Carbon footprint report

Battery electric XC40 Recharge and the XC40 ICE

VOLVO

Contents

Appendix

Executive summary

In October 2019, Volvo Cars launched one of the most ambitious climate action plans in the automotive industry. It aims to reduce the lifecycle Carbon Footprint per average vehicle by 40 per cent between 2018 and 2025, as a first step towards becoming a climate neutral company by 2040. The plan represents concrete actions in line with the Paris Agreement[1] of 2015, which seeks to limit global temperature rise to 1.5 degrees Celsius above pre-industrial levels. Volvo Cars also committed to communicating improvements from concrete short-term actions in a trustworthy way, including the disclosure of the Carbon Footprint of all new models, starting with the XC40 Recharge – a battery electric vehicle (BEV).

This report covers the Carbon Footprints of the fully electric XC40 Recharge and an XC40 with an internal combustion engine (ICE) for comparison. The Carbon Footprints presented in this report includes emissions from upstream supplier activities, manufacturing and logistics, the use phase of the vehicle and the end-of-life phase. The functional unit chosen is “The use of a specific Volvo vehicle driving 200,000 km”.
The work was carried out during 2020 in collaboration with Polestar.

The Carbon Footprints presented in this report are based on a Life Cycle Assessment (LCA), performed according to the ISO LCA standards[2].

In addition, the “Product Life Cycle Accounting and Reporting Standard”[3] published by the Greenhouse Gas Protocol has been used as guidance in methodological choices. Given the great number of variables and possible methodological choices in LCA studies, these standards generally provide few strict requirements to be followed. Instead they mostly

---

[1] https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement

[2] ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines” and ISO 14040:2006 “Environmental management – Life cycle assessment – Principles and framework”

[3] https://ghgprotocol.org/sites/default/files/standards/Product-Life-Cycle-Accounting-Reporting-Standard_041613.pdf

provide guidelines for the practitioner. For this reason, care should be taken when comparing these results with results from other vehicle manufacturers' Carbon Footprints. In general, assumptions have been made in a conservative way, in order to not underestimate the impact from unknown data.

The LCA and the underlying methodology will be used as the metric for assessing the Carbon Footprint of Volvo Cars' vehicles. The assessment will be performed regularly and serve as a framework for measuring greenhouse gas (GHG) reduction related activities[4]. The methodology will be continuously developed and used to compile future Carbon Footprints for Volvo Cars vehicles.

According to the methodology described in this report the Carbon Footprint of a XC40 ICE is 58 tonnes CO_2e, whereas the footprint for the XC40 Recharge is between 27–54 tonnes CO_2e. The reason for the variation in the XC40 Recharge result is because different electricity mixes with varying carbon intensity in the use phase have been analysed. The size of the variation illustrates the impact of the choice of electricity mix on the result. *Figure i* shows a detailed breakdown of the Carbon Footprint for the XC40 Recharge and XC40 ICE, with different electricity mixes in the use phase used for the XC40 Recharge.

As the production of the XC40 Recharge's Li-ion battery has a relatively large Carbon Footprint and significant impact on the total Carbon Footprint of a vehicle, a separate Carbon Footprint study has been performed in collaboration with Volvo Cars' battery module suppliers. The Carbon Footprint from the rest of the BEV battery pack is included in the category "Materials production and refining".

The two main differences in the Carbon Footprint between the XC40 Recharge and the XC40 ICE appear in the categories "materials production and refining" (including the Li-ion battery modules) and

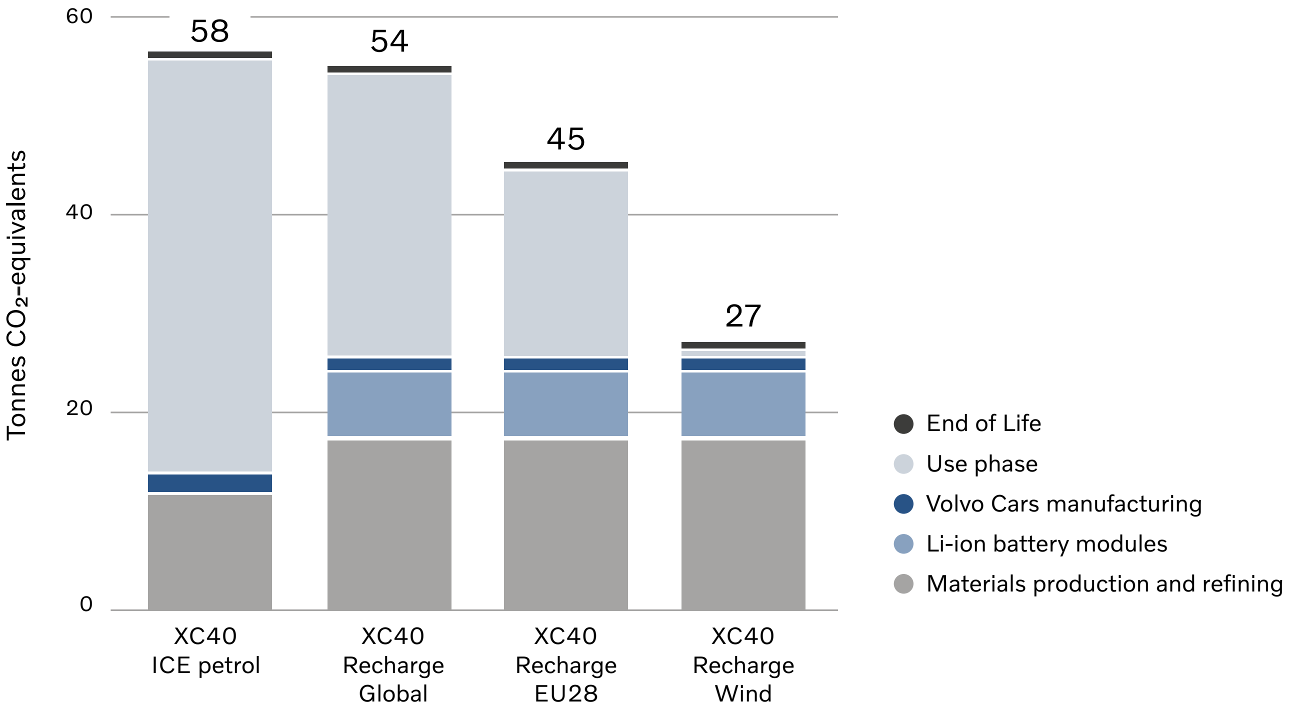


Figure i. *Carbon Footprint for XC40 ICE and XC40 Recharge, with different electricity-mixes in the use phase used for the XC40 Recharge. Results are shown in tonne* CO_2*-equivalents per functional unit (200 000 km lifetime range).*

---

[4] GHG emissions, e.g. carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) are measured in tonnes CO_2e, where e stands for equivalents.

"use phase". The emissions from Materials production and refining of the ICE are roughly 40 per cent less than for the BEV.

Under "Materials production and refining" the five main contributors for the XC40 ICE are aluminum (34 per cent), steel and iron (34 per cent), electronics (13 per cent), polymers (11 per cent) and fluids and undefined (4 per cent) – *see Figure 7* in the main report for more details. For the XC40 Recharge the main contributors to the Carbon Footprint of the material production (including Li-ion battery modules) are aluminum (30 per cent), Li-ion battery modules (28 per cent), steel and iron (18 per cent), electronics (9 per cent) and polymers (7 per cent) – *see Figure 8* in the main report for more details.

It should be noted that the Carbon Footprint measurement was performed to represent a globally sourced version of the models. Other methodological choices that have a large impact on the result are choice of allocation method regarding scrap, and choice of datasets for steel and aluminium production.

Total use phase greenhouse gas (GHG) emissions from the XC40 Recharge vary greatly depending on the carbon intensity of the electricity used. It should be noted that a BEV sold on a market with carbon-intensive electricity production can be charged with electricity from renewable energy. This would decrease the Carbon Footprint substantially. Furthermore, the results assume a constant carbon intensity throughout the vehicle lifetime.

Figure ii below shows the total GHG emissions, depending on kilometres driven, from the XC40 Recharge (with different electricity mixes in the use phase in the diagram), and the XC40 ICE (ICE in the diagram). Where the lines cross, the Carbon Footprint of the BEV becomes less than that of the ICE.

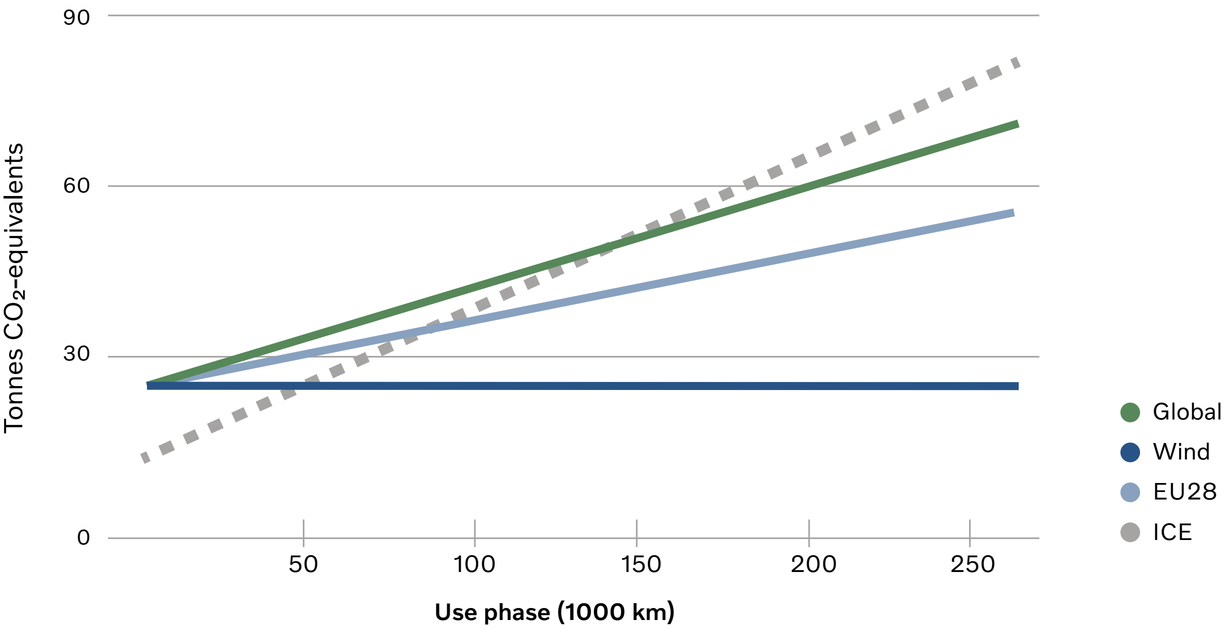


Figure ii. *Total cumulated amount of GHG emissions, depending on total kilometres driven, from XC40 ICE (ICE in the diagram, dashed line) and XC40 Recharge (with different electricity mixes in the use phase). Where the lines cross, break-even between the two vehicles occurs. The functional unit for the LCA is "The use of a specific Volvo vehicle driving 200 000 km". All life cycle phases except use phase are summarized and set as the starting point for each line at zero distance.*

Table i below shows the number of kilometres needed to be driven in order to reach break-even for the XC40 Recharge with different electricity mixes in the use phase compared to the XC40 ICE.

This report contains a general description of the LCA methodology (Chapter 1), a description of the methodological choices (Chapter 2) as well as some specific input data (Chapter 3) and results concerning the Carbon Footprint connected to the XC40 ICE and XC40 Recharge (Chapter 4). It also contains a discussion and interpretation of results (Chapter 5) and the main conclusions (Chapter 6).

