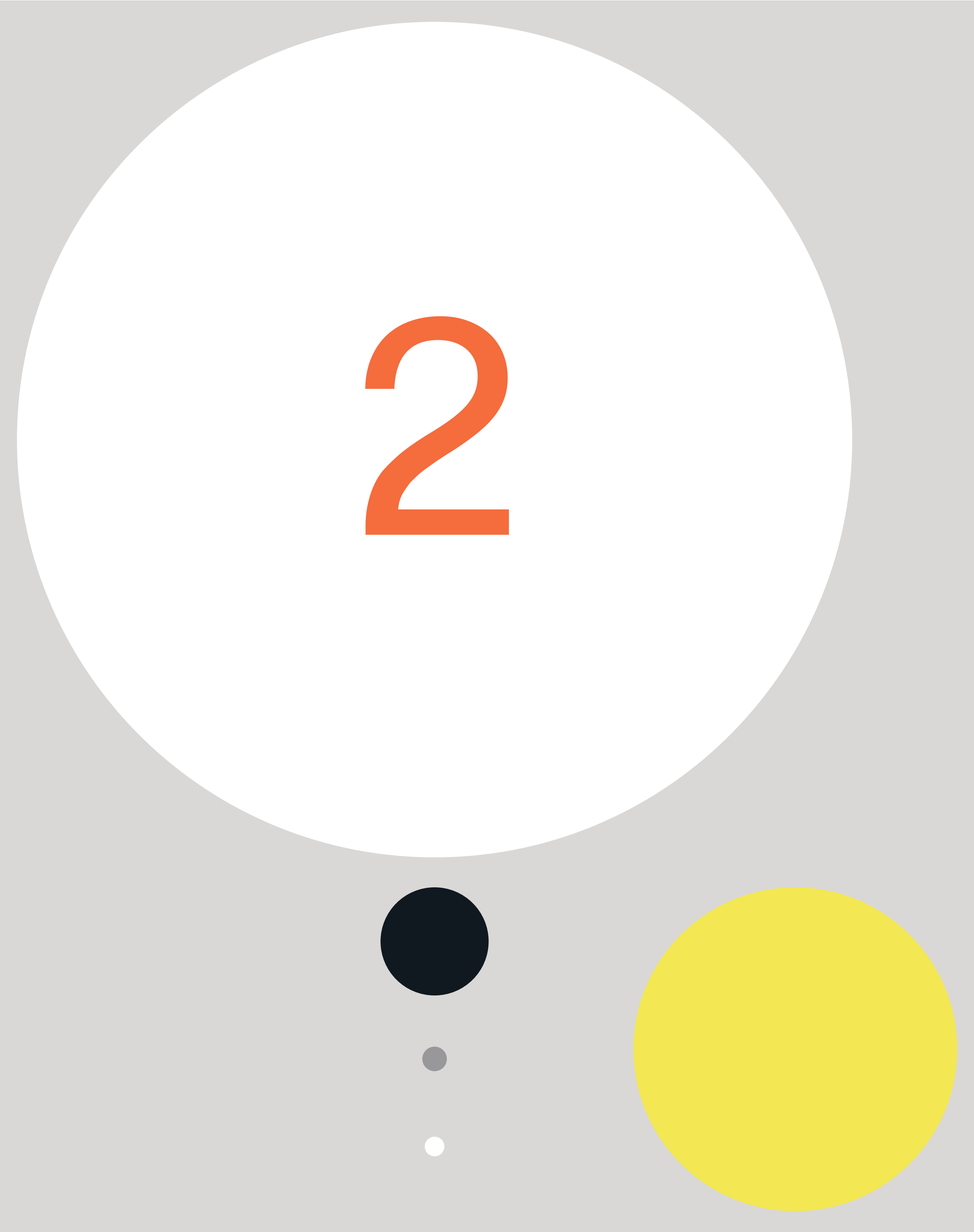
Polestar

Life cycle assessment

Carbon footprint of Polestar 2



Disclaimer

This report is informational only and (1) is based solely on an analysis of Polestar 2 (model year 2020) and Volvo XC40 petrol internal combustion engine (model year 2020) and does not include information regarding any other Polestar or Volvo Cars vehicle and (2) does not create any commitment regarding current or future products or carbon footprint impacts.

Contents

Executive summary

The carbon footprint presented in this report is based on a Life Cycle Assessment (LCA), performed in this study according to ISO LCA standards[1]. In addition, the “Product Life Cycle Accounting and Reporting Standard”[2] published by the Greenhouse Gas Protocol has been used for 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 provide guidelines for the practitioner. For this reason, care should be taken when comparing our 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 Polestar’s cars. The calculation will be performed regularly and serve as a framework for measuring green house gas (GHG) reduction related activities. Major work has been put in to building the methodology. The methodology will be continuously developed and used to compile future carbon footprints for Polestar vehicles. The methodology will also be expanded to incorporate additional environmental impact categories. The work was carried out during 2020 as a collaboration between Polestar and Volvo Cars, and as a comparison a carbon footprint has also been determined for the Volvo Cars XC40 petrol internal combustion engine vehicle (XC40 ICE).

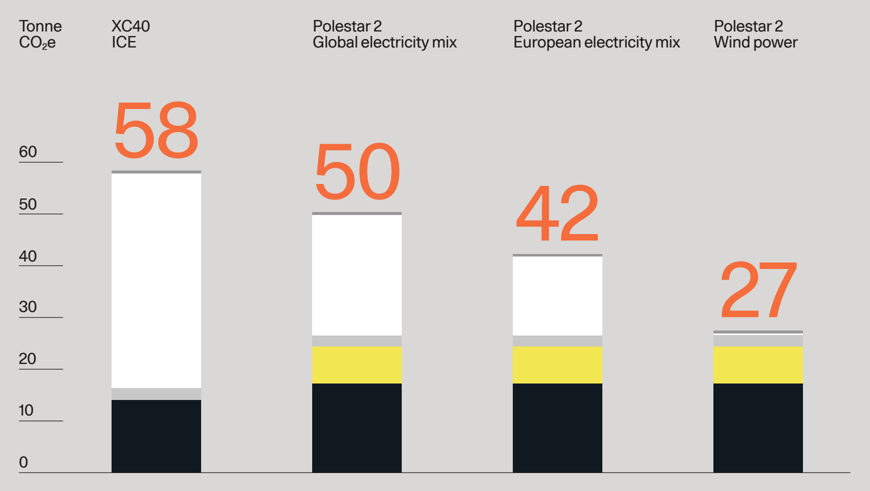


Figure 1

Carbon footprint for Polestar 2 and XC40 ICE, with different electricity mixes in the use phase used for Polestar 2. Results are shown in tonne CO_2-equivalents per functional unit (200,000 km lifetime range).

■ Materials production
■ Li-ion battery modules
■ Manufacturing
□ Use phase
■ End-of-life

The carbon footprint includes emissions from upstream supplier activities, manufacturing and logistics, use phase of the vehicle and the end-of-life phase. The functional unit chosen is “The use of a specific Polestar vehicle driving 200,000 km”.

As the production of the BEV’s Li-ion battery has a relatively large carbon footprint and contribution to the total carbon footprint of a vehicle, a separate carbon footprint study has been performed in collaboration with our battery module suppliers. The carbon footprint from the rest of the BEV battery pack is included in the “Materials production”.

