vehicles removed in the hybrid vehicles.

Lead-acid battery	**Weight:** 119 kg	Used to power the starter motor, the lights and the ignition system of the engine.	 **(**Made in China 2012)

The following components present in Figure 2-8 are excluded from this LCA since they are either considered by Volvo to have minor relevance, or they are a part of the conventional vehicle as well.

- Tanks, boxes and filters
  - *Urea tank:* Is used to eliminate as much NO_x as possible from the diesel exhaust (Hargrove 2008).
  - *Front and rear ES (Electric System) boxes:* Used to keep all electrical equipment in place. New to the hybrid vehicle.
  - *Crash protection*
  - *ES rear panel:* Protects the rear end of the battery pack. New to the hybrid vehicle.
  - *Rear steering tank*
  - *Rear steering filter*
  - *Front steering filter*
  - *Front steering tank*
  - *Fuel tank*
- Cooling and heating systems
  - *Cooling package:* Cools the battery. New to the hybrid vehicle.
  - *Components H2O tank:* Water tank for the cooling package. New to the hybrid vehicle.
  - *3 ways valve:* Controls and directs the cooling fluid.
  - *Standalone heater pump*
  - *EM (Electric Motor) H2O tank short cab:* New to the hybrid vehicle.
  - *Rear steering electro pump*
  - *Front steering electro pump*
  - *Safety steering pump*
  - *Steering manifold*
  - *4th air tank for 6x2*
- Electrical equipment
  - *24 Volt JB (Junction Box):* Storage of electrical equipment.
  - *HIC (Hybrid Interface Connector):* Hybrid connectors have housings that allow for inter-mixing of many connector types, even non-electrical connector types, for example pneumatic line connectors and optical fiber connectors. New to the hybrid vehicle.

3. Goal and Scope Definition

3.1 Goal

The goal of this study has been to evaluate the environmental impacts of the different components and life cycle stages of two different I-SAM (Integrated Starter Alternator Motor) hybrid heavy vehicles (HHV:s). The HHV:s considered were a distribution truck and a waste collection vehicle, with two different drivetrain configurations, hybrid and plug-in hybrid, and diverse driving patterns in Gothenburg urban area. Questions to be answered are:

1. How large are the emissions and the environmental impact for the different configurations, hybrid and plug-in hybrid during their lifecycle, using the conventional vehicle as baseline?
2. Which life cycle stages have the largest environmental impacts?
3. Which components contribute most to the environmental burden?

The study has been conducted with learning and internal use at Volvo as the main objective.

3.2 Scope

The different types of vehicles included in the study were:

- hybrid electric distribution truck (Volvo FE Hybrid),
- plug-in hybrid electric distribution truck (modified Volvo FE Hybrid),
- hybrid electric waste collection vehicle (Volvo FE Hybrid),
- plug-in hybrid electric waste collection vehicle (modified Volvo FE Hybrid).

The reference vehicles were:

- conventional diesel distribution truck (Volvo FE),
- conventional diesel waste collection vehicle (Volvo FE).

Volvo Group Trucks Technology has performed LCA:s on the reference vehicles. The results have not been published yet and they have therefore not been included in the life cycle inventory of this study. The drivetrains of the studied vehicles were divided into a reference part and an additional electric part. The reference part is identical to the conventional reference vehicle drivetrain. The rest of the vehicle such as chassis and load are identical for the distribution- and waste collection vehicles respectively, except parts of the body (see section 3.2.4.1).

For this reason the study only includes additional electrical components, i.e. the ICE is not included in this study. Thus, the study is an assessment of the electric part of the drivetrain configuration for the hybrid- and the plug-in hybrid- vehicle. Major components in the drivetrain identified as being additional to the conventional vehicle are: electric motor, Li-ion battery, hybrid powertrain control unit, electrical converters, junction box, battery heater and high voltage cables. Only one component, the 24 V lead-acid starter battery, has been removed from the reference vehicle as it is not part of any of the hybrid configurations.

In addition, different driving patterns for both vehicle types, distribution- and waste collection vehicle, were considered in the use phase.

3.2.1 Type of LCA

The hybrid vehicles assessed in this study are already for sale and in use in selected test markets. The design of the plug-in hybrid configuration is currently in an advanced engineering phase, with no industrialization decided. However, the aim for Volvo is to learn which environmental impact that these two configurations of electrification can be held accountable for in a future state, in a case study for Gothenburg where the plug-in hybrid is operated on a small scale. For this reason this study was chosen to be a comparative accounting LCA, where all life cycle stages for the electric part of the drivetrain were included.

3.2.2 Functional Unit

For both the different vehicle types the functional unit (FU) was chosen to be one truck over its lifetime, giving two different FU:s as they are based on two different functions, distribution of goods and waste collection, and different lifetimes.

The lifetime of the conventional waste collection vehicle was estimated to 300 000 km by Henriksson (2008), this value has been used in an earlier LCA. The same value was used in this study for the waste collection vehicle, both hybrid and plug-in hybrid. Yearly driving distance for a waste collection vehicle is 21 000 km according to Volvo.[2]

The lifetime of the distribution truck was set to 1 million km, according to Volvo. The wearing of the distribution truck was considered to be lower compared to the waste collection vehicle and therefore this value was set. The yearly driving distance of a distribution truck is 66 000 km.

3.2.3 System Boundaries

Given that the study was decided to be accounting and thereby expected to cover all processes from cradle-to-grave according to Baumann and Tillman (2009), all processes from raw material production, through manufacturing, transportation, use and end of life treatment were included for all parts relevant for the drivetrain. However, in the well-to-wheel phase (use phase including diesel- and electricity production), see Figure 3-1, the data for the fuel consumption and energy use refers to the complete vehicle, as the function provided by the drivetrain is to propel all weight carried by the vehicle and this is different depending on the configuration of the drivetrain. In addition, maintenance during the use phase was included.

Note that the drivetrain configurations studied have been based on the conventional Volvo FE truck, and all other parts of the vehicle except the drivetrain can be regarded as identical. Also, as mentioned before, a large part of the drivetrain itself, for example the internal combustion engine, is the same as in the reference vehicles, and has not been included in the model. The inventory results in the LCA made by Wallenius-Henriksson (2012) thereby constitutes the baseline in our study.

As specified and described in chapter 2, the following components were decided by Volvo Group Trucks Technology as relevant to include in the study:

- Energy System Storage (ESS), LFP-battery with a printed circuit board
- ESS Heater

[2] Niklas Thulin (Senior research engineer, Volvo) e-mail conversation Spring 2012

- Hybrid Powertrain Control Unit (HPCU)
- DC/AC Converter, 600VDC to 400 VAC
- High Voltage Junction Box (HEV JB)
- DC/DC Converter, 600V to 24V
- Electric Motor (EM)
- Power Electronic Converter (PEC)
- High Voltage Cables (HV Cables)

For the plug-in hybrid the ESS was different, and one additional component was added:

- Modified Energy System Storage (Modified ESS), LFP-battery with a printed circuit board
- Onboard Charger

3.2.4 Geographical and Time Boundaries

According to Volvo the vehicles have a use phase of approximately 14-15 years, with the year 2020 as a mid-point. This means that the production of raw materials and components, transports and assembly takes place in 2012-2013, and the end of life around year 2027. These time periods have therefore been matched to the corresponding processes and lifecycle stages in the model.

Raw material production takes place all around the world. In the modeling of material production, global averages or data from the region where the component is manufactured was used. The documentation of the data sets in the stated databases (chapter 3.2.11) in GaBi, were checked and only used for global averages, regional averages and in some cases the largest producing country. For example in the case of lithium, Chile is by far the largest supplier, while for neodymium it is China.

Manufacturing of the components was assumed to take place in the locations listed inTable 3-1, based on production sites of the companies.

Assembly of the entire truck, hence also the drivetrain, is done in Gent, Belgium.

The use phase contained two different urban driving patterns for the distribution truck and the waste collection vehicle, and the entire use phase was assumed to take place in the Gothenburg urban area. In line with this, it was also assumed that the end of life treatment will take place in Sweden.

For this purpose different electricity mixes were used for different years and countries depending on which stage in the life cycle that were considered. For material extraction and transformation and component assembly, present time electricity mixes were used. For the use phase, electricity mix for Sweden year 2020 was used, and in the end of life stage electricity mix for Sweden year 2027 was used.

Table 3-1: The manufacturing location of each component.

Component	Manufacturing location
HEV Junction Box	USA
DC/DC converter	France
DC/AC converter	Czech Republic
Power Electronic Converter	USA
Electric Motor	USA
ESS and Modified ESS	China
ESS heater	Sweden
HV-cables	Germany
Hybrid Powertrain Control Unit	USA

In addition, a modeling of the transports, corresponding to the locations of the manufacturing sites of the components through the supply chain was set up. Transportation was assumed to be carried out by cargo liners on sea, and trucks on land, with several stops to the final destination Gent, Belgium, where the components are assembled into the final drivetrain. Second order suppliers, the suppliers to Volvo's suppliers, have not been modeled because no data was available.

3.2.4.1 *Excluded processes*

In earlier sections it is stated that the electric parts of the drivetrain have been accounted for. However, the hybrid drivetrain package includes more components than the ones selected by Volvo in section2.4.3.

The following components are included in the hybrid drivetrain unit and also exist in the conventional vehicle but with different packaging and design. However in this study they are regarded as equivalent and not included in the model.

- Rear steering tank
- Rear steering electro pump
- Rear steering filter
- Front steering filter
- Front steering electro pump
- Safety steering pump
- Steering manifold
- Front steering tank
- Standalone heater pump
- 3 ways valve
- 24 V junction box
- 4^{th} air tank for 6x2
- Urea tank
- Fuel tank
- Crash protection

A few components were excluded with regards to the complete life cycle and only included in the use phase as the total weight of these components have been included in the fuel consumption figures, since they are included in the total weight of the vehicle.

- Hybrid Interface Connector
- EM H_2O tank short cab
- Rear ES box
- Front ES box
- ES rear panel
- Components H_2O tank
- Cooling package

In addition, the waste collection unit and distribution load unit, part of the body, were excluded from the study. However, respective weight has been accounted for correspondingly in the use phase for fuel consumption.

Other aspects not considered in the LCA are:

- Packaging materials
- Water treatment
- Travelling by employees
- Surface treatment of materials and components

3.2.5 Characterization Indicators

In collaboration with Volvo Group Trucks Technology, the impact categories, explained more in section 5.1, considered to be most relevant to include in the study were:

- Global Warming Potential (GWP100)
- Acidification Potential (AP)
- Human Toxicity Potential (HTP)
- Abiotic Resource Depletion Potential (RDP)

Global warming is a well-known environmental threat, always relevant when discussing environmental load in the transport sector. Since the hybrid vehicles are expected to save fuel, it is important to see the effect of this on the GWP.

The vehicles are modeled to drive in high-populated urban environment; therefore HTP is also relevant for the study. AP is also studied since in an urban environment, acidification causes damage to for example buildings and monuments (Baumann and Tillman 2009). Acidification is also known to harm the environment such as forests, fish in lakes and the release of toxic metals from soils.

Finally, RDP is considered relevant to study since some potentially rare elements are needed in parts of the drivetrain, for example lithium in the battery, gold and platinum in the circuit boards.

3.2.6 Weighting Indicators

In collaboration with Volvo Group Trucks Technology, the weighting indicators considered to be most relevant to include in the study were:

- Environmental Priority Strategies (EPS) described more in detail in section 5.3.1.1.
- Eco Indicator 99 (Hierarchist) (EI-99 HA) described more in detail in section 5.3.1.2.

3.2.7 Life Cycle Flowchart

A simplified flowchart of the life cycle is seen in Figure 3-1.

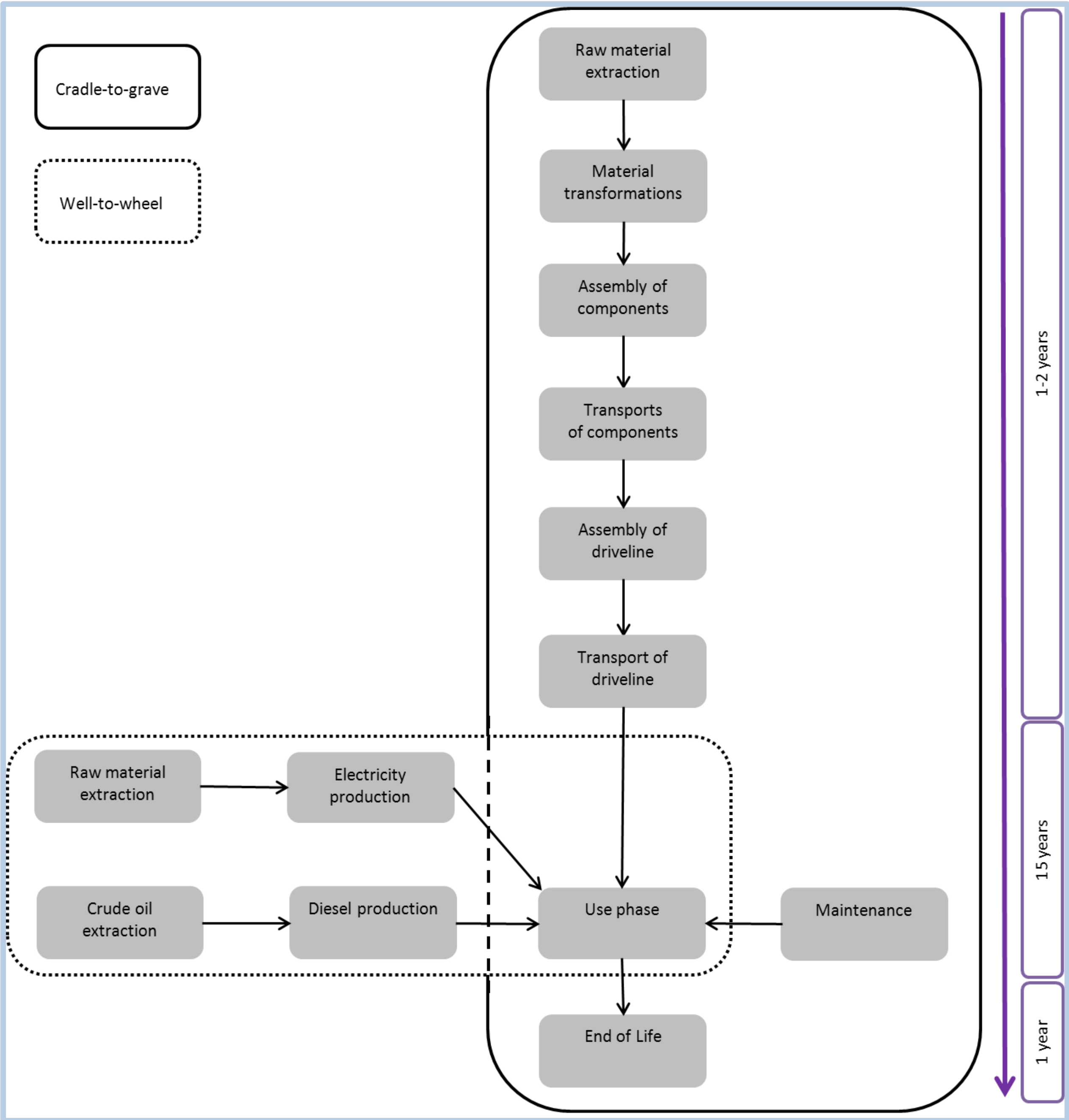


Figure 3-1: Simplified flowchart of the basic processes in the life cycle. The solid box marks the processes included in the cradle-to-grave model, and the dashed box marks the processes included in the well-to-wheel phase.

3.2.8 Limitations

No specific charging infrastructure has been modeled for the operation of the plug-in hybrid vehicle, since the on-board charger has been designed to be connected to a standard wall socket, i.e. 230 VAC. The maximum charging time was set to 4 hours, which gives a charging power of 2.1 kW for a 60% discharged battery with 14 kWh capacity.

The economic and social aspects of the hybridization have not been included.

3.2.9 Allocation

As this is an accounting LCA, attributional partitioning has been used for allocation in accordance with Baumann and Tillman (2009). In line with the ISO standard it has been based on physical properties such as time for the assembly of the drivetrain, energy and weight, for the production of components and end of life treatment.

3.2.10 Intended Audience

The report is a master thesis work and the data is presented in both a detailed and an aggregated manner. Due to confidentiality issues two separate reports have been written, one for Volvo Group Trucks Technology and one for Chalmers. They are intended to be used internally for learning by Volvo Group Trucks Technology and to be published publically at Chalmers website, respectively.

The indicators are presented in an aggregated manner in order to get a quick and simple overview of the results. The intended audiences are LCA-specialists and development engineers within Volvo.

3.2.11 Data Acquisition

Component data was collected from databases provided together with the LCA software GaBi. The databases used were (PE International AG 2012):

- PE: Database created by PE International.
- BUWAL: Database created by ETH Zürich. Most data from 1996. Contains packaging materials like aluminium, paper etc. Only used if no other data available.
- PlasticsEurope: Created by PlasticsEurope in Belgium. Contains mostly plastics and intermediates, preferred for all types of plastic in Europe.
- Ecoinvent: Created by the Ecoinvent Centre in Switzerland. Contains inventory data for various services and products.
- ELCD: European Reference Life Cycle Data System.
- EAA: European Aluminium Association. Contains data on aluminium.
- Worldsteel: Worldsteel Association represents approximately 170 steel producers around the world.
- ISSF: International Stainless Steel Federation.

The validity of the material process data used in GaBi ranges from 1997 to 2015 which means a lot of data can be considered to be out of date.

3.2.12 **Critical Review**

The report has been reviewed by Maria Wallenius Henriksson and Niklas Thulin at Volvo Group Trucks Technology; Anders Nordelöf and Ann-Marie Tillman at Chalmers University of Technology.

4. Inventory Analysis

4.1 Introduction

The inventory analysis describes the processes in the life cycle of the components in the drivetrain, and the procedure of the data collection and modeling.

4.2 Overview

The processes in the life cycle are taking place in various locations around the world. In Table 4-1 all major processes and their corresponding locations are seen. These geographical locations served as a starting point when trying to find data for the material production and component manufacturing. Locations are based on information from Volvo[3] and on supplier production sites. When various supplier sites were available, the most likely location was chosen.

Table 4-1: Overview of the main processes and their corresponding locations and time horizon.

Process	**Representative location**	**Time**
Raw material extraction	Global average or country/region specific (depending on the component it is extracted for or where most extraction takes place)	2012
Material production	Global average or country specific (depending on the component it is produced for or where most production takes place)	2012
Manufacturing of ESS	China and Europe	2012
Manufacturing of ESS heater	Sweden	2012
Manufacturing of HPCU	USA	2012
Manufacturing of DC/AC converter	Czech Republic	2012
Manufacturing of HEV JB	USA	2012
Manufacturing of PEC	USA	2012
Manufacturing of DC/DC converter	France	2012
Manufacturing of EM	USA	2012
Manufacturing of HV cables	Germany	2012
Manufacturing of modified ESS	China and Europe	2012
Manufacturing of onboard charger	Czech Republic	2012
Use phase	Sweden	2020
Maintenance and repair	Sweden	2020
End of life	Sweden	2027

[3] Niklas Thulin (Senior research engineer, Volvo) e-mail conversation Spring 2012

To be in line with the geographical and time boundaries specified in section 3.2.4, projected future state country specific electricity mixes were used. Table 4-2 shows the projected electricity mix for Sweden 2027, which has been approximated by using data for 2030, since no data was found for 2027.

Table 4-2: Projected electricity grid mixes.

Primary energy demand, shares by fuel (%)	Combined heat and power	Produced in industry (assumed oil)	Nuclear	Hydro	Wind	Solar
Sweden 2020 (Gustavsson, Särnholm et al. 2011)	3.4	3.3	40.8	38.5	11.7	2.3
Sweden 2027 (Gustavsson, Särnholm et al. 2011)	3.1	2.7	30.6	40.4	18.3	4.9

4.3 Raw Material Extraction and Material Production

For all the included components material data has been gathered from different sources. In two cases, for the ESS heater and the DC/AC converter, International Material Data System (IMDS) reports from Volvo suppliers were received. For the other components data was received from Volvo employees, or approximated from data for similar components.

For some of the components a part of the mass was not possible to allocate to a certain material, since the datasets received contained a fraction of unspecified materials. To avoid counting this as zero environmental impact, it has been assumed to have the same composition as the rest of that component.

In agreement with Volvo, a modeling in GaBi LCA software was done for raw material extraction. The following general material choices were done in the GaBi modeling.

- Stainless steel grade 304 was assumed, which is the most widely used grade. It has a carbon content of approximately 20% and a chromium content of 10%. (Azom 2011)
- For copper a mix between 40% recycled from scrap and 60% virgin were used, which is the global average. (Dahllöf 2010)
- For indium, lead, platinum, chromium, manganese, zinc and tin cradle-to-storage data from Ecoinvent was generally used.
- For lithium, nickel, graphite, cadmium, ferrite, magnesium, neodymium, silicone, aluminium oxide and glass fibre cradle to plant data from Ecoinvent was generally used.
- For plastics like PET, LDPE, HDPE, PBT and PUR data from PE or ELCD was used. Granulate form if no other was specified.
- For steel usually data from Worldsteel was used.
- For synthetic rubber styrene-butadiene or EPDM data from PE was used.
- For Aluminium ingot mix, European average was used.
- Recycled iron from scrap was usually used.
- Global averages were used for silver and gold mixes.

In addition material production and transformation processes were included for as many materials as possible. In cases where no suitable process were found in the GaBi databases, the GREET (Greenhouse gases, Regulated Emissions, and Energy use in Transportation) model developed by Sullivan, Burnham et al. (2010) was used to calculate energy use for material production. Appropriate processes for the materials were assumed depending on which component they belonged to. For the metals iron, steel and aluminium, a casting process was usually assumed, wire production or sheet rolling processes were used for copper and for plastics, an injection molding process was used. For some substances no appropriate material production process was identified, for example for nickel, gold and tin.

Table 4-3: Summary of sources used for acquiring material composition data in all components described in section 4.4.

Components	Source for material composition in components
EM	Material data provided by supplier in earlier LCA study (scaled by weight)
HPCU	Generic material data from similar component used from earlier LCA study (scaled by weight)
DC/DC	Material data provided by the supplier from earlier LCA study (scaled by weight)
DC/AC	Material data from MDS
PEC	Material data provided by the supplier from earlier LCA study (scaled by weight)
Onboard charger	Same materials as in the DC/AC (scaled by weight); PCB assumed not to weigh more than 1 kg
HV cables	Material composition known; assumptions made on material share
HEV JB	Components data from KOLA; component material composition from KOLA
ESS Heater	Material data from MDS
ESS	Material data from MDS
Modified ESS	Material data from MDS; additional LiFePO4 has been calculated based on energy allocation

4.4 Manufacturing of Components

4.4.1 Energy System Storage and Modified Energy System Storage

The description of the ESS has been divided into the battery module and the printed circuit board (PCB).

4.4.1.1 *LFP-Battery*

The material content of the battery was received from Henriksson (2008), based on original data from an IMDS (International Material Data System) report provided by the supplier. No first hand production data was received by the supplier, but from a literature study the energy consumption in the production stage could be approximated (Zackrisson et al. 2010). The cells were assumed to be manufactured in China, and the final assembly of the battery modules was assumed to take place in Europe.