	Break-even (km)
XC40 Recharge, Global Electricity Mix/XC40 ICE	146 000
XC40 Recharge, EU28 Electricity Mix/XC40 ICE	84 000
XC40 Recharge, Wind Electricity/XC40 ICE	47 000

Table i. *Number of kilometres driven at break-even between XC40 ICE (petrol) and XC40 Recharge with different electricity mixes in the use phase*

Key Findings

- The XC40 Recharge has a lower total Carbon Footprint than the XC40 ICE for all the analysed electricity mixes.
- The Carbon Footprint of a XC40 ICE is 58 tonnes CO_2e, while the footprint for the XC40 Recharge is 27–54 tonnes CO_2e. The reason for the variation in the XC40 Recharge result is due to different electricity mixes with varying carbon intensity in the use phase.
- When considering GHG emissions from the materials production and refining phase, producing an XC40 Recharge and its battery pack results in roughly 70 per cent more carbon emissions than producing an XC40 ICE.
- The production of the XC40 Recharge Li-ion battery has a relatively large Carbon Footprint and constitutes 10–30 per cent of the total Carbon Footprint, depending on the electricitymix in the use phase.
- Choice of methodology, for example inclusion of carbon emissions for scrap, has a significant impact on the total Carbon Footprint. Care should be taken when comparing results from this report with results from other vehicle manufacturers' Carbon Footprints.

Authors

Andrea Egeskog,
Sustainability Center, Volvo Cars

Karl-Henrik Hagdahl,
Sustainability Center at Volvo Cars

Christoffer Krewer,
Sustainability Center at Volvo Cars

Ingrid Råde,
Sustainability Center at Volvo Cars

Lisa Bolin,
Sustainability at Polestar

IVL Swedish Environmental Research Institute

Contacts

Andrea Egeskog,
Sustainability Center, Volvo Cars
andrea.egeskog@volvocars.com

Terms and definitions

BEV
Battery electric vehicle. A BEV is a type of electric vehicle that exclusively uses chemical energy stored in rechargeable battery packs, with no secondary source of propulsion.

Characterization
A calculation procedure in LCA where all emissions contributing to a certain impact category, e.g. greenhouse gases (GHGs) that contribute to global warming, are characterized into a single 'currency'. For global warming, the carbon footprint is often expressed as mass unit of CO_2e, where e is short for equivalents.

Cradle-to-gate
A cradle-to-gate assessment includes parts of the product's life cycle, i.e. from the cradle to the factory gate. It includes primary production of materials and the production of the studied product, but it excludes the use and end-of-life stages of the product. A supplier can provide a component, part or sub-assembly cradle-to-gate LCA to an OEM, for the OEM to include in the LCA of the OEM's product.

Cradle-to-grave
A cradle-to-grave assessment, compared to a cradle-to-gate assessment, also includes the use and end-of-life stages of the product, i.e. it covers the full life cycle of the product.

Dataset (LCI or LCIA dataset)
A dataset containing life cycle information of a specified product or other reference (e.g., site, process), covering descriptive metadata and quantitative life cycle inventory and/or life cycle impact assessment data, respectively. [6]

End of life
End of life means the end of a product's life cycle. Traditionally it includes waste collection and waste treatment, e.g. reuse, recycling, incineration, land-fill etc.

Functional unit
Quantified performance of a product system for use as a reference unit.

GaBi
GaBi is a LCA modelling software, provided by Sphera, and has been used for the modelling in this study.[7]

GHG
Green house gases. Green house gases are gases that contributes to global warming, e.g. carbon dioxide (CO_2), methane (CH_4), nitrous oxide/laughing gas (N_2O), but also freons/CFCs. Green house gases are often quantifed as mass unit of CO_2e, where e is short for equivalents. See characterization for further description.

ICE
Internal combustion engine. Sometimes used as a category when referring to a vehicle running with an ICE. An ICE vehicle uses exclusively chemical energy stored in a fuel, with no secondary source of propulsion.

Impact category
Class representing environmental aspects of concern to which life cycle inventory analysis results may be assigned.

---

[6] "The Shonan guidelines", https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2011%20-%20Global%20Guidance%20Principles.pdf
[7] GaBi, Sphera, http://www.gabi-software.com/sweden/index/

Life cycle
Consecutive and interlinked stages of a product system, from raw material acquisition or generation from natural resources to final disposal.

Life Cycle Assessment LCA
Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

LCA modelling software
LCA modelling software, e.g. GaBi, is used to perform LCA. It is used for modelling, managing internal databases, contains databases from database providers, calculate LCA results etc.

Life Cycle Inventory analysis LCI
Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle.

Life Cycle Impact Assessment LCIA
Phase of life cycle assessment aiming to understand and evaluate the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product.

Life cycle interpretation
Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations.

Process
Set of interrelated or interacting activities that transforms inputs into outputs. Processes can be divided into categories, depending on the output of the process, e.g. material, energy, transport or other service.

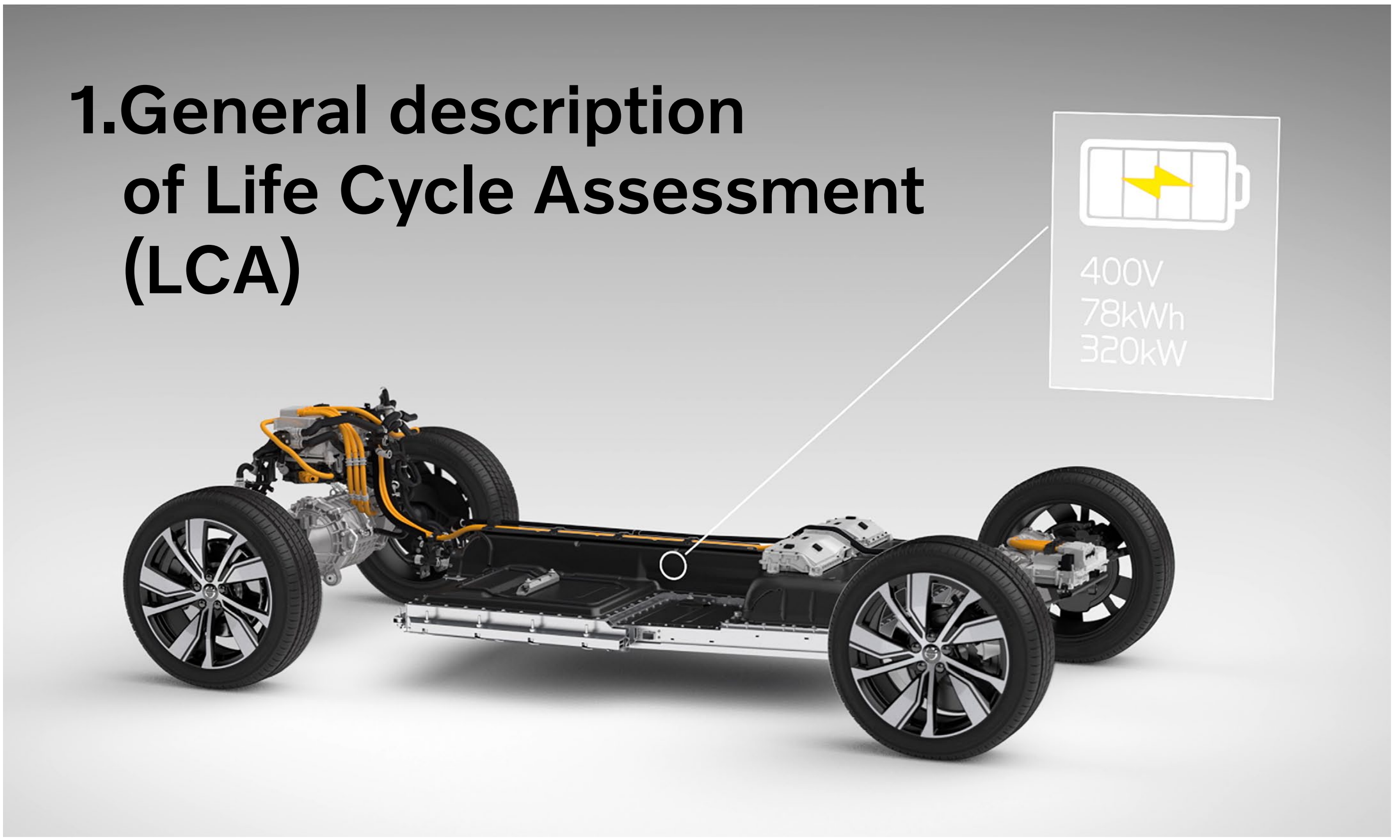
Raw material
Primary or secondary material that is used to produce a product.

Simple cut-off
The simple cut-off is a method for modeling recycling. It implies that each product is assigned the environmental burdens of the processes in the life cycle of that product. It means that using recycled material comes with the burdens from the collection and recycling of the material, which often are less than for production of primary material. At the same time no credits are given for recycling or creating recycled material. It is also called the recycled content approach and the 100/0 method.

System boundary
Set of criteria specifying which unit processes are part of a product system.

Waste
Substances or objects which the holder intends or is required to dispose of.

1.General description of Life Cycle Assessment (LCA)



1.1 Principles of LCA

The Life Cycle Assessment methodology (LCA) is used to determine which impacts a product or a service has on the environment, and The European Commission has concluded that Life Cycle Assessments provide the best framework for assessing the potential environmental impacts of products currently available.[8] The methodology was developed because there was a need to consider the whole life cycle of a product when examining environmental impacts, instead of just looking into one process at a time. A peril with focussing on only one process at a time is that a decrease in environmental impact in one area can lead to increased environmental impact in another. To prevent this phenomenon, known as sub-optimization, an LCA aims to include all processes from cradle to grave. However, an LCA is always a study of the environmental impacts from the processes inside the system boundary, defined in the goal and scope of the LCA. Therefore, it is important to remember that all environmental impacts, from a product or service, can never be considered.

In *Figure 1* the different stages of LCA are shown. First, the goal and scope of the LCA should be defined. The system boundaries must be clearly stated, since it has a direct impact on the result of the LCA. When the goal and scope are defined the inventory analysis can start. This is where data regarding all processes inside the system boundaries are gathered; these data can be presented in a report and are then called LCI (Life Cycle Inventory). In addition, in an LCA the data from the inventory analysis are further processed in the impact assessment phase, where different emissions (e.g. CO_2, SO_2, NO_x etc.) are sorted into different categories depending on what environmental impact they contribute to. These categories can be for example, global warming, acidification and

---

[8] Communication on Integrated Product Policy (COM (2003)302)

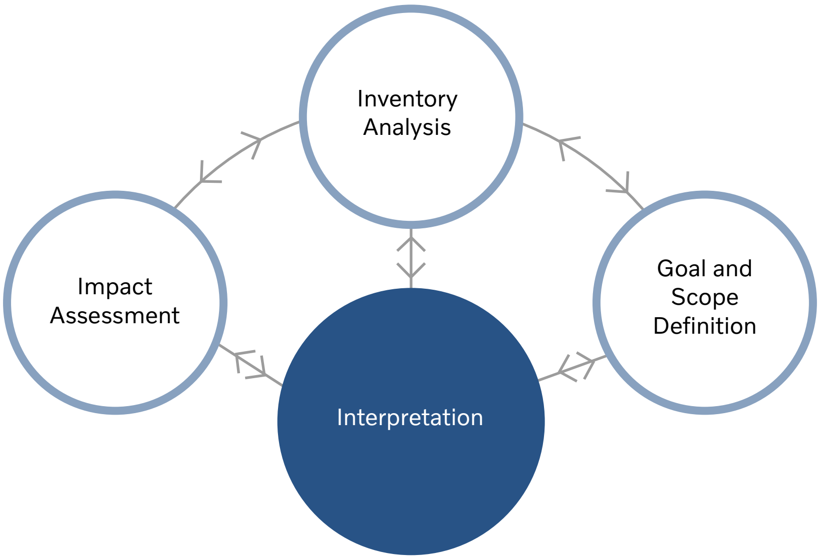


Figure 1. *Illustration of the general phases of a life-cycle assessment, as described by ISO 14040*

eutrophication. Through the impact assessment the total environmental impact of the studied system can be quantified. LCA is an iterative process where e.g. interpretation of the results might lead to a need to revisit goal and scope definition, inventory analysis or impact assessment, in order to create a final assessment that in the best way addresses the question that one wants to answer.

A fourth step may also be included in LCA, called weighting. In this step, results are further aggregated. The different environmental impacts are weighed against each other based on e.g. political goals, economical goals or the critical load of different substances in the environment. The LCA methodology undertaken for this study does not include weighting as only one impact category (climate change) is studied.

