

Life cycle assessment
Carbon footprint
of Polestar 3

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List of abbreviation

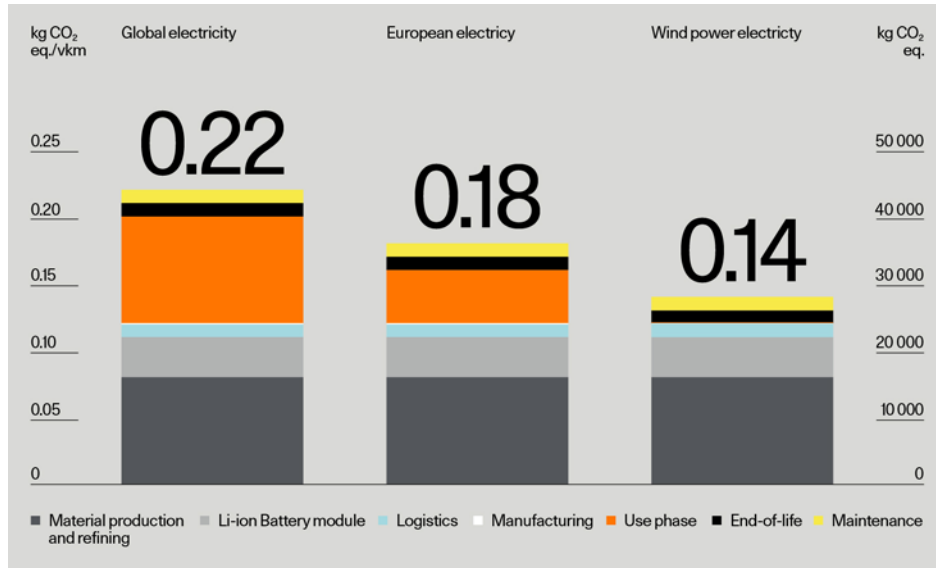
ABS: Acrylonitrile Butadiene Styrene
BEV: Battery Electric Vehicle
BOM: Bill of Materials
EoL: End-of-Life
GEC: Global Energy and Climate
GHG: Greenhouse Gas
GWP: Global Warming Potential
IEA: International Energy Agency
IMDS: International Material Data System
iPCA: iPoint compliance agent CA
IPCC: Intergovernmental Panel on Climate Change
LCA: Life Cycle Assessment
NMC: Nickel Manganese Cobalt
OEM: Original Equipment Manufacturer
PC: Polycarbonate
PCB: Printed Circuit Board
PET: Polyethylene Terephthalate
PE: Polyethylene
PP: Polypropylene
RER: Rest of Europe
STEPS: Stated Policies Scenario
VCC: Volvo Cars Company
WLTP: Worldwide Harmonized Light Vehicle Test Procedure
WTW: Well-to-Wheel

Polestar is dedicated to ensuring transparency regarding the environmental impact of its vehicles. This investigation aims to enhance openness by disclosing the carbon footprint associated with their passenger vehicles. The audience includes customers, Polestar employees, investors, automotive OEMs, and other stakeholders with an interest in the environmental performance of our vehicles.

The conducted analysis is a Life Cycle Assessment (LCA) focused exclusively on greenhouse gas (GHG) emissions, commonly referred to as a carbon footprint analysis. This assessment analyses the global warming potential (GWP) in accordance with ISO 14067 guidelines, utilising characterization factors established by the Intergovernmental Panel on Climate Change (IPCC, 2021). The scope of the study spans the entire life cycle of the vehicle, from the extraction and refinement of raw materials to the end-of-life stage.

This report shows the carbon footprint of the new Polestar 3, which goes into manufacturing in 2024. The study is a life cycle assessment (LCA), considering a driving distance of 200 000 kilometers and with a functional unit of "1 vehicle-kilometer". In general, this study adopts conservative assumptions to prevent underestimating the climate impact. Consequently, there is currently no official standard for LCA for vehicles so the findings of this study should be approached with caution when making comparisons with those of other manufacturers. The study's objective is to comprehend the carbon footprint of the vehicle in its entire lifespan. The aim is to offer valuable insights that can help in making well-informed decisions, including identifying areas where vehicles can minimise their carbon footprint. From previous reports conducted by Polestar, aluminium production and battery module manufacturing has been pointed out as high contributing factors of emission in the vehicles life time. Due to this, Polestar is actively working towards reducing these impacts.

In conclusion the climate impact of the cradle-to-gate study reveals that 68% is credited to the materials utilised in the vehicle's production, aluminium representing 24% of the emissions, and iron and steel contributing with 17%. Following closely, the production of battery modules emerges as a significant factor, constituting 24% of the cradle-to-gate climate impact. This battery has relatively low impact, this is mainly due to the use of 100% renewable electricity in the production of the anode and cathode in cell production of the battery module.