The two main differences in the carbon footprint between the Polestar 2 and the ICE appear in the materials production (including the Li-ion battery modules) and the use phase. The carbon footprint from materials production (including the Li-ion battery modules) of the ICE is roughly 40% less than for Polestar 2. Looking at the category “Materials production” the five main contributors for the XC40 ICE are aluminum 34%, steel and iron 34%, electronics 13%, polymers 11% and fluids and undefined 4% (see Figure 10 for more details). For Polestar 2 the main contributors to the carbon footprint of the material production (including Li-ion battery modules) are aluminum 29%, Li-ion battery modules 29%, steel and iron 17%, electronics 10% and polymers 7% (see Figure 10 for more details).

It should be noted that the carbon footprint was performed to represent a globally sourced version of the car 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.

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

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

Total use phase GHG emissions from the Polestar 2 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 2 below shows the total of GHG emissions, depending on kilometres driven, from Polestar 2 (with different electricity mixes in the use phase in the diagram), and XC40 ICE (ICE in the diagram). Where the lines cross, break-even between the two vehicles occurs.

Table 1 below shows the number of kilometres needed to be driven in order to reach break-even for Polestar 2 with different electricity mixes in the use phase compared to XC40 ICE.

Figure 2

Total amount of GHG emissions, depending on kilometres driven, from Polestar 2 (with different electricity mixes in the use phase in the diagram), and XC40 ICE. All life cycle phases except use phase are summarised and set as the starting point for each line at “LCA excluding use”.

- 🟧 XC40 ICE
- 🟨 Polestar 2 – global electricity mix
- 🟦 Polestar 2 – european (EU28) electricity mix
- 🟫 Polestar 2 – wind power

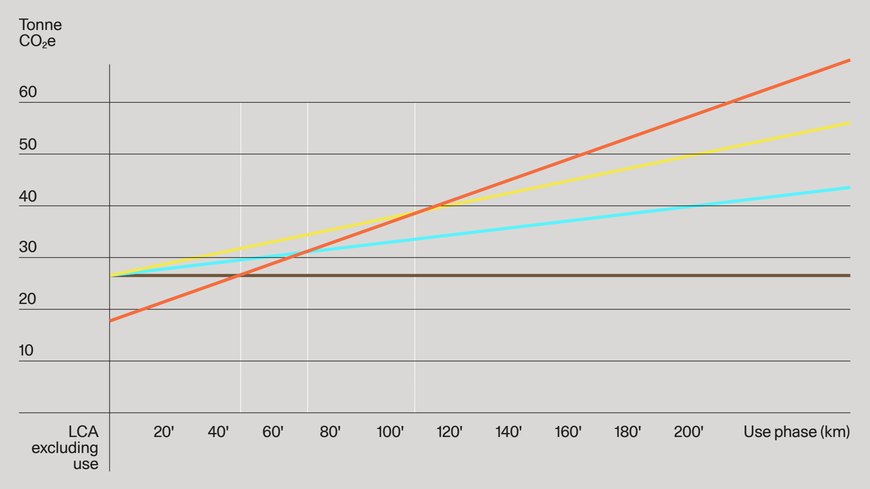

Table 1

Number of kilometres driven at break-even between Polestar 2 with different electricity mixes and XC40 ICE.

Electric mix	Break-even (km)
Polestar 2 – global electricity mix / XC40 ICE	112 000
Polestar 2 – european (EU28) electricity mix / XC40 ICE	78 000
Polestar 2 – wind power / XC40 ICE	50 000

The two stages “Manufacturing” and “End-of-life” are similar for the BEV and ICE and constitute very small fractions of the Carbon Footprints compared to the materials production and use phase.

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 Polestar 2 and the XC40 ICE (Chapter 4). It also contains a discussion and interpretation of results (Chapter 5) and the main conclusions (Chapter 6).

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Terms and definitions

BEV

Battery Electric Vehicle. A BEV is a type of electric vehicle (EV) that exclusively uses chemical energy stored in rechargeable battery packs, with no secondary source of propulsion.[3]

Characterisation

A calculation procedure in LCA where all emissions contributing to a certain impact category, e.g. GHGs that contribute to global warming, are characterised 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

An assessment that includes part of the product's life cycle, including material acquisition through the production of the studied product and excluding the use or end-of-life stages. However, for a component that is to be assembled in a product, a cradle-to-gate assessment can be carried out that covers the production of the component and parts of the logistics chain to the producer that assembles the component into a product.

Cradle-to-grave

A cradle-to-grave assessment considers impacts at each stage of the product's life cycle, from the time natural resources are extracted from the ground and processed through each subsequent stage of manufacturing, transportation, product use, recycling, and ultimately, disposal. [4]

Cut-off criteria

Specification of the amount of material or energy flow, or the level of environmental significance, associated with unit processes or product systems to be excluded from a study.[4]

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.[5]

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, landfill, etc.

Functional unit

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

GaBi

GaBi is LCA modelling software, provided by Sphera, which has been used for the modelling in this study.[5]

GHG

Greenhouse gases. Greenhouse gases are gases that contribute to global warming, e.g. carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), as well as freons/CFCs. Greenhouse gases are often quantifed as a mass unit of CO_2e, where e is short for equivalents. See characterisation 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.

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.

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[3] Wikipedia, battery electric vehicle, https://en.wikipedia.org/wiki/Battery_electric_vehicle

[4] "The Shonan guidelines", https://www.lifecycleinitiative.org/wp-content/uploads/2012/12/2011%20-%20Global%20Guidance%20Principles.pdf

[5] GaBi, Sphera, http://www.gabi-software.com/sweden/index/

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

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.

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

Scrap
1) A small piece or amount of something, especially one that is left over after the greater part has been used. 2) Discarded metal for reprocessing.

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 LCAs provide the best framework for assessing the potential environmental impacts of products currently available. The methodology evolved 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. When only dealing with one process at a time, the improvement in one area might lead to increased environmental impact in another. To prevent this phenomenon, known as sub-optimisation, an LCA aim is 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 study. Therefore, it is important to remember that all environmental impacts, from a product or service, can never be considered.

In Figure 3 the different stages of LCA are shown. First, the goal and scope of the study should be defined. The system boundaries must be clearly stated, since it has a direct impact on the result of the study. 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. This data can then be presented in a report and is referred to as Life Cycle Inventory (LCI). In addition, in an LCA the data from the inventory analysis is further processed in the impact assessment phase, where the 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 eutrophication. Through the impact assessment the total environmental impact of the studied system can be evaluated. 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.

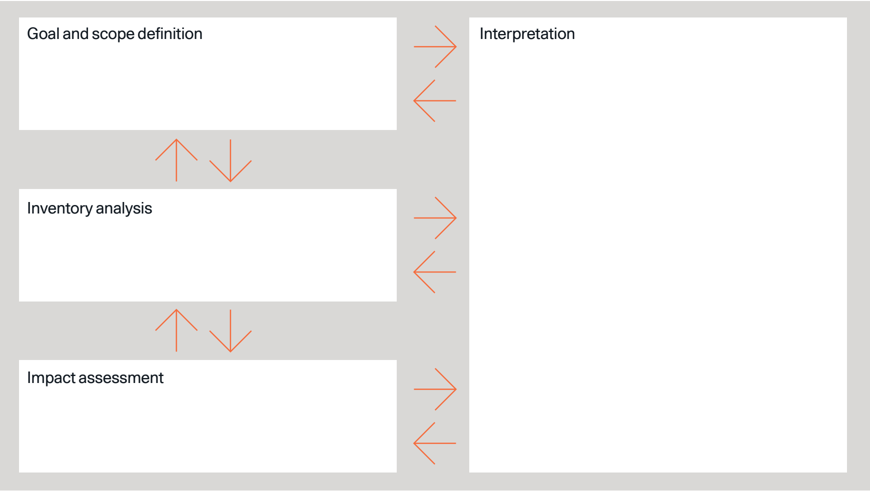


Figure 3

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

Sometimes a fourth step is included in LCA, called weighting. This is a step where the result is aggregated even more. 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. In the Polestar LCA methodology weighting is not included as only one impact category is studied.