1.2 LCA standards

The methodology developed for this study estimates the Carbon Footprints for Volvo Cars vehicle models XC40 ICE (petrol) and XC40 Recharge (BEV). The only impact category is "global warming potential". The methodology can be further developed to include other environmental impacts, if needed.

The methodology follows the standards set by ISO 14044:2006 "Environmental management — Life cycle assessment — Requirements and guidelines" and ISO 14040:2006 "Environmental management – Life cycle assessment – Principles and framework"[2]. These standards differ from other standards that are commonly used by the vehicle industry, e.g. for testing or certification of the products, since they contain very few strict requirements. Instead they mostly provide guidelines for LCA including: definition of the goal and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment (LCIA) phase, the life cycle interpretation phase, reporting and critical review of the LCA, limitations of the LCA, relationship between the LCA phases and conditions for use of value choices and optional elements. The standards are valid for LCAs of all product and services, and do not provide detail enough to make LCAs of vehicles from different OEMs comparable.

> These standards differ from other standards commonly used by the vehicle industry, e.g. for testing or certification of the products, since they contain very few strict requirements

In addition to ISO 14044 the standard on "Product Life Cycle Accounting and Reporting Standard" published by the Greenhouse gas protocol[3] has been used for guidance in methodological choices.

2.Methodology

2.1 The products

Volvo Cars vehicles can be categorized as:

- **ICE** – Internal Combustion Engine
- **mHEV** – mild Hybrid Electric Vehicle
- **PHEV** – Plug-in Hybrid Electric Vehicle
- **BEV** – Battery Electric Vehicle

The methodology in this study was developed when performing LCAs of the vehicles XC40 ICE (petrol) and XC40 Recharge, which only covers the vehicle types ICE and BEV. However, the methodology can also be used to perform Carbon Footprints for PHEVs and mHEVs.
The studied vehicles are presented in *Table 1*.

Vehicles	Total weight	Li-ion battery modules weight (71–78kWh)
XC40 Recharge	2170	350
XC40 ICE	1690	-

Table 1. *Studied vehicles and their corresponding weight in kg*

2.2 Way of working overview

Figure 2 provides a high-level overview of how the work to obtain the Carbon Footprints of the vehicles is carried out. There are four main ways that data needed for the final LCA is retrieved. The import to GaBi (*see Terms and definitions*) is made in a specific mapping tool, provided by Sphera, called GaBi-DFX[9]. The input to GaBi comes from;

- IMDS[10] (International Material Data System) datasheets which contains information on material compositions of the components
- The LCA databases ecoinvent[11] 3.6 and GaBi LCA databases[12]
- Data from operations run by Volvo Cars, such as factories and logistics
- LCA of battery modules, performed by our battery suppliers with Volvo Cars and Polestar guidance and support

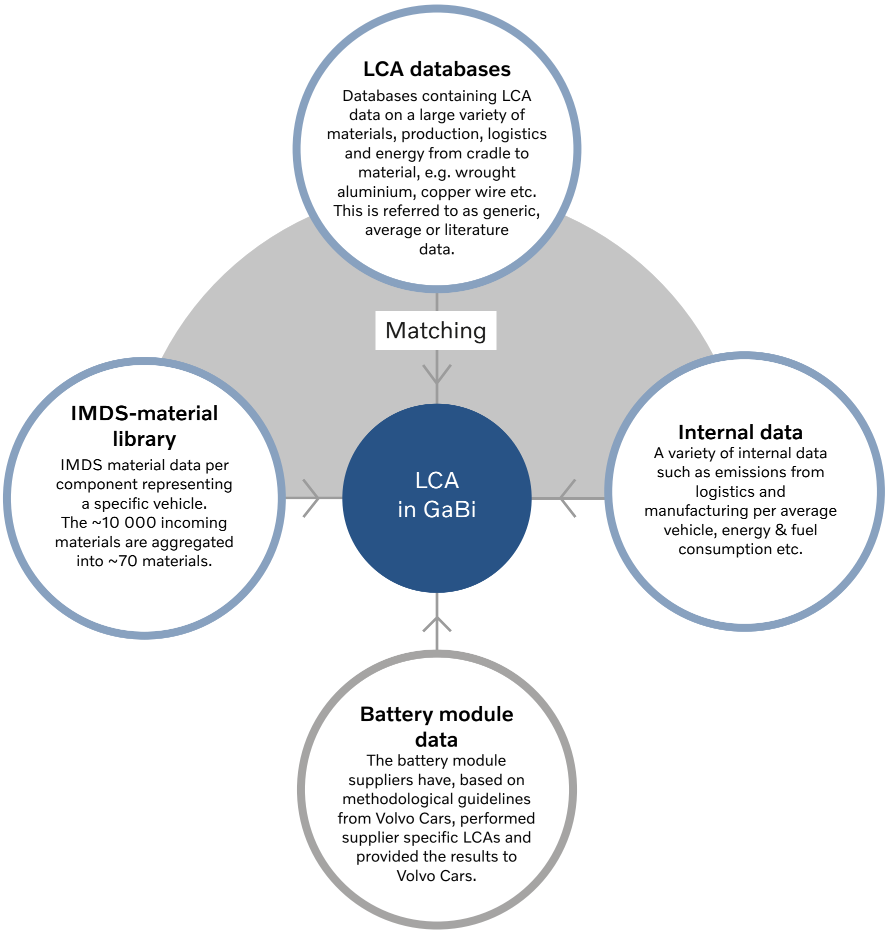


Figure 2. *Overview of LCA "way of working"*

---

[9] GaBi DfX, http://www.gabi-software.com/international/software/gabi-dfx/

[10] IMDS, www.mdsystem.com

[11] ecoinvent, www.ecoinvent.org

[12] GaBi LCA databases, http://www.gabi-software.com/databases/gabi-databases/

2.3 Methodology to define vehicle material composition

The Bill of Materials (BoM) is an important input to the LCA and consists of the parts used in the vehicle and their respective weights and materials composition. The part number vehicle BoM is extracted from Volvo Product data management system KDP. However, this BoM cannot be used as direct input to the LCA-model in GaBi but must be developed and aggregated in several steps into a suitable material BoM.

The material information, except for the Li-ion battery modules, comes from datasheets in IMDS. A complete vehicle in IMDS consists of about 10 000 different materials. To make the number of materials manageable in GaBi, they are aggregated to about 70 Volvo Cars defined material categories in a Volvo Cars developed materials library, Volvo IMDS ML.

The part number BoM from KDP is uploaded to Volvo Cars IMDS in-house system iPoint Compliance Agent (iPCA). In iPCA a materials BoM is generated that is imported into Volvo IMDS ML where all materials are mapped into the Volvo Cars defined material categories.

In order to have an effective and systematic approach, this mapping is automated. The rules to categorise the materials are determined by IMDS material category, material name and substance content. It is also possible to manually allocate materials in the Volvo IMDS ML, however, this is done as restrictively as possible. For these LCAs, Volvo IMDS ML release 5 is used with the material categories listed in *Table 2*. For the complete list of material categories, see "*Appendix 2 – complete list of Volvo Cars Material Library material categories*".

The BoM from Volvo IMDS ML must then be further formatted in order to be imported into GaBi. A formatting tool is used to apply the format required by GaBi and this step is also automated.

The import to GaBi is made in a specific mapping tool, provided by Sphera, called GaBi-DFX. In the mapping, each material is connected to a specific Life Cycle Inventory dataset and, if relevant, a manufacturing process dataset.

For the Li-ion battery modules, supplier specific Carbon Footprint data was used instead of IMDS data. The production of the Li-ion battery modules have a high impact on the result and consists of complex manufacturing steps. Also, the variety and accuracy of datasets available is limited for Li-ion batteries.

Material type	Number of material categories
Steel	5
Aluminium	1
Magnesium	1
Copper	2
Zinc	1
Lead, battery	1
Neodymium magnets	1
Polymers	About 40*
Natural materials	3
Ceramics & Glass	3
Electronics	1
Fluids	10
Undefined	1

** Including filled/unfilled*

Table 2. *Volvo Cars defined material categories in Volvo IMDS ML release 5*

2.4 Goal and scope definition

The goal of the methodology in this study is to be able to evaluate the Carbon Footprint of specific vehicle models. More specifically, the goal has been to develop a methodology that can be used to produce Carbon Footprints on complete vehicles to be communicated internally and externally. Another goal is to be able to use the complete vehicle Carbon Footprints to examine the effects of changes in e.g. material composition, efficiency of the vehicle or Volvo manufacturing, or changes in the energy systems.

This methodology follows an attributional approach and is developed considering exclusively the environmental impact global warming potential (GWP) and on the detail level of a complete vehicle.

2.4.1 System boundaries

The performed study is a life cycle assessment (LCA) for greenhouse-gas emissions only: a so-called Carbon Footprint.

Regarding the tail-pipe emissions from the ICE vehicles, only carbon dioxide emissions are included whereas methane and nitrous oxide emissions (CH_4 and N_2O) are excluded. CH_4 and N_2O contribute a minor fraction of total tailpipe GHG emissions from a petrol vehicle and exclusion of these emissions is not considered to influence the conclusions of this study.[14]

The study includes the vehicle life cycle from cradle-to-grave, starting at extracting and refining of raw materials and ends at the end-of-life of the vehicle, see *Figure 3*. Major assumptions, uncertainties and cut-offs are described under ”*2.4.5 Assumptions and Limitations*”.

The emissions from the life cycles of infra-structure have been included when it has been available in the LCA databases. No active data collection or modelling of infra-structure has been carried out in this study.

Generic data, as opposed to supplier specific data, has been used for most of the upstream processes, such as raw materials production and manufacturing processes. Thus, there are steps in some of the manufacturing value chains, specific to vehicle components, that might not be included. It is likely that these processes are assembly processes at Volvo cars Tier 1 suppliers. Although the contribution to the total Carbon Footprint from these processes are likely to be very small.

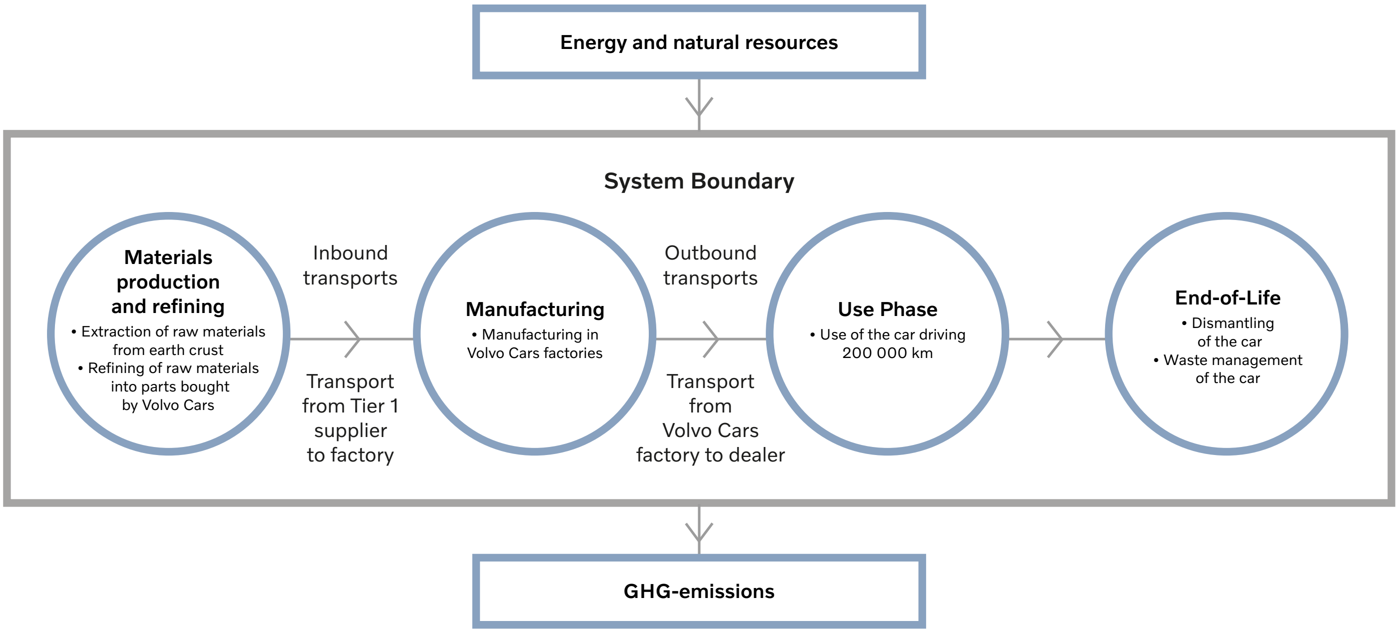


Figure 3. *Schematic description of the studied system and its different life cycle phases*

---

[14] Analysis of GaBi data for passenger car, EURO 6

The study is made with a global approach, which means that the generic datasets used for raw materials production and refining are not specific for any region. As far as possible global averages have been applied.