← Figure 1

Total carbon footprint cradle-to-grave kg CO₂-eq for the different electricity mixes. The axis to the left presents the functional unit of 1 vkm and the axis to the right presents the vehicle's lifetime of 200 000km.

The results of cradle-to-grave study, showed in figure 1, reveals a total carbon footprint for the complete LCA for the vehicle an emission of 44 tonnes CO₂-eq. with global electricity mix in the use phase. 38% of the total climate impact is credited to the material production and refining, with aluminium representing 14% of the material and refining emissions, and iron and steel contributing with 10% in the same category. Following is the use phase contributing 37% of the vehicle's total climate impact, and then the battery modules, constituting 16% of the overall climate impact.

Renewable energy sources, particularly wind power, demonstrate potential in reducing lifetime emissions during the use phase. Sensitivity analysis indicates lower emissions per kilometer for longer distances, emphasizing the importance of optimizing vehicle usage for sustainability. Promoting the prolonged use and lifespan of vehicles can be a strategic approach to curbing emissions. By extending the time a vehicle remains in service, the overall demand for new vehicles is reduced. The environmental burden from the manufacturing of the vehicle is also being reduced in a prolonged lifespan.

Anticipated improvements in regulatory (WLTP) energy consumption values are expected to reduce energy usage, contributing to environmental sustainability. However, considering alternative future energy scenarios alongside current assessments, such as STEPS, could further enhance energy resource efficiency. Additionally, alternative future energy evolution scenarios, beyond the IEA STEPS scenario assumed in current assessments, could further enhance energy resource efficiency.

Key findings:

- The life cycle assessment cradle-to-grave for the vehicle reveals a total carbon footprint emission of 44 tonnes CO₂-eq. with global electricity mix in the use phase. 38% of the total climate impact is due to the material production and refining, with aluminium representing 14% of the material and refining emissions, and iron and steel contributing with 10% in the same category. Following is the use phase contributing 37% of the vehicle's total climate impact, and then the battery modules, constituting 16% of the overall climate impact.
- Renewable energy sources, particularly wind power, demonstrate potential in reducing lifetime emissions during the use phase. Sensitivity analysis indicates lower emissions per kilometer for higher lifetime activity longer distances, emphasizing the importance of optimizing vehicle usage for sustainability from a total fleet perspective.

This chapter describes the methodology of the conducted life cycle assessment (LCA) study.

1.1 The Product

Polestar has developed one plug-in hybrid electric vehicle (Polestar 1) and two battery electric vehicles (BEV) (Polestar 2 and Polestar 4). This study assesses the third BEV produced by Polestar, the Polestar 3. The study assesses the first Polestar 3 variant that is introduced to the market: the long-range dual motor variant produced in Volvo Car's factory in Chengdu, China 2024. The variant is produced with different specifications. This study encompasses the specifications expected to have the largest sales volumes within the first year of production.

The studied vehicle is presented in Table 1.

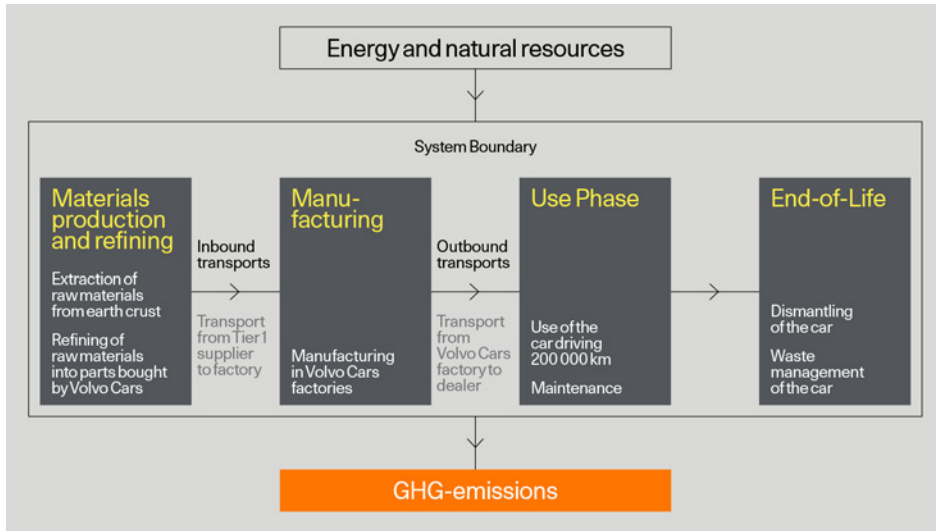
Table 1 →
Studied vehicle.