A LCA of lithium ion batteries in cars, by Zackrisson et al. (2010), claims that the total module- and battery assembly energy consumption corresponds to 11.7 kWh electricity and 8.8 kWh of thermal energy from natural gas per kg lithium-ion battery. The manufacturing of the active material, $LiFePO_4$, requires two heatings, first to 400 – 500 ^oC then to 700 – 800 ^oC. After the first increase the milled material and graphite are added. Assuming a specific heat capacity of 0.9 kJ/kgK, the two temperature elevations would need approximately 1 kJ/gram $LiFePO_4$. The grinding and chemical reactions also require energy and accounting for heat losses a total of 3 kJ/gram $LiFePO_4$ has been assumed.

The energy used for the assembly was calculated using a weight estimation approach based on the manufacturing energy of the electric motor. Gate-to-gate energy for the EM assembly, both electricity and heat, was divided by the weight, 152 kg, of the EM. These values were then multiplied by the weights of the ESS and modified ESS to obtain assembly energy. For the ESS the assembly energy is 234 MJ electricity and 198 MJ heat. The values for the modified ESS are 258 MJ electricity and 218 MJ heat.

The battery in Zackrisson et al.'s study is a 10 kWh battery weighing 107 kg and operating at 370V. In our case the LFP-battery in the hybrid vehicle weighs 217.6 kg with an energy content of 5 kWh operating at 600V. The plug-in hybrid vehicle battery has an energy content of 14 kWh. According to Volvo[4] the extra active material needed constitutes all the extra weight. The amount of $LiFePO_4$ present in the plug-in hybrid battery pack has been calculated by using an energy based estimation to match the electric charge (measured in Ah), as this is an indication of the available energy. The same calculation has been done for the hybrid battery system which shows how close this assumption is to the real value, see Table 4-4, where values marked with * and ** are the assumptions. The weight of the modified ESS was then calculated to be 239.5 kg, 21.88 kg more than in the hybrid vehicle. To be able to give the correct assembly energy for our battery systems an estimation has been made based on the total weight of the battery systems.

[4] Niklas Thulin (Senior research engineer, Volvo) e-mail conversation Spring 2012

Table 4-4: Comparison between two differently optimized battery systems.

	Energy content (kWh)	Operating voltage (V)	Total weight (kg)	Ah	Cathode ($LiFePO_4$) weight (kg)	Assembly energy electricity (kWh_e)	Assembly energy natural gas (kWh_{ng})	Production electricity $LiFePO_4$ (kWh_e)
						Per kg ESS	*Per kg ESS*	*Per kg $LiFePO_4$*
[kWh]/[kg]						11.7	8.8	0.8333
						Total	**Total**	**Total**
Zackrisson, Avellán et al. (2010)	10	370	107	27	42.2	1251.9	941.6	35.167
Hybrid battery	5	600	217.6	8.33	14.59 (13.02*)	2545.9	1914.9	12.16
Plug-in hybrid battery	14	600	239.5	23.33	36.47**	2779.9	2090.9	30.40

There are different substances and manufacturing techniques available for the production of $LiFePO_4$. A study made by Myeong-Hee Lee (2010) shows one of many production procedures using Li_3PO_4 and $Fe_3(PO_4)_2$ combined with a hydrothermal and calcination treatment to get the final $LiFePO_4$ product. Below a schematic procedure, Figure 4-1, is demonstrated for this process which is also modeled in GaBi.

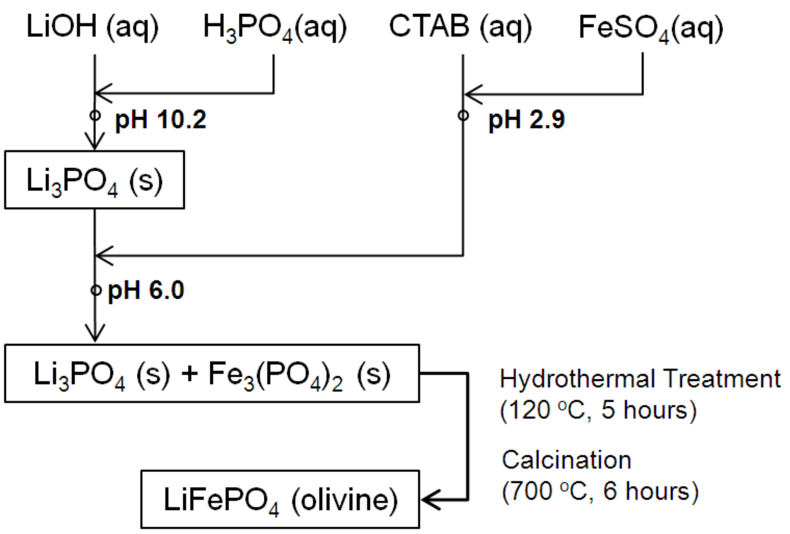


Figure 4-1: Schematic model over $LiFePO_4$ production (Myeong-Hee Lee 2010).

It is important to note that the three battery systems are optimized for different purposes. The 14 kWh battery in our study is discharged by 60% of its total energy content and is optimized to deliver the highest amount of energy and power per charge cycle (plug-in hybrid electric vehicle) whereas the battery in the hybrid vehicle, 5 kWh, is optimized to withstand the highest possible amount of charge-discharge cycles and is only discharged 15% in order to maximize its lifetime.

Finally the total manufacturing energy needed for the two different two battery systems, 5 and 14 kWh, is 9209.2 $MJ_{electricity}$ and 6893.6 $MJ_{natural\ gas}$,10117.1 $MJ_{electricity}$ and 7527.2 $MJ_{natural\ gas}$ respectively.

4.4.1.2 *Integrated Printed Circuit Board*

The printed circuit board (PCB) was assumed to be produced in Europe together with the assembly of the battery. Material composition and chosen data for the PCB in the material composition has been taken from Henriksson (2008) (original data from an IMDS report) in an earlier LCA on the hybrid drivetrain made by Volvo. The PCB has a relatively high amount of gold which probably is due to its high corrosion resistance.[5]

Material processing modeled for the PCB includes aluminium casting, copper sheet rolling and injection molding for plastics. For the assembly of the PCB the electricity data found in a dataset in the CPM database were used (CPM 2010).

4.4.2 ESS Heater

The ESS Heater is manufactured in Sweden. An IMDS report of the constituents was used to determine the materials. Material processing modeled includes casting of iron and steel, injection molding of plastics and wire drawing of copper.

The energy used for the ESS heater manufacturing was calculated using an estimation approach based on the manufacturing energy of the other components. The following model was used to calculate manufacturing energy share: gate-to-gate energy was divided by cradle-to-gate energy (from GaBi) for: DC/DC converter, DC/AC converter, on-board charger, EM, HPCU, PEC and HV-cables. These seven values were added together and divided by 7 to get the mean value which is about 0.031 MJ for electricity and 0.012 MJ for heat. This means that the average manufacturing energy is 2.9% and 1.1% of the cradle-to-gate energy for electricity and heat respectively. The mean values were multiplied with the cradle-to-gate value for the ESS heater in order to get an approximation of the manufacturing energy.

4.4.3 Hybrid Powertrain Control Unit (HPCU)

The HPCU has a total weight of 1.9 kg according to KOLA, Volvo’s product data management system. No accurate material data was found, but data for a more generic control unit was found in Dahllöf (2010) to be 55% PCB, 30% polyamide and 15% unspecified.

To include material production, injection molding for the polyamide was modeled, and for the PCB the same PCB as in the ESS was used. To model assembly energy a similar component was used as a reference, a control unit in an automobile, where an LCA has been conducted by Suyang and Jingjing (2010). The gate-to-gate energy value, 8.93×10^{-7} MJ electricity, was used for a PCB board weighing 46.6 grams and rescaled to match a HPCU with a PCB weighing 1.23 kg.

[5] Istaq Ahmed (Advanced Technology and Research, VGTT). Study visit spring 2012

4.4.4 **DC/AC Converter**

For the DC/AC converter data was received in an IMDS report from the manufacturer. For the PCB in the converter the material data from the PCB in the ESS was used, with less gold and silver according to the IMDS report.[6]

Material production and transformation data were used where suitable processes were found. For aluminium die casting was modeled, wire production was assumed for copper and a casting process of iron. For rubber and plastic, injection molding according to Sullivan, Burnham et al. (2010) was modeled.

To estimate the energy consumption for the assembly of the converter, several EPDs for converters made by ABB were studied and the one with most similar material content was chosen, the ACS 100/140 frequency converter (ABB 2002). The electricity and heat consumption used in the manufacturing stage was assumed to correspond to the assembly energy consumption. After rescaling according to weight, the gate-to-gate assembly energy was found to be 210 MJ electricity and 118 MJ heat.

4.4.5 **High Voltage Junction Box**

The supplier of the High Voltage Junction Box (HEV JB) is located in USA. In Volvo’s product data management system KOLA all included subcomponents (not materials) in the HEV JB are listed.

The material processing is modeled with steel casting, sheet production of aluminium alloy, injection molding of plastics and wire drawing of copper.

The energy used for the assembly was calculated using an estimation approach based on the manufacturing energy of the other components. The following model was used to calculate manufacturing energy share: gate-to-gate energy for the assembly was divided by cradle-to-gate energy for raw material extraction and material production for: DC/DC converter, DC/AC converter, on-board charger, EM, HPCU, PEC and HV-cables. The mean of these seven values was calculated to be approximately 0.031 MJ for electricity and 0.012 MJ for heat. This means that the average assembly energy is 2.9% and 1.1% of the cradle-to-gate energy for electricity and heat respectively. This value was multiplied with the cradle-to-gate value for the HEV JB in order to get the assembly energy.

4.4.6 **DC/DC Converter**

The DC/DC converter was assumed to be manufactured in France. Data was provided by the manufacturer to the earlier LCA by Henriksson (2008), and scaled to the weight of the converter found in Volvo’s product data management system KOLA. The material production processes modeled includes aluminium die casting, sheet production of aluminium alloy, copper wire drawing and injection molding of plastics.

To include data for the assembly of the converter a screening study of LCAs and EPDs of similar components was done. A series of EPDs of frequency converters made by ABB was scanned

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[6] Istaq Ahmed (Advanced Technology and Research, VGTT). Study visit spring 2012

through to find which one appeared to resemble the converter in this study the most. The ACS 160 frequency converter was chosen (ABB 2002). The gate-to-gate energy consumption was assumed to represent the assembly energy. The result was scaled to our DC/DC converter on a weight basis, and the resulting energy was calculated to be 88.5 MJ electricity and 49.8 MJ heat.

4.4.7 Electric Motor

The electric motor is manufactured in USA. The supplier of the motor had already supplied material data to an earlier LCA on the hybrid drivetrain by Henriksson (2008). This data was used, adjusted to the correct weight. The weight of the motor in that report was 162 kg, while the motor in this study weighs 152 kg. According to Volvo[7] the lower mass does not affect the magnets and the copper. The other materials share this mass reduction.

Also a more accurate material composition of the magnets was achieved by consulting Johan Hellsing. According to him the NdFeB-magnets weigh 7.6 kg and consist of approximately 30% neodymium, and a small fraction of dysprosium (0.3 kg). The rest of the material in the magnets is shared between copper, boron, niobium and aluminium according to the table from e-Magnets UK (2012).

For the material production die casting of aluminium, casting of iron and steel, sheet rolling of copper and injection molding of plastics were modeled. The magnets are manufactured through creating an alloy of the included materials, crushing it to powder and finishing with a sintering process (E-Magnets UK 2012). To account for some of this process energy, sintered iron was used in the modeling.

For the assembly of the motor, several LCAs were studied and an EPD of an electric motor made by ABB was chosen. The reference motor is a flameproof 400 V AC motor with 22 kW rated power output, and a weight of 279.2 kg (ABB 2002). After rescaling based on weight and assuming that the manufacturing energy in the EPD corresponds to the assembly energy, result was calculated to be 164 MJ electricity and 138 MJ heat.

4.4.8 Power Electronic Converter

The power electronic converter (PEC) is manufactured in USA. Material data was provided by the supplier to the report by Henriksson (2008). The data was scaled to the weight of the PEC found in KOLA.

For the assembly data, an EPD by ABB on the ACS 160 frequency converter was chosen, since the material composition resembled that of the PEC. The net assembly energy was found to be 118 MJ electricity and 66.4 MJ heat.

4.4.9 High Voltage Cables

The HV cables are manufactured in Europe. There are four different high voltage cables connected to the HEV JB as can be seen in Table 4-5. The cables are assumed to have similar characteristics and also similar compositions. The conductor in the wire consists of many small

[7] Johan Hellsing (Alternative drivetrains, Volvo) e-mail conversation Spring 2012

copper threads. It is assumed to have a packing density of 80% compared to pure copper. A similar assumption is made for the screen copper braid, 40% packing density. The braid is made of tinplated copper where the amount of tin has been acquired for a similar process, tin plated chromium steel plate. The amount of tin on the chromium-steel plate is 42.748 g/m^2 (Ecoinvent 2005). Inner and outer insulation is made of elastomers (a type of elastic polymer, rubber is one example), here assumed to be Thermo Plastic Elastomer (TPE). TPE is allocated to the remaining weight of the cable.

Table 4-5: Density and weights of the included high voltage cables.

HV cables	**Density**	**Mass (kg)**
HEV JB-PEC	610 g/m	3.032
HEV JB-ESS	610 g/m	2.382
HEV JB-ESS	610 g/m	2.303
HEV JB-DCDC	610 g/m	0.380
Total		**8.097**

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Data regarding manufacturing of copper wire production has been taken from the article by Sullivan, Burnham et al. (2010). The value used is 7.1 MJ/kg.

4.4.10 Onboard Charger

Exactly what kind of onboard charger that will be used for the future plug-in hybrid is not decided on yet. However, in principle it is a DC/AC converter which shall convert AC from the power supply (a standard wall socket) to DC for battery charging. The battery needs to be charged with 8.4 kWh in 4 h, which yields a power tolerance of 2.1 kW for the converter. The weight of the charger is assumed to be 6.2 kg, equal to a similar battery charger described by Brusa Elektronik AG (2012). According to Volvo[8] it is reasonable to assume that the weight of the PCB is no more than 1 kg. For the other constituents the same ratio as in the DC/AC converter was assumed.

For the assembly of the charger an EPD by ABB on the ACS 100/140 frequency converter was used. According to this the cradle-to-gate manufacturing energy of the on-board charger was 93.2 MJ electricity and 52.4 MJ heat.

[8] Valero Maxime (3P Hybrids power network components owner, Volvo) e-mail conversation Spring 2012

4.5 Assembly

4.5.1 Components

shows a summary of the assembly data, the literature that the values are based on and the cradle-to-gate (raw material extraction and material transformation) energy use.

Table 4-6: Summary of assembly energy for all components.

Components	**Raw material extraction and transformation**	**Data source for assembly calculation**	**Assembly electricity**	**Assembly heat**
	(MJ)	*(Source or method)*	*(MJ)*	*(MJ)*
EM	15400	ABB (2002) EPD AC motor	163.77	137.98
HPCU	1260	CPM (2010)	2.36E-05	-
DC/DC	4650	ABB (2002) EPD ACS 160	88.51	49.79
DC/AC	6080	ABB (2002) EPD ACS 100/140	210.37	118.33
PEC	5090	ABB (2002) EPD ACS 160	118.01	66.38
Onboard charger	2090	ABB (2002) EPD ACS 100/140	93.16	52.40
HV cables	820	Sullivan (2010)	56.80	-
HEV JB	3820	Estimation based on energy.	109.85	42.15
ESS Heater	110	Estimation based on energy.	3.16	1.21
ESS	60470	Estimation based on weight.	234	198
Modified ESS	67660	Estimation based on weight.	258	218

4.5.2 Drivetrain

The Volvo FE Hybrid is assembled in Volvo's factory located in Gent, Belgium. The factory assembles different kinds of heavy vehicles including the conventional FE truck. The energy and emissions allocated to the hybrid drivetrain assembly has been based on the difference in assembly times for the FE truck and the hybrid FE truck.

Data was received for the assembly time of the conventional and hybrid vehicle. For the plug-in hybrid vehicle, it was assumed that the additional assembly time is 10% more than for the hybrid. On basis of this extra time and an environmental report from the Gent factory, the environmental load for assembling the drivetrains were calculated. The emissions and energy use are seen in Appendix A.2.

4.6 Well-to-Wheel Phase

The well-to-wheel phase includes the following:

- Production and distribution of diesel.
- Production and distribution of urea.
- Combustion of diesel (Euro 5).
- Production and use of electricity, forecast data for 2020 used for Sweden (only plug-in hybrid configuration).

The diesel production includes exploration, extraction of crude oil in the North Sea, transportation of crude oil to Sweden and refining crude oil into diesel. The estimated life cycle distance of the waste collection vehicle was set to 300 000 km (14 years) and the distribution truck to 1 000 000 km (15 years), as described in section 3.2.2.

In this study a European average for diesel has been used. The EU binding target of 10% of renewables in transport fuels by 2020 indicates a gradual transformation from pure diesel to adding more biodiesel, for example FAME[9] in the fuel. Today 5% of the diesel is biodiesel. In order to be able to compare the well-to-wheel stage with earlier studies made by Volvo and because the GaBi software does not include the process for biodiesel in diesel, EU-15 diesel mix was used.

Table 4-7 below shows the emissions, in grams, for a Euro 5 vehicle per kilowatt hour effective energy and per liter diesel consumed. The emissions are predefined and are the highest amount allowed for a certified Euro 5 truck. The low emissions are achieved by combining the use of urea and catalyst. The fuel was mixed with urea, by 5% volume added to the diesel. (Walenius-Henriksson 2012)

The energy put into useful work in the vehicle is about 41.4% of the fuel energy content, so the assumed effective (useful) energy content of diesel is calculated from Table 4-7 below, 4.11 kWh/L, compared to the calorific value of diesel which is about 9.951 kWh/L.

$\left.\frac{1.2}{0.29153}\right/ 9.951 \approx 0.414 \rightarrow 41.4\%$ (Used values are from carbon monoxide in Table 4-7 (below) and the energy content of diesel (above)).

[9] FAME (Fatty Acid Methyl Esters) is the collective name for a type of biodiesel

Table 4-7: Emissions from the combustion of diesel fuel, Euro 5. (Henriksson 2012)

Substance	Emission	g/kWh	g/L
Diesel		198	815
Carbon monoxide (CO)	Air	0.29153	1.2
Carbon dioxide (CO_2)	Air	656	2700.2
Nitrogen oxides (NO_X)	Air	1.7	7.0
Particulates	Air	0.024	0.099
Sulphur dioxide (SO_2)	Air	0.002	0.008
Ammonia (NH_3)	Air	0.04	0.16

The fuel consumption for the conventional distribution truck has been calculated to be *0.38 L/km*. Based on the total life time driving distance of 1 million km over 15 years, as defined in section 3.2.2. The driving distance per working day, assuming a working day of 8 hours in five days a week in Sweden has been calculated to be *254 km/day*. According to Volvo's online information on Volvo FE Hybrid, fuel savings up to *15%* can be made with the distribution truck (Volvo Trucks 2012). The plug-in version of Volvo FE has an available battery capacity of *14 kWh* for pure electric driving and can be discharged up to *60%*, before going into hybrid mode. With a charge time of approximately 4 hours this means that the battery can be charged once a day at most. The electricity grid consumption is thus *8.84 kWh/day* (assuming 5% electricity grid loss). The energy consumption of the truck, when in electric mode, is *1 kWh/km*.[10]

(For details on Li-ion battery chemistry see section 2.3.)

The fuel consumption of the conventional waste collection vehicle is *0.5 L/km*. The driving distance is set to *81 km/day*, 21 000 km/year divided by total amount of working days per year, 5 working days per week.[10] According to Volvo's online information on Volvo FE Hybrid, fuel savings up to *20%* can be made with the refuse truck (Volvo Trucks 2012). The plug-in version of Volvo FE refuse also has a battery capacity of *14 kWh* discharged up to *60%* before going into hybrid mode. With a charge time of approximately 4 hours this means that the battery can be charged once a day at most. The electricity grid consumption is thus *8.84 kWh/day*. The energy consumption of the truck, when in electric mode, is *1.3 kWh/km.*[10]

The italic values, also seen in

[10] Niklas Thulin (Senior research engineer, Volvo) e-mail conversation Spring 2012

Table 4-8, serve as initial values for calculating the new fuel and electricity consumption values for the different types of distribution and waste collection vehicles.

Table 4-8: Initial and calculated values for the different drive patterns and vehicles. X is either C, H or P (conventional, hybrid or plug-in) and Y is D or R (distribution or refuse) in the equations in Appendix A.4.

Vehicle Configuration	Vehicle type	Fuel consumption (L/km)	Electric drive mode consumption (kWh/km)	Driving distance (km/day)	Battery charge (kWh/day)	Fuel saving (%)
		F_c^X	E_c^Y	D^Y	E_{ch}	F_s^X
Conventional	**DV**	*0.38*	0	*254*	0	0
	WCV	*0.5*	0	*81*	0	0
Hybrid	**DV**	[11]0.323	0	*254*	0	*15*
	WCV	0.4	0	*81*	0	*20*
Plug-in	**DV**	[12]0.310	*1*	*254*	*8.84*	20
	WCV	0.360	*1.3*	*81*	*8.84*	30

Calculated fuel consumption for hybrid drive mode for distribution truck with 15% fuel reduction is demonstrated in Appendix A.4.

When calculating the fuel consumption in the plug-in version of the distribution truck we first assumed electric drive mode until battery is 60% discharged[13] continuing with hybrid drive mode, 15% fuel reduction. During electric drive mode 25% of the delivered energy was assumed to be regenerated by braking, regenerative braking (described in section 2.2.4.) For calculation see Appendix A.4.

Calculations on refuse truck were done in similar manner. Extending the preceding calculations by multiplying with respective functional unit gave the results in Table 4-9 below.

Table 4-9: Fuel, electricity and battery consumption for the different vehicles per FU.

Vehicle configuration	Vehicle type	Fuel consumption (×1000 L/FU)	Electricity grid consumption (5% loss) (MWh/FU)	Batteries used during lifetime (# ESS/FU)
Conventional	**DV**	380	0	0
	WCV	150	0	0
Hybrid	**DV**	323	0	1
	WCV	120	0	1
Plug-in hybrid	**DV**	309.6	[14]34.8	2
	WCV	108.0	32.7	2

Electricity grid consumption was calculated by dividing the functional unit (FU) with respective daily driving distance to get total charging cycles and multiplying this value with the amount of

[11] For calculation see eq.1 in Appendix A.4
[12] For calculation see eq.2 in Appendix A.4
[13] Niklas Legnedahl (Volvo) e-mail conversation Spring 2012
[14] For calculation see eq.3 in Appendix A.4

energy needed to get a fully charged battery, 8.4 kWh per day in our case. We assumed a 5% loss in the AC/DC charger during charging according to Volvo.[15] For calculation see Appendix A.4.

Finally, the plug-in version of the waste collection vehicle uses pure electric mode 8.0% of its driving distance compared to 3.3% for the distribution truck.

4.7 Maintenance and Repair

There are additional maintenance stages added due to the additional components, mostly some cleaning and inspection of components and checking for damages, corrosion, etc. These are not accounted for in the study, since they are considered to have a minor impact. Some lubrication of rotating parts such as the electric motor will be needed but is not accounted for either. Oil changes addressed to the engine- and brake systems are assumed to be the same for all three vehicle types.

The overall impact of the maintenance stage is slightly different for both the hybrid and plug-in hybrid compared to the conventional vehicle. No details concerning this were found, so the only modeled maintenance is one battery change for the plug-in hybrid vehicle during its lifetime, according to Volvo.[15]

4.8 End of Life

Trucks have a long lifetime and when they are out of date in Sweden, they are usually exported to other markets.[15] Used truck parts have a significant economic value and a large part of the components in a truck are sold as spare parts. The following section is a description of the general principles of waste management for the different components and materials as well as how they have been modelled in this LCA study.