2.4.2 Function, functional unit and reference flows

The functional unit defines precisely what is being studied. It defines and quantifies the main function of the product under study, provides a reference to which the inputs and outputs can be related, and is the basis for comparing/analysing alternative goods or services.

The functional unit of this study is:

- The use of a specific Volvo vehicle driving 200 000 km

The results are being presented as kg CO_2-equivalents per functional unit.

2.4.3 Allocations

100% of total emissions from scrap has been allocated to the vehicles. That means that for example the produced amount of steel and aluminum included in the Carbon Footprint calculation does not only include the amount of material in the vehicle, but also the scrap produced in the whole manufacturing chain.

More specifically, the methodology uses the cut-off approach, which is the recommended method according to the EPD[15] system. This method follows the "polluters pay principle" meaning that if there are several product systems sharing the same material, the product causing the waste shall carry environmental impact. This means that the system boundary is specified to occur at the point of "lowest market value". However, if the material does not go to a new product system, the final disposal is included within the life cycle of the vehicle.

2.4.4 System expansion

No system expansion has been applied in this study i.e. no credits have been given for e.g. materials being recycled and offsetting other material production, or for energy generated in waste incineration offsetting other energy production.

2.4.5 Assumptions and Limitations

In general, assumptions have been made in a conservative fashion following the precautionary principle, in order to not underestimate the impact from unknown data. Additional processes have been added to the model when judged needed to more accurately represent actual emissions.

The inventory does not include:

- Volvo Cars processes such as business travels, R&D-activities or other indirect emissions
- Volvo Cars infrastructure e.g. the production and maintenance of buildings, inventories or other equipment used in the production
- Construction and maintenance of roads in the use phase
- Emissions from tires and road wear in the use phase
- Maintenance of the vehicles in the use phase

This study does not investigate changes, i.e. it is not consequential[16], nor take rebound effects into consideration.

Carbon Footprints developed using this methodology should not be broken down to lower levels, e.g. system or component level, without reassuring that an acceptable level of detail is also reached on the studied sub-system.

---

[15] https://www.environdec.com/The-International-EPD-System/General-Programme-Instructions/

[16] Consequential LCA, https://consequential-lca.org/clca/why-and-when/

3. Life cycle inventory analysis (LCI)

In this chapter all input data and methodological choices concerning the inventory is presented.

3.1 Material production and refining

Material production and refining (see Figure 3) are based on a BoM containing material composition and material weight. The BoM used for modelling in GaBi is specifically developed for LCA-modelling in GaBi and reports the composition of the vehicle based on about 70 material categories. The total weight of the vehicle is divided into these material categories.

In GaBi, each material has been coupled with one or several datasets (containing LCI-data) representing the production and refining of the material in each specific material category. *See Appendix 1 – Chosen datasets*.

Material production and refining are modelled using datasets from GaBi Professional database and ecoinvent 3.6 database, system model cut-off. The datasets have been chosen according to the Volvo Cars methodology for choosing generic datasets. For some raw materials there were no datasets for the exact materials and have been approximated by using datasets for similar materials.

The material content corresponding to the entire weight of the vehicle is included in the LCA, but for the different vehicles a small amount of materials have been categorized as undefined material in Volvo IMDS ML.

Vehicle model	Share of undefined material
XC40 ICE	1.5%
XC40 Recharge	2.0%

Table 3. *Share of undefined material in the different vehicles*

Table 3 shows the share of undefined material of the total vehicle weight (including battery modules) for each vehicle. Since the undefined category seems to contain mostly undefined polymers, a dataset for Polyamide (Nylon 6) has been used as approximation. This assumption is based on the fact that Polyamide is the polymer with the highest Carbon Footprint, out of the polymer data used in the LCA.

All filled polymers have been assumed to contain 81% polymer, 11% glass fibre and 8% talc representing an average of filled polymers as reported in IMDS.

In most cases datasets that include both production of raw material as well as component manufacturing ready to be assembled in the vehicle are not available. Therefore, several datasets representing the refining and production of parts have been used for most material categories. The datasets used to represent further refining and manufacturing of parts are listed in *Appendix 3 – Summary of data-choices and assumptions for component manufacturing*.

For most database datasets representing materials production and refining processes it has not been possible to modify the electricity, i.e. the built in electricity has been used.

3.1.1 Aluminium production and refining

The share of aluminium that is cast aluminium and wrought aluminium has been assumed to be 59% cast aluminium and 41% wrought aluminium. This is based on the report "Aluminium content in European passenger cars"[17]. All wrought aluminium has been assumed to go through the process of making aluminium sheets. The assumption of wrought aluminium being aluminium sheets is a conservative assumption, since sheet production has a higher amount of scrap than most other wrought processes. The cast aluminium goes through a process for die casting aluminium.

The scrap produced in the processes of making the aluminium parts for the vehicle is included in the Carbon Footprint, and since a cut-off is applied at the point of scrap being produced in the factory, the total footprint of producing the scrap is allocated to the vehicle even though the aluminium scrap is sent to recycling and used in other products. The material utilization rate for the manufacturing processes of both cast aluminium and wrought aluminium can be seen in *Appendix 3 – Summary of data-choices and assumptions for component manufacturing*.

3.1.2 Steel production and refining

The raw material dataset used for the material category "Unalloyed steel" has an output of rolled and galvanized steel. A manufacturing process was added to all steel. Which manufacturing process that was chosen depends on whether the steel is stamped by Volvo Cars or not. Hence, the steel categorised as unalloyed steel in the material library has been divided into two sub-groups depending on the manufacturing process following the rolling and galvanizing of the steel:

1. The steel that is processed and stamped in Volvo Cars factories. The Material Utilization Degree is according to Volvo Cars data.

2. The rest of the steel, which is distributed in various components of the car. The Material Utilization Degree is according to the chosen database dataset, i.e. literature value.

The scrap produced in the processes of making the steel parts for the car, independent of processes, is included in the Carbon Footprint, and the same cut-off as for aluminium is applied. The material utilization rate for the manufacturing processes of steel processed at Volvo Cars and steel processed at suppliers can be seen in *Appendix 3 – Summary of data-choices and assumptions for component manufacturing*.

3.1.3 Electronics production and refining

The material category "electronics" includes printed circuit boards (PCB) and the components mounted on them. It does not include chassis, cables or other parts that are present in electronic components. All materials that are used in electronic devices that are not PCBs have been sorted into other categories, such as copper or different types of polymers.

For the category "electronics" a generic data set from ecoinvent 3.6 has been used. This dataset represents the production of lead-free, mounted PCBs.

---

[17] https://www.european-aluminium.eu/media/2802/aluminum-content-in-european-cars_european-aluminium_public-summary_101019-1.pdf

3.1.4 Plastics production and refining

For polymer materials an injection moulding process has been used to represent the processing of plastic parts from a polymer raw material. The material utilization rate for the manufacturing processes of plastics can be seen in *Appendix 3 – Summary of data-choices and assumptions for component manufacturing*.

3.1.5 Minor material categories, production and refining

There are raw materials for which data on processing is missing in the LCA-databases. In those cases, the material weight was doubled as an estimation for the processing. This means that the manufacturing process is assumed to have the same Carbon Footprint as the production of the raw material itself. This has been applied only for minor materials (by weight).

3.1.6 Electricity use in materials production and refining

The electricity-mix used in the manufacturing processes in the supply chain is based on the locations of Volvo Cars production facilities. As a basis for calculation it is assumed that a large part of the materials in the vehicle are sourced on the same continent where the production takes place. Although the general methodology for choosing datasets takes on a global perspective where the sourcing region is not considered, an electricity mix that is based on the number of cars produced in each region for one year has been compiled to better represent reality. Hence, this electricity-mix is not specific for any vehicle model, but specific for the company on a global level. The number of produced cars in Volvo Cars factories in 2019 is presented in *Table 4*.

Based on these figures the supply chain manufacturing processes electricity mix consists of 69% EU-28 average electricity mix, 26% Chinese average electricity mix and 5% US average electricity mix. This electricity mix is only used for a few[18] partially aggregated processes in the GaBi databases where it is possible to add an electricity mix by choice.

Region	2019 produced vehicles	Share
Europe	484236	69 %
Asia	185640	26 %
Americas	35160	5 %
Total	**705036**	**100 %**

Table 4. *Produced Volvo vehicles in 2019*

3.2 Battery modules

A BEV battery pack consists of a carrier, battery management system, cooling system, busbars, cell modules, thermal barriers, manual service disconnect and a lid. Volvo Cars purchase cell modules from CATL and LG Chem, who, in collaboration with the report authors, performed cradle to gate (up until Volvo Cars logistics take over) Carbon Footprint LCAs of their cell modules. The cell modules have therefore been removed from the BoM based on IMDS data and modelled separately in the Complete Vehicle LCA.
All other parts of the battery pack are included in the materials BoM, based on IMDS data.

---

[18] The processes that use the special electricity mix are cast iron production, rubber vulcanization and five additional manufacturing processes.

3.3 Volvo Cars Manufacturing and logistics

3.3.1 Logistics

For GHG emissions from transports from Tier 1 suppliers to Volvo Cars manufacturing sites (inbound transport), the Volvo Cars total emissions from inbound transports divided by the total number of cars produced during the same year has been applied. In the same way, emissions from transports from Volvo Cars manufacturing sites to the dealer (outbound transport), have been compiled based on the Volvo Cars total emissions from outbound transports divided by the total number of cars sold during the same year. Network for transport measures[19] has been used as basis for the calculations.

3.3.2 Volvo Cars factories

GHG emissions from electricity usage, heat usage and use of different fuels in each of the factories was calculated using site-specific input data. The GHG emissions per vehicle was then calculated by dividing the total GHG emissions from the factory by the total amount of produced vehicles or engines from that factory during the same year.

XC40 ICE and XC40 Recharge are produced in both Luqiao and Ghent. For the XC40 ICE the emissions from the Volvo Cars manufacturing have been calculated in proportion to the number of cars produced in each factory during 2019. For XC40 Recharge the emissions from the Volvo Cars manufacturing has been calculated in proportion to the planned production during 2020.

3.4 Use phase

To be able to calculate the emissions in the use phase of the car, the distance driven is needed together with the tailpipe emissions per driven kilometer and the well to tank emissions from fuel and electricity production.

The vehicle driving distance for Volvo vehicles has been set to 200 000 km, which is also the functional unit in this study.

The fuel and energy related GHG emissions associated with the actual driving of the vehicle are divided into two categories:

- **Well-to-tank (WTT)** – Includes the environmental impact caused during production and distribution of the fuel or electricity used. The fuel used in the ICE is assumed to be gasoline blended with 5% ethanol, production related emissions from both fuels are included. Electricity production is modelled according to regional (global or EU28) grid mix or as specific energy source (wind)[20].
- **Tank-to-wheel (TTW)** – Includes the tailpipe emissions during use. This is zero for XC40 Recharge and assumed to be 163 g CO_2/km for the XC40 ICE (based on an average of our XC40 ICE petrol vehicles).

The TTW emission data for the XC40 ICE was based on the WLTP driving cycle (Worldwide Harmonized Light Vehicle Test Procedure used for certification of vehicles in EU). WLTP data was also used for obtaining energy consumption figures for the XC40 Recharge. Losses during charging are included in the electricity use of the BEVs. The electricity use for XC40 Recharge used in this study was 240 Wh/km (based on an average of our XC40 Recharge vehicles).