1.2 LCA standards

This methodology is developed in order to produce Carbon Footprints for Polestar and Volvo Cars vehicle models Polestar 2 and XC40 ICE (petrol). Therefore, only the impact category “global warming potential” is used here. If there is a need to assess other environmental effects, the methodology can be further developed to include those impacts.

The methodology follows the ISO 14044:2006 “Environmental management – Life cycle assessment – Requirements and guidelines” and ISO 14040:2006 “Environmental

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

management – Life cycle assessment – Principles and framework" standards. 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 products and services, and do not provide enough detail to make LCAs of vehicles from different OEMs comparable.

In addition to ISO 14044, the standard called "Product Life Cycle Accounting and Reporting Standard" published by the Greenhouse Gas Protocol has been used for guidance in methodological choices.

2 Methodology

2.1 The products

Polestar has developed one PHEV (Polestar 1) and one BEV (Polestar 2). 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 Polestar 2 and XC40 ICE (petrol), which only covers the BEV and ICE vehicle types. However, the methodology can also be used to perform carbon footprints for PHEVs and mHEVs.

The studied cars are presented in Table 2.

Table 2

Studied cars and their corresponding weight in kg.

Car	Total weight	Li-ion battery modules weight (71–78kWh)
Polestar 2	2110	350
XC40 ICE	1690	–

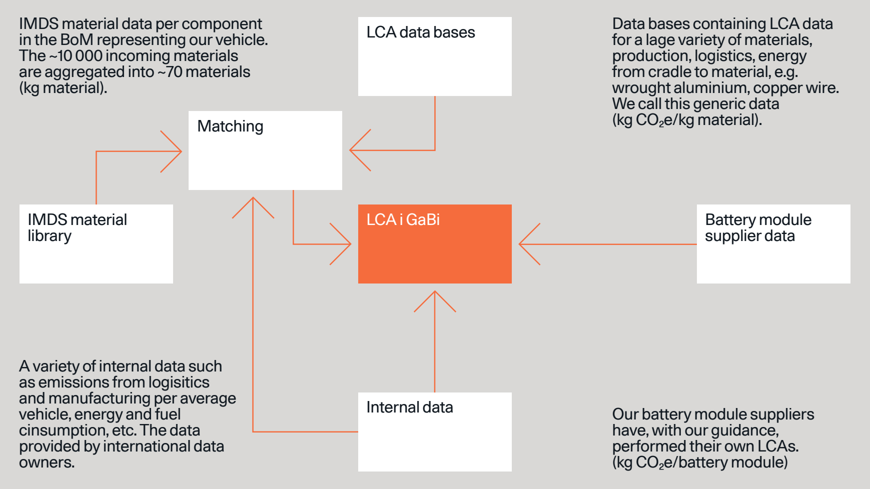
2.2 Way of working overview

Figure 4 shows a high-level overview of how Polestar works to obtain carbon footprints of vehicles. There are four main ways that data needed for the final LCA is retrieved. The import to GaBi (see Terms and definitions) is then made in a specific mapping tool, provided by Sphera, called GaBi-DFX[7]. The input to GaBi comes from:

- IMDS[8] (International Material Data System) datasheets which contain information on material compositions of the components
- the LCA databases ecoinvent[9] 3.6 and GaBi LCA databases[10]
- data from operations run by Polestar or Volvo Cars, such as factories and logistics
- LCA of battery modules, performed by our battery suppliers with Polestar's guidance and support

Figure 4

Overview of Polestar LCA way of working.



IMDS material data per component in the BoM representing our vehicle. The ~10 000 incoming materials are aggregated into ~70 materials (kg material).

Data bases containing LCA data for a lage variety of materials, production, logistics, energy from cradle to material, e.g. wrought aluminium, copper wire. We call this generic data (kg CO_2e/kg material).

A variety of internal data such as emissions from logisitics and manufacturing per average vehicle, energy and fuel cinsumption, etc. The data provided by international data owners.

Our battery module suppliers have, with our guidance, performed their own LCAs. (kg CO_2e/battery module)

2.3 Methodology to define vehicle material composition

The Bill of Materials (BoM) is an important component of 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 the 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 to a suitable material BoM.

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

[8] IMDS, www.mdsystem.com

[9] ecoinvent, www.ecoinvent.org

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

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 defined material categories in a materials library developed by Volvo Cars (IMDS ML).

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

In order to have an effective and systematic approach, this mapping is done in an automated way. The rules to categorise the materials are set up based on IMDS material category, material name and substance content. It is also possible to manually allocate materials in the IMDS ML, however, this is done in the most restrictive way possible. For these LCAs, IMDS ML release 5 is used with the material categories listed in Table 3 For the complete list of material categories, see "Appendix 3 – complete list of IDMS Material Library material categories".

Table 3

Polestar defined material categories in IMDS ML release 5.

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 (including filled/unfilled)
Natural materials	3
Ceramics and glass	3
Electronics	1
Fluids	10
Undefined	1

The materials BoM from 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, this step is also automized.

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, specific supplier carbon footprint data was used instead of IMDS data (see Figure 4). The production of the Li-ion battery modules has a high impact on the result and consists of complex manufacturing steps.[11] Also, the variety and accuracy of datasets available is limited for Li-ion batteries.

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 Polestar and Volvo Cars 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 Polestar manufacturing, or changes in the energy systems.

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

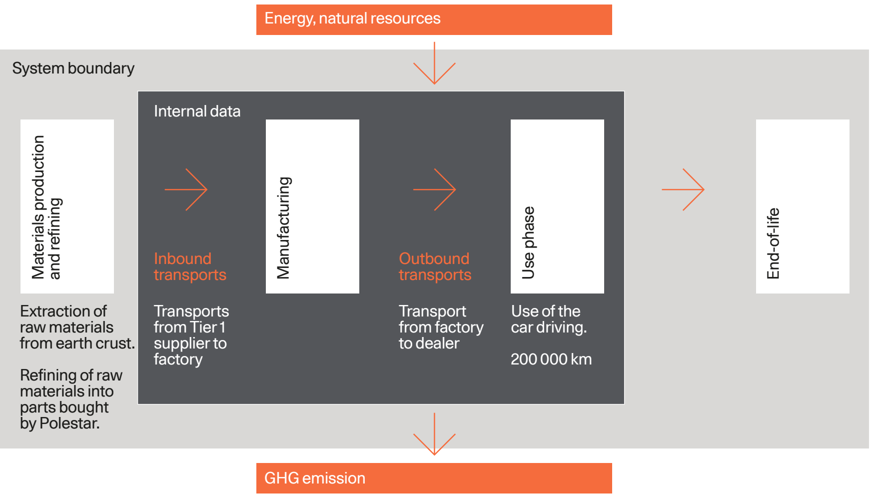
[11] Dai et al., 2019

2.4.1 System boundaries

The performed study is a Life Cycle Assessment (LCA), but is only considering GHG emissions, a so-called carbon footprint. However, for the tail-pipe emissions from the ICE vehicles, only carbon dioxide emissions are included and methane and nitrous oxide emissions (CH_4 and N2O) are not included. CH_4 and N_2O contribute to only a minor fraction of the total tailpipe GHG emissions from a petrol car and exclusion of these emissions is not considered to influence the conclusions of this study.[12]

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 5). Major assumptions, uncertainties and cut-offs are described under "2.4.5 Assumptions and limitations".