4.8.1 Electronics

Electronics are dismounted and disassembled by hand to separate larger metal and plastic casings. Smaller components are fragmented and most metal components are recycled (see below) and plastics incinerated with energy recovery (T.E. Graedel et al 2011).

4.8.2 ESS

Before shredding and incinerating the Li-ion battery it has to be discharged and emptied on its electrolyte content. In case the electrolyte comes into contact with air and heat it can generate toxic substances such as CO, PF5 and HF. The electrolyte has to be extracted in an inert atmosphere in order to prevent fire from a sudden discharge.[16]

4.8.3 Metal Scrap

Metal scrap has been modelled to be recycled according to the following rates:

[15] Niklas Thulin (Senior research engineer, Volvo) e-mail conversation Spring 2012
[16] Sravyja Kosaraju (PhD student Chalmers) interview Spring 2012

- Aluminium, copper, and lead (if lead is from lead-acid battery) was recycled to 100% (Leifsson 2009).
- Lead in other components was assumed not to be recycled, because of the low lead content, and therefore goes to landfill.
- Quality losses of steel and stainless steel when recycled was modelled with closed-loop recycling where 70% is recycled and 30% goes to landfill (T.E. Graedel et al 2011).
- Gold and silver recycling was modelled with a closed-loop were 15% is recycled and 85% goes to landfill (T.E. Graedel et al 2011).
- Platinum was also modelled with a closed-loop with 5% recycled and 95% landfill (T.E. Graedel et al 2011).

4.8.4 **Handling of Materials After Separation**

The following section describes how metals and plastics end of life were modeled and the assumptions made.

4.8.4.1 ***Aluminium***

Aluminium was modelled by choosing a process where the metal scrap is re-melted and casted. The recycling process has been modelled with 50% aluminium scrap re-melting and casting (same as above) and 50% aluminium ingot mix going through an extrusion profile process. All processes used are European averages.

4.8.4.2 ***Copper***

Copper recycling has been modelled by using a process for secondary copper from electronic scrap. The Swedish electricity mix for 2027 was selected for this process, in line with the Goal and Scope definition. The recycling has been credited with the avoidance of 40% primary copper (Global average) and 60% copper mix (Germany). This division, 40/60, is also used as input and is therefore chosen for recycling here as well. German copper mix was chosen because it was assumed to be representative for Sweden as well.

4.8.4.3 ***Lead***

Lead from lead-acid batteries is part of the system modelled and accounted for as it is not used as a power source in the hybrid and plug-in hybrid vehicles. The conventional vehicle uses 98.8 kg lead and 19.6 kg acid mix (40% sulphuric acid) in the batteries. The battery pack is changed once during the vehicles lifetime, doubling the mentioned values for lead and acid mix.

Lead in electronic components has been assumed not to be recycled (Henriksson 2008).

4.8.4.4 ***Steel***

In order to account for the reduction in quality of recycled steel for each recycling round, this has been modelled as a closed-loop recycling process for 70% of the steel going back into the loop and 30% going to landfill. The recycling of steel is modelled with the avoidance of 50% cold rolled coil steel and 50% engineering steel.

4.8.4.5 ***Stainless steel***

In order to account for the reduction in quality of recycled stainless steel for each recycling round, this has been modelled as a closed-loop recycling process for 70% of the stainless steel going back into the loop and 30% going to landfill. The recycling is modelled with the avoidance of 50% primary stainless steel and 50% secondary stainless steel.

4.8.4.6 ***Gold***

15% of the gold content in the printed circuit boards and ESS are recycled. The recycling process used in GaBi is a precious metal refinery in Sweden. The refinery requires electricity, light fuel oil and liquid oxygen. The electricity used is Swedish electricity mix for 2027. Light fuel oil and liquid oxygen are European averages. The recovered gold is modelled with the avoidance of global average gold mix.

4.8.4.7 ***Silver***

Silver has been modelled in the same way as gold except that the values in the precious metal refinery were changed to silver recovery process values. Recovered silver is also modelled with the avoidance of global average silver mix.

4.8.4.8 ***Platinum***

5% of the platinum in the PCB’s has been assumed to be recovered. The recovery process selected in Gabi is secondary platinum at refinery. This process describes the collection of auto catalysts in Germany, the dismantling of the catalysts and the pyro metallurgical processing followed by a hydrometallurgical purification step delivering the co-product secondary platinum at refinery. The refinery uses electricity, natural gas, copper and hydrated lime. Swedish electricity mix for 2027 and European averages for burned natural gas and copper has been used. The recovered platinum is modeled with the avoidance of global platinum mix.

4.8.5 Plastics

All plastics, including nylon, PVC, PET, SBR, PE, PS, PP and PUR, in respective drivetrains were assumed to be incinerated with energy recovery in Sweden. Incineration takes place in a municipal waste incinerator. The process used applies to German waste incinerators. The electricity and steam generated during incineration is modeled with the avoidance of using Swedish electricity mix for 2027 and Norwegian process steam from natural gas (94% efficiency). Steam can be generated from various sources such as coal, light- and heavy- fuel oil and natural gas. In this case natural gas has been assumed to be used for this process.

According to Renova, plastics in electronics are recycled. In this study incineration with energy recovery was assumed instead. (Renova AB 2010)

4.9 Transports

The transports accounted for in this study are transports between Volvo's suppliers and Volvo's assembly factory in Gent, Belgium. The components included in the motor drive system, electric motor and PEC, are pre-assembled in Sweden and the battery pack has been assumed to be pre-assembled in a place in continental Europe before being transported to Gent. All other components have been assumed to be transported directly from respective supplier factory to Gent assembly factory.

Transport on land has been assumed to be made by truck only and in this study a Euro III certified truck was chosen, with 27 tons payload capacity. Transport by sea has been assumed to be made by cargo ships, with 27 500 tons payload capacity.

New York, Antwerpen, Hamburg, Göteborg and Shanghai have been identified as the major ports used in the sea transports.

Land transportation distances have been calculated by using Google maps and a website with similar functions specialized in sea transports has been used for the distances by sea (Google Maps 2012; Sea-Rates 2012).

Table 4-10, shows a list of the aggregated distances on land and at sea for all components in kilometers. It shows the start-, intermediate- and final destinations of the components.

Table 4-10: Transportation distance for each component.

Component	**Weight (kg) Hybrid**	**Weight (kg) Plug-in hybrid**	**Distance by land (km)**	**Distance by sea (km)**
HVJB	22.625	22.625	1371	6054
DCDC converter	21	21	845	N/A
DCAC converter	14	14	1160	N/A
PEC	28	28	3239	6354
EM	152	152	3239	6354
ESS (both)	217.6	239.4	2260	19737
ESS heater	1.835	1.835	1470	N/A
HV-cables	8.097	8.097	570	N/A
HPCU	1.9	1.9	1347	6054
On-board charger	6.2	6.2	1160	N/A
Drivetrain	467.06	495.06	1237	N/A

Table 4-11: Assumed start- and destination- locations for all components.

Component	Truck	Sea	Truck	Truck
HVJB	Within USA to New York	New York to Antwerpen	Antwerpen-Gent	-
DCDC converter	Within Europe to Gent	-	-	-
DCAC converter	Within Europe	-	-	-
PEC	Within USA	New York - Göteborg	Göteborg to within Europe	Within Europe to Gent
EM	Within USA	New York - Göteborg	Göteborg to within Europe	Within Europe to Gent
ESS (both)	-	Shanghai - Hamburg	Göteborg to within Europe	Within Europe to Gent
ESS heater	Within Europe to Gent	-	-	-
HV-cables	Within Europe to Gent	-	-	-
HPCU	Within USA to New York	New York to Antwerpen	Antwerpen-Gent	-
Drivetrain	Gent to Göteborg	-	-	-

Finally, the emissions and energy consumption for the transportation of the entire drivetrain from Gent to Gothenburg is modeled in the same way as for the components with truck transport.

5. Impact Assessment

5.1 Characterization Procedure

The following impact categories were used in the study with CML 2001 characterization factors for all categories.

The *Global Warming Potential (GWP)* in a 100 years perspective is calculated in CO_2-equivalents. Examples of substances contributing to GWP are carbon dioxide, methane and nitrous oxide.GWP is probably the most commonly used indicator when assessing products from an environmental point of view, since global warming is a well-known environmental threat to our planet.

Acidification Potential (AP) is calculated in SO_2-equivalents. Important contributing substances are ammonium, nitrogen oxide and phosphoric acid, which all are proton donors that contribute to a lower pH-value in the environment. AP is a relevant indicator since lakes and forests in Sweden are sensitive to acidification, as well as buildings and monuments in Gothenburg.

Human Toxicity Potential (HTP) is measured in DCB-equivalents (1,4-dichlorobenzene), and among the substances contributing to this potential are cadmium, arsenic and dioxins. Vehicles are used in an urban environment close to a lot of people. In addition, hybrid and plug-in hybrid vehicles in general generate more fuel saving in urban traffic (mixed driving) than in highway driving. These are reasons for choosing HTP as an impact category in this study.

The *Resource Depletion Potential (RDP)* is calculated in Sb-equivalents (antimony). The indicator reflects the use of non-renewable substances, which could eventually lead to resource depletion. Examples of materials that contribute a lot to this potential are gold, silver, platinum and fossil fuels. RDP is a relevant indicator since the hybrid and plug-in hybrid drivetrain consists of a lot of electronics and state-of-the-art equipment, such as printed circuit boards (containing scarce metals) and Li-ion battery technology. In addition the vehicles consume large amounts of diesel.

Finally, net energy use during the life cycles of the different vehicle configurations was studied. It is an indicator aggregating all energy input during the whole life cycle, for example the input use of electricity and fossil fuels.

5.2 Weighting Procedure

In this chapter the two weighting methods used in the study, Environmental Priority Strategies and Eco-indicator 99 are described.

5.2.1 Environmental Priority Strategies (EPS)

The EPS system is a weighting method, with the aim of comparing different environmental impacts with each other on a single scale. The system is based on the willingness to pay principle, which is how much society is willing to pay to avoid a certain environmental load. In the EPS system, a "currency" called Environmental Load Units (ELU) is used. Processes, emissions or resource extraction are expressed in terms of ELU, for more details on EPS see Steen (1994).

One purpose of the EPS system is to be able to provide quick information to product developers to aid them in their material choices. The system has been developed since 1989 in co-operation with Volvo, the Swedish Environmental Research Institute (IVL) and the Swedish Federation of Industries. Volvo wanted to have a single score to compare different products, with emphasis on resource use. The intended application is for choosing between design options in product development. (Steen 1994)

5.2.2 **Eco-Indicator 99 (EI99-Hierarchist)**

Eco-indicator 99 is both a science based impact assessment method for LCA and a pragmatic eco-design method. It offers a way to measure various environmental impacts, and shows the final result in a single score.

Damage models have been developed linking inventory results into three damage categories:

- Damage to Human Health [*unit*: [17]DALY[17]]
- Damage to Ecosystem Quality [*unit*: [18]PDF*m2*a[18]]
- Damage to Resources [*unit*: [19]MJ surplus energy[19]]

The most fundamental problem in LCA impact assessment is that in order to compare different types of impact, their rank of importance must be decided based on societal values. No single correct or true ranking list can be established due to the fact that many different opinions on what is most important are present in society. For example, a substance that is classified as "possible carcinogenic" can be seen as extremely dangerous by one person, whilst another would not be bothered at all. To deal with this problem, three different perspectives were developed in the EI99-system; hierarchist, individualist and egalitarian.

In the *Hierarchist* perspective contribution of Human Health and Ecosystem Quality is 31% and 54% each. Respiratory effects and greenhouse effects dominate Human Health damages. Land use dominates Ecosystem Quality; Resources is dominated by fossil fuels (PE International AG 2012).

In the *Egalitarian* perspective, Ecosystem Health contributes 50% to the overall result. The relative contributions within the damage categories are about the same as in the Hierarchist perspective, except for carcinogenic substances. A Hierarchist would consider a substance as carcinogenic if sufficient scientific proof of a probable or possible carcinogenic effect is available.

In the *Individualist* perspective, Human Health is by far the most important category. Carcinogenic substances however play virtually no role. The individualist would only include those substances for which the carcinogenic effect is fully proven. The Individualists would also not accept (based on experience) that there is a risk that fossil fuels can be depleted. This category is left out. For this reason *minerals* become quite important. (Harry Baayen 2000)

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[17] DALY = Disability adjusted life years; this means different disability caused by diseases are weighted.
[18] PDF = Potentially Disappeared Fraction of plant species.
[19]MJ surplus energy = Additional energy requirement to compensate lower future ore grade.

In this study the *Hierarchist* weighting model has been used. The distribution- and waste collection- vehicles are driven in urban areas where both humans and ecosystems are present. Therefore it is seems relevant to favor these two damage categories equally. The EI99 Hierarchist model has been used by Volvo in earlier studies, in order to have a second weighting method to compare with the EPS-weighting.

5.3 Results of the Characterization

The results will be presented for the above mentioned characterization indicators, in line with Goal and Scope focusing on the following questions:

1. Which vehicle configuration has least environmental impact over the whole life cycle?
2. Which life cycle stages have the largest environmental impact?
3. Which component in the drivetrain has the largest environmental impact?

5.3.1 Results for Global Warming Potential

The first graph, Figure 5-1, shows the GWP100 for the different life cycle stages of the drivetrain and the emissions saved in the well-to-wheel phase. Well-to-wheel phase values include both distribution and waste collection vehicle driving patterns. These values have been scaled down 25 times, to simplify a comparison with the other stages. In the *Production of drivetrain* bar the avoided emissions for not using a lead-acid battery are included.

The savings in the well-to-wheel phase are much bigger than the emissions from the other stages, since so much diesel combustion is avoided during the life time of the trucks. The *Maintenance* bar consists solely of one Li-ion battery change and is only applied to the plug-in hybrid version. When this battery change is compared to the *Production of drivetrain* bar, we can see that the battery is responsible for more than half of the emissions for all components in the hybrid and plug-in hybrid drivetrain. It is also obvious that the assembly and transport stages are very small compared to the other stages, which means that most of the environmental burden from the production comes from the material extraction and transformation (included in the *Production of drivetrain* category).

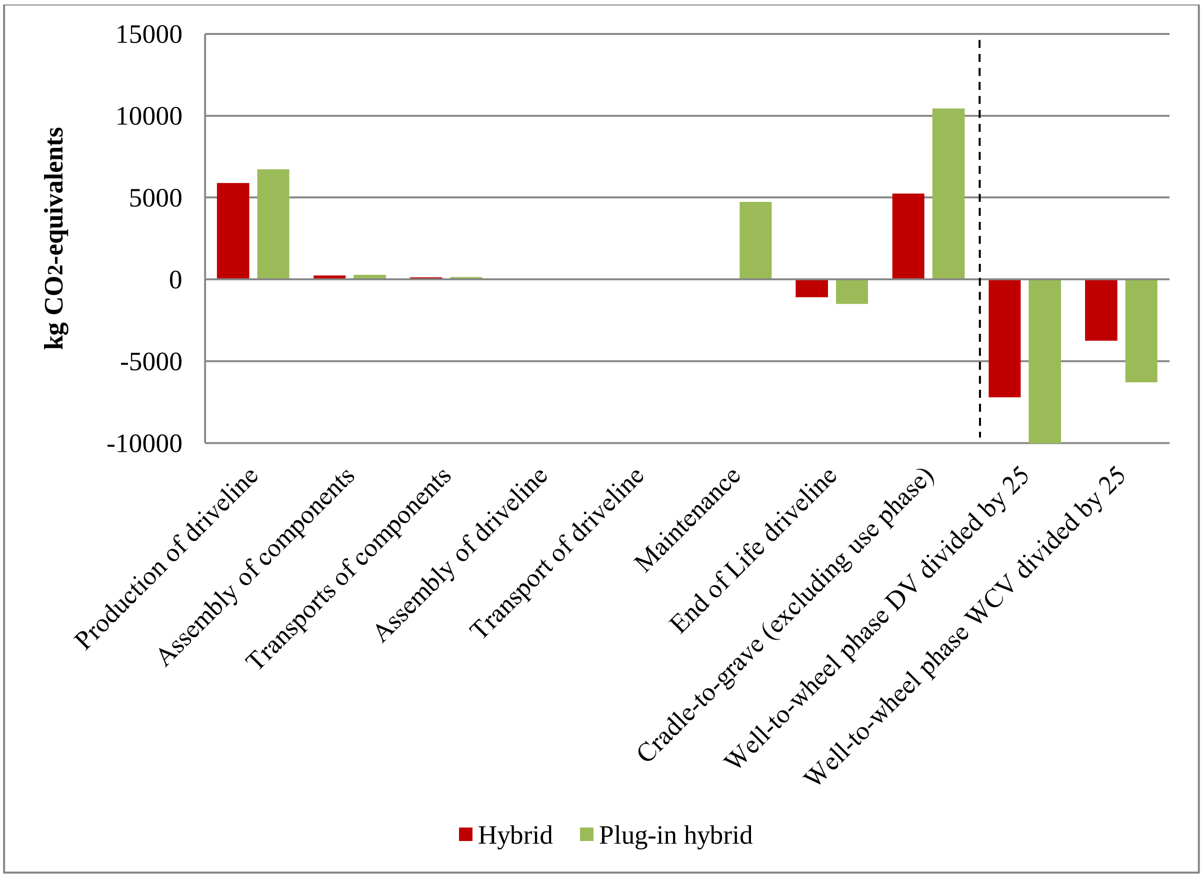

Figure 5-1: Global warming potential in CO_2-equivalents for the different life cycle stages with the conventional vehicles as a baseline. The saved emissions from the well-to-wheel phase are divided by a factor of 25. Included in the *Production of drivetrain* are also the avoided emissions from the lead-acid battery. Data left of the dashed line represents cradle-to-grave processes, excluding the use phase and data to the right of the dashed line represents well-to-wheel processes.

Next bar charts, Figure 5-2 and Figure 5-3, show the Global warming potential for the different components in the drivetrain. This way of presenting the results is good for design purposes, as it makes it easy to switch one component with another and compare the environmental burden.

There is a clear dominance of the emissions of the ESS. More than half of the GWP emissions from the battery are caused by the use of natural gas and Chinese electricity in the production of the battery modules, the latter having the highest impact. Next in line is the aluminium sheet, 38.4 kg, and cold rolled steel coil, 74.7 kg used in the production of the ESS.

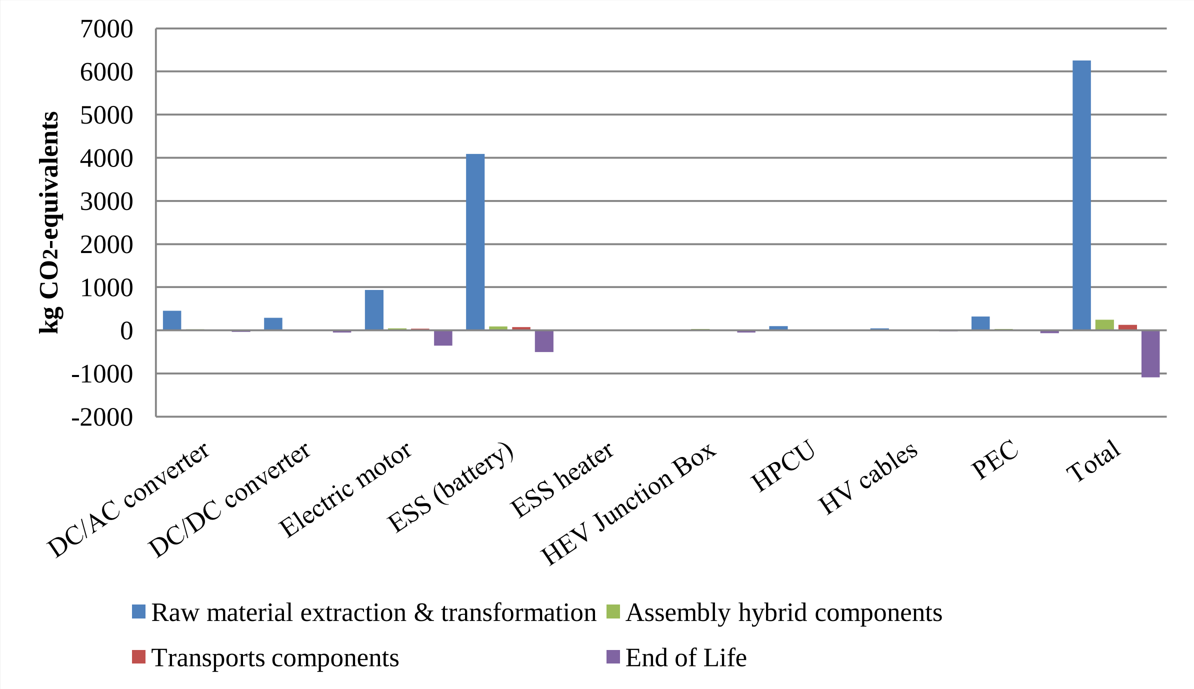

Figure 5-2: Global warming potential in CO_2-equivalents for the components in the drivetrain of the hybrid vehicle.

The same pattern is seen in Figure 5-3 for the plug-in hybrid components except for the higher impact of the modified battery system. Also the additional on-board charger is seen.

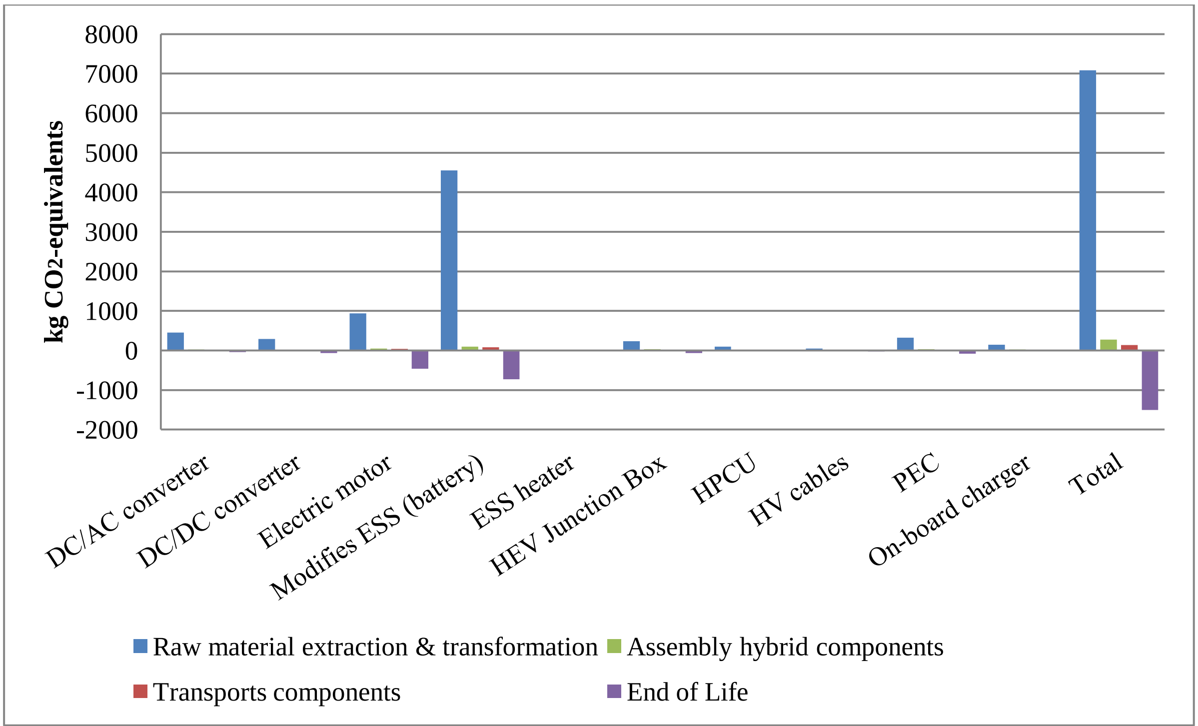

Figure 5-3: Global warming potential in CO_2-equivalents for the components in the drivetrain of the plug-in hybrid vehicle.