---

[19] https://www.transportmeasures.org/en/

[20] The data on WTT emission for electricity used in BEVs comes from the GaBi professional data base and can be chosen either as country grid mixes or for a specific energy source.

3.5 End-of-life of the vehicle

3.5.1 Process description

At their end of life, all vehicles are assumed to be collected and sent for end of life treatment.

The same methodology as described in chapter 2.4.3 Allocations is applied. Focusing on the point of lowest market value, according to the polluter pays principle, implies inclusion of steps like dismantling and pre-treatment (like shredding and specific component pre-treatment), but it does not include material separation, refining or any credit for reuse in another product system.

End of life was modelled to represent global average situations as far as possible. Handling consists of a disassembly step to remove hazardous components and components that are candidates for specific recycling efforts. After this the disassembled parts are treated, and the remaining vehicle is shredded. According to material type the resulting fractions go either to material recycling, incineration or landfill. *Figure 4* gives an overview of the entire phase.

In the disassembly stage hazardous and/or valuable components are removed from the vehicle including:

- Batteries
- Fuel
- Wheels, tyres
- Liquids:
  – coolants,
  – antifreeze,
  – brake fluid,
  – air-conditioning gas,
  – shock absorber fluid and
  – windscreen wash
- Oils:
  – engine,
  – gearbox,
  – transmission and
  – hydraulic oils
- oil filters
- catalytic converter
- Airbags and seat belt pretensioners removed or set off

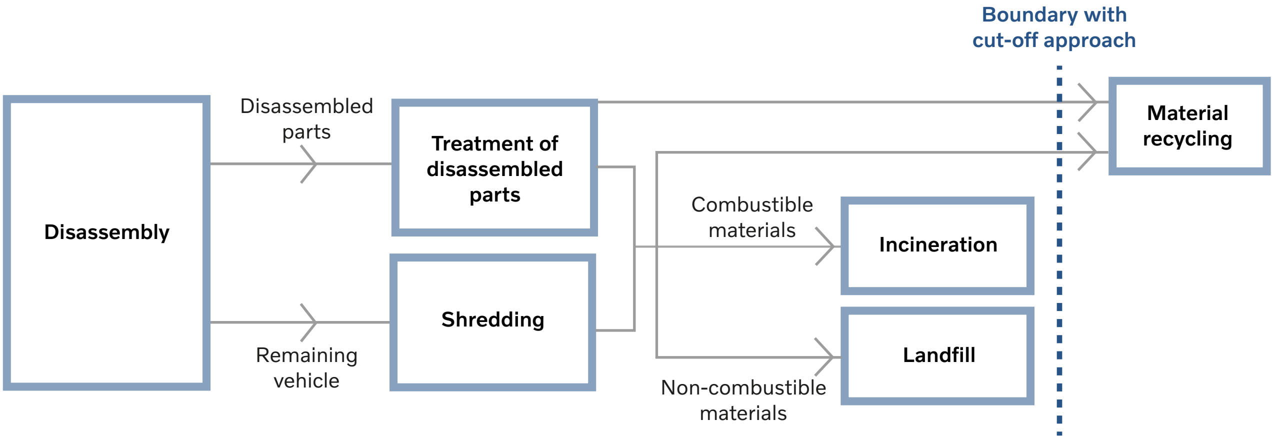


Figure 4. End of life system boundaries

In a global perspective the treatment of fuels, oils and coolant generally implies incineration. The tires are assumed to be salvaged for rubber recovery, and the lead batteries for lead recovery. The catalytic converter contains valuable metals and is disassembled for further recycling efforts. Oil filters are assumed to be incinerated, as are airbags and seat belt pretensioners, which are disassembled for safety reasons rather than the potential recycling value. The Li-ion battery is assumed to be taken out of the vehicle and sent to recycling.

All other parts of the vehicle are sent to shredding. In this process the materials in the vehicle are shredded and then divided into fractions depending on different physical and magnetic properties. Typical fractions are

- ferrous metals (steel, cast iron etc)
- non-ferrous metals (stainless steel, aluminium, copper, etc)
- shredder light fraction (plastics, ceramics etc)

The metal fractions can be sent for further refining and in the end material recycling. The combustible part of the light fraction can be incinerated for energy, or the entire fraction can end up in landfill. For the purpose of this study it is assumed the combustible streams of materials are incinerated, while the non-combustible materials are landfilled.

Due to the global focus, no energy recovery is included for the incineration steps, even though in some Volvo Cars markets, there is indeed energy recovery from incineration of waste. This somewhat conservative assumption has been made since there are many markets with no energy recovery, and data on how common the case with energy recovery is for the combustible streams is unknown. Assessment of material losses after shredding and in refining are outside the system boundaries set by the cut-off approach.

4. Results for XC40 ICE, XC40 Recharge

Functional unit: The use of a specific Volvo vehicle driving 200 000 km

4.1 XC40 Recharge compared to XC40 ICE (petrol)

In *Figure 5* and *Table 5* the results of the XC40 Recharge and XC40 ICE LCAs are presented in graphical and numerical terms. The choice of electricity mix in the use phase has a large impact on the total Carbon Footprint. With a global electricity mix, the XC40 Recharge gets a slightly smaller Carbon Footprint than the XC40 ICE, and with the wind power mix the reduction is more than 50% compared to the XC40 ICE.

Another interesting point to note regarding the Materials production and refining phase is that the XC40 Recharge has approximately 20% higher Carbon Footprint than the XC40 ICE, mainly due to the higher weight of the XC40 Recharge and larger share of aluminium and weight of electronics. The most significant addition, however, is the Li-ion battery. All in all, the carbon footprint of the materials production and refining category including the Li-ion battery increases by 70%. This increase is smaller than the decrease found in the use phase for all three electricity-mixes.

The results of the LCAs gives an interesting insight into a potential future shift of which life cycle phase is the most dominant. When comparing the XC40 Recharge driven with wind electricity to the XC40 ICE, dominance is shifted from the use phase to the production phase.

Volvo Cars manufacturing and end of life treatment only gives a small contribution to the life cycle.

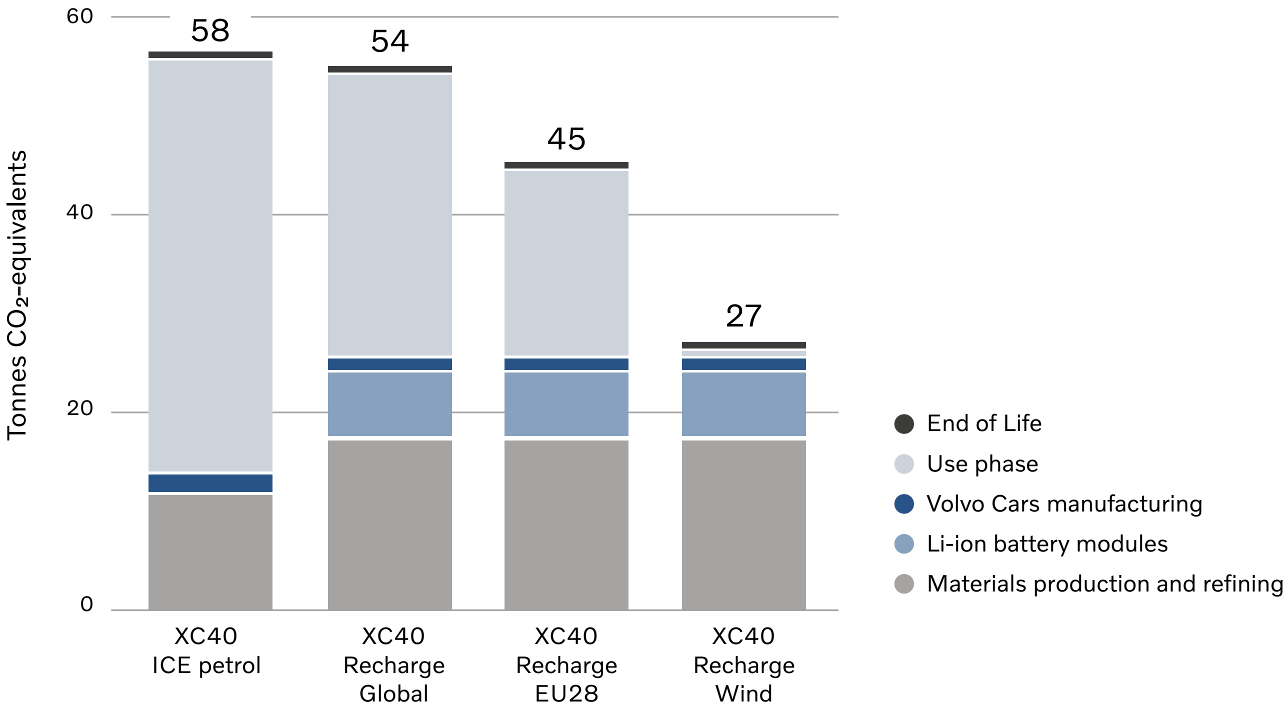


Figure 5. *Carbon Footprint for XC40 ICE and XC40 Recharge, with different electricity-mixes used for the XC40 Recharge. Results are shown in tonne CO_2-equivalents per functional unit*

Vehicle type	Materials production and refining	Li-ion battery modules	Volvo Cars manufacturing	Use phase emissions	End of Life	Total
XC40 ICE Petrol	14	-	2,1	41	0,6	**58**
XC40 Recharge Global	17	7	1,4	28	0,5	**54**
XC40 Recharge EU28	17	7	1,4	18	0,5	**45**
XC40 Recharge Wind	17	7	1,4	0,4	0,5	**27**

Table 5. *Carbon Footprint for XC40 ICE and XC40 Recharge, with different electricity-mixes used for the XC40 Recharge. Results are shown in tonne CO_2-equivalents per functional unit (rounded values).*

Figure 6 and *Table 6* highlight the break-even point that occurs when comparing the XC40 Recharge with the XC40 ICE. Because the XC40 ICE has a lower Carbon Footprint in the Materials production and refining phase it starts out having a lower Carbon Footprint than the XC40 Recharge, but as the vehicles are driven the cumulated Carbon Footprint increases more rapidly. At a certain driving distance, the vehicles break even and after this point the XC40 Recharge has a lower total life cycle Carbon Footprint. Where this break-even occurs depends on the difference in Carbon Footprint of the Materials production and refining phase, and how carbon-intense the electricity-mix is. For the three electricity mixes in the LCA the break-even occurs at 47 000, 84 000 and 146 000 km respectively. All within the assumed life cycle of the vehicle (200 000 km).