Figure 5



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

The inventory does not include any processes such as business travel, R&D activities or other indirect emissions. Nor does it include infrastructure e.g. the production and maintenance of buildings, inventories or other equipment used in the production, construction and maintenance of roads or electricity grids. Emissions from tires and road wear is not included in the study. Maintenance of the vehicles is not included in the study due to lack of data.

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 Tier 1 suppliers. The contribution to the total carbon footprint from these processes is likely to be very small.

The study is performed with a global approach, which means that the generic datasets used for raw materials production and refining are not specific for any region. Global averages have been applied as often as possible. The methodology for choosing generic data is further described in "Appendix 1 – General methodology when choosing datasets for CV Carbon Footprints".

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 Polestar vehicle driving 200,000 km.
The results are being presented as kg CO_2-equivalents per functional unit.

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

2.4.3 Allocations

We have allocated 100% of total emissions from scrap 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 throughout the whole manufacturing chain.

More specifically, the methodology uses the cut-off approach, which is the recommended method according to the EPD[13] 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.

This study does not include impact from charging or fuel infrastructure which means that the differences from car-to-car will be assessed. It does not include changes in these systems nor take rebound effects into consideration.

Carbon footprints developed using this methodology should not be broken down to the component level without reassuring that an acceptable level of detail is also reached on the studied sub-system.

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

3 Life cycle inventory analysis

3.1 Material production and refining

Material production and refining (see Figure 5) is based on a Bill of Materials (BoM) containing material composition and material weight. The BoM used for modelling in GaBi is specifically developed to be used for the LCA modelling in GaBi and states 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 2 – Chosen datasets.

The material production and refining is modelled using datasets from GaBi Professional database and ecoinvent 3.6 data. The datasets have been chosen according to the Polestar methodology for choosing generic datasets, the methodology can be found in Appendix 1. For some raw materials there were no datasets representing the exact materials, these are listed in Appendix 2 together with the assumptions made.

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 has been categorised as "undefined material" in the material library. Table 4 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.

Table 4

Share of undefined material in the different vehicles.

Vehicle	Share of undefined material
Polestar 2	1.4 %
XC40 ICE	1.5 %

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 4.

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".[14] 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 car 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 car even though the aluminium scrap is sent to recycling and used in other products. The material utilisation rate for the manufacturing processes of both cast aluminium and wrought aluminium can be seen in Appendix 4.

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

3.1.2 Steel production and refining

The raw material dataset used for the material category “unalloyed steel” has an output of rolled and galvanised steel. A processing process has then been added to all steel. Which processing process has been chosen depends on whether the steel is stamped in the factory 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 galvanising of the steel:

1. The steel that is processed and stamped in the factory. The Material Utilisation Degree is according to Volvo Cars data.
2. The rest of the steel, which is distributed in various components of the car. The Material Utilisation 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 utilisation rate for the manufacturing processes of steel processed at Volvo Cars and steel processed at suppliers can be seen in Appendix 4.

3.1.3 Electronics production and refining

The material category called “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.

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 utilisation rate for the manufacturing processes of plastics can be seen in Appendix 4 .

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 processing 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 the 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 a larger volume of cars produced in each region for one year has been compiled to better represent reality. Hence, Volvo Cars data has been used to set the electricity mix. This electricity mix is not for any specific Volvo Cars model, but for Volvo Cars vehicles as a whole on a global level. The number of produced Volvo Cars vehicles in 2019 is presented in Table 5.

Table 5

Produced Volvo vehicles in 2019

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

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 partially aggregated processes in the GaBi databases where it is possible to add an electricity mix by choice.

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. Polestar purchases cell modules from CATL and LG Chem, who, in collaboration with the report author, performed cradle-to-gate (up until Polestar 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 are modelled separately in the Complete Vehicle LCA. All other parts of the battery pack are included in the materials BoM, based on IMDS data.

3.3 Manufacturing and logistics

3.3.1 Logistics

Volvo Cars data has been used to calculate GHG emissions for transports from Tier 1 suppliers to the manufacturing site (inbound transport). Volvo Cars' total emissions from inbound transports divided by the total number of Volvo Cars vehicles produced during the same year has been applied. Volvo Cars data has also been used to calculate GHG emissions for transports from the manufacturing site to customer handover (outbound transport). Volvo Cars' total emissions from transports of Volvo Cars vehicles from Volvo Cars manufacturing sites to Volvo Cars dealers divided by the total number of Volvo Cars vehicles sold during the same year has been applied.

3.3.2 Manufacturing

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 were 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.

Polestar 2 is only produced in Luqiao. XC40 ICE is produced in both Luqiao and Ghent and the emissions have been calculated in proportion to the number of cars produced in each factory during 2019.

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

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

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

- Well-to-tank (WTT) – Includes the environmental impact caused during production and distribution of the 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 a specific energy source (wind)[16].
- Tank-to-wheel (TTW) – Includes the tailpipe emissions during use. This is zero for Polestar 2 and assumed to be 163g CO_2/km for the XC40 ICE (based on an average of 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 Polestar 2. Losses during charging are included in the electricity use of the BEV. The electricity use for Polestar 2 used in this study was 198 Wh/km.

3.5 End-of-life of the vehicle

3.5.1 Process description

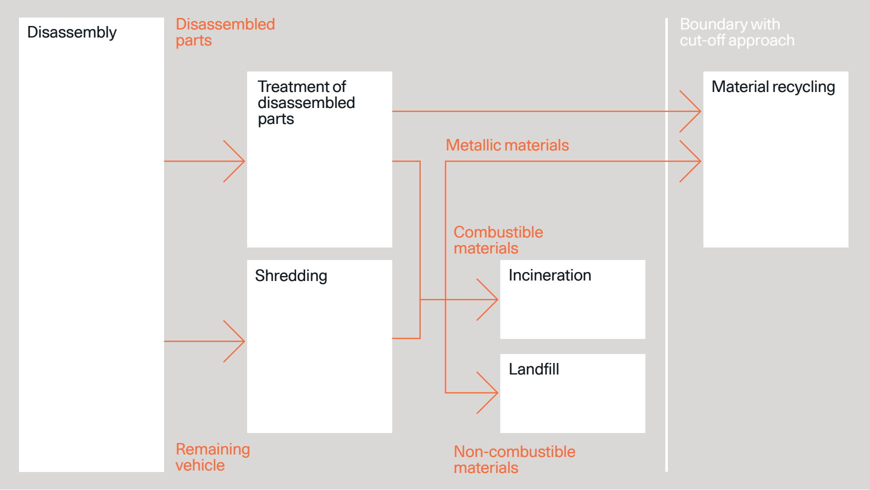
It is assumed that all vehicles, at their end-of-life, are collected and sent to end-of-life treatment.

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.

The end-of-life was modelled to represent global average situations as far as possible. The 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 6 gives an overview of the entire stage.

Figure 6

End-of-life boundaries



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

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[16] The data on WTT emissions 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.