Figure 5-4 shows the GWP from the well-to-wheel phase of the three drivetrain configurations, for the two vehicle types, distribution and waste collection vehicle (6 cases in total). Because diesel consumption and yearly travelling distance is known, a comparison can be made along with diesel savings data for the modified drivetrains.

Most of the GWP emissions for the conventional vehicle come from the combustion of diesel, about 85%. The rest is shared between the production of diesel (10%) and the production of urea (5%).

The emissions from the plug-in hybrid are slightly lower than from the hybrid, which in turn are lower than from the conventional. However, most of the savings are found when transforming from conventional to hybrid drivetrain. Further transformation to a plug-in hybrid does not result in much avoided emissions.

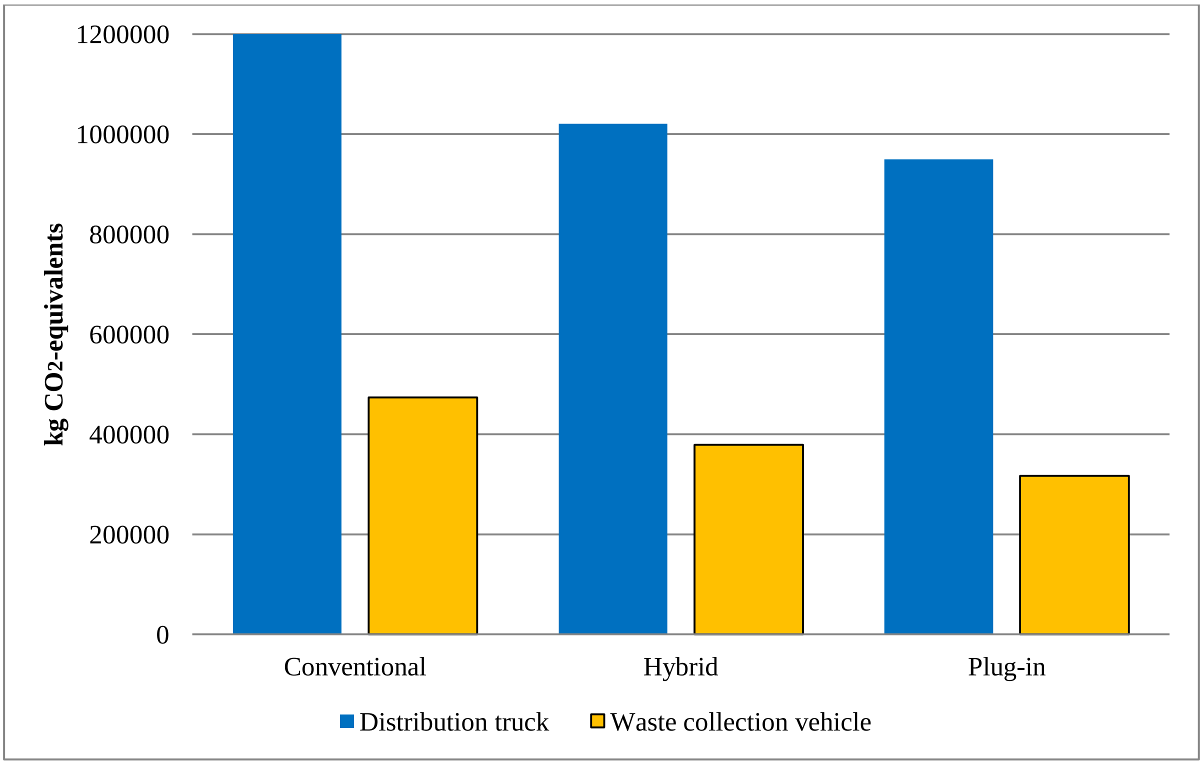

Figure 5-4: Total global warming potential in CO_2-equivalents during the well-to-wheel phase for the different vehicle configurations.

Finally when studying the whole life cycle, the savings in global warming emissions for the different hybrid configurations are seen in Figure 5-5. Once again it is seen that the extra savings of the plug-in hybrid are small compared to the savings of the hybrid drivetrain. This is mainly due to the small saving in the well-to-wheel phase of the plug-in, and not so much due to the higher emissions from the production phase since they are small in comparison.

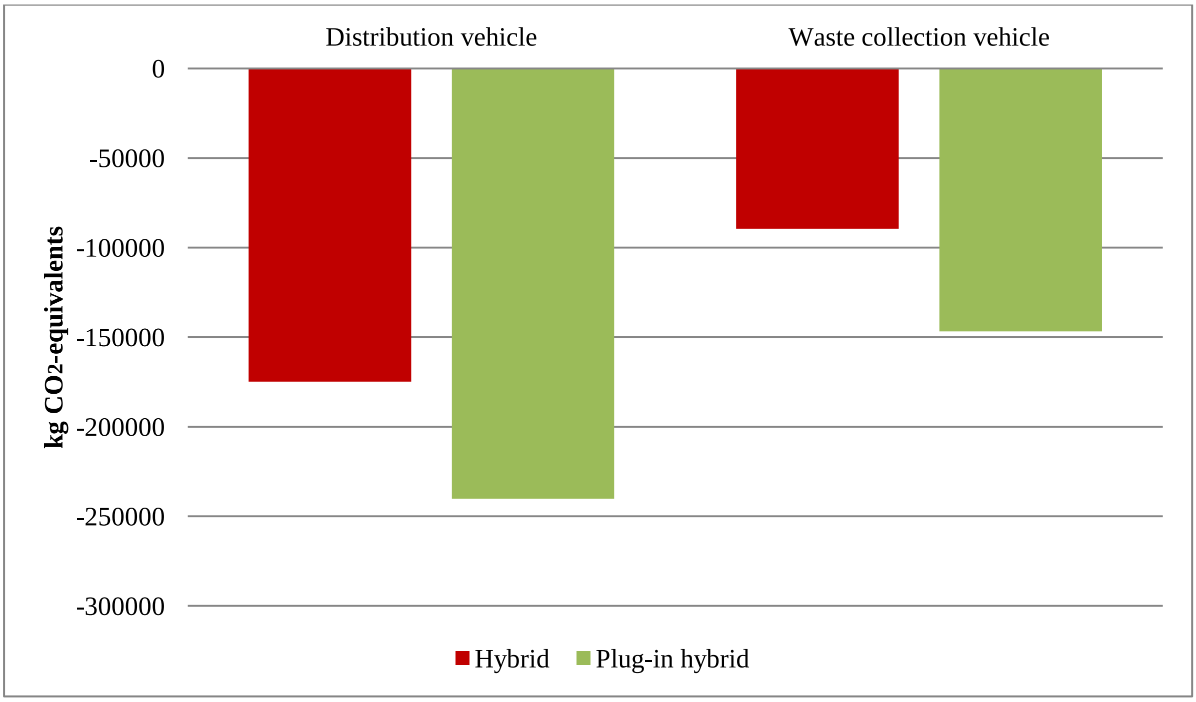

Figure 5-5: Global warming potential in CO_2-equivalents for the whole life cycle, including well-to-wheel and cradle-to-grave processes, of the hybrid configurations with the conventional vehicles as a baseline.

5.3.2 Results for Acidification Potential

The first bar chart for acidification potential, Figure 5-6, shows a comparison of the impact during the different life cycle stages of the drivetrain, and the saved impact from the well-to-wheel phase due to savings in fuel consumption. All values are in relation to the conventional vehicle, which is why the well-to-wheel phase values are negative. Also, the avoided impact from the lead-acid battery gives a negative contribution to the *Total* bar.

As seen, most of the impact during the life cycle comes from raw material extraction and material transformation for the drivetrain components, *Production of drivetrain*. Only a minor contribution comes from transport and assembly. For the hybrid distribution truck, the saved emissions in the well-to-wheel phase are about 10 times larger than the total emissions from the drivetrain. For the waste collection vehicle they are roughly 5 times larger, and for the plug-in versions the relations are approximately the same.

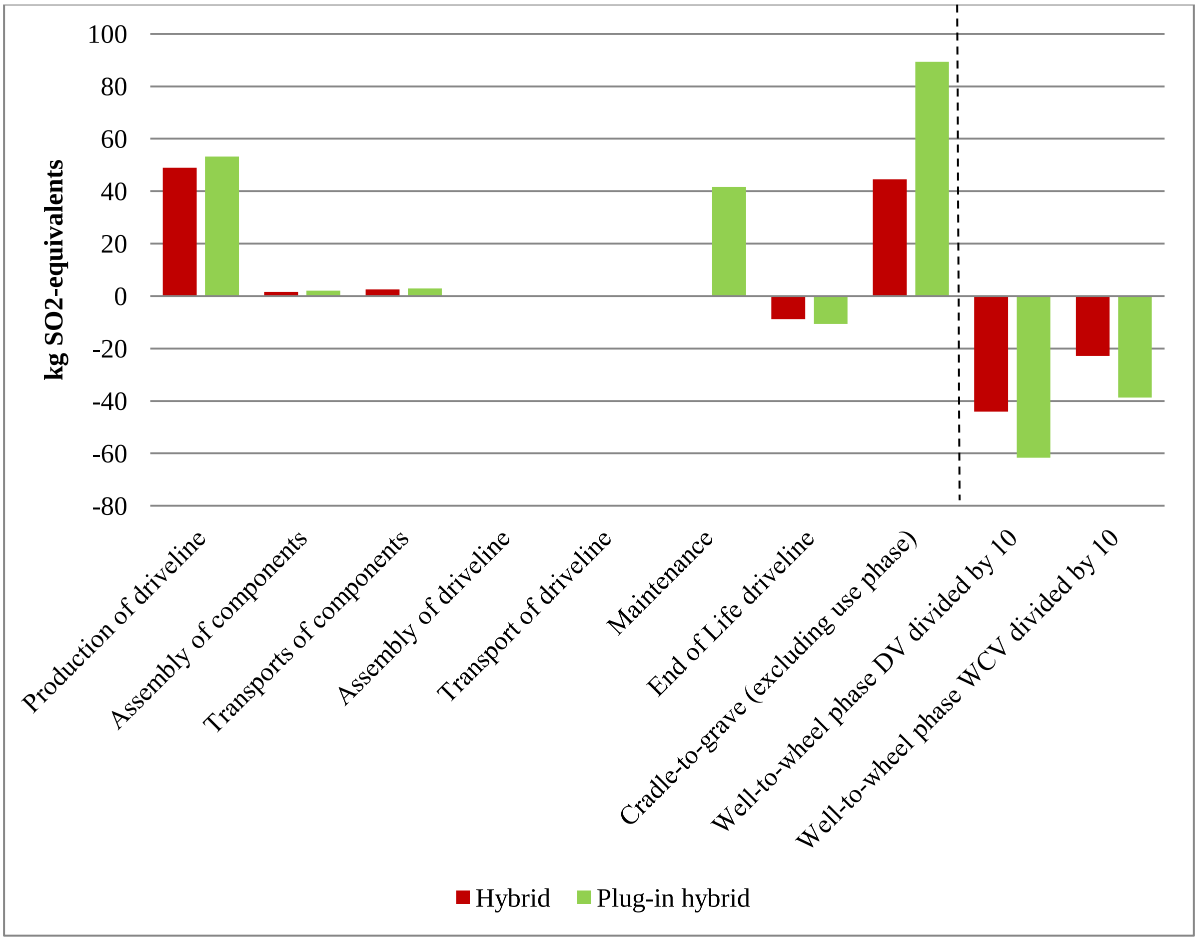

Figure 5-6: Acidification potential in SO_2-equivalents for the different life cycle stages in comparison with the conventional vehicles. The saved emissions from the well-to-wheel phase are divided by a factor of 10. Included in the *Production of drivetrain* bar are also the avoided emissions from the lead-acid battery. Data left of the dashed line represents cradle-to-grave processes, excluding the use phase and data to the right of the dashed line represents well-to-wheel processes.

Figure 5-7 and Figure 5-8 show the acidification potential for the different components in the drivetrain, for the hybrid and the plug-in hybrid configuration. As in the case of global warming the Li-ion battery is responsible for more than two thirds of the acidification potential for the components.

Once again it's seen that the *Raw material extraction and material transformation* contribute to a major part of the components' life cycle. The *End of life* treatment contributes to a small but significant reduction in the acidification potential of the components.

It is not surprising that the ESS is the largest contributor for the acidification emissions of all components. Most of it comes from sulphur dioxide emissions from the electricity use in China, where a lot of brown coal is used. More surprising are the low emissions related to the electric motor compared to the converters. The reason for this is the high amount of gold used in the printed circuit boards for these components, since the production of gold contributes a lot to acidification potential (SO_2-emissions).

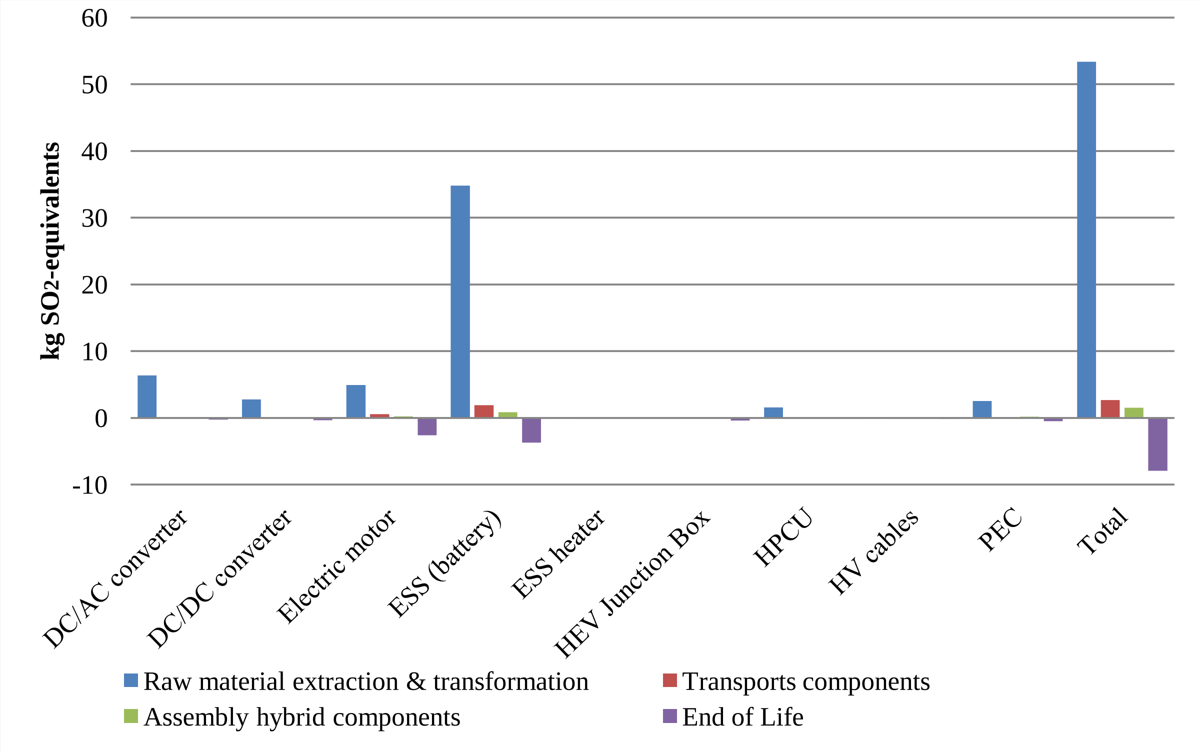

Figure 5-7: Acidification potential in SO_2-equivalents for the components in the drivetrain of the hybrid vehicle.

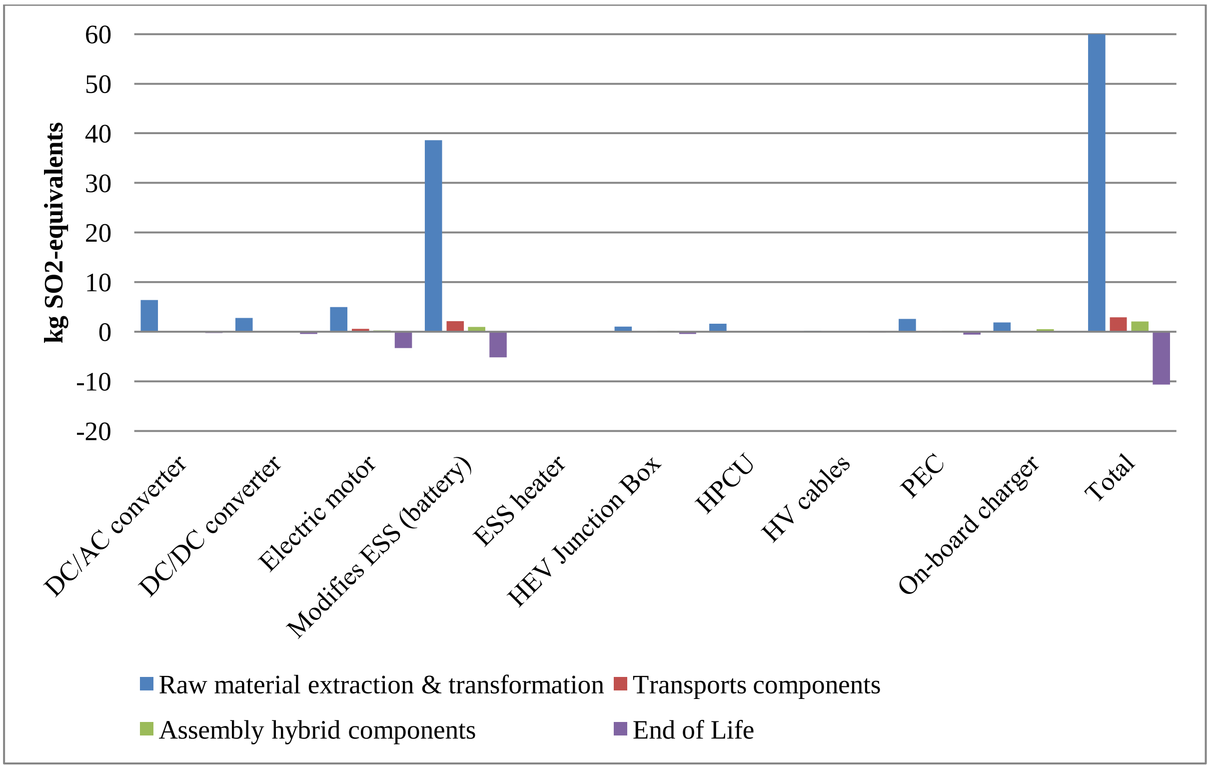

Figure 5-8: Acidification potential in SO_2-equivalents for the components in the drivetrain of the plug-in hybrid vehicle.

Figure 5-9 shows the total acidification potential from the well-to-wheel phase of the different vehicle configurations. The bar chart shows that the savings when going from a conventional vehicle to a hybrid vehicle are larger than for the transformation from hybrid- to plug-in hybrid vehicle. The distribution truck has almost three times more emissions due to its longer lifetime. Most of the AP-emissions come from the combustion of the diesel, in particular the NO_x-emissions contribute a lot.

As we can see, the bar chart is similar to that of the global warming potential results.

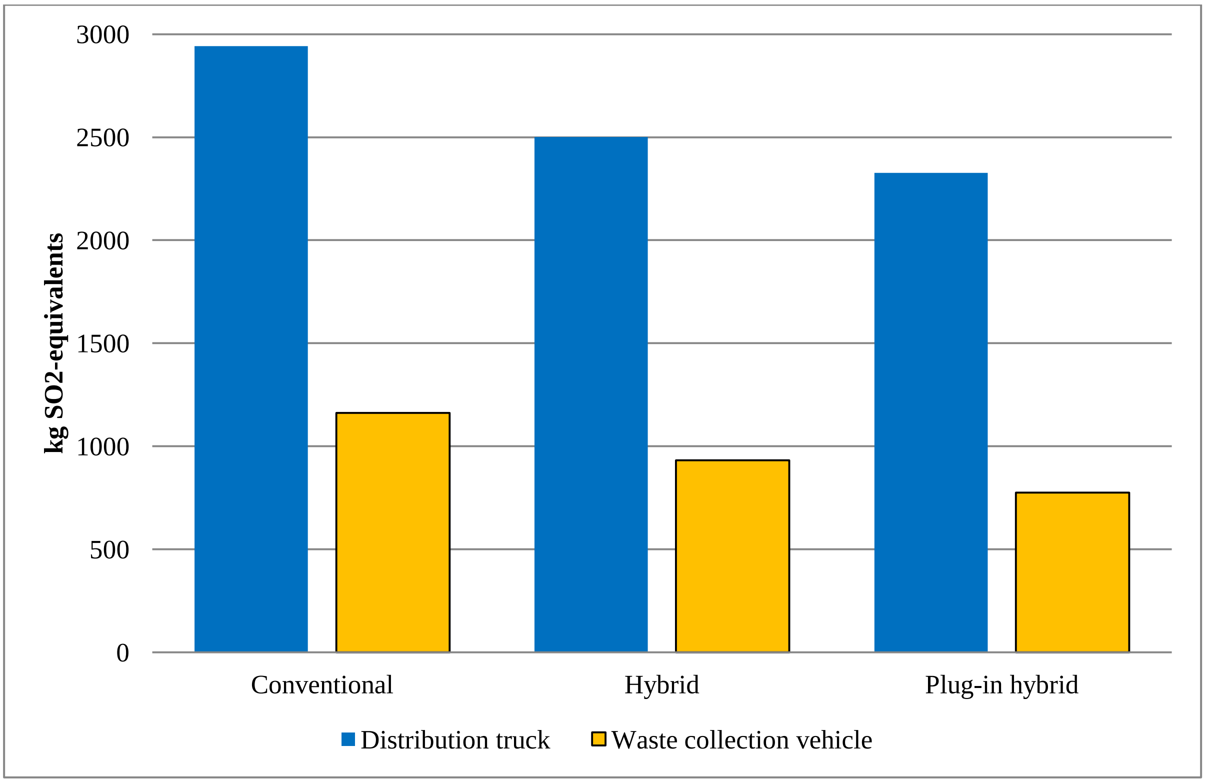

Figure 5-9: Acidification potential in SO_2-equivalents for the well-to-wheel phase for the different vehicle configurations.

Figure 5-10 shows the total acidification potential during the whole lifecycle of the vehicles, with the conventional vehicles as a baseline. In other words it shows the impact of the different hybrid configurations compared to that of the conventional vehicles, which are set to 0.

For the distribution truck it is clear that the major savings are found when going from a conventional to a hybrid configuration, and only minor additional savings for the plug-in vehicle. For the waste collection vehicle the plug-in shows a greater saving potential, almost doubling that of the hybrid vehicle. This is due to many reasons, one being a shorter driving range each day, so that the battery charging each night affects the result more. Most important though is that the total well-to-wheel phase for the waste collection vehicle is smaller so that the production phase affects the final result more, in particular the maintenance for the plug-in waste collection vehicle.