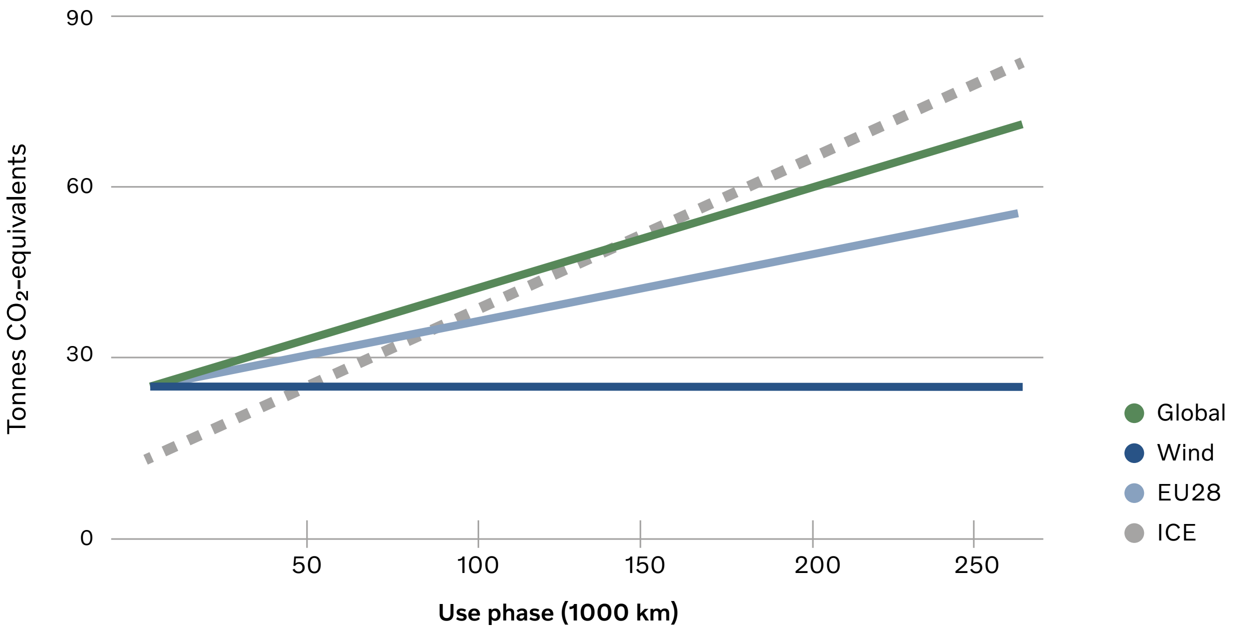


Figure 6. *Total cumulated amount of GHG emissions, depending on total kilometres driven, from XC40 ICE (ICE in the diagram) and XC40 Recharge (with different electricity mixes in the use phase). Where the lines cross, break-even between the two vehicles occurs. The functional unit for the LCA is "The use of a specific Volvo vehicle driving 200 000 km". All life cycle phases except use phase are summarized and set as the starting point for each line at zero distance.*

	Break-even (km)
XC40 Recharge, Global Electricity Mix/XC40 ICE	146 000
XC40 Recharge, EU28 Electricity Mix/XC40 ICE	84 000
XC40 Recharge, Wind Electricity/XC40 ICE	47 000

Table 6. *Number of kilometres driven at break-even between XC40 ICE (petrol) and XC40 Recharge with different electricity mixes*

Figure 7 and *Figure 8* give an insight into how different material groups contribute to the total Carbon Footprint of the Materials production and refining phase. Steel and aluminium give a significant contribution, especially for the XC40 ICE, but also for the XC40 Recharge. Electronics and polymers are also interesting to note as they contribute around 10% each for both vehicles (although out of different totals).

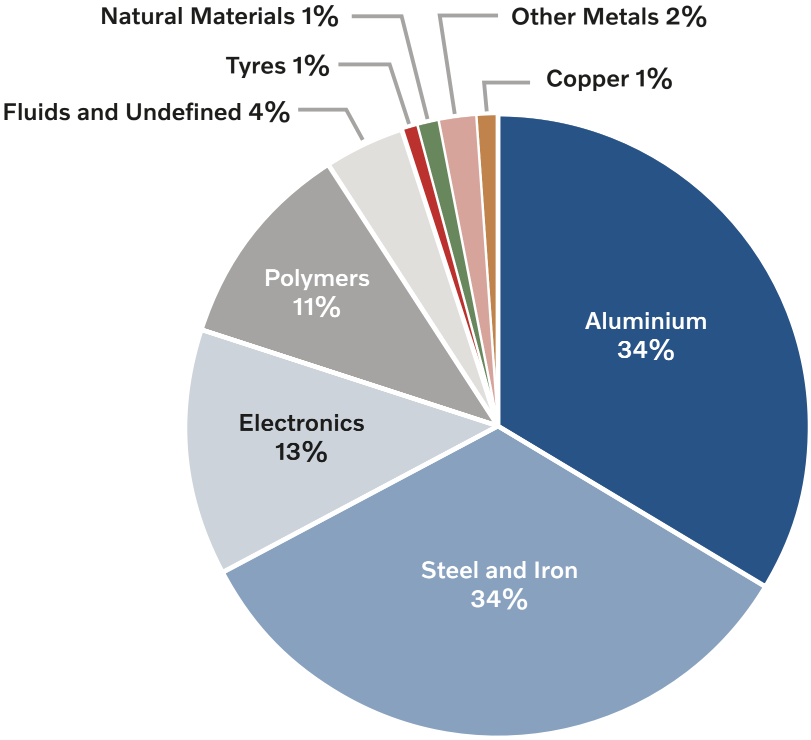


Figure 7. *Contribution from different material groups to the Carbon Footprint from "Materials production and refining" for XC40 ICE*

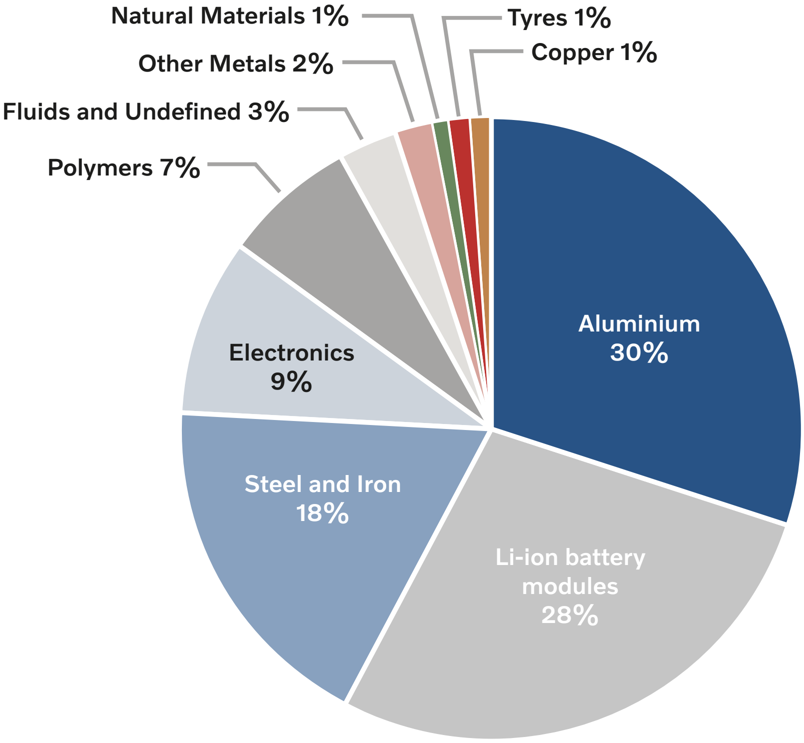


Figure 8. *Contribution from different material groups to the Carbon Footprint from "Materials production and refining, and the Li-ion battery modules" for XC40 Recharge*

5.Discussion

This LCA of the Carbon Footprint of an XC40 ICE and an XC40 Recharge gives insight into both the relative contribution to the Carbon Footprint from different life cycle phases (*see Figure 5*) as well as the underlying causes for the emissions. In turn, these insights can be used to guide efforts into understanding and reducing the emissions. The comparison between the XC40 Recharge and the XC40 ICE shows the differences and similarities between the ICE and the BEV technology, and the potential benefits of electrification.

Testing alternative electricity mixes for the XC40 Recharge in the use phase shows that the choice of electricity source in the use phase is a crucial factor in determining the total life cycle Carbon Footprint. As stated in Chapter 4, an XC40 Recharge run on wind power has only half the carbon footprint of an XC40 ICE. Forecasts for the global electricity market indicate the carbon intensity of electricity production will further decrease in all markets. This would mean there will be a continuous reduction of the BEVs Carbon Footprints even if no active choice of using renewable energy in the use phase is made.

The choice of electricity source in the use phase will also determine which life cycle phase dominates the result. When considering a global average electricity mix, the life cycle impact is split roughly 50/50 between the Materials production and refining stages and the use phase (*Table 5*). In contrast, a choice of wind-based electricity gives a life cycle carbon footprint that is significantly lower compared to driving with EU-28 or global mixes, and consequently the Materials production and refining phase dominates. This will shift the focus more to the Materials production and refining phase and further emphasize the importance of efforts to reduce the Carbon Footprint in this phase. Volvo Cars' strategy of aiming to reduce the Carbon Footprint from the Materials production and refining phase by 25% per average vehicle from 2018 to 2025 is an ambitious start towards achieving net zero Carbon Footprint emissions by 2040.

The choice of electricity source in the Materials production and refining phase also has an impact on the total Carbon Footprint, e.g. some metal production processes like electrical furnace are very energy intensive. However, changing electricity has not yet been tested due to the fact that many of the background data-sets are aggregated into 'black box' datasets, where modifying the electricity production is not possible.

When considering the Materials production and refining phase and comparing the result of the XC40 Recharge to the results of the XC40 ICE, the XC40 Recharge has a higher Carbon Footprint. This is mainly due to the addition of the Li-Ion battery. This increase in emissions is compensated for by a lower Carbon Footprint in the use phase, resulting in a total lower Carbon Footprint. Further improvements in the Materials production and refining phase will result in an even further reduced total Carbon Footprint.

The BEV driveline technology is still young compared to the ICE driveline implying a relatively higher potential of improvements. Recent studies have shown a general decrease in Carbon footprint of battery production over recent years, and it is a probable expectation that it will continue decreasing in the future. Other material-related improvements are also probable and beneficial, and since the ICEs and BEVs share many bulk materials (aluminum, steel, plastics) and electronic components the effects of these improvements will result more in a lower total Carbon Footprint of both vehicles, and less in an increase of the difference between them.

Production of steel and aluminum has a relatively large contribution to the total Carbon Footprint, accounting for roughly 20% of the total Carbon Footprint when a global energy mix is used in the use phase. The Li-ion battery modules account for almost 15% and electronics and plastics for almost 5% each. Thus, efforts to reduce the impact from these materials, for example with increased use of recycled content and more renewable energy in the production, is also an important part of reducing the Carbon Footprint.

> Volvo Cars' strategy of aiming to reduce the Carbon Footprint from the Materials production and refining phase by 25% per average vehicle from 2018 to 2025 is an ambitious start towards achieving net zero Carbon Footprint emissions by 2040.

As long as the XC40 Recharge has a higher Carbon Footprint from the Materials production and refining phase than the XC40 ICE, the question of break-even will remain. At what distance will GHG emissions from Materials production and refining be outweighed by lower emissions in the use phase? This study shows a break-even point of almost 50 000 km for the wind powered XC40 Recharge, significantly below the driving distance of 200 000 km used as the functional unit. When considering a global average electricity mix the break-even point is at about 146 000 km for XC40 Recharge, also below the 200 000 km. After the break-even points the global warming related benefits of the XC40 Recharge compared to the XC40 ICE continue to increase over the rest of the life cycle. This means that the longer the lifetime, the lower the Carbon Footprint of the XC40 Recharge compared to the XC40 ICE.

The choice of allocation method results in all GHG emissions from producing scrap being allocated to the vehicles. It also results in all GHG emissions from waste in the end of life treatment being allocated to the vehicles, even if the material is being recycled. This in turn results in a relatively high Carbon Footprint of the Volvo Cars vehicles compared to some other studies where production of material ending up as scrap in the manufacturing is excluded[21]. Furthermore, the metal production datasets that have been used are average data, and further investigation is needed to assess to what extent this data differs from Volvo Cars actual supply network. There are indications that Volvo Cars suppliers perform significantly better than the average global production in some cases, which is another indication that the results may be overestimated. This is in line with the conservative approach, i.e. to rather over-estimate rather than under-estimate the Carbon Footprints.

---

[21] E.g. GREET calculation modell, https://greet.es.anl.gov/

6.Conclusions

In this study Carbon Footprints of XC40 ICE and XC40 Recharge have been calculated, including all life cycle phases, i.e. Materials production and refining, Manufacturing, Use phase and End of life (*see Figure 5*).

Life Cycle Analysis (LCA), has been used, which has been identified by the EU Commission as the best framework for assessing the environmental performance of products has been used. LCA is well suited for assessing improvements in the whole life cycle and avoiding sub-optimization, i.e. decreasing the environmental impact in one step while increasing it in another step.

According to the methodology described in this report the Carbon Footprint of an XC40 ICE and XC40 Recharge is 58 tonnes CO_2e and 27–54 tonnes CO_2e respectively. The reason for the variation in the result of the XC40 Recharge is because different electricity mixes with varying carbon intensity in the use phase have been analysed. The size of the variation clearly shows the impact the choice of electricity mix has on the end result.