Vehicle	Total weight vehicle (kg)	Li-ion battery modules type and capacity (kWh)	Weight of battery modules (kg)	Energy usage WLTP (kWh/100 km)
Polestar 3	2 585	NMC, 111 kWh	474	20.1

The development of the methodology for this study was initiated jointly by Polestar and Volvo Cars when performing carbon footprint studies of Volvo XC40 Recharge and Polestar 2 in 2020. This methodology has been further developed and now incorporates changes such as predicted energy mix in use phase, inclusion of emissions from maintenance and an updated functional unit. This will be further explained in the sections below.

1.2 Goal of study

Polestar has the ambition to become a climate neutral company by 2040 and strives to be transparent about the climate impact of Polestar vehicles. The goal of this study is to contribute to transparency by disclosing the carbon footprint of the Polestar 3. The purpose of the vehicle is to transport passengers and their belongings. The intended audience of this report are customers, employees at Polestar, investors, automotive OEMs (Original Equipment Manufacturers), and other stakeholders who are interested in the environmental performance of our vehicles. The study was carried out to increase the knowledge about the carbon footprint of the Polestar 3, and which underlying materials and processes that contribute the most. The aim is that this information can be utilised to make informed decisions, for example, on where to put effort in reducing greenhouse gas (GHG) emissions. The report is made public at the Polestar webpage March 2024. It contains the complete study, there is no additional separate documentation.



← Figure 2

System boundary of study.

1.3 Scope of study

The study has been performed according to the carbon footprint standard ISO 14067 and explores the global warming potential (GWP), using characterisation factors for 100-year global warming potential (GWP) from the Intergovernmental Panel on Climate Change (IPCC, 2021), see Table 22 in Appendix 6. According to ISO 14067, emissions and removals in the following categories are included:

- Fossil GHG emissions and removals
- Biogenic GHG emissions and removals
- GHG emissions and removals from direct land use and land use change
- Aircraft GHG emissions

All significant GHGs emissions and removals from the processes included in the study (see “Main assumptions and exclusions”) are quantified. Carbon offsetting is not included. The study follows an attributional approach, i.e. it is not aimed at capturing systemic changes.

In the use phase, planned maintenance of the vehicle is taken into account, i.e. what is expected to be exchanged during the lifespan due to wear and tear of the vehicle is included, like change of tyres and windscreen wipers, but not changes due to accidents.

The study includes the vehicle life cycle from cradle-to-grave, starting at extracting and refining of raw materials and ending at the End-of-Life (EoL) of the vehicle (see Figure 2).

No cut-off criteria have been applied for the mass of the product content or energy use. In other words, the intent is that the included inventory together gives rise to the full carbon footprint. Mass that has not been declared as a specific material by the suppliers is still included but approximated by modeling it as polyamide (the polymer with the highest carbon footprint out of the polymer data used in the LCA). For more information on how this has been handled, see section 2.1 “Material production and refining”.

The time boundary of the study is manufacturing of the vehicle in 2024, and operating the vehicle over 15 years, after which EoL handling occurs.

The geographical boundary of the study is vehicle manufacturing in China, and use of the vehicle in Europe and the world, i.e. average figures for the electricity mix in Europe and the world are used for the use phase (as well as a scenario of using electricity generated from wind power). EoL geographical system boundary is set to global. For upstream processes, i.e. before the vehicle manufacturing, generic datasets for raw material production and refining in a specific country or region have been used when it is known or likely that production/refining takes place there, if available. This is one step towards better data quality compared to the previous carbon footprint study on Polestar 2 which used global datasets for upstream processes as a first option. The methodology for choosing generic data is further described in the Polestar 2 carbon footprint report¹ “Appendix 1: General methodology when choosing datasets for complete vehicle carbon footprints”.

1 <https://www.polestar.com/dato-assets/11286/1600176185-20200915polestarlcafinala.pdf>

Another contrast to the Polestar 2 carbon footprint study is that this study uses primary aluminium using hydropower electricity in the smelting step. Use of recycled aluminium and steel, and use of biobased material, have not been considered in the modelling due to lack of data on the specific amounts in the vehicle. For the polymers, excluding biobased content means that the climate impact is slightly overestimated for the polymers, but the effect on the overall result is minor. The dataset on steel production already contains a default percentage of recycled content, which is not the case for the aluminium dataset. The lack of inclusion of data on recycled aluminium content thus means that the climate impact for the aluminium production is overestimated.

Generic data, as opposed to supplier-specific data, has been used for most of the upstream processes, over which Polestar does not have financial control. This means that the modelling of production of components in the vehicle have been based on the material composition of the components, using generic datasets for materials and adding a generic manufacturing process for each material. Hence, there are steps in some of the manufacturing value chains, specific to vehicle components, that might not be included, such as assembly processes at tier 1 suppliers. However, the contribution of these processes to the total carbon footprint is likely to be very small.