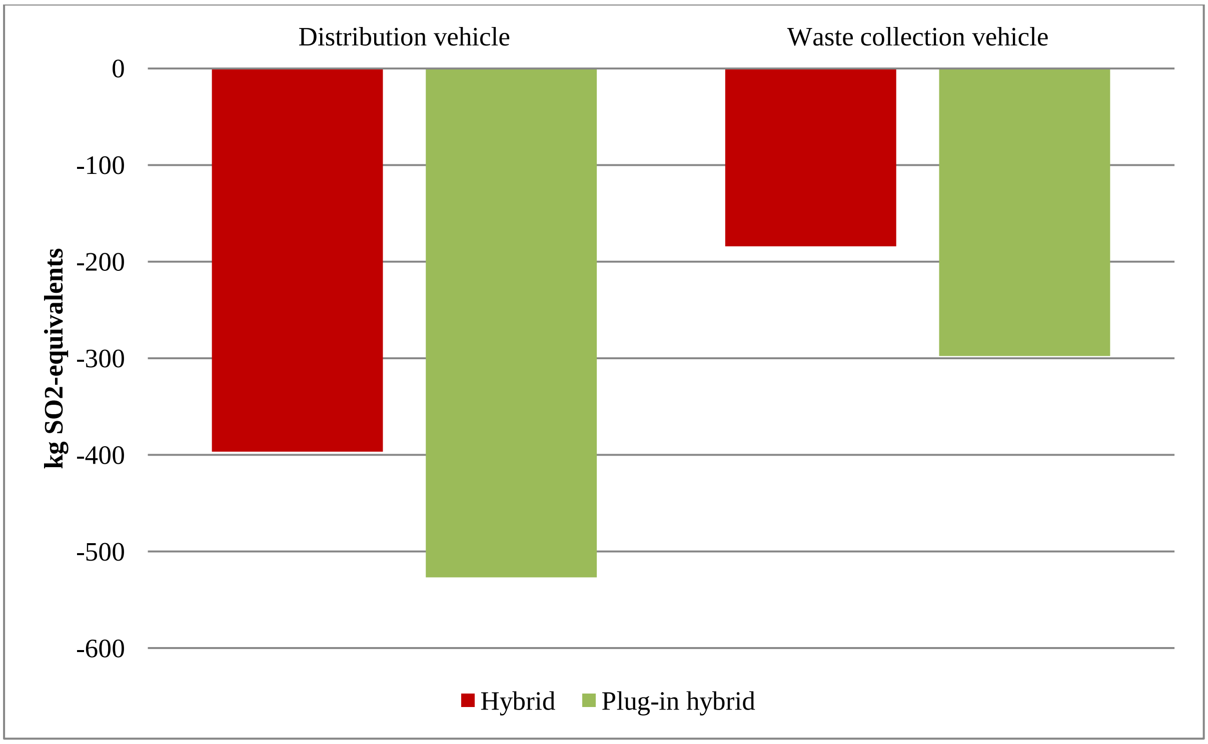

Figure 5-10: Acidification potential in SO_2-equivalents for the whole life cycle, including well-to-wheel and cradle-to-grave processes, of the hybrid configurations with the conventional vehicles as a baseline.

5.3.3 Results for Human Toxicity Potential

In Figure 5-11 the HTP for the life cycle of the drivetrain and for the well-to-wheel phase are shown. The conventional vehicles are set as a baseline, which means that the well-to-wheel phase bars show the saved emissions for the hybrid configurations, and the avoided impact of the lead-acid battery is included in the *Production of drivetrain* category.

The well-to-wheel phase values are divided by a factor 2, thus it is clear that the cradle-to-grave phase of the drivetrain is comparable in order of magnitude with the well-to-wheel phase. However, use phase emissions are in populated areas with a lot of people, compared to where components are produced and metals are mined.

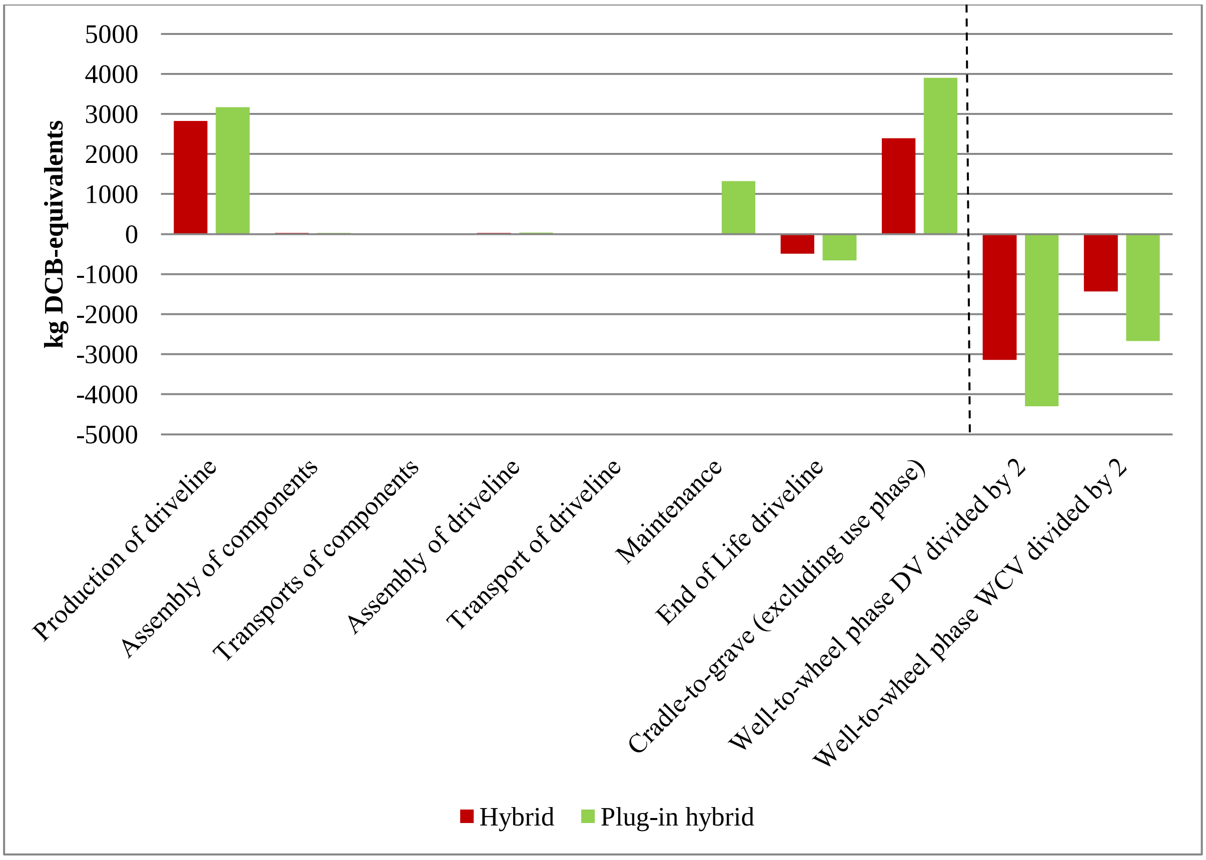

Figure 5-11: Human toxicity potential in DCB-equivalents for the different life cycle stages with the conventional vehicles as a baseline. The saved emissions from the well-to-wheel phase are divided by a factor of 2. Included in the *Production of drivetrain* components are also the avoided emissions from the lead-acid battery. Data left of the dashed line represents cradle-to-grave processes, excluding the use phase and data to the right of the dashed line represents well-to-wheel processes.

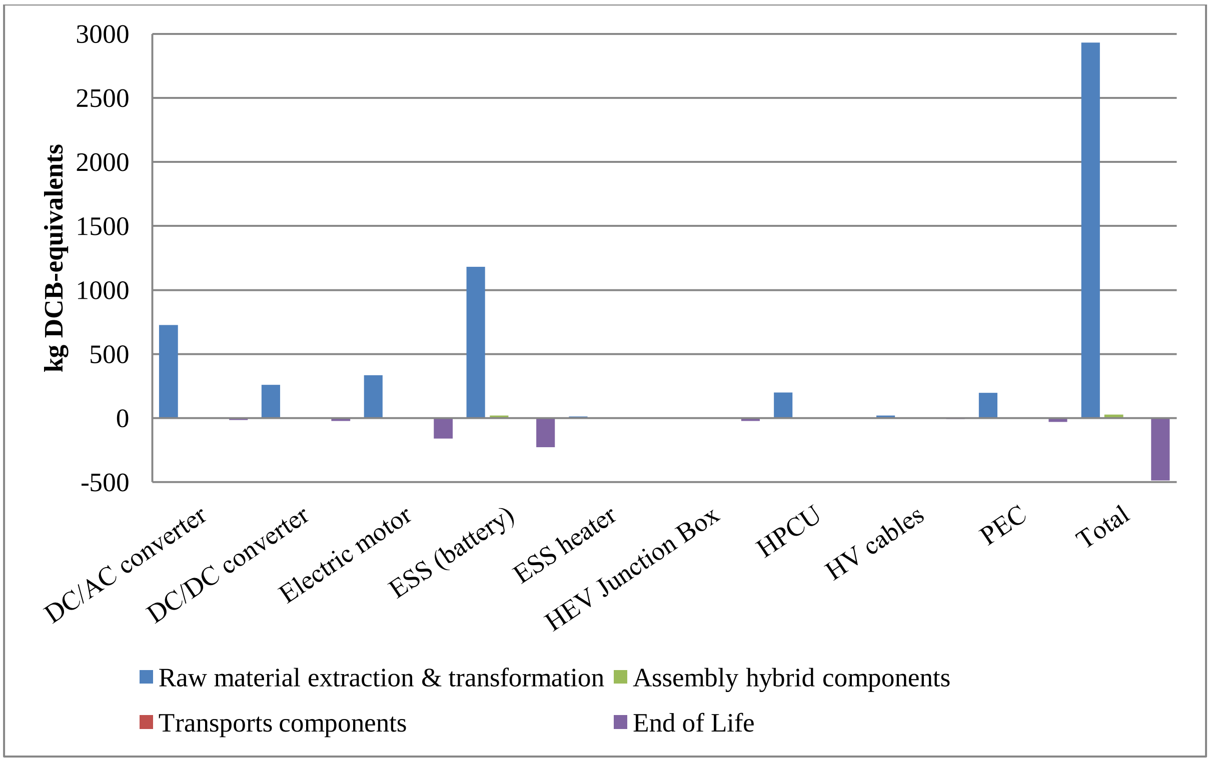

Figure 5-12: Human toxicity potential in DCB-equivalents for the components in the drivetrain of the hybrid vehicle.

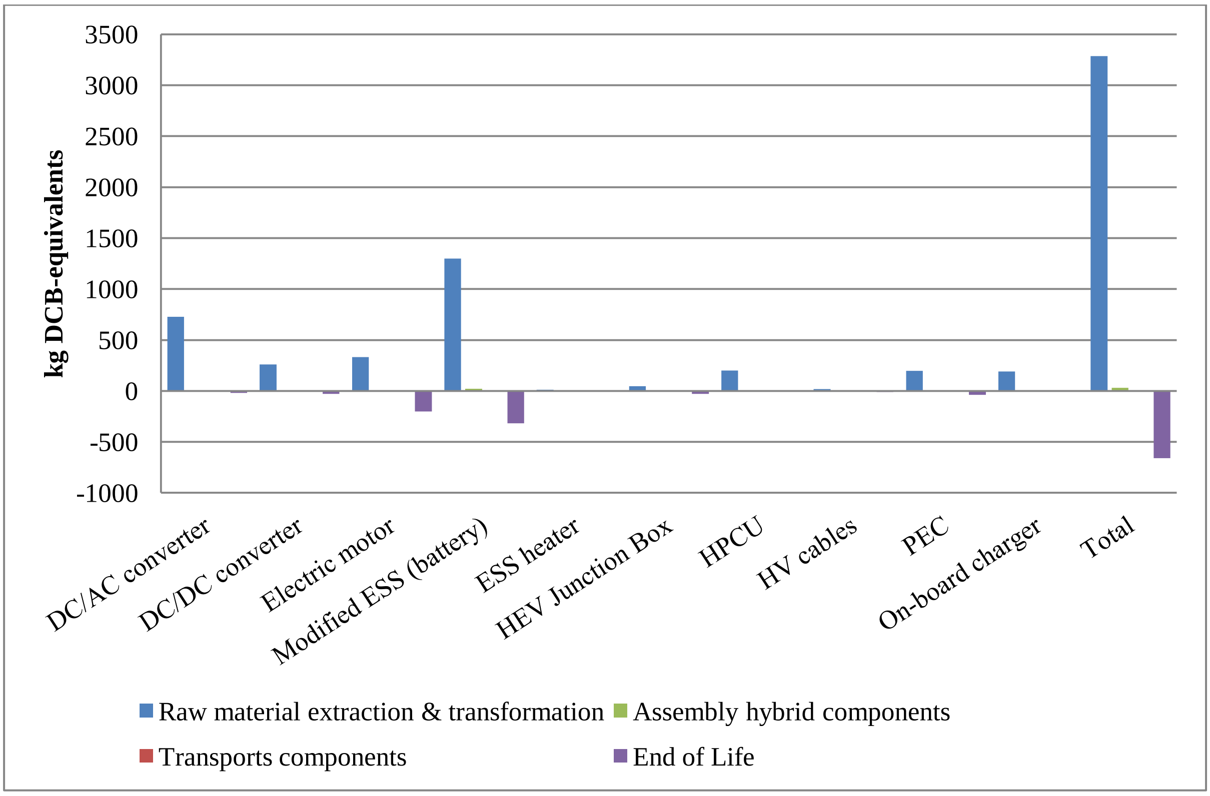

Figure 5-13: Human toxicity potential in DCB-equivalents for the components in the drivetrain of the plug-in hybrid vehicle.

Figure 5-12 and Figure 5-13 shows the HTP of the different components for the hybrid and plug-in hybrid drivetrains respectively. Major contributing components here are the ESS and DC/AC converter, but also the electric motor and other components with lots of electronics. For the ESS it is the electricity use in China that is the main cause, major contributing substances are chromium and hydrogen fluoride. Most emissions from the electronics come from the production of gold which causes emissions of arsenic, and for the electric motor the production of neodymium causes release of hydrogen fluoride and chromium.

Figure 5-14 shows the total HTP of the well-to-wheel part for the vehicle configurations. The same pattern as for GWP and AP is seen, with a decrease in emissions for the hybrid compared to the conventional and a slightly smaller decrease when going from hybrid to plug-in hybrid. Most of the HTP is due to the urea production (about 75%), with emissions of chromium, nickel, arsenic and cadmium. The diesel production releases elements like barium, vanadium and nickel which contribute to HTP. The combustion of diesel is just a minor contributor to this impact category, corresponding to less than 10% for the conventional vehicle. However, this might still be important since it is released in an urban area. Most of the impact comes from NO_x-emissions.

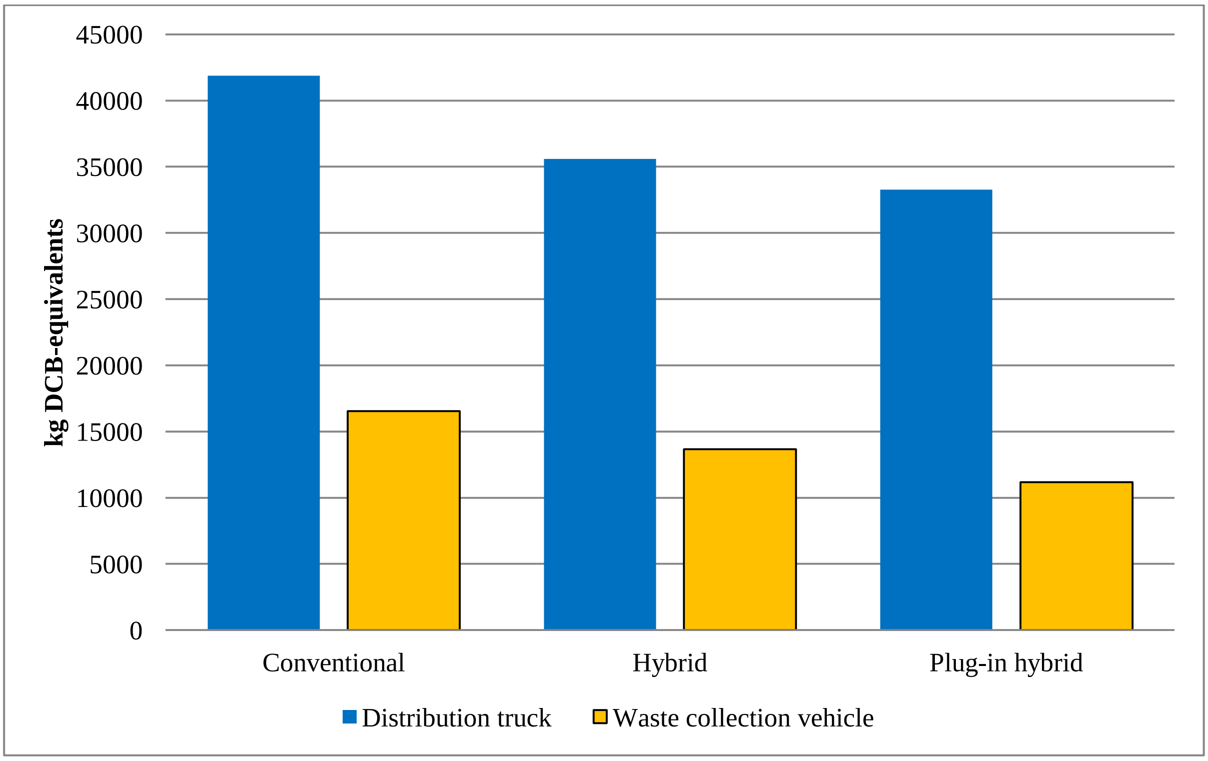

Figure 5-14: Total human toxicity potential in DCB-equivalents during the well-to-wheel phase for the different vehicle configurations.

HTP results for the whole lifecycle in reference to the conventional vehicles are seen in Figure 5-15. These results differ slightly from the other categorization indicators, in particular for the waste collection vehicle. For the hybrid waste collection vehicle the savings compared to the conventional are small, and the plug-in shows almost three times more savings. This is explained by the fact that the impact from the production of the drivetrain is of the same magnitude as that of the well-to-wheel phase. For the hybrid waste collection vehicle in particular, the savings during the well-to-wheel phase are almost outweighed by the production of the drivetrain.

The waste collection vehicles are also driving a shorter distance each day, which makes the plug-in version more beneficial since the battery is only charged once per day. This explains the larger difference between the hybrid and plug-in hybrid for the waste collection vehicle than for the distribution vehicle.

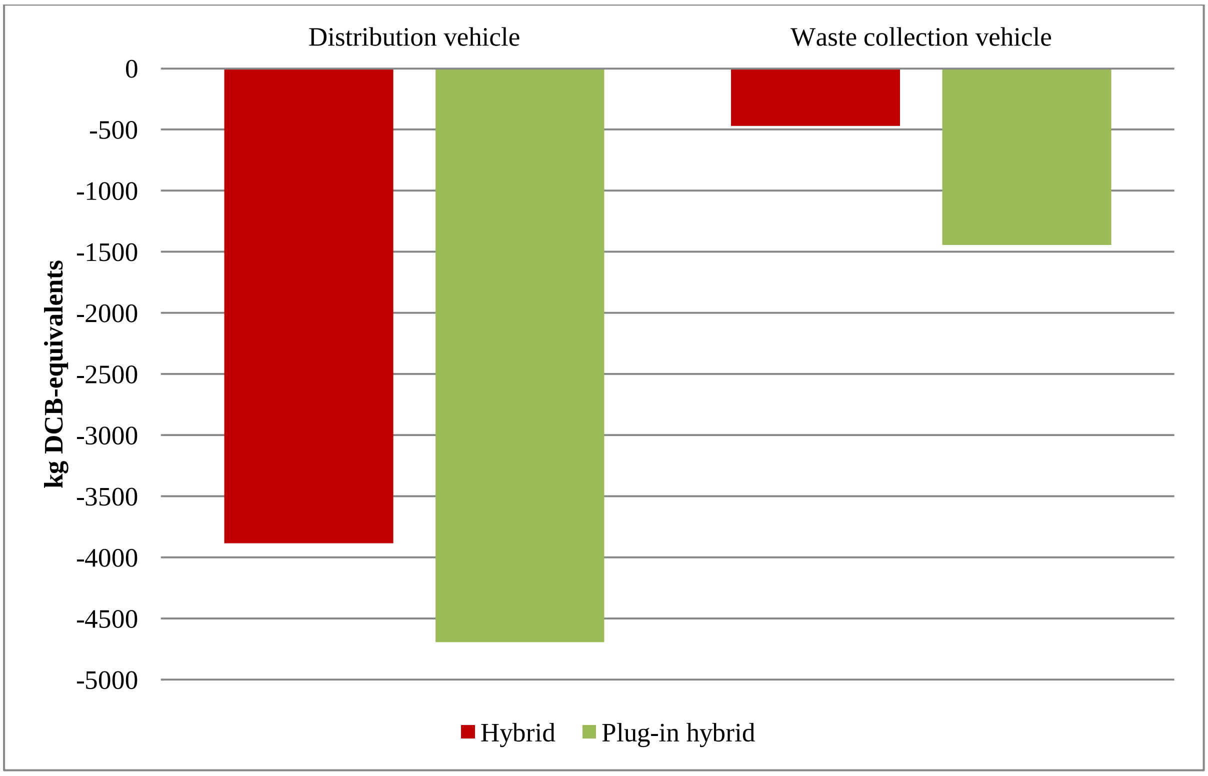

Figure 5-15: Human toxicity potential in DCB-equivalents for the whole life cycle, including well-to-wheel and cradle to grave processes, of the hybrid configurations with the conventional vehicles as a baseline.

5.3.4 Results for Resource Depletion Potential

Figure 6-16 shows the resource depletion potential during the different life cycle stages for the hybrid configurations, measured in Sb-equivalents (antimony). The *Production of drivetrain* and *Maintenance* bars contribute to most of the cradle-to-grave impact of the drivetrain, but also the end of life treatment has a small contribution. The savings in the well-to-wheel phase in reference to the baseline are approximately 25 times larger than the total impact from the remaining cradle-to-grave of the drivetrain.