- oil filters
- catalytic converter
- airbags and seat belt pretensioners removed or set off

From a global perspective, the treatment of fuels, oils and coolant generally implies incineration. The tyres 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 car 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 a landfill. For the purposes 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 of the study, no energy recovery is included for the incineration steps, even though in some Polestar markets, there is indeed energy recovery from incineration of waste. This somewhat conservative assumption has been made due to the fact that 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 Polestar 2

4.1 Polestar 2 compared to XC40 ICE (petrol)

When looking at the results for the Polestar 2 life cycle (see figure 13 and table 9) the choice of electricity mix in the use phase has a large impact on the total Carbon Footprint. With a global electricity mix, the Polestar 2 has a 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 Polestar 2 has an approximately 20% higher carbon footprint than the XC40 ICE, mainly due to the higher weight of the Polestar 2 and larger share of aluminium and weight of electronics. The most significant addition, however, is that of the Li-ion battery. If this is included in the materials production category, the increase in carbon footprint is around 70%. It is important to keep in mind, however, that this increase is smaller than the decrease found in the use phase for all three electricity mixes.

The results of the LCAs give an interesting insight into a potential future shift of which life cycle phase is the most dominant. When comparing the Polestar 2 driven with wind electricity to the XC40 ICE, dominance is shifted from the use phase to the production phase.

Manufacturing and end-of-life treatment only give a small contribution to the life cycle.

Figure 7

Carbon footprint for Polestar 2 and XC40 ICE, with different electricity mixes in the use phase used for Polestar 2. Results are shown in tonne CO_2-equivalents per functional unit (200,000 km lifetime range).

- ■ Materials production
- 🟨 Li-ion battery modules
- ▨ Manufacturing
- ☐ Use phase
- ▩ End-of-life

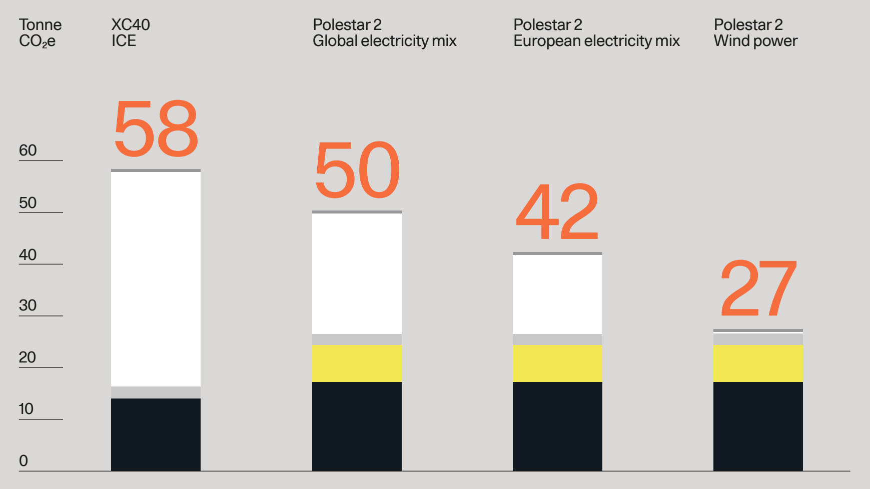


Table 6

Carbon footprint for Polestar 2 and XC40 ICE, with different electricity mixes used in the use phase for Polestar 2. Results are shown in tonne CO_2-equivalents per functional unit.

	Materials production	Li-ion battery modules	Manu-facturing	Use phase	End-of-life	Total
XC40 ICE	14	0	2.1	41	0.6	58
Polestar 2 – global electricity mix	17	7	2.2	23	0.5	50
Polestar 2 – european (EU28) electricity mix	17	7	2.2	15	0.5	42
Polestar 2 – wind power	17	7	2.2	0.4	0.5	27

Figure 8 and Table 7 below show the total amount of GHG emissions, depending on total kilometres driven, from Polestar 2 (with different electricity mixes in the use phase in the diagram) and a XC40 ICE. Where the lines cross, break-even between the two vehicles occurs.

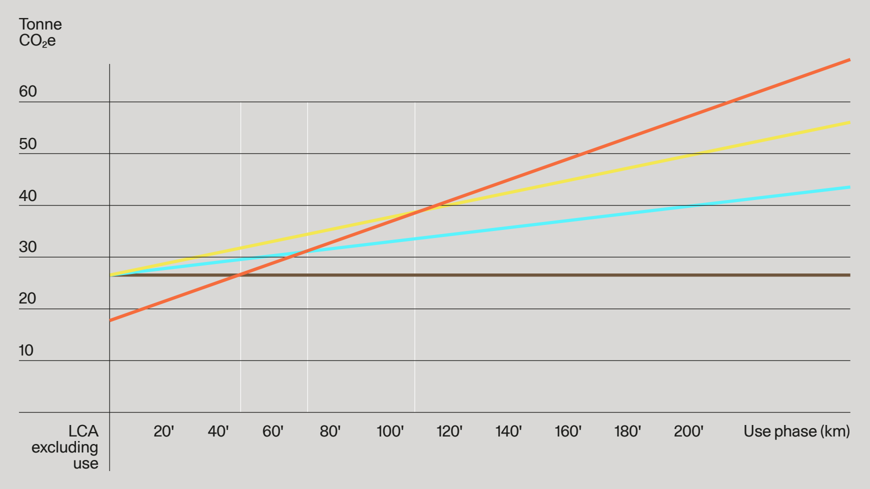


Figure 8

Total cumulated amount of GHGs emitted, depending on total kilometres driven, from Polestar 2 (with different electricity mixes in the diagram) from XC40 ICE. The functional unit for the LCA is "The use of a specific Polestar vehicle driving 200,000 km".

- 🟥 XC40 ICE
- 🟨 Polestar 2 – global electricity mix
- 🟦 Polestar 2 – european (EU28) electricity mix
- 🟫 Polestar 2 – wind power

Table 7

Number of kilometres driven at break-even between Polestar 2 with different electricity mixes in the use phase XC40 ICE (petrol).

Electric mix	Break-even (km)
Polestar 2 – global electricity mix / XC40 ICE	112 000
Polestar 2 – european (EU28) electricity mix / XC40 ICE	78 000
Polestar 2 – wind power / XC40 ICE	50 000

The main difference between the Polestar 2 and the XC40 ICE is the Li-ion battery, this can be seen in Figure 9 and Figure 10. As for the ICE, aluminium and steel/iron are still important, as are electronics and polymers.

Figure 9

Contribution from different material groups to the carbon footprint from “Materials production and refining” for Polestar 2.