The XC40 Recharge, and BEVs in general, can have even lower Carbon Footprints in the near future because of potential improvements in e.g. battery technology, vehicle energy efficiency and in the energy systems.

The break-even analysis in the study, investigates at what driving distance the Carbon Footprints of the XC40 Recharge become less than the XC40 ICE based on alternate electricity mixes. It shows that all break-even points for the tested electricity mixes occur within the used driving distance of 200 000 km. After the break-even point the Carbon Footprint of the XC40 Recharge improves linearly compared to the XC40 ICE. The longer the lifetime the better the relative Carbon Footprint of the XC40 Recharge.

It should be noted that a BEV sold on a market with carbon intensive electricity production indeed can be charged with electricity from renewable energy, which would decrease the Carbon Footprint substantially. Furthermore, the results assume a constant carbon intensity within the alternate electricity mixes throughout the vehicle lifetime which is likely to overestimate the total Carbon Footprint.

LCA and the underlying methodology will be used as the metrics for assessing the Carbon Footprint of Volvo vehicles. LCAs will be performed regularly and serve as the framework for guiding the GHG reduction related activities, applying a product perspective. The methodology, practice, data collection procedures etc. will be continuously developed.

Appendix 1 – Chosen datasets

Material	Location	Name	Type	Source	Date used
ABS					
ABS	GLO	Market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
ABS (filled)					
ABS (filled)	GLO	Market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
ABS (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
ABS (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
ABS (unfilled)					
ABS (unfilled)	GLO	Market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
AdBlue					
AdBlue	EU-28	Urea (46% N)	agg	Fertilizers Europe	2020-04-20
AdBlue	EU-28	Tap water from surface water	agg	ts	2020-04-20
Aluminium, cast (matcat)					
Aluminium, cast (matcat)	GLO	Aluminium ingot mix IAI 2015	agg	IAI/ts	2020-04-20
Aluminium, wrought (matcat)					
Aluminium, wrought (matcat)	GLO	Aluminium ingot mix IAI 2015	agg	IAI/ts	2020-04-20
ASA					
ASA	GLO	Market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
ASA (filled)					
ASA (filled)	GLO	Market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
ASA (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
ASA (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
ASA (unfilled)					
ASA (unfilled)	GLO	Market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
Brake fluid					
Brake fluid	GLO	Market for diethylene glycol	agg	ecoinvent 3.6	2020-05-19
Cast iron (matcat)					
Cast iron (matcat)	DE	Cast iron part (automotive) – open energy inputs	p-agg	ts	2020-04-20
Catalytic coating					
Catalytic coating	ZA	Market for platinum group metal concentrate	agg	ecoinvent 3.6	2020-06-01

Material	Location	Name	Type	Source	Date used
Copper					
Copper	EU-28	Copper Wire Mix (Europe 2015)	agg	DKI/ECI	2020-04-20
Copper alloys					
Copper alloys	GLO	Copper mix (99,999% from electrolysis)	agg	ts	2020-04-20
Copper alloys	GLO	Market for zinc	agg	ecoinvent 3.6	2020-04-20
Cotton					
Cotton	GLO	Market for textile, woven cotton	agg	ecoinvent 3.6	2020-04-20
Damper					
Damper	RER	Polymethylmethacrylate sheet (PMMA)	agg	PlasticsEurope	2020-04-20
Damper	RoW	Market for lime	agg	ecoinvent 3.6	2020-04-20
Diesel					
Diesel	EU-28	Diesel mix at filling station	agg	ts	2020-04-20
E/P					
E/P	RoW	Polyethylene production, low density, granulate	agg	ecoinvent 3.6	2020-04-20
E/P (filled)					
E/P (filled)	RoW	Polyethylene production, low density, granulate	agg	ecoinvent 3.6	2020-04-20
E/P (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
E/P (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
E/P (unfilled)					
E/P (unfilled)	RoW	Polyethylene production, low density, granulate	agg	ecoinvent 3.6	2020-04-20
Electronics					
Electronics	GLO	Market for printed wiring board, surface mounted, unspecified, Pb containing	agg	ecoinvent 3.6	2020-05-26
EPDM					
EPDM	DE	Ethylene Propylene Diene Elastomer (EPDM)	agg	ts	2020-04-20
Epoxy					
Epoxy	RoW	Market for epoxy resin, liquid	agg	ecoinvent 3.6	2020-04-20
EVAC					
EVAC	RoW	Market for ethylene vinyl acetate copolymer	agg	ecoinvent 3.6	2020-04-20
EVAC (filled)					

Material	Location	Name	Type	Source	Date used
EVAC (filled)	RoW	Market for ethylene vinyl acetate copolymer	agg	ecoinvent 3.6	2020-04-20
EVAC (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
EVAC (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
EVAC (unfilled)					
EVAC (unfilled)	RoW	Market for ethylene vinyl acetate copolymer	agg	ecoinvent 3.6	2020-04-20
Ferrite magnet					
Ferrite magnet	GLO	Market for ferrite	agg	ecoinvent 3.6	2020-04-24
Filled Thermoplastics (matcat)					
Filled Thermoplastics (matcat)	RoW	Market for nylon 6	agg	ecoinvent 3.6	43941
Filled Thermoplastics (matcat)	EU-28	Talcum powder (filler)	agg	ts	43941
Filled Thermoplastics (matcat)	GLO	Market for glass fibre	agg	ecoinvent 3.6	43941
Float glass					
Float glass	EU-28	Float flat glass	agg	ts	2020-04-20
Glycol					
Glycol	EU-28	Ethylene glycol	agg	PlasticsEurope	2020-01-01
Lead, battery					
Lead, battery	DE	Lead (99,995%)	agg	ts	2020-04-20
Leather					
Leather	DE	Cattle hide, fresh, from slaughterhouse (economic allocation)	agg	ts	2020-04-20
Leather	DE	Leather (varnished; 1 sqm/0.95 kg) – open input cattle hide	p-agg	ts	2020-04-20
Lubricants (matcat)					
Lubricants (matcat)	EU-28	Lubricants at refinery	agg	ts	2020-04-20
Magnesium					
Magnesium	CN	Magnesium	agg	ts	2020-04-20
NdFeB					
NdFeB	GLO	Market for permanent magnet, electric passenger car motor	agg	ecoinvent 3.6	2020-04-24
NR					
NR	DE	Natural rubber (NR)	agg	ts	2020-04-20
PA					

Material	Location	Name	Type	Source	Date used
PA	RoW	Market for nylon 6	agg	ecoinvent 3.6	2020-04-20
PA (filled)					
PA (filled)	RoW	Market for nylon 6	agg	ecoinvent 3.6	2020-04-20
PA (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
PA (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
PA (unfilled)					
PA (unfilled)	RoW	Market for nylon 6	agg	ecoinvent 3.6	2020-04-20
PBT					
PBT	DE	Polybutylene Terephthalate Granulate (PBT) Mix	agg	ts	2020-04-20
PBT (filled)					
PBT (filled)	DE	Polybutylene Terephthalate Granulate (PBT) Mix	agg	ts	2020-04-20
PBT (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
PBT (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
PBT (unfilled)					
PBT (unfilled)	DE	Polybutylene Terephthalate Granulate (PBT) Mix	agg	ts	2020-04-20
PC					
PC	GLO	Market for polycarbonate	agg	ecoinvent 3.6	2020-04-20
PC (filled)					
PC (filled)	GLO	Market for polycarbonate	agg	ecoinvent 3.6	2020-04-20
PC (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
PC (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
PC (unfilled)					
PC (unfilled)	GLO	Market for polycarbonate	agg	ecoinvent 3.6	2020-04-20
PC+ABS					
PC+ABS	GLO	Market for polycarbonate	agg	ecoinvent 3.6	2020-04-20
PC+ABS	GLO	Market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
PC+ABS (filled)					
PC+ABS (filled)	GLO	Market for polycarbonate	agg	ecoinvent 3.6	2020-04-20
PC+ABS (filled)	GLO	Market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
PC+ABS (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
PC+ABS (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
PC+ABS (unfilled)					
PC+ABS (unfilled)	GLO	Market for polycarbonate	agg	ecoinvent 3.6	2020-04-20

Material	Location	Name	Type	Source	Date used
PC+ABS (unfilled)	GLO	Market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
PE					
PE	RoW	Polyethylene production, low density, granulate	agg	ecoinvent 3.6	2020-04-20
PE (filled)					
PE (filled)	RoW	Polyethylene production, low density, granulate	agg	ecoinvent 3.6	2020-04-20
PE (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
PE (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
PE (unfilled)					
PE (unfilled)	RoW	Polyethylene production, low density, granulate	agg	ecoinvent 3.6	2020-04-20
PET					
PET	GLO	Market for polyethylene terephthalate, granulate, amorphous	agg	ecoinvent 3.6	2020-04-20
PET (filled)					
PET (filled)	GLO	Market for polyethylene terephthalate, granulate, amorphous	agg	ecoinvent 3.6	2020-04-20
PET (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
PET (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
PET (unfilled)					
PET (unfilled)	GLO	Market for polyethylene terephthalate, granulate, amorphous	agg	ecoinvent 3.6	2020-04-20
Petrol					
Petrol	EU-28	Gasoline mix (regular) at refinery	agg	ts	2020-04-20
PMMA					
PMMA	RER	Polymethylmethacrylate sheet (PMMA)	agg	PlasticsEurope	2020-04-20
PMMA (filled)					
PMMA (filled)	RER	Polymethylmethacrylate sheet (PMMA)	agg	PlasticsEurope	2020-04-20
PMMA (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
PMMA (filled)	GLO	market for glass fibre	agg	ecoinvent 3.6	2020-04-20
PMMA (unfilled)					
PMMA (unfilled)	RER	Polymethylmethacrylate sheet (PMMA)	agg	PlasticsEurope	2020-04-20
Polyurethane (matcat)					

Material	Location	Name	Type	Source	Date used
Polyurethane (matcat)	RoW	Market for polyurethane, rigid foam	agg	ecoinvent 3.6	2020-04-20
POM					
POM	EU-28	Polyoxymethylene (POM)	agg	PlasticsEurope	2020-01-01
POM (filled)					
POM (filled)	EU-28	Polyoxymethylene (POM)	agg	PlasticsEurope	2020-01-01
POM (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
POM (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
POM (unfilled)					
POM (unfilled)	EU-28	Polyoxymethylene (POM)	agg	PlasticsEurope	2020-01-01
PP					
PP	GLO	Market for polypropylene, granulate	agg	ecoinvent 3.6	2020-04-20
PP (filled)					
PP (filled)	GLO	Market for polypropylene, granulate	agg	ecoinvent 3.6	2020-04-20
PP (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
PP (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
PP (unfilled)					
PP (unfilled)	GLO	Market for polypropylene, granulate	agg	ecoinvent 3.6	2020-04-20
PS					
PS	GLO	Market for polystyrene, general purpose	agg	ecoinvent 3.6	2020-04-20
PS (filled)					
PS (filled)	GLO	Market for polystyrene, general purpose	agg	ecoinvent 3.6	2020-04-20
PS (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
PS (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
PS (unfilled)					
PS (unfilled)	GLO	Market for polystyrene, general purpose	agg	ecoinvent 3.6	2020-04-20
PVB					
PVB	DE	Polyvinyl butyral granulate (PVB) by-product ethyl acetate	agg	ts	2020-04-20
PVB (filled)					
PVB (filled)	DE	Polyvinyl butyral granulate (PVB) by-product ethyl acetate	agg	ts	2020-04-20
PVB (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20