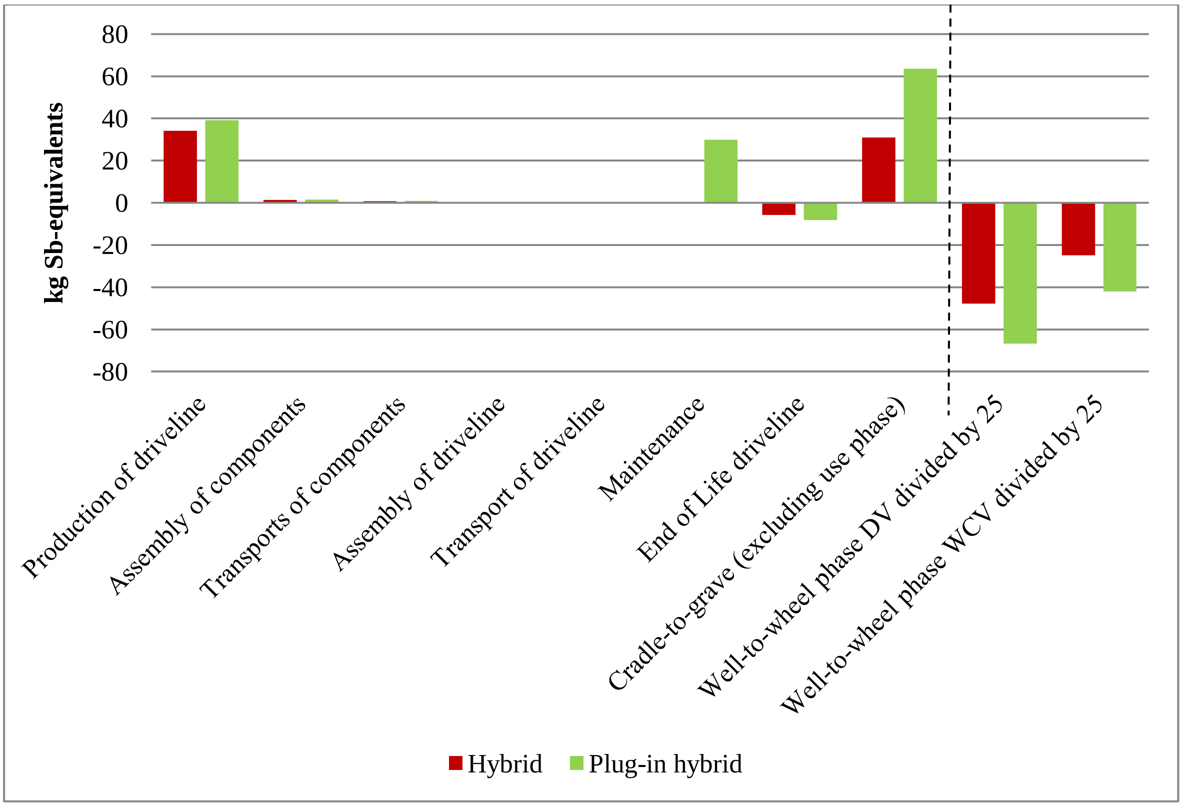

Figure 5-16: Resource depletion potential in Sb-equivalents for the different life cycle stages with the conventional vehicles as a baseline. The saved emissions from the well-to-wheel phase are divided by a factor of 25. Included in the *Production of drivetrain* are also the avoided emissions from the lead-acid battery. Data left of the dashed line represents cradle-to-grave processes, excluding the use phase and data to the right of the dashed line represents well-to-wheel processes.

Figure 5-17 and Figure 5-18 shows the RDP for the components in the drivetrain, for different lifecycle stages. More than half of the total impact comes from the production of the ESS, where hard coal used for the electricity production in China represents two thirds of the impact from the ESS. Use of natural gas and production of aluminium sheets also contribute. For the electric motor the aluminium ingot production has the largest impact.

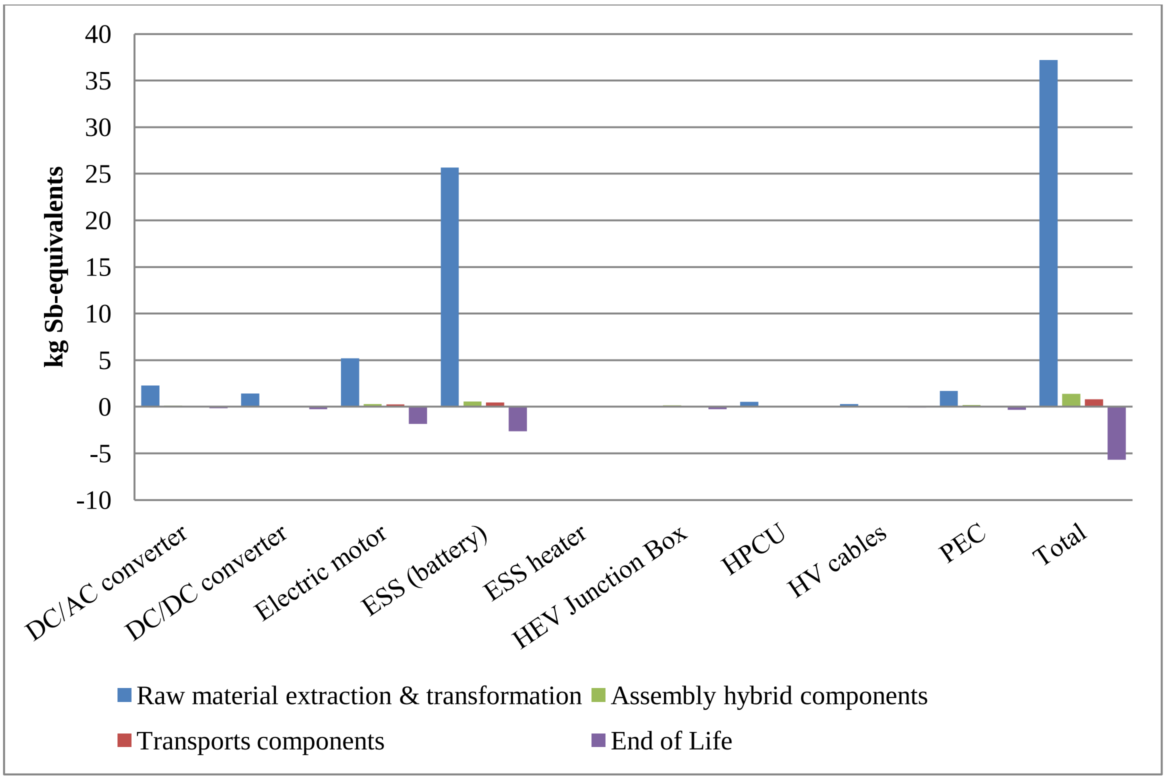

Figure 5-17: Resource depletion potential in Sb-equivalents for the components in the drivetrain of the hybrid vehicle.

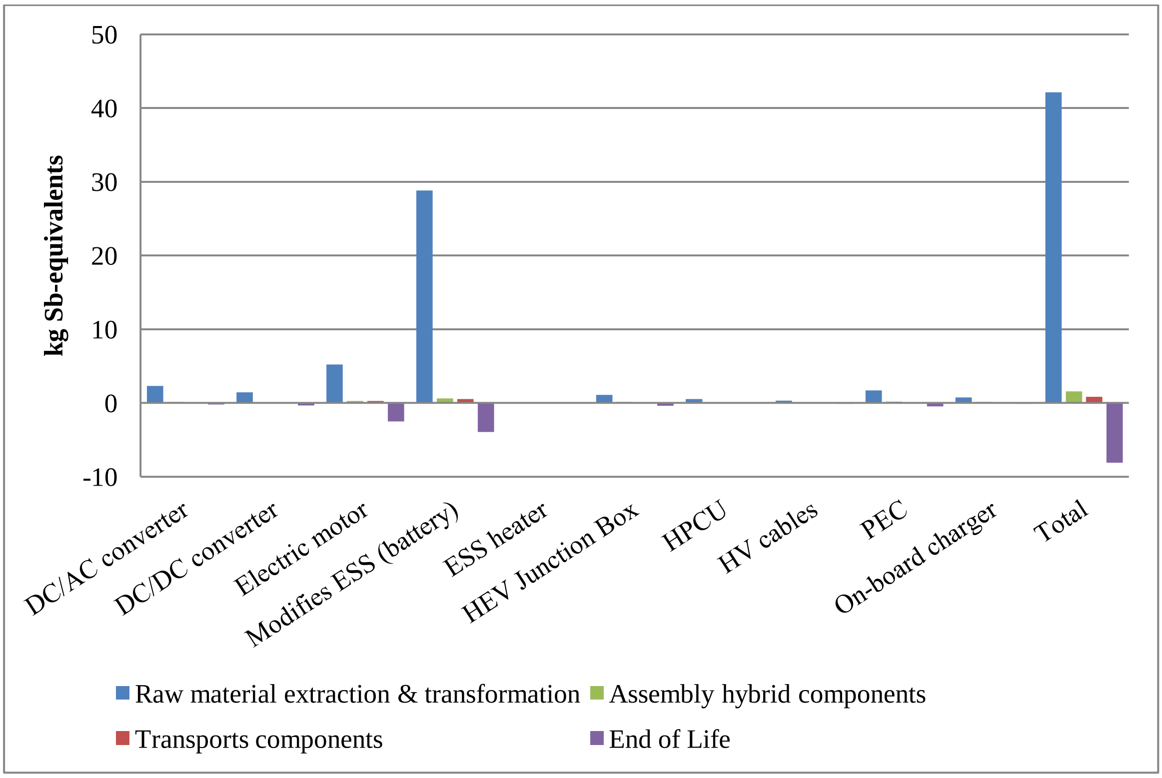

Figure 5-18: Resource depletion potential in Sb-equivalents for the components in the drivetrain of the plug-in hybrid vehicle.

In Figure 5-19 the total RDP for the well-to-wheel phase for the different vehicles is seen. As for the other impact categories the hybrid saves a bit more when going from conventional to hybrid than from hybrid to plug-in hybrid. For the distribution vehicle the savings are about 15% for the hybrid and 20% for the plug-in hybrid. For the waste collection vehicle it's about 20% for the hybrid and 30% for the plug-in hybrid. It is the extraction of crude oil for the diesel production that contributes most to the RDP in the well-to-wheel phase.

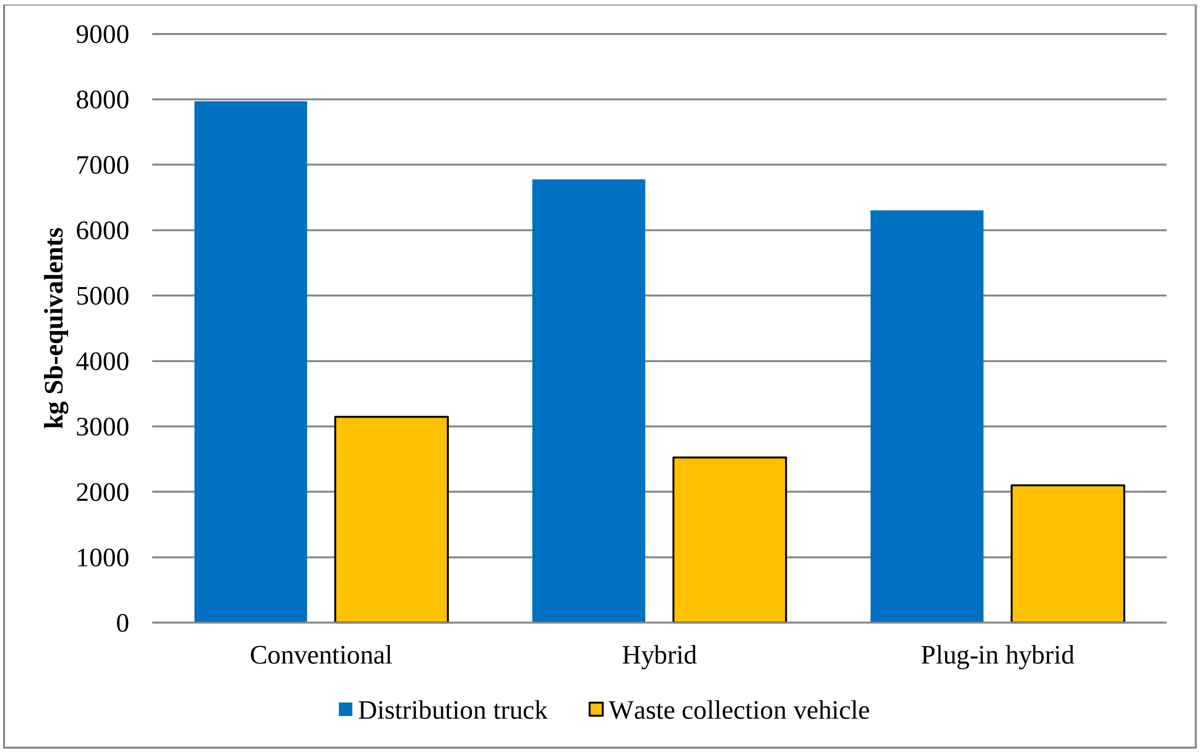

Figure 5-19: Total resource depletion potential in Sb-equivalents for the well-to-wheel phase for the different vehicle configurations.

Figure 5-20 shows the total RDP for the different vehicle configurations, with the conventional vehicles as the baseline. As seen, most of the savings in RDP comes when transforming from conventional to hybrid vehicle, but in particular for the waste collection vehicle a significant further saving is associated with the modification to a plug-in hybrid.

The total results for the RDP are very much dominated by the well-to-wheel phase, since it is so much larger than the life cycle of the drivetrain. The reason for this is the large use of fossil fuels in the well-to-wheel phase which contributes a lot to RDP.

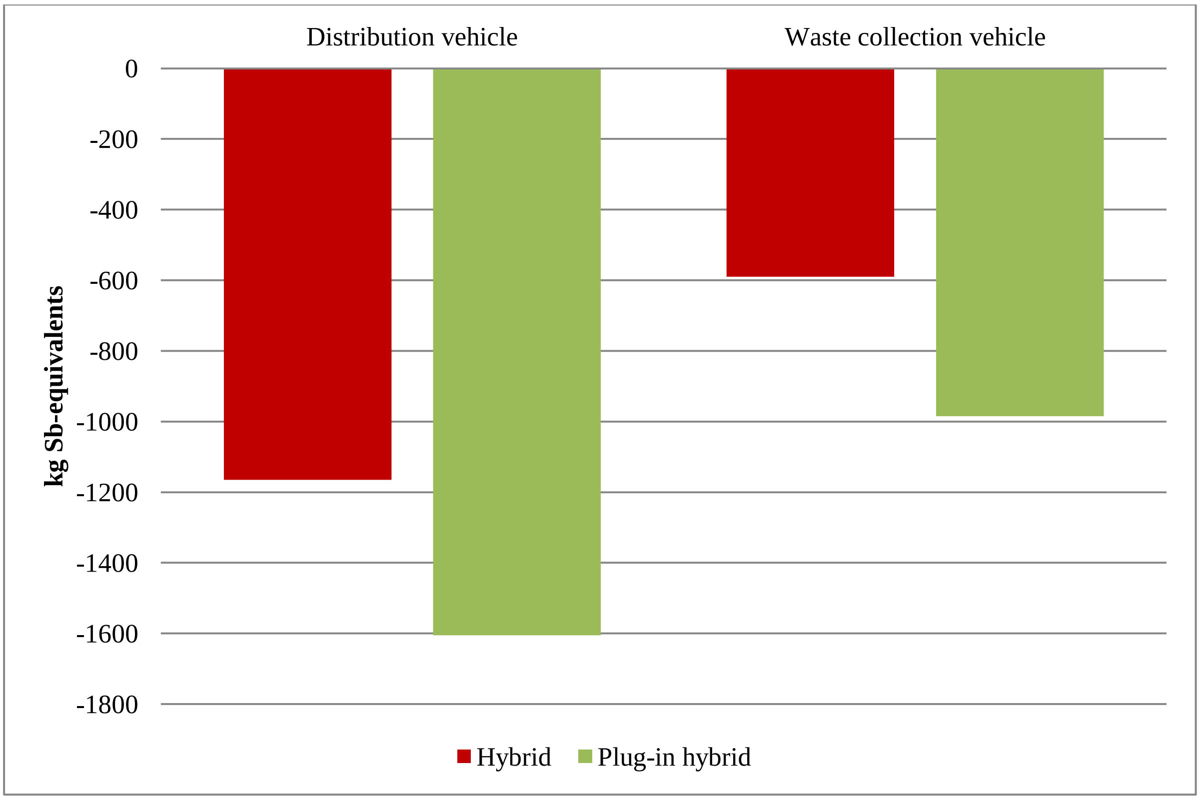

Figure 5-20: Resource depletion potential in Sb-equivalents for the whole life cycle, including well-to-wheel and cradle-to-grave processes, of the hybrid configurations with the conventional vehicles as a baseline.

5.3.5 Results for Energy Use

Figure 5-21 shows the energy use in GJ, measured in net calorific value[20], during the different lifecycle stages. The *Production of drivetrain* and *Maintenance* stages contribute to most of the energy use during the cradle-to-grave of the drivetrain, but the savings during the well-to-wheel phase are much larger, about 40 times for the plug-in distribution vehicle for example.

[20]Primary energy demand from renewable and non-renewable energy sources.

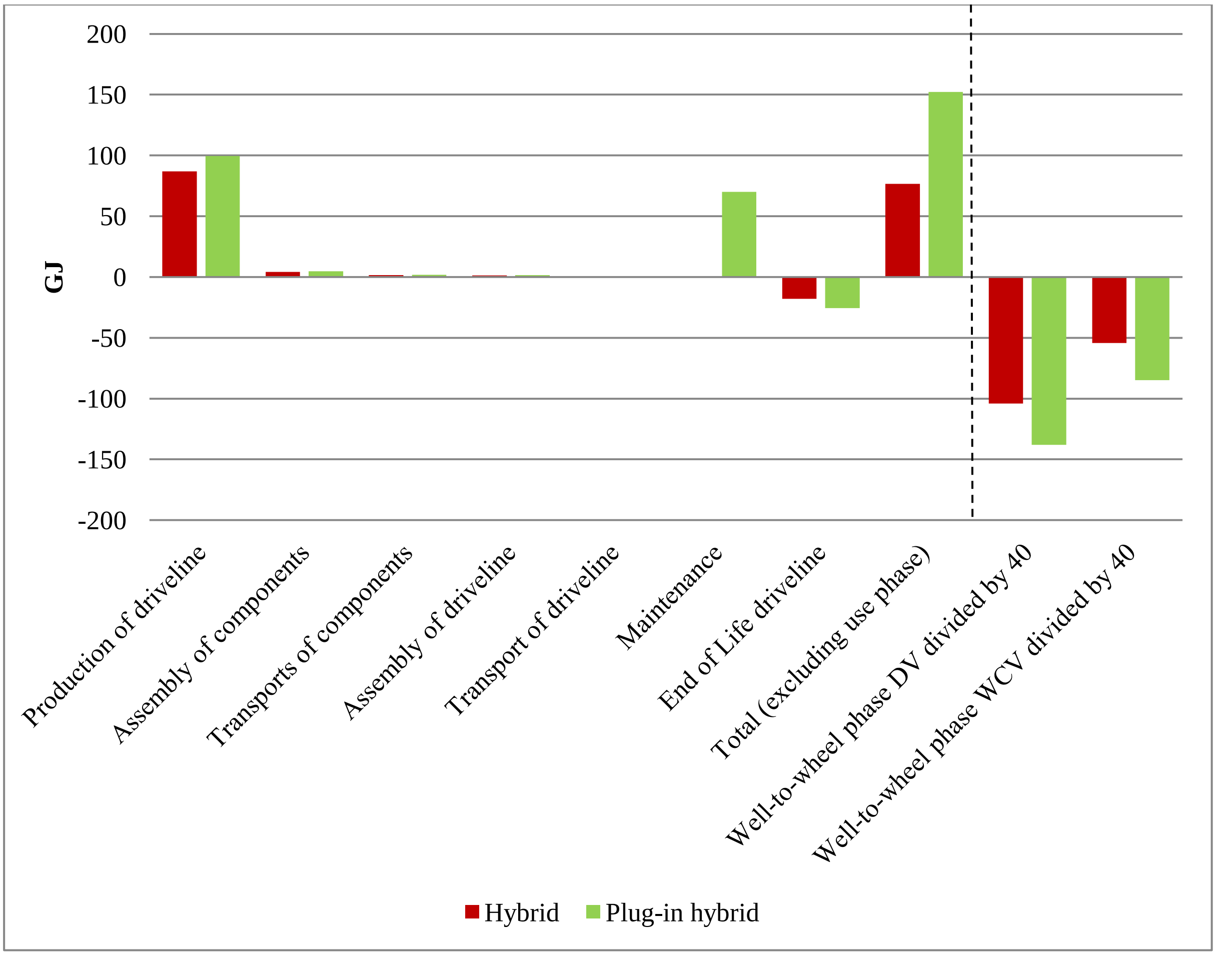

Figure 5-21: Energy use in GJ for the different life cycle stages with the conventional vehicles as a baseline. The saved energy from the well-to-wheel phase is divided by a factor of 20. Included in the *Production of drivetrain* bar is also the avoided energy use from the lead-acid battery. Data left of the dashed line represents cradle-to-grave processes, excluding the use phase and data to the right of the dashed line represents well-to-wheel processes.

Figure 5-22 and Figure 5-23 shows the energy use for the components of the hybrid and plug-in hybrid configuration respectively. The battery production is in both cases responsible for more than two thirds of the total energy use, mostly due to the electricity use in China, but also due to natural gas use and aluminium sheet production. For the electric motor production of aluminium ingot represents more than half of the energy use, but also neodymium, steel and epoxy resin produciton contributes.

In general, raw material extraction and transformation comprise most of the energy use. Energy use for assembly and transports of components is very small, but the end of life treatment has a significant effect on the total result.

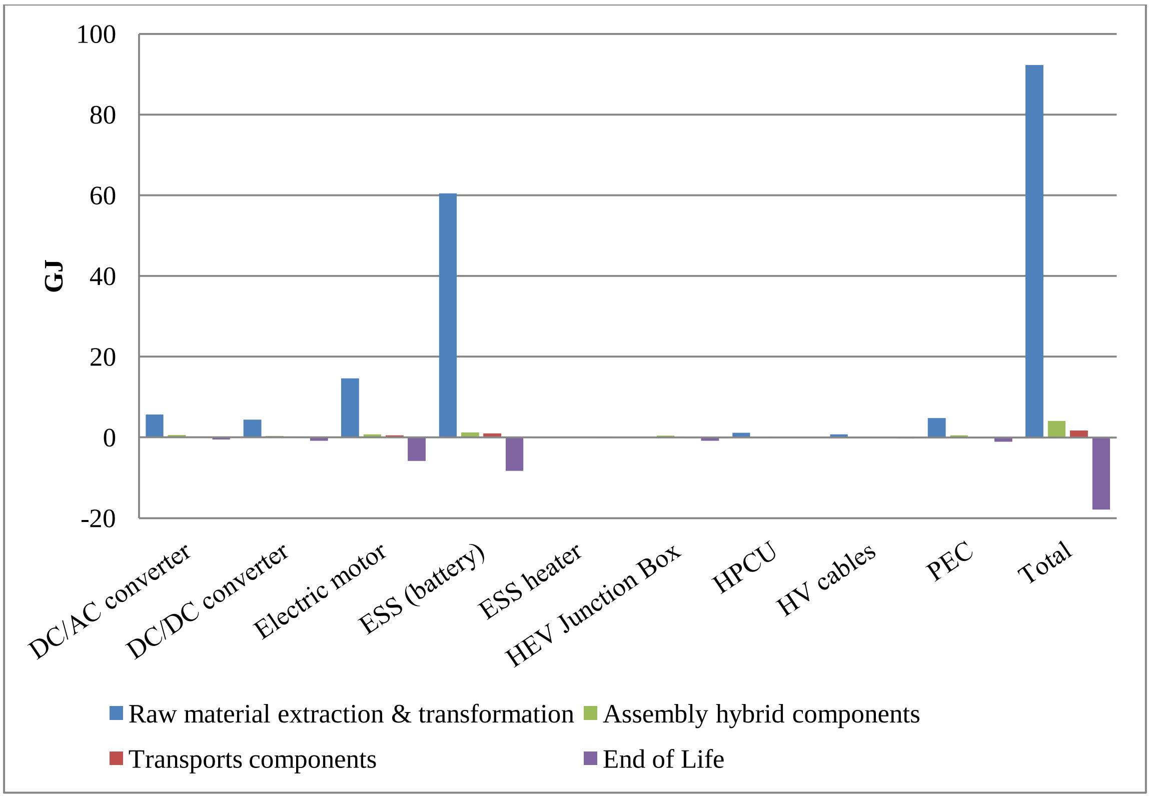

Figure 5-22: Energy use in GJ for the components in the drivetrain of the hybrid vehicle.