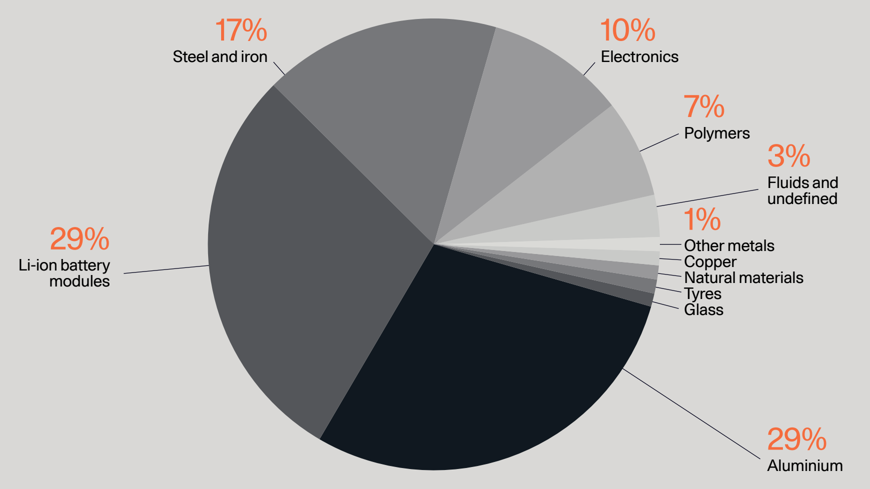
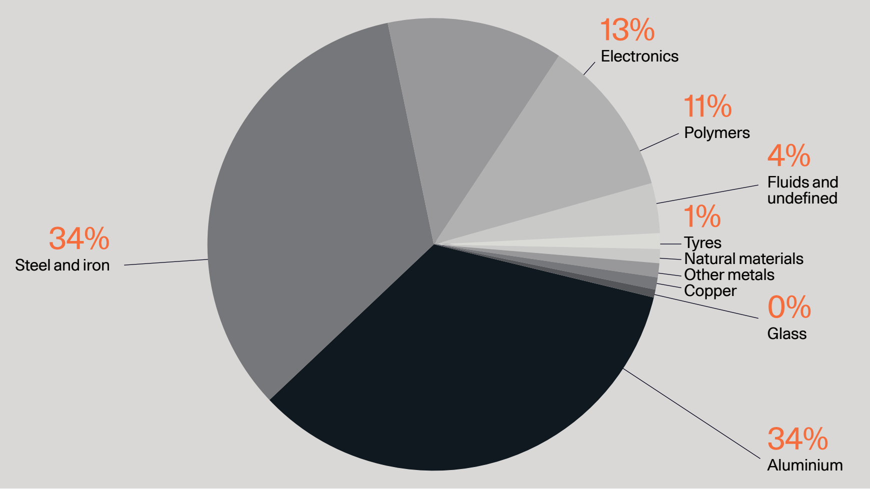


Figure 10

Contribution from different material groups to the carbon footprint from “Materials production and refining” for a XC40 ICE.



5 Discussion

Using LCA for assessing the carbon footprint of cars gives insights 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 Polestar 2 and the XC40 ICE shows the differences and similarities between BEV technology and ICE technology, and the potential current benefits of electrification as well as the future potential of BEVs.

Testing alternative electricity mixes for the Polestar 2 in the use phase shows that the electricity source stands out as a crucial factor in determining the total life cycle Carbon Footprint. As stated in Chapter 4, a Polestar 2 run on wind power has only half the carbon footprint compared to the XC40 ICE over 200,000 kilometers. As the global predictions for the electricity market point to further reduced Carbon Footprints of electricity production on all markets, it indicates 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 is most dominant in the result. When considering a global average electricity mix, the life cycle impact is split 50/50 between the materials production and refining stages and the use phase (Table 7). In contrast, a choice of wind-based electricity gives a life cycle carbon footprint that is significantly lower compared to driving with european or global mixes, and consequently the materials production and refining phase becomes dominating. 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.

When considering the materials production and refining phase and comparing the result of the Polestar 2 to the results of the XC40 ICE, the Polestar 2 has a higher Carbon Footprint. This is mainly due to the addition of the Li-Ion battery. This increase in emissions is compensated by a lower carbon footprint in the use phase, resulting in a lower total Carbon Footprint. Further improvements in the materials production and refining phase will result in an even further reduced total Carbon Footprint.

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 BEVs and ICEs share many bulk materials (aluminum, steel, plastics) as well as electronic components, the effects of these improvements will result more in a lower total carbon footprint of both vehicles, and less of an increase of the difference between them.

Production of steel and aluminum has a relatively large contribution to the total Carbon Footprint, comprising 20% of the total carbon footprint when a global energy mix is used in the use phase. The Li-ion battery modules stand 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 during production, is also an important part of reducing the Carbon Footprint.

As long as the Polestar 2 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 the GHG emissions of the 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 Polestar 2, significantly below the driving distance of 200,000 km used as functional unit. When considering a global average electricity mix, the break-even point is at about 112,000 km for Polestar 2, also below the 200,000 km mark. After the break-even points, the global warming related benefits of the Polestar 2 compared to the XC40 ICE increase linearly for the rest of the life cycle. This also means that the longer the lifetime, the lower the carbon footprint of the Polestar 2 compared to the XC40 ICE.

5.1 Qualitative sensitivity analysis

The combination of the chosen allocation method and the chosen background datasets results in a relatively high carbon footprint for the Polestar 2 compared to other studies. The choice of the allocation method resulted in all GHG emissions from producing scrap being allocated to the cars and all GHG emissions from waste in the end-of-life treatment being allocated to the cars even if

[17] https://greet.es.anl.gov

the material is recycled. In LCA it is important that the methodology is followed consistently, and in this case the same method should be applied in the same manner to scrap flowing from other product systems into production of metals used in Polestar's cars. It is unclear whether the same method has been applied in all of the background datasets that have been used to represent metal production or not, and might have resulted in an overestimation of the Carbon Footprint. This discussion is not only valid for scrap and metals, but for all materials used in the study.

Furthermore, the metal production datasets that have been used are average data, and further investigation is needed to assess to what extent data differs from Polestar's actual supply network. There are indications that Polestar's suppliers, in some cases, perform significantly better than the average global production, which is another indication that the results may be overestimated.

5.2 Possible future work

In this study, many new ideas and suggestions for improvements have been identified.

Further investigation and selection of database/literature data would improve the quality of the study, e.g. in order to verify that the methodology is applied consistently. This has proven to be especially important regarding steel and aluminium recycling. Selection of database/literature data could be refined, e.g. in order to further distinguish between different wrought manufacturing processes.

Since production of PCBs has a relatively high carbon footprint per mass unit compared to other vehicle components, there is a need to investigate this category further in the future, and possibly find data more representative for the specific applications in Polestar's cars.

More supplier specific data and more site-specific data would further improve the accuracy and precision of the results. This would require even deeper collaboration with suppliers (Tier 1 and Tier 2+). The results from this study could be used as a basis for prioritising the work, e.g. starting with the material category with the highest Carbon Footprint. Regarding the battery, it could be seen that the accuracy of the result was higher when using data obtained directly from the suppliers rather than using IMDS data. Given the relatively large carbon footprint from the battery, increased collaboration with battery suppliers should be prioritised.

Tailpipe emissions of methane and nitrous oxide could also be included in the future.

Infrastructure could also be included in the future to further complete the results. It would be interesting to include maintenance of cars in the use phase, especially for assessing possible differences between the carbon footprint of maintenance for BEVs and ICEs. Maintenance is also relevant to incluce in order to ensure avoidance of sub-optimisations by e.g. reducing carbon footprint in the materials production and refining phase but increasing it in the use phase. Relevant aspects could be e.g. leakage of AC fluids, change of tyres, change of other parts that may break, etc. Including maintenance of Li-ion battery modules would result in a more complete comparison between BEVs and ICEs.

Polestar has ambitious sustainability goals. Therefore, future LCA results will be even more linked to these goals for the internal work to be more coordinated.

The methodology will be continuously developed and improved as new vehicle models are assessed and as more knowledge about supply chains and suppliers is accumulated.

Standardisation of methodology for performing Carbon Footprints of cars would increase the transparency, by making it easier to compare the results between different studies.

The use of new technologies, e.g. blockchain/cryptocurrency, could prove beneficial for further improving data quality.