Material	Location	Name	Type	Source	Date used
PVB (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
PVB (unfilled)					
PVB (unfilled)	DE	Polyvinyl butyral granulate (PVB) by-product ethyl acetate	agg	ts	2020-04-20
PVC					
PVC	RoW	Polyvinylchloride production, suspension polymerisation	agg	ecoinvent 3.6	2020-04-20
PVC (filled)					
PVC (filled)	RoW	Polyvinylchloride production, suspension polymerisation	agg	ecoinvent 3.6	2020-04-20
PVC (filled)	EU-28	Talcum powder (filler)	agg	ts	2020-04-20
PVC (filled)	GLO	Market for glass fibre	agg	ecoinvent 3.6	2020-04-20
PVC (unfilled)					
PVC (unfilled)	RoW	Polyvinylchloride production, suspension polymerisation	agg	ecoinvent 3.6	2020-04-20
R-1234yf					
R-1234yf		R-123yf	u-so		43943
R-134a					
R-134a	GLO	Market for refrigerant R134a	agg	ecoinvent 3.6	2020-04-20
SBR					
SBR	DE	Styrene-butadiene rubber (S-SBR) mix	agg	ts	2020-04-20
Silicone rubber					
Silicone rubber	DE	Silicone rubber (RTV-2, condensation)	agg	ts	2020-04-20
Steel, Sintered					
Steel, Sintered	GLO	Steel hot dip galvanised	agg	Worldsteel	2020-04-20
Steel, Stainless, Austenitic					
Steel, Stainless, Austenitic	EU-28	Stainless steel cold rolled coil (304)	p-agg	Eurofer	2020-04-20
Steel, Stainless, Ferritic					
Steel, Stainless, Ferritic	EU-28	Stainless steel cold rolled coil (430)	p-agg	Eurofer	2020-04-20
Steel, Unalloyed					
Steel, Unalloyed	GLO	Steel hot dip galvanised	agg	Worldsteel	2020-04-20
Sulphuric acid					
Sulphuric acid	EU-28	Sulphuric acid (96%)	agg	ts	2020-04-20
Thermoplastic elastomers (matcat)					

Material	Location	Name	Type	Source	Date used
Thermoplastic elastomers (matcat)	DE	Polypropylene / Ethylene Propylene Diene Elastomer Granulate (PP/EPDM, TPE-O) Mix	agg	ts	43941
Thermoplastics (matcat)					
Thermoplastics (matcat)	RoW	Market for nylon 6	agg	ecoinvent 3.6	2020-04-20
Tyre					
Tyre	DE	Styrene-butadiene rubber (S-SBR) mix	agg	ts	43941
Tyre	EU-28	Water (deionised)	agg	ts	43941
Tyre	GLO	Vulcanisation of synthetic rubber (without additives)	u-so	ts	43831
Undefined					
Undefined	RoW	Market for nylon 6	agg	ecoinvent 3.6	43941
Unfilled Thermoplastics (matcat)					
Unfilled Thermoplastics (matcat)	DE	Polypropylene / Ethylene Propylene Diene Elastomer Granulate (PP/EPDM, TPE-O) Mix	agg	ts	43941
Washer fluid					
Washer fluid	DE	Ethanol	agg	ts	2020-04-20
Wood (paper, cellulose...)					
Wood (paper, cellulose...)	EU-28	Laminated veneer lumber (EN15804 A1-A3)	agg	ts	2020-04-20
Zinc					
Zinc	GLO	Special high grade zinc	p-agg	IZA	2020-04-20
Aluminium, manufacturing (DE, EU-28)					
	DE	Aluminium die-cast part	u-so	ts	2020-01-01
	EU-28	Aluminium sheet - open input aluminium rolling ingot	p-agg	ts	2020-04-20
	DE	Aluminium sheet deep drawing	u-so	ts	2020-01-01
Manufacturing (general assumption)					
		Manufacturing (general assumption)	u-so		2020-05-15
Manufacturing, Leather (general assumption)					
		Manufacturing, leather	u-so		2020-06-01
Polymers (all categories) manufacturing (GLO)					

Material	Location	Name	Type	Source	Date used
	DE	Plastic injection moulding part (unspecific)	u-so	ts	2019-02-01
Stainless steel manufacturing (DE)					
	DE	Steel sheet deep drawing (multi-level)	u-so	ts	2020-01-01
Steel unalloyed, manufacturing (DE, VCC data)					
	DE	Steel sheet deep drawing (multi-level)	u-so	ts	2020-01-01
		Steel manufacturing (VCC data)	u-so		2020-05-11

Appendix 2 – complete list of Volvo Cars Material Library material categories

Material name	Material group
Steel, Sintered	Steel and Iron
Steel, Unalloyed	Steel and Iron
Steel, Stainless, Austenitic	Steel and Iron
Steel, Stainless, Ferritic	Steel and Iron
Cast iron (matcat)	Steel and Iron
Aluminium, cast (matcat)	Aluminium
Aluminium, wrought (matcat)	Aluminium
Magnesium	Other Metals
Copper	Copper
Copper alloys	Copper
Zinc	Other Metals
Lead, battery	Other Metals
NdFeB	Other Metals
ABS (filled)	Polymers
ASA (filled)	Polymers
E/P (filled)	Polymers
EVAC (filled)	Polymers
PA (filled)	Polymers
PBT (filled)	Polymers

Material name	Material group
PC (filled)	Polymers
PC+ABS (filled)	Polymers
PE (filled)	Polymers
PET (filled)	Polymers
PMMA (filled)	Polymers
POM (filled)	Polymers
PP (filled)	Polymers
PVB (filled)	Polymers
PVC (filled)	Polymers
ABS (unfilled)	Polymers
ASA (unfilled)	Polymers
E/P (unfilled)	Polymers
EVAC (unfilled)	Polymers
PA (unfilled)	Polymers
PBT (unfilled)	Polymers
PC (unfilled)	Polymers
PC+ABS (unfilled)	Polymers
PE (unfilled)	Polymers
PET (unfilled)	Polymers

Material name	Material group
PMMA (unfilled)	Polymers
POM (unfilled)	Polymers
PP (unfilled)	Polymers
PVB (unfilled)	Polymers
PVC (unfilled)	Polymers
Thermoplastic elastomers (matcat)	Polymers
EPDM	Polymers
NR	Polymers
SBR	Polymers
Silicone rubber	Polymers
Tyre	Tyres
Epoxy	Polymers
Polyurethane (matcat)	Polymers
Damper	Polymers
Cotton	Natural Materials
Leather	Natural Materials
Wood (paper, cellulose ...)	Natural Materials
Catalytic coating	Glass

Material name	Material group
Ferrite magnet	Other Metals
Float glass	Glass
Anode*	
Cathode*	
Electronics	Electronics
Diesel	Fluids and Undefined
Petrol	Fluids and Undefined
Lubricants (matcat)	Fluids and Undefined
Brake fluid	Fluids and Undefined
Glycol	Fluids and Undefined
R-1234yf	Fluids and Undefined
R-134a	Fluids and Undefined
Sulphuric acid	Fluids and Undefined
Washer fluid	Fluids and Undefined
AdBlue	Fluids and Undefined
Separator, Li battery*	
Undefined	Fluids and Undefined

* Not used in any Carbon Footprint presented in this report, since the Li-ion battery is modelled separately.

Appendix 3 – Summary of data-choices and assumptions for component manufacturing

Material	Assumption on component manufacturing	Comment	Material utilization rate in additional component manufacturing
Cast iron	No extra manufacturing processes	The chosen dataset already includes the production of a finished part to be used in automotive applications	
Fluids	No extra manufacturing processes	Assumed that fluids do not need further refining after production of the raw material (the fluid itself)	
Tires	No extra manufacturing processes	Assumed that the processes after vulcanisation only has minor GHG-emissions	
Copper (wire)	No extra manufacturing processes	Assumed that processing after manufacturing into copper wire has negligible emissions and waste	
NdFeB magnets	No extra manufacturing processes	The chosen dataset already includes the production of a finished magnet to be used in electric motors for automotive applications	
Electronics (PCBs)	No extra manufacturing processes	The chosen dataset already includes the production of a finished printed circuit board	
Cast Aluminium	Die-casting process		96%
Wrought Aluminium	Rolling + Aluminium sheet deep drawing	Assumed to represent different types of wrought processes	62%
Steel (in parts, processed at suppliers)	Steel sheet deep drawing	Sheet is assumed in line with the conservative approach	63%
Steel (stamped in a Volvo factory)	Steel scrap generated at Volvo Cars factories	The steel scrap generated at stamping in the Volvo factories, that is the steel in workstream “vehicle structures”	Confidential
Stainless steel	Steel sheet deep drawing	Sheet is assumed in line with the conservative approach	63%
Polymers	Injection moulding process	Assumed to represent different types of processes	98%
Other materials	Raw material weight x2	Emissions from raw material production has been multiplied by two, to compensate for further refining and processing	50%

Appendix 4 – End-of-life assumptions and method

A4.1 Transport

Transportation of materials sent to material recycling is included and is assumed to be transported 1500 km by truck.

A4.2 Disassembly

The disassembly stage is globally still a mostly manual process. The energy consumption of this stage was therefore disregarded. As the weight of the disassembled parts are low, potential additional transport of these component was disregarded.

A4.3 Pre-treatment

Pre-treatment was included for the following disassembled components:

- Lead acid battery
- Catalytic converter (only ICE vehicles)
- Tyres
- Lithium ion batteries (only electric vehicles)

For the lead acid batteries, catalytic converter and tyres, ecoinvent datasets were used for the pre-treatment stage.

The lithium-ion battery is assumed to be transported 1500 km by truck to the recycling facility.

For the remaining disassembled parts, no inventory was made since their disassembly mainly is done as a safety precaution and they will after this be handled similarly to the rest of the vehicle. The fluids and oils that are incinerated likewise do not go through any pre-treatment.

A4.4 Shredding

In the shredding process the vehicles are milled to smaller fractions. This process uses electricity. In order to estimate the amount of energy needed the energy consumption per kg in the dataset “treatment of used glider,” passenger car, shredding from ecoinvent 3.6 was used. The electricity used for this process was modelled as Volvo Cars specific electricity grid mix as described in 3.1.6. Emissions of metals to water and air where omitted based on the scope focusing on climate change.

The entire vehicle except the parts sent for specific pre-treatment is sent through the shredding process. No additional transport is included as shredding is modelled as occurring at the same site as dismantling.

A4.5 Material recycling

This is the fate of the flows of metals from the shredding, as well as for the materials in the pre-treated components. Based on the choice of cut-off approach for end of life modelling, this stage is outside the boundaries of the life cycle and is not included in the inventory, except for the transportation to the material recycling, as mentioned above.

A4.6 Final disposal – incineration and landfill

The disassembled fluids and oils, as well as the combustible part of the shredder light fraction are modelled to be incinerated without energy recovery. The choice to not include energy recovery relates to the global scope of the LCA. To model the incineration of the waste oils an ecoinvent dataset for treatment of waste oil was used.

To model the emissions from the combustion of material from the shredder a dataset for incineration of mixed plastics where used, based on the main content of the flow going to this stage. The main part of the weight will be from the plastics in the vehicle. The dataset chosen was a Thinkstep dataset of EU-28 incineration of mixed plastic.

Non-combustible materials, like ceramics and glass are a small part of the vehicle but make up the part of the shredder light fraction that cannot be combusted. This flow is either landfilled or recycled as filler material, both cases modelled with a dataset for landfilling of glass/inert matter, from Thinkstep.

Transportation of materials which are separated in the shredding processes and which are assumed to be recycled is estimated to 1500 km by truck.

A4.7 Data collection

This section provides an overview of the data collection activities relating to each life cycle stage. For a full list of datasets *see Appendix 2 – Chosen datasets*.

According to the cut-off methodology, the processes presented in *Table 8* are included in the data collection effort.

Disassembly stage	Pre-processing stage	Final disposal
Batteries	Separate handling. Lead recovery from lead acid and designated Li-ion battery dismantling	According to material category*
Fuel		Incineration
Tyres	Pre-treatment for tyre recycling	None (sent to material recycling)
Liquids (coolants, brake fluid etc)		Incineration
Oils (engine, gearbox etc)		Incineration
Oil filters		Incineration
Catalytic converter	Pre-treatment to allow extraction of precious metals	None (sent to material recycling)
Airbags and seat belt pretensioners	Disarming of explosives. Shredding	None (sent to material recycling)
Rest of vehicle	Shredding	According to material category*

**Metals to material recycling, combustible material to incineration (mainly plastics) and residue to landfill*

Table 8. *Processes included in the data collection effort for End of Life*

VOLVO