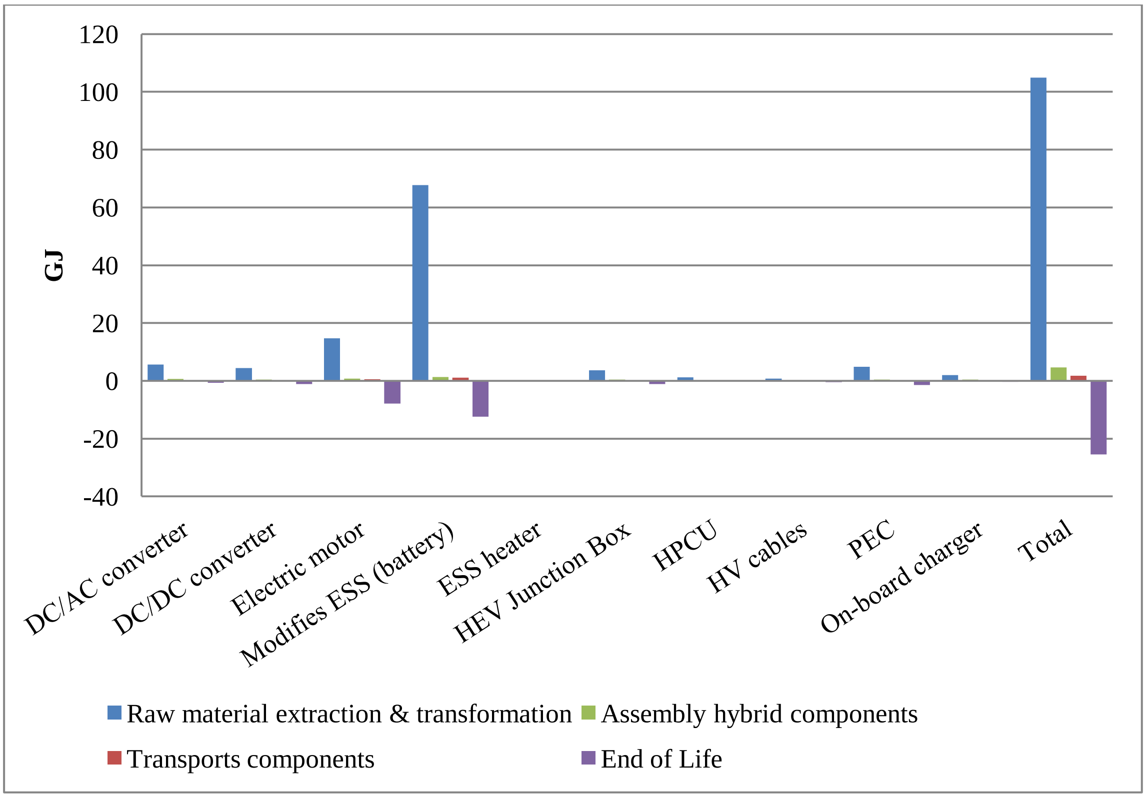

Figure 5-23: Energy use in GJ for the components in the drivetrain of the plug-in hybrid vehicle.

Figure 5-24 shows the total energy use in terajoules (TJ) during the well-to-wheel phase for the different vehicle configurations. For the distribution truck the largest savings are found when going from conventional to hybrid, and only a minor saving when going from hybrid to plug-in hybrid. For the waste collection vehicle the same pattern is seen, but the relative savings are slightly larger when going from hybrid to plug-in hybrid.The energy use here is calculated as the energy in the well-to-wheel chain, i.e. the energy content in the diesel used and the energy needed to extract and process the oil. For the plug-in hybrid some electricity use is also included.

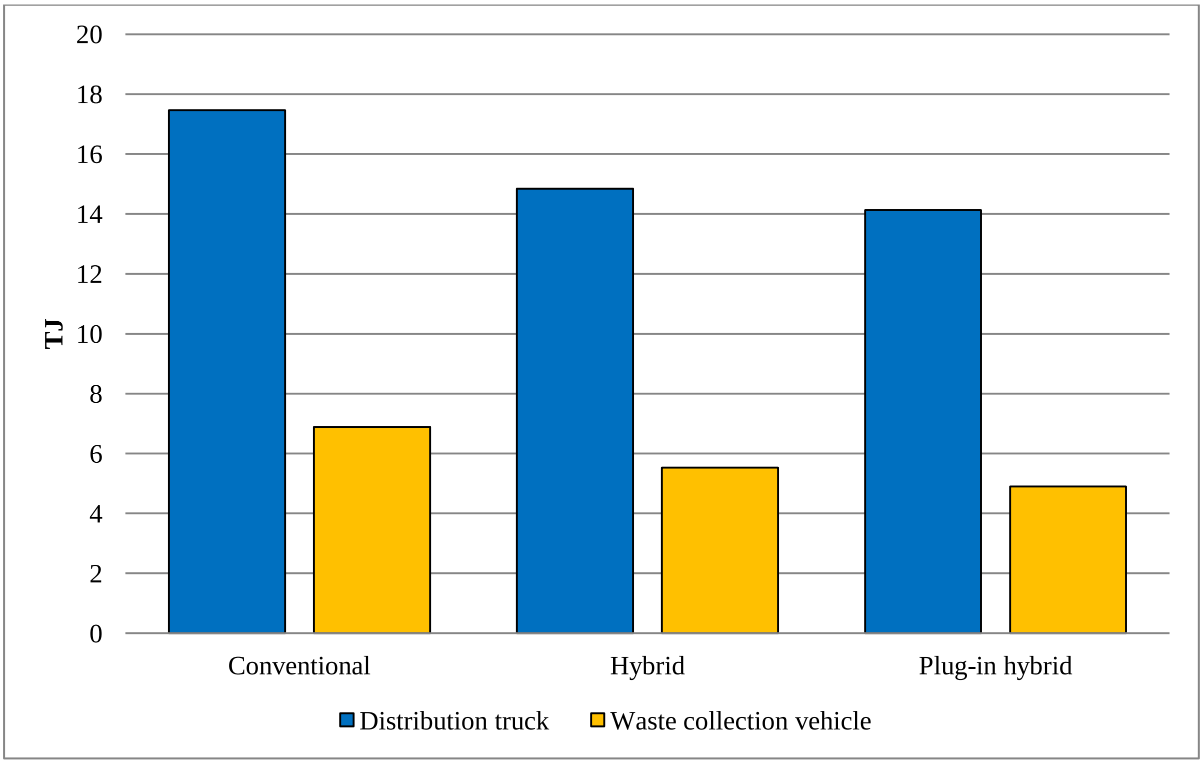

Figure 5-24: Total energy use in TJ in the well-to-wheel phase for the different vehicle configurations.

Figure 5-25 shows the total energy use for the different vehicle configuration with the conventional vehicles as a baseline. That is, it shows the sum of the savings of the well-to-wheel phase and the burden from the remaining cradle-to-grave of the drivetrain. For both the distribution vehicle and waste collection vehicle most of the savings are found when going from a conventional to a hybrid vehicle. For the transformation from hybrid to plug-in hybrid the relative savings are smaller for the distribution vehicle than for the waste collection vehicle.

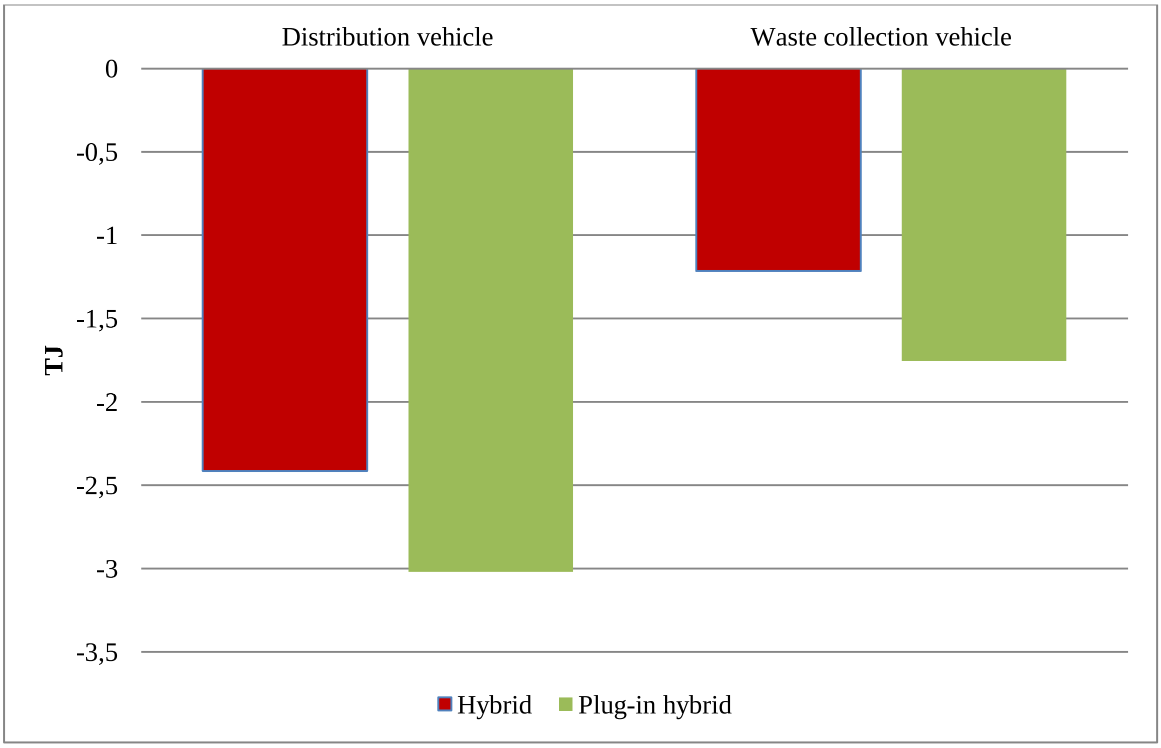

Figure 5-25: Energy use in TJ for the complete life cycle, including well-to-wheel and cradle-to-grave processes, of the hybrid configurations, with the conventional vehicles as a baseline.

5.3.6 **Weighted Results**

Figure 5-27 shows the results from the EPS weighting, measured in Environmental load units (ELU). The conventional vehicles are the baseline. For the distribution vehicle the savings during the well-to-wheel phase outweigh the impact from the lifecycle of the drivetrain, resulting in about 28000 ELU lower for the hybrid distribution vehicle compared to the conventional. For the plug-in the result is about 40000 ELU lower.

For the waste collection vehicle on the other hand, the EPS weighting shows about the same impact for the hybrid as for the conventional. For the plug-in hybrid there is a small saving compared to the conventional vehicle, about 11000 ELU.

Platinum, gold, silver, mercury and cadmium are examples of elements used in the drivetrain components. The ELU value for these elements range from 7.4 million to 29 000 per kilogram substance. The numbers for natural gas and crude oil are 1.1 and 0.5 respectively. This is the explanation why the bar *Cradle-to-grave of drivetrain excluding use phase* is comparable, in ELU, to *Saved emissions in the well-to-wheel phase*. The EPS weighting system puts more weight on scarce and toxic elements than the use of oil and natural gas. The elements mentioned above are just a handful compared to the total amount of scarce and toxic elements included in the components.

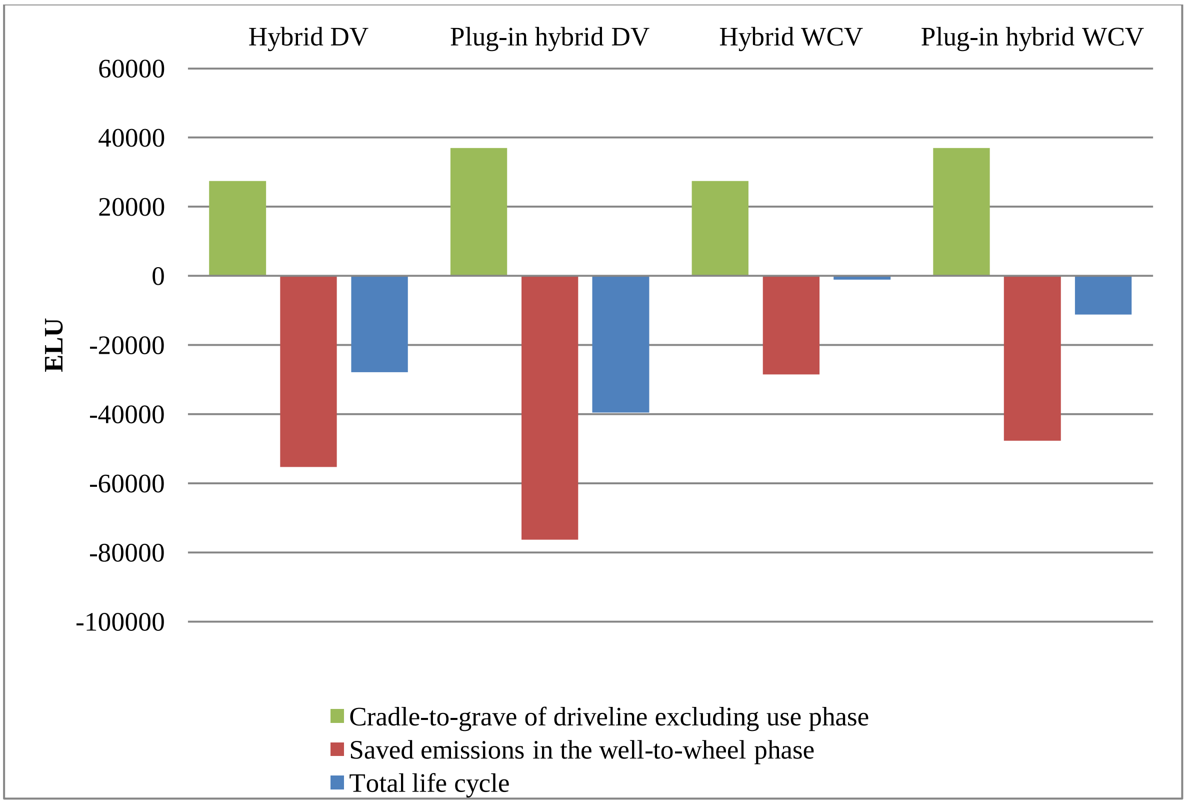

Figure 5-26: EPS-weighting results in reference to the conventional vehicles, measured in Environmental load units.

Figure 5-27 shows EI99-weighting values for the drivetrain lifecycle, well-to-wheel phase (saved diesel and urea consumption in reference with the conventional vehicle) and total life cycle values for the distribution and waste collection vehicles, hybrid- and plug-in hybrid versions. The total life cycle values are the sum of the drivetrain life cycle and saved well-to-wheel phase values.

When going from hybrid to plug-in hybrid distribution truck the EI99 value improves by approximately 35%. The improvement made for the waste collection vehicle is around 75%. The higher improvement rate for the waste collection vehicle is due to the higher share of grid electricity (charged batteries) used in the well-to-wheel phase compared to that of the distribution truck.

As explained in section 5.2.2, the *Hierarchist* perspective weights the result as follows:

- 31% Human health, where respiratory effects and greenhouse effect dominate (weighting factor variation: 278-1.8)
- 54% Ecosystem Quality, where land-use dominate (weighting factor variation: 308-29)
- 15% Resources, dominated by fossil fuels (weighting factor variation: 196-3.5)

The weighting factors do not vary as much as in the EPS weighting system and the main contributing quantities are resources, fossil fuels, both belonging to the well-to-wheel stage which is why *Saved emissions in the well-to-wheel phase* bar dominates in Figure 5-27. The use of natural gas and crude oil (diesel) dominates the entire weighting system. Human health and Ecosystem Quality factors are negligible in comparison to Resources even though these are weighted higher. The green staple in Figure 5-27 represents natural gas and coal, in CCPP, used for the production of the ESS, hybrid configuration, and modified ESS in the plug-in hybrid configuration.

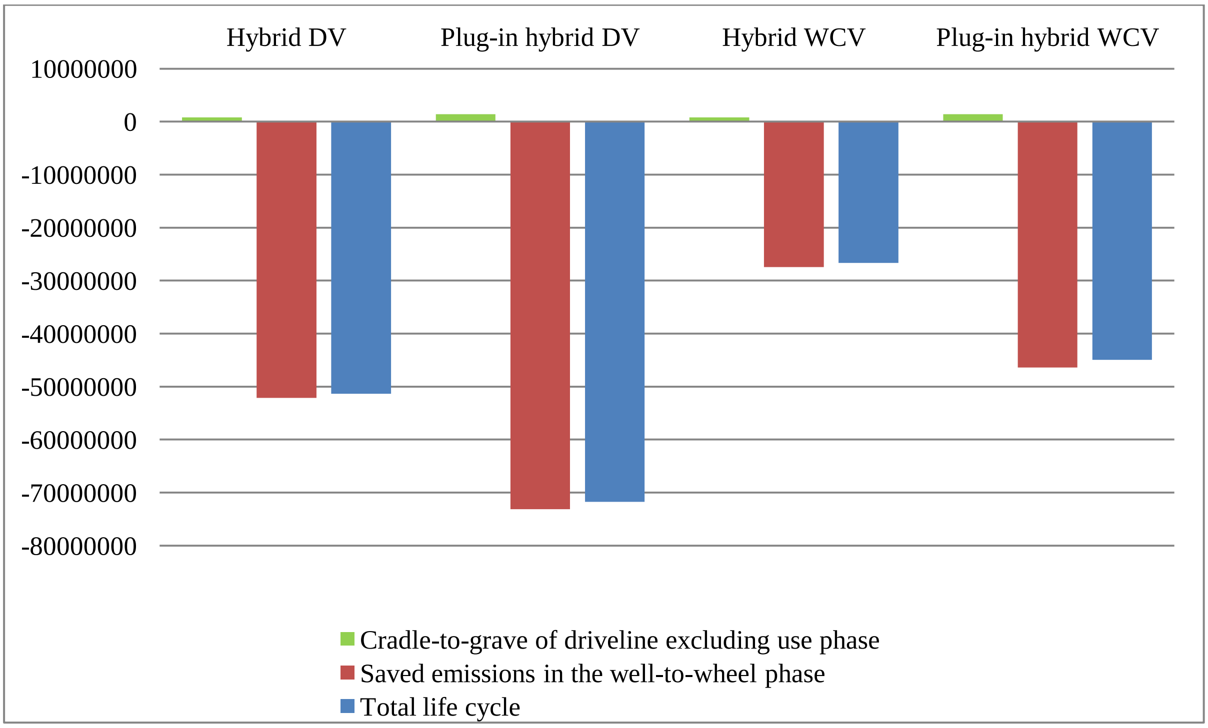

Figure 5-27: EI-99 weighting results with the conventional vehicles as a baseline.

6. Sensitivity and Uncertainty Analysis

6.1 Sensitivity Analysis

The purpose of a sensitivity analysis is to identify key data and assumptions that have most influence on the results. Some parameters used are known with a higher degree of accuracy and these will remain fixed throughout the analysis e.g. diesel consumption, hybrid and plug-in hybrid diesel savings for distribution- and waste collection vehicle.

6.1.1 Charging Cycles

In order to illustrate how sensitive the well-to-wheel model is to changes in charge cycles a sensitivity analysis has been done for the global warming potential characterization factor. The reason for this is because the well-to-wheel stage, as shown earlier, has the largest impact of all lifecycle stages. GWP100 indicator was chosen because a lot of greenhouse gases are emitted in the use phase thus giving a good indication of the relative changes. The GWP profile is similar to the other characterization indicators giving an indication of the relative changes for those as well.

Parameters varied are the amount of charges per day for both vehicle types and type of power source for grid electricity used for charging the batteries. There is some uncertainty of how many times the battery will be charged on a working day depending on the type of AC/DC converter used. What is marginal electricity is not always straightforward, depending on the definition[21].It was modeled with a worst case scenario, CCPP, releasing 0.95 kg CO_2 per kWh (Elforsk AB 2008). The original value used (Swedish electricity mix 2020) released 0.08 CO_2-equivalents per kWh (PE International AG 2012). The result is presented in Figure 6-1.

[21] Marginal electricity is defined as the electricity produced at an increase in electricity demand. There are different kinds of marginal electricity, such as short term, long term etc.

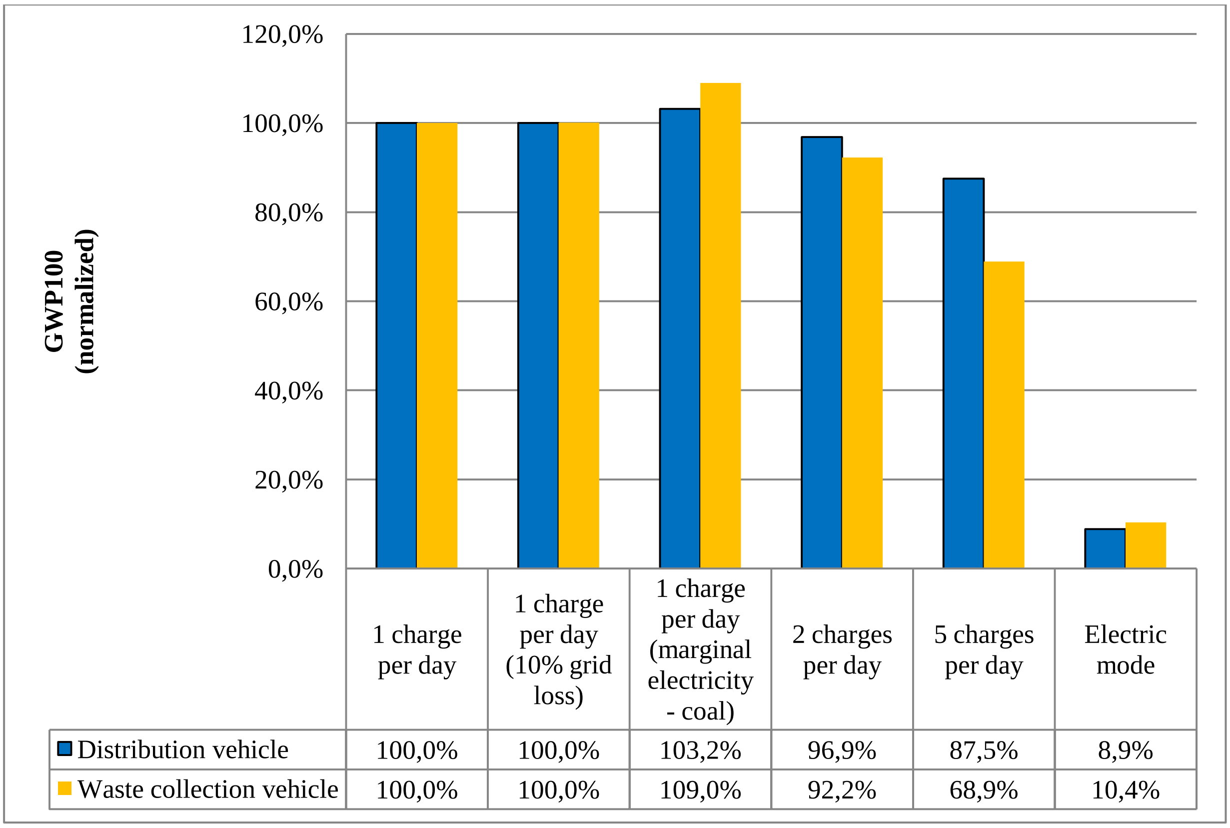

Figure 6-1: The bars show the difference in GWP100 during the use phase when the amount of charges per day is varied between 1, 2 and 5 times per day with Swedish electricity mix 2020. All charges include a 5% grid loss except for the second pair where 10% grid loss is assumed. The third bar set shows the change when assuming battery charge with marginal electricity (one charge per day). All values are normalized to the original one charge per day values for both vehicle cycles (first pair).