Future scenario analyses will be performed to better assess the potential of different technologies and will be used for strategy development on how to reach Polestar's climate targets.

The scope of the methodology could be expanded to include more impact categories, e.g. biodiversity, social performance, cumulative energy demand, etc.

6 Conclusions

In this study, the carbon footprints of Polestar 2 and XC40 ICE have been calculated, including all life cycle phases, i.e. materials production and refining, manufacturing, use phase and end-of-life (see Figure 5).

LCA, 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 supply chain 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 a Polestar 2 and an XC40 ICE is 58 tonne CO_2e and 27–50 tonne CO_2e respectively. The reason for the interval in the result of the Polestar 2 is because different electricity mixes with varying carbon intensity in the use phase have been tested. The width of the interval clearly shows the impact the choice of electricity mix has on the end result.

The Polestar 2, and BEVs in general, can have even lower Carbon Footprints in the near future because of potential improvements in battery technology, vehicle-energy efficiency and in the energy systems.

Break-even analysis has been performed, identifying at what driving distance the Carbon Footprints of the Polestar 2 and the XC40 ICE break even when alternating the electricity mix. The analysis 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 Polestar 2 improves linearly compared to the XC40 ICE, i.e. the longer the lifetime the better the relative carbon footprint of the Polestar 2.

LCA and the underlying methodology will be used as the metrics for assessing the carbon footprint of Polestar cars. 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.

The methodological choices, such as a choice of allocation method, have a high impact on the end result. Changing the methodology might lead to other conclusions, e.g. there will be a larger focus on the end-of-life phase since the carbon footprint of waste is allocated to other product systems when it is recycled. The methodology needs to be further improved in order to reach a stability of results over time and to increase the quality of conclusions, e.g. further develop allocation methods, include infrastructure and maintenance, increase data quality, etc.

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

Appendix 1 – General methodology when choosing datasets for complete vehicle carbon footprints

This methodology applies when determining the global Carbon Footprints of Polestar cars.

For most of the raw materials in our cars, as well as the manufacturing processes taking place outside our own manufacturing sites, data from LCA databases is used as source for the environmental impact. In order to be able to choose datasets in a consistent and relevant way, the following methodology has been developed.

Disclaimer

- When choosing datasets for an LCA assessing environmental impacts other than global warming potential, this methodology should not be used.
- When choosing datasets for a carbon footprint representing a specific region this methodology should not be used.

Things to consider when choosing datasets

Datasets in the GaBi-professional database and the ecoinvent database representing specific raw materials differ in several ways, stated in the documentation of the dataset:

- Region – All datasets represent a specific region, e.g. Global, EU, Asia, specific countries or other.
- Data source – Some datasets are produced by branch organisations, some by the data provider itself. We do not value any data source higher than any other.
- Date – All datasets contain information regarding when the dataset was created and for how long it is assumed to be representative. Avoid using a very old dataset if there are other options. If there is a pressing reason need to use old data, perform a validity check in order to determine that the dataset is relevant.

Apart from this information, documented in the actual dataset, there are several other aspects that should be considered. When choosing datasets, use the method below and consider all the aspects stated within.

Checklist for choosing datasets

When choosing which generic datasets for raw materials to use in the carbon footprints of Polestar cars, this general method is used:

1 Search for the specific raw material

- If there is no dataset available for the specific raw material, read under the header “No dataset available for the specific raw material” at the end of this Appendix.
- If there is only one dataset representing the specific raw material, this dataset should be used.
- However, there are often several datasets representing the specific raw material. In those cases, adhere to the steps below.

2 What is the effect of this choice of data on the whole carbon footprint?

- Do not put too much effort into investigating the different datasets if the raw material constitutes a very minor part of the whole vehicle.
- Use the materials list for the vehicle, ranked by weight, in order to get an understanding of how big or small the effect of choosing this dataset is.
- Consider the total carbon footprint (carbon footprint for the dataset * total weight of the material in the vehicle) for the material when determining the effort investigating the different datasets.

3 Comparing the global warming potential

Compare the global warming potential for the different datasets. Often, they have a similar value, but sometimes the difference can be quite significant. If the dataset you end up choosing differs significantly from the others, try to get an understanding of why and if this big difference is reasonable or not. If a dataset with significantly different global warming potential was selected, a motivation as to why this dataset was chosen must be provided.

4 Chose data that represents as many markets as possible

If there is a global (GLO) dataset use this one, if not use "Rest of world" (RoW). If that is not available use a European dataset (RER, EU-28). As a last option use datasets representing specific countries. If a non-global dataset was selected, a motivation to why this dataset has been chosen has to be given specifically.

No dataset available for the specific raw material

- If there is no dataset available for the exact material, consult an expert on the specific material within the organization in order to be able to choose the dataset that can best represent it.
- In these cases, an explanation as to why this dataset was chosen must be provided.

Appendix 2 – Chosen datasets

Material	Location	Name	Type	Source	Date used
ABS	GLO	market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
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)	GLO	market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
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)	GLO	aluminium ingot mix IAI 2015	agg	IAI/ts	2020-04-20
Aluminium, wrought (matcat)	GLO	aluminium ingot mix IAI 2015	agg	IAI/ts	2020-04-20
ASA	GLO	market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
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)	GLO	market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
Brake fluid	GLO	market for diethylene glycol	agg	ecoinvent 3.6	2020-05-19
Cast iron (matcat)	DE	cast iron part (automotive) – open energy inputs	p-agg	ts	2020-04-20
Catalytic coating	ZA	market for platinum group metal concentrate	agg	ecoinvent 3.6	2020-06-01
Copper	EU-28	copper wire mix (Europe 2015)	agg	DKI/ECI	2020-04-20
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	GLO	market for textile, woven cotton	agg	ecoinvent 3.6	2020-04-20
Damper	RER	polymethylmethacrylate sheet (PMMA)	agg	PlasticsEurope	2020-04-20
Damper	RoW	market for lime	agg	ecoinvent 3.6	2020-04-20
Diesel	EU-28	diesel mix at filling station	agg	ts	2020-04-20
E/P	RoW	polyethylene production, low density, granulate	agg	ecoinvent 3.6	2020-04-20

Material	Location	Name	Type	Source	Date used
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)	RoW	polyethylene production, low density, granulate	agg	ecoinvent 3.6	2020-04-20
Electronics	GLO	market for printed wiring board, surface mounted, unspecified, Pb containing	agg	ecoinvent 3.6	2020-05-26
EPDM	DE	Ethylene Propylene Diene Elastomer (EPDM)	agg	ts	2020-04-20
Epoxy	RoW	market for epoxy resin, liquid	agg	ecoinvent 3.6	2020-04-20
EVAC	RoW	market for ethylene vinyl acetate copolymer	agg	ecoinvent 3.6	2020-04-20
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)	RoW	market for ethylene vinyl acetate copolymer	agg	ecoinvent 3.6	2020-04-20
Ferrite magnet	GLO	market for ferrite	agg	ecoinvent 3.6	2020-04-24
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	EU-28	float flat glass	agg	ts	2020-04-20
Glycol	EU-28	Ethylene glycol	agg	PlasticsEurope	2020-01-01
Lead, battery	DE	lead (99.995%)	agg	ts	2020-04-20
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)	EU-28	lubricants at refinery	agg	ts	2020-04-20
Magnesium	CN	Magnesium	agg	ts	2020-04-20
NdFeB	GLO	market for permanent magnet, electric passenger car motor	agg	ecoinvent 3.6	2020-04-24
NR	DE	Natural Rubber (NR)	agg	ts	2020-04-20
PA	RoW	market for nylon 6	agg	ecoinvent 3.6	2020-04-20

Material	Location	Name	Type	Source	Date used
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)	RoW	market for nylon 6	agg	ecoinvent 3.6	2020-04-20
PBT	DE	Polybutylene Terephthalate Granulate (PBT) Mix	agg	ts	2020-04-20
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)	DE	Polybutylene Terephthalate Granulate (PBT) Mix	agg	ts	2020-04-20
PC	GLO	market for polycarbonate	agg	ecoinvent 3.6	2020-04-20
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)	GLO	market for polycarbonate	agg	ecoinvent 3.6	2020-04-20
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)	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)	GLO	market for polycarbonate	agg	ecoinvent 3.6	2020-04-20
PC+ABS (unfilled)	GLO	market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.6	2020-04-20
PE	RoW	polyethylene production, low density, granulate	agg	ecoinvent 3.6	2020-04-20
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)	RoW	polyethylene production, low density, granulate	agg	ecoinvent 3.6	2020-04-20
PET	GLO	market for polyethylene terephthalate, granulate, amorphous	agg	ecoinvent 3.6	2020-04-20
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

Material	Location	Name	Type	Source	Date used
PET (unfilled)	GLO	market for polyethylene terephthalate, granulate, amorphous	agg	ecoinvent 3.6	2020-04-20
Petrol	EU-28	gasoline mix (regular) at refinery	agg	ts	2020-04-20
PMMA	RER	Polymethylmethacrylate sheet (PMMA)	agg	PlasticsEurope	2020-04-20
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)	RER	Polymethylmethacrylate sheet (PMMA)	agg	PlasticsEurope	2020-04-20
Polyurethane (matcat)	RoW	market for polyurethane, rigid foam	agg	ecoinvent 3.6	2020-04-20
POM	EU-28	Polyoxymethylene (POM)	agg	PlasticsEurope	2020-01-01
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)	EU-28	Polyoxymethylene (POM)	agg	PlasticsEurope	2020-01-01
PP	GLO	market for polypropylene, granulate	agg	ecoinvent 3.6	2020-04-20
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)	GLO	market for polypropylene, granulate	agg	ecoinvent 3.6	2020-04-20
PS	GLO	market for polystyrene, general purpose	agg	ecoinvent 3.6	2020-04-20
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)	GLO	market for polystyrene, general purpose	agg	ecoinvent 3.6	2020-04-20
PVB	DE	Polyvinyl butyral granulate (PVB) by-product ethyl acetate	agg	ts	2020-04-20
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
PVB (filled)	GLO	market for glass fibre	agg	ecoinvent 3.6	2020-04-20
PVB (unfilled)	DE	Polyvinyl butyral granulate (PVB) by-product ethyl acetate	agg	ts	2020-04-20

Material	Location	Name	Type	Source	Date used
PVC	RoW	polyvinylchloride production, suspension polymerisation	agg	ecoinvent 3.6	2020-04-20
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)	RoW	polyvinylchloride production, suspension polymerisation	agg	ecoinvent 3.6	2020-04-20
R-1234yf		R-123yf	u-so		43943
R-134a	GLO	market for refrigerant R134a	agg	ecoinvent 3.6	2020-04-20
SBR	DE	Styrene-butadiene rubber (S-SBR) mix	agg	ts	2020-04-20
Silicone rubber	DE	Silicone rubber (RTV-2, condensation)	agg	ts	2020-04-20
Steel, Sintered	GLO	steel hot dip galvanised	agg	worldsteel	2020-04-20
Steel, Stainless, Austenitic		EU-28	Stainless steel cold rolled coil (304) Eurofer <p-agg>		
Steel, Stainless, Austenitic	EU-28	stainless steel cold rolled coil (304)	p-agg	Eurofer	2020-04-20
Steel, Stainless, Ferritic		EU-28	Stainless steel cold rolled coil (430) Eurofer <p-agg>		
Steel, Stainless, Ferritic	EU-28	stainless steel cold rolled coil (430)	p-agg	Eurofer	2020-04-20
Steel, Unalloyed		GLO	Steel finished cold rolled coil worldsteel		
Steel, Unalloyed	GLO	steel hot dip galvanised	agg	worldsteel	2020-04-20
Sulphuric acid	EU-28	Sulphuric acid (96%)	agg	ts	2020-04-20
Thermoplastic elastomers (matcat)	DE	Polypropylene / Ethylene Propylene Diene Elastomer Granulate (PP/EPDM, TPE-O) Mix	agg	ts	43941
Thermoplastics (matcat)	RoW	market for nylon 6	agg	ecoinvent 3.6	2020-04-20
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	RoW	market for nylon 6	agg	ecoinvent 3.6	43941
Unfilled Thermoplastics (matcat)	DE	Polypropylene / Ethylene Propylene Diene Elastomer Granulate (PP/EPDM, TPE-O) Mix	agg	ts	43941
Washer fluid	DE	Ethanol	agg	ts	2020-04-20

Material	Location	Name	Type	Source	Date used
Wood (paper, cellulose ...)	EU-28	laminated veneer lumber (EN15804 A1-A3)	agg	ts	2020-04-20
Zinc	GLO	Special high grade zinc	p-agg	IZA	2020-04-20
Aluminium, manufacturing (DE, EU-28)					
Aluminium, manufacturing (DE, EU-28)	DE	aluminium die-cast part	u-so	ts	2020-01-01
Aluminium, manufacturing (DE, EU-28)	EU-28	aluminium sheet – open input aluminium rolling ingot	p-agg	ts	2020-04-20
Aluminium, manufacturing (DE, EU-28)	DE	aluminium sheet deep drawing	u-so	ts	2020-01-01
Manufacturing		manufacturing (general assumption)	u-so		2020-05-15
Manufacturing		manufacturing, leather	u-so		2020-06-01
Polymers (all categories) manufacturing (GLO)	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)					
Stainless steel manufacturing (DE)	DE	steel sheet deep drawing (multi-level)	u-so	ts	2020-01-01
Stainless steel manufacturing (DE)		steel manufacturing (VCC data)	u-so		2020-05-11

Appendix 3 – Complete list of IDMS 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
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
PMMA (unfilled)	Polymers
POM (unfilled)	Polymers
PP (unfilled)	Polymers
PVB (unfilled)	Polymers
PVC (unfilled)	Polymers
Thermoplastic elastomers (matcat)	Polymers
EPDM	Polymers

Material name	Material group
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
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 4 – 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 and 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 to adhere to 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 to adhere to 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 5 – End-of-life assumptions and method

A5.1 Transport

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

A5.2 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 is low, potential additional transport of these components was disregarded.

A5.3 Pre-treatment

Pre-treatment was included for the following disassembled components:

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

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

The Li-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 is mainly done as a safety precaution. After this stage, they will be handled similarly to the rest of the vehicle. The fluids and oils that are incinerated likewise do not go through any pre-treatment.

A5.4 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 Polestar's specific electricity grid mix, as described in "Electricity use in supply chain manufacturing processes". Emissions of metals to water and air have been omitted due to the focus 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.

A5.5 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 material recycling, as mentioned above.

A5.6 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 study. To model the incineration of the waste oils, an ecoinvent dataset for the 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 was 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, such as 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, in 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 be 1500 km by truck.

A5.7 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 below 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	According to material category*
Rest of vehicle	Shredding	According to material category*

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