Table 6-1: Summary of assumptions made in Figure 6-1.

Bar in Figure 6-1	**1**	**2**	**3**	**4**	**5**	**6**
Type of electricity used	Swedish mix 2020	Swedish mix 2020	Marginal (CCPP)	Swedish mix 2020	Swedish mix 2020	Swedish mix 2020
Grid loss [%]	5	10	5	5	5	5
Charges/day	1	1	1	2	5	30 (DV) 13 (WCV)

A higher electricity grid loss does not change emissions considerably as can be seen in Figure 6-1. Two charges per day lower the GWP100 with 3.1% for the distribution truck and 7.8% for the waste collection vehicle. Charging the trucks 5 times per day lowers the GWP100 impact with 12.5% for distribution truck and 31.1% for the waste collection vehicle. Pure electric driving mode (diesel engine not used) has the lowest impact but could be impractical because of the total amount of charges that has to be done per day; 30 and 13 charges per day for distribution and waste collection vehicle respectively. In addition the electric motor is not designed to propel the vehicle alone.

Because there is a linear relation between the amount of charges per day and the decrease of GWP100 impact, more charges will always result in decreased impact. The conclusion is that charging should be carried out whenever there are long pauses, e.g. lunch and night for practical reasons.

6.1.2 Metal Recycling

Metals can be modeled with open or closed loop recycling. Depending on the purity, quantity, and method of separation (technology used) of the metals present, different qualities (purities) are obtained after separation. All metals are usually downgraded, quality is reduced, for each time separation takes place. In this study this has been modeled with an open loop recycling for the metals mentioned in section 4.8.3. Because of the uncertainty of the quality reduction after separation a sensitivity analysis has been carried out, for GWP100 indicator, by increasing the recycling rates of all metals to 100 percent, a standard assumption made by Volvo. The impact of this is shown in Table 6-2 below.

Table 6-2: Effect of changing end of life treatment of all metals to 100% recycling.

End of Life (GWP100)	**Hybrid (CO_2-equivalents)**	**Plug-in hybrid (CO_2-equivalents)**
EoL lifecycle stage (Original recycling rates)	-1067	-1482
EoL lifecycle stage (100% recycling of all metals)	-1653	-2200
Relative change EoL-stage	**-54.9%**	**-48.4%**
Cradle-to-grave, excluding use phase (original recycling rates)	5604	10798
Cradle-to-grave, excluding use phase (100% recycling of all metals)	5018	10081
Relative change cradle-to-grave, excluding use phase	**-10.5%**	**-6.6%**

Table 6-2 shows the difference in GWP100 in comparison to the original end of life recycling values, see section 4.8.3 Metal Scrap for more details. Recycling of all metals to 100% decreases global warming potential in end of life stage by approximately 50% for both hybrid and plug-in hybrid configurations. Comparing the whole lifecycle of the drivetrain for the two configurations with 100 percent metal recycling rates shows a GWP100 decrease between 10.5% and 6.6% for the distribution and waste collection vehicle respectively. The much lower result for the plug-in hybrid configuration is mainly because of the GWP100 emissions released during production and from additional raw material needed for the modified ESS.

The conclusion is that recycling metals included in the hybrid- and plug-in hybrid drivetrain configurations have a major impact when considering the end of life stage only, and a relatively high impact when considering cradle-to-grave excluding the use phase. The additional GWP100 savings are due to the higher recycling rates of especially precious metals like gold, platinum and silver.

A qualitative sensitivity analysis can be made for the other characterization indicators. Using the same model as in section 4.8.3, impact categories such as acidification potential and human toxicity potential causes larger negative net differences than GWP100, when recycling all metals to 100 percent. The reason for this is that the extraction of precious metals like gold emits high amounts of sulphur dioxide and other acid elements. Arsenic is another element released when extracting gold, decreasing the human toxicity impact.

6.2 Uncertainty Analysis

There are some uncertainties regarding materials, material transformations, geographical locations, etc. In this section we address to these uncertainties in a general manner.

Two major uncertainties in the study that have a large impact on the final result are the fuel consumption in the well-to-wheel phase for all vehicles, and the life cycle of the plug-in hybrid. Since the plug-in is not an industrialized product but rather under development it has not been thoroughly tested yet, and all its specifications are much more uncertain, such as fuel consumption, battery chemistry, battery size and battery lifetime etc. The plug-in battery, for example, was calculated to need about 20 kg additional active material compared to the hybrid battery, while all other material quantities stayed the same. The wearing of the battery is also uncertain, only one battery change during the lifetime of the truck might not be enough. This is also valid for the hybrid, for which a battery change might very well be needed.

Concerning the fuel consumption of the different vehicle configurations, and the fuel savings for the hybrid configurations, uncertainties here give large uncertainties for the final result since the well-to-wheel phase is such a large part of the whole study. The figures used for the fuel saving were received from Volvo. The fuel saving for the hybrid vehicles are claimed to have been tested, and are conservative figures that the trucks well should perform. The figures for the plug-in hybrid are based more on theoretical calculations, and therefore there is room for more uncertainty here.

The operation of the waste collection unit was excluded from the study in agreement with Volvo. If it had been included the diesel consumption figures for the waste collection vehicle would have been higher, resulting in more savings in the well-to-wheel phase. An earlier study made by Anna

Boss (2005) indicates that the diesel consumption of the additional waste collection unit, lifting and compression, represents about 13% of the total consumption during a collection route.

A lot of effort in this study has been put on the data gathering for the inventory analysis. Considering cradle-to-grave of the drivetrain, excluding the use phase, we see that most of the environmental impact comes from the raw material extraction and material transformation. Appropriate transformation processes for most of the materials in the components have been included, for example casting or sheet rolling of metals and injection molding of plastics. All these processes showed to have quite large impact in comparison with the other stages like assembly of components and transports. Still, there are some uncertainties associated with this lifecycle stage since it was difficult to find accurate processes for all materials.

In addition, there is some uncertainty about the materials themselves. In the bills of material (BOM) used for the study it was often just specified “steel”, “stainless steel” or “copper” for example, so assumptions had to be made regarding in what form, grade etc. the material had in each module.

Concerning the geographical locations of process choices these were to as large extent as possible in line with Goal and Scope. For many processes regional data, for example European averages, was chosen for processes taking place in a European country. The impact from these processes might differ slightly from reality. However, regional data is often preferable in an LCA as it makes the result a bit more general than in the case of using site specific data.

Since the well-to-wheel phase dominates all impact categories, uncertainties are important to be aware of. Estimated distances were received from Volvo and are yearly European averages for distribution and waste collection vehicles. The size of cities vary a lot across Europe, therefore statistical distance data for specific geographical areas should give more accurate calculations regarding lifetime and emissions. The lifetime of a truck can be quite uncertain though, they are often used on one market during the first years, then sold to secondary markets before being scrapped. Also the same lifetime was assumed for conventional, hybrid and plug-in hybrid configurations. Since the use of the combustion engine (and electric motor) varies between the configurations, there might be reason to believe that the lifetimes are different. Concerning the intervals for battery change, which were set to one change for the plug-in hybrid and no change for the hybrid, there might be some uncertainty there as well.

Another uncertainty is the energy consumption of the waste collection unit. This compression and loading of garbage has not been included in this study. The reason for this is that Volvo is not responsible for the assembly or for the use of this unit. The type of collection unit to be used and how to mount it is entirely up to the customer. It can be assumed that the battery will be discharged at a faster rate resulting in higher hybrid drive mode for the plug-in hybrid configuration, i.e. higher diesel consumption and in turn leading to a higher well-to-wheel impact.

7. Interpretation

7.1 Discussion

Studying the cradle-to-grave of the drivetrain, excluding the use phase, we see that for all impact categories, assembly of components and drivetrain and transports of components and drivetrain all have minor impacts in the context. The end of life treatment on the other hand has a slightly larger effect as the sensitivity analysis in section 6.1.2 showed, a radical change of the recycling ratios for metals had a considerable effect on the drivetrain cradle-to-grave result, excluding the use phase. Raw material extraction and material transformation has the largest impact though, for all categories and for all components, cradle-to-grave (use phase excluded).

Among the components, the battery has by far the largest impact for all characterization indicators except for HTP and AP where the DC/AC converter also has a high impact, but still less than the battery. The other converters also have a relatively high HTP impact, due to the release of toxic elements in the production of electronics. In all other cases the electric motor has the second largest impact. This is valid for both the hybrid and plug-in hybrid configurations.

Taking into account the total lifecycle though, the well-to-wheel phase is dominating for all characterization indicators except HTP where the production of components almost reaches the same level of impact as the well-to-wheel phase. However, that is when studying the savings in the well-to-wheel phase. The total impact is still much larger than the production of the drivetrain. As mentioned in section 5.3.3, Chinese electricity use in the battery production and toxic substances in the electronics like arsenic and cadmium are the reason for the high impact of the production of the drivetrain. This is particularly remarkable for the hybrid waste collection vehicle, which has the least savings during the well-to-wheel phase, and therefore only shows a negligible improvement in HTP compared to the reference vehicle.

Apart from HTP, for AP the difference between well-to-wheel phase and the life cycle of the drivetrain is smallest, around a factor 10. The emissions from the use phase would have been much more acidifying if it was not for the use of urea, which decreases the release of nitrogen oxides.

With the exception of HTP in mind, the other impact categories show a clear pattern, where the transition to a hybrid vehicle shows the largest improvement, and the transition from hybrid to plug-in hybrid results in a relatively small further improvement for the distribution vehicle and a slightly larger improvement for the waste collection vehicle. To keep in mind when studying the results of the plug-in vehicle, is that no infrastructure changes were included in the study, and also the uncertainty of the vehicle data itself.

The results imply that the environmental benefit when going from hybrid- to plug-in hybrid-configuration increases with decreasing driving distance. This is due to the fact that the plug-in function, battery charging, is used to a higher degree when driving distance decreases (linear function). This is why the relative environmental benefit is higher for the waste collection vehicle than for the distribution vehicle when comparing the two configurations (the distribution vehicle has more than 3 times driving distance, between charges, compared to the waste collection vehicle). Increased battery energy density and/or more frequent charging would definitely increase the motivation for using plug-in hybrid configuration for distribution vehicle.

Weighting indicators EPS and EI-99 (HA) show quite different results. The EPS system indicates that the largest saving is done for the plug-in hybrid distribution truck and the lowest, close to zero, for the hybrid waste collection vehicle. The pattern is quite similar to that of the HTP characterization indicator when looking at the total result values, even though EPS puts a lot of weight in resource depletion along with HTP in toxic elements. Another interesting point of the EPS weighting is that the well-to-wheel phase has roughly the same size as the life cycle of the drivetrain. This is due to the large weighting factors of certain elements in the drivetrain components, such as platinum (due to resource depletion) and arsenic (due to toxicity).

The EI-99 (HA) model shows quite large savings for all vehicle types with the largest saving potential for the plug-in hybrid distribution vehicle and lowest for the hybrid waste collection vehicle. The additional savings going from hybrid to plug-in hybrid is still higher for the waste collection vehicle than for the distribution vehicle in relative terms. For this weighting method the well-to-wheel phase totally dominates the final result, due to the high resource use dominated by natural gas and crude oil.

A general observation regarding EI-99 (HA) weighting system is that it weighs already weighted results, i.e. first it weighs the impacts according to an Eco-indicator weighting, and then a second weighting depending on which model used (hierarchist, egalitarian etc.). This can easily lead to misinterpretation of the resulting values. An example of this is the weighting of Human Health. It represents 31% of the total *Hierarchist* approach, where 15% of the 31% are due to *climate change* effects. The multiplying factor for *climate change* effects is 62 in the EI-99 (HA) model. It is easy to make the conclusion that climate change should be the main reason for the resulting values in Figure 5-27 considering of the high CO_2-equivalent values in Figure 5-4. Digging deeper and analyzing what the weighting factors look like for different elements within Human Health (*climate change*), we can see that the weighting factor for CO_2 is only $2.1 * 10^{-7}$, outweighing the *climate change* factor totally (in comparison with other factors). It appears that the human health factor of climate change is considered to be very low, while other aspects of climate change such as ecosystem damage is not considered. The main conclusion is that *resources* is the dominant factor in the EI-99 (HA) result, Figure 5-27, although only 15% of the weighting factors can be assigned to *resources*.

A limitation of this study is that the environmental impact from the different lifecycle stages for the conventional vehicles were not included in the scope. Therefore the total impacts for the hybrid configurations could not be presented, instead just the impacts in relation to the conventional vehicles, set as the baseline, were found. Due to this limitation no conclusions about how large the impacts for the complete vehicles' lifecycle stages could be done, for example how large is the production phase for the whole truck compared to the use phase. On the other hand it is possible to conclude that except for EPS and HTP, this relationship will be roughly the same as for the conventional vehicle.

7.2 Conclusions

Based on the results and discussion the answers to the questions asked in Goal and Scope are the following:

1. How large are the emissions and the environmental impact for the different configurations, hybrid and plug-in hybrid during their lifecycle, using the conventional vehicle as baseline?

- For the distribution vehicle most savings are found when going from a conventional- to a hybrid- configuration, and only a slightly further environmental benefit is accomplished when transforming to plug-in hybrid. In the case of global warming potential, the plug-in hybrid shows 38% further savings compared to the hybrid.
- For the waste collection vehicle the transformation from hybrid to plug-in hybrid yields a larger environmental improvement compared to the configuration transformation for the distribution vehicle. In the case of global warming potential, the plug-in hybrid shows a 64% further savings compared to the hybrid.

2. Which life cycle stages have the largest environmental impacts?

- The well-to-wheel phase has the largest environmental impact of all lifecycle stages for all vehicle configurations, i.e. the reduction of impact due to fuel savings clearly outweighs the additional impact of the new components.

3. Which components contribute most to the environmental burden?

- The lithium ion battery has the largest environmental impact among the drivetrain components for all impact categories studied. The raw material extraction and material transformation have the largest impact of the lifecycle stages of the components.

A final conclusion to sum it up:

- The plug-in hybrid vehicle has the least environmental impact for all impact categories and weighting methods. The largest relative saving is found in the EPS weighted results, where the plug-in hybrid waste collection vehicle shows around ten times larger savings compared to the hybrid, while the least relative saving is found for the HTP, where the plug-in hybrid distribution vehicle has only 20% larger savings than the hybrid.

7.3 Recommendations

Based on the previous sections the following recommendations regarding choice of drivetrain and methodological choices when doing an LCA were done:

Recommendations regarding choice of vehicle:

- Distribution truck:
    - Hybridization shows a clear environmental saving for all impact categories and weighted results.

    - The additional savings of the plug-in hybrid are small, and combined with the uncertainties surrounding this vehicle no certain conclusions that it is the preferred choice can be drawn.
        - Therefore the hybrid distribution truck is recommended.

- Waste collection vehicle:
    - Hybridization shows some environmental improvement for most categories. However, for HTP it is very small and for EPS none at all.
    - The transformation from hybrid to plug-in hybrid shows large savings for all impact categories, ranging from about 60% - 1000% compared to the savings of the hybrid.
        - Therefore the plug-in hybrid vehicle is recommended.

Some differences in methodological choices in this study compared to the routine normally used by Volvo were identified, and we recommend the following:

- Methodological consistency regarding material choices and processes is recommended. There is often a lack of data regarding the geographical location of factories and origin of raw materials used for manufacturing different components. In case no data is available literature data and/or assumptions regarding processes can be used to estimate energy consumption, material transformations, raw material origin, etc.

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Appendix A

A.1 Assembly Emissions

Table A-1: Assembly emissions, conventional vehicle

Energy	**MJ/FU**	**MJ/FU**	**kg/FU**	**Notes**
	Renewable	**Non-renewable**		
Electricity	1731.60			
Natural gas		64.45	1.32	
Propane		13.32	0.29	
3 Gas				
1 Diesel		206.02	4.54	
Bio-oil and wood	1645.70		54.86	ethanol
Water use	**kg/FU**			
	Process water	*Cooling water*		
City water	1434.29			
Storm/ surface water	257.66			
Waste	**kg/FU**			
	Material recycled	**Incineration**		**Landfill**
	Recycled, incl. metal scrap	*With energy recovery*	*Without energy recovery*	*Landfill*
Non- hazardous waste	53.11	17.22		
Hazardous waste	1.58	0.51		0.20
	kg/FU			
Solvents	0.57			
Emissions to water	**kg/FU**			
COD	0.27			
BOD	4.80E-02			
Chromium	1.31E-05			

Copper	3.44E-05			
Lead	9.63E-07			
Nickel	2.42E-05			
Zinc	3.20E-04			

Table A-2: Assembly emissions, hybrid vehicle

Energy	**MJ/FU**	**MJ/FU**	**kg/FU**	**Notes**
	Renewable	**Non-renewable**		
Electricity	1978.97			
Natural gas		73.66	1.50	
Propane		15.23	0.33	
3 Gas				
1 Diesel		235.46	5.19	
Bio-oil and wood	1880.8		62.69	ethanol
Water use	**kg/FU**			
	Process water	*Cooling water*		
City water	1639.19			
Storm/ surface water	294.47			
Waste	**kg/FU**			
	Material recycled	**Incineration**		**Landfill**
	Recycled, incl. metal scrap	*With energy recovery*	*Without energy recovery*	*Landfill*
Non- hazardous waste	60.69	19.68		
Hazardous waste	1.81	0.58		0.23
	kg/FU			
Solvents	0.65			
Emissions to water	**kg/FU**			
COD	0.31			

BOD	0.05			
Chromium	1.5E-05			
Copper	3.93E-05			
Lead	1.1E-06			
Nickel	2.77E-05			
Zinc	0.00037			

Table A-3: Assembly emissions, plug-in hybrid vehicle

Energy	**MJ/FU**	**MJ/FU**	**kg/FU**	**Notes**
	Renewable	**Non-renewable**		
Electricity	2003.70			
Natural gas		74.58	1.52	
Propane		15.42	0.33	
3 Gas				
1 Diesel		238.40	5.25	
Bio-oil and wood	1904.31		63.48	ethanol
Water use	**kg/FU**			
	Process water	*Cooling water*		
City water	1659.68			
Storm/ surface water	298.15			
Waste	**kg/FU**			
	Material recycled	**Incineration**		**Landfill**
	Recycled, incl. metal scrap	*With energy recovery*	*Without energy recovery*	*Landfill*
Non- hazardous waste	61.45	19.92		
Hazardous waste	1.83	0.59		0.23
	kg/FU			
Solvents	0.66			

Emissions to water	**kg/FU**			
COD	0.31			
BOD	0.056			
Chromium	1.51E-05			
Copper	3.98E-05			
Lead	1.11E-06			
Nickel	2.8E-05			
Zinc	0.00037			

A.2 **Assembly in Gent Factory**

Table A-4: Inputs and outputs modeled in GaBi with values taken from Gent environmental report 2011.

	Flow in GaBi	**Process in GaBi**	**Quantity**	**Hybrid**	**Plug-in Hybrid**	**Unit**
Input	Power (from wind power) [System-dependent]	RER: Power from wind power ELCD/PE-GaBi	Energy (net calorific value)	260	286	MJ
Input	Water for industrial use [Operating materials]	RER: Process water ELCD/PE-GaBi	Mass	215	237	kg
Input	Water (surface water) [Water]	RER: tap water, at user	Mass	38.6	42.5	kg
Input	Ethanol from wheat [Biomass fuels]	BR: ethanol, 95% in H2O, from sugar cane, at fermentation plant	Mass	8.23	9.05	kg
Input	Diesel [Crude oil products]	EU-15: Diesel ELCD/PE-GaBi	Mass	0.681	0.749	kg
Input	Natural gas free customer EU-15 [Natural gas products]	EU-15: Natural gas mix PE	Mass	0.197	0.217	kg
Input	Propane [Organic intermediate products]	RER: propane/ butane, at refinery	Mass	0.0431	0.0474	kg
Output	Assembly Gent 2010 [Automotive assemblies]		Number of pieces	0.150	0.165	pcs.
Output	Biological oxygen demand (BOD) [Analytical measures to fresh water]		Mass	0.00719	0.00791	kg
Output	Chemical oxygen demand (COD) [Analytical measures to fresh water]		Mass	0.0406	0.0446	kg
Output	Chromium (unspecified) [Heavy metals to fresh water]		Mass	1.96E-06	2.16E-06	kg
Output	Copper (+II) [Heavy metals to fresh water]		Mass	5.16E-06	5.67E- 06	kg
Output	Hazardous waste to landfill [Hazardous waste for disposal]		Mass	3.01E-02	3.31E- 02	kg
Output	Hazardous waste treated [Hazardous waste for recovery]		Mass	0.314	0.345	kg
Output	Hybrid drivetrain (pcs) [Automotive assemblies]		Number of pieces	0.150	0.165	pcs.
Output	Incineration good [Waste for disposal]		Mass	2.58	2.84	kg
Output	Lead (+II) [Heavy metals to fresh water]		Mass	1.44E-07	1.59E-07	kg
Output	Nickel (+II) [Heavy metals to fresh water]		Mass	3.63E-06	4.00E-06	kg
Output	Solvent [Hazardous waste for recovery]		Mass	0.0849	0.0934	kg
Output	Waste for recovery (unspecific) [Waste for recovery]		Mass	7.97	8.76	kg
Output	Zinc (+II) [Heavy metals to fresh water]		Mass	4.80E-05	5.28E-05	kg

A.3 Transports

Table A-5: Transports used in GaBi models.

Material	Flow in GaBi	Process in GaBi	Database	In accordance with Goal and Scope	Comment
Heavy fuel oil, cargo ship from China	Heavy fuel oil [Crude oil products]	EU-15: Fuel oil heavy at refinery	ELCD/PE	No	No process for heavy fuel oil was found for China so European average was used.
Heavy fuel oil, cargo ship from US	Heavy fuel oil [Crude oil products]	US: Fuel oil heavy at refinery	PE	Yes	
Diesel, truck, EU	Diesel [Crude oil products]	EU-15: Diesel	ELCD/PE	Yes	
Diesel, truck, US	Diesel [Crude oil products]	US: Diesel	PE	Yes	

A.4 Well-to-Wheel Calculations

Calculated fuel consumption for hybrid drive mode for distribution truck, 15% fuel reduction:

$$F_c^H = F_c^C \times (1 - F_s^H) = 0.38 \times (1 - 0.15) = 0.323\ L/km$$
(eq.1)

Calculated fuel consumption for plug-in hybrid distribution vehicle, 20% fuel reduction:

$$F_c^P = \left[(D^D - \frac{E_{ch}}{E_c^D} \times B_{regen}) \times F_c^H\right]/D^D = \left[(254 - \frac{8.4}{1} \times 1.25) \times 0.323\right]/254 = 0.310\ L/km$$
(eq.2)

Where B_{regen} is the regenerative braking, 25% of the energy was assumed to be regenerated.

Calculated total electricity grid consumption for plug-in distribution vehicle:

$$Electricitygridconsumtion = \frac{FU^D}{D^D} \times E_{ch}/0.95 = \frac{1{,}000{,}000}{254} \times 8.4/0.95 \approx 34.8\ MWh/FU$$
(eq.3)