1.4 Function and functional unit

The functional unit is 1 vehicle-kilometre (1 vkm). In the Polestar 2 carbon footprint study, the vehicle lifetime mileage was used as the functional unit¹. The functional unit has been changed since 1 vkm better captures the function of the vehicle – the mobility – and also captures the effect of the lifetime mileage of the vehicle; the longer the lifetime mileage, the lower life cycle climate impact per 1 vkm. In practice, this means that the climate impact is calculated for the total life cycle and divided by the total km driven during the lifetime of the vehicle. The result will also be provided cradle-to-gate per produced vehicle and cradle-to-grave for a lifetime of 200 000km distance driven.

The reference flow in the study is the weight of the vehicle divided by the lifetime distance driven of 200 000 km. Table 1 shows the weight of the vehicle in the study.

1.5 Allocation

The total of assigned inputs and outputs for a unit process will match the inputs and outputs of the unit process prior to allocation.

When it comes to material sent to recycling, the emissions from producing this material have been allocated to the vehicle. That means that, for example, the produced amount of steel and aluminium included in the carbon footprint calculation does not only include the amount of the material in the vehicle, but also the production of metal that is removed during processing and sent to recycling throughout the whole manufacturing chain.

More specifically, this study uses the simple cut-off approach (also called the recycled content approach), which is the recommended method according to the EPD² system. This method follows the "polluter pays principle" meaning that if there are several product systems sharing the same material, the product causing the waste shall carry the 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.

1 <https://www.polestar.com/dato-assets/11286/1600176185-20200915polestarcafina.pdf>

2 <https://www.datocms-assets.com/37502/1617181375-general-programme-instructions-v-4.pdf>

3 <https://op.europa.eu/en/publication-detail/-/publication/1f494180-bc0e-11ea-811c-01aa75ed71a1>

This means that the user of recycled material carries the burden of the recycling process, and that no credit is given to the system that generates the material that is sent to recycling. This is applied both for the material that is sent to recycling from the manufacturing process and at EoL of the vehicle.

In the manufacturing facilities, total number of completed vehicles is used as the allocation basis, since there is a strong correlation between the use of resources and the total number of vehicles produced, irrespective of size of the vehicles.

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

1.6 Main assumptions and exclusions

In general, assumptions have been made in a conservative fashion following the precautionary principle, in order to not underestimate the climate impact from unknown data. For example, when no suitable dataset has been available to represent the manufacturing process for a certain material (from raw material to finished vehicle component), the emissions from the raw material production has been multiplied by two to compensate for the emissions from further processing. This is described in 2.7. "Minor material categories, production and refining".

The use phase considers a lifespan of 15 years of the vehicle; probable changes in the electricity mix during this time is considered in the study based on the stated policies scenario (STEPS) from the International Energy Agency (IEA). This scenario is a slightly conservative benchmark for the future, since it does not take for granted, that governments will reach their announced commitments, Nationally Determined Contributions or other long-term climate targets, but instead only considers forecasted effects of decided policies.

The energy use of the vehicle corresponds to driving according to the WLTP driving cycle; it includes losses occurring during charging and in the drive-train during driving, and only essential auxiliary systems are run while driving (excluding e.g. infotainment, air conditioning). The energy use in the use phase is explored in a sensitivity analysis.

The lifetime mileage of the vehicle is 200 000 km. As larger personal vehicles as the ones studied here can be argued to have a longer lifetime distance driven³, the effect of this is explored in a sensitivity analysis. The battery is assumed to last the full lifetime mileage of the vehicle.

The study does not include:

- Non-manufacturing operations such as business travels, R&D activities or other indirect emissions
- Manufacturing infrastructure e.g., the production and maintenance of buildings, inventories or other equipment used in the vehicle manufacturing plant in Chengdu, China. However, when generic datasets are used, which is the case for energy generation, transportation means, and production of ingoing materials, manufacturing infrastructure is automatically included
- Construction and maintenance of roads and charging infrastructure in the use phase

Aspect	Description	Requirements in this study
Time-related coverage	Desired age of data.	General data should represent the current situation of the date of study (2023), or as close as possible. All data should be less than 10 years old.
Geographical coverage	Area from which data for unit processes should be collected.	Material production and refining should be representative of region where the material/component is produced, when known. Vehicle manufacturing should be representative of the manufacturing site location. The use phase data should be representative of European and global average. End-of-life data should be representative of global average.
Technology coverage	Type of technology (specific or average mix).	Data should be representative of the technology used in production processes.
Representativeness	Degree to which the data set reflects the true population of interest.	Primary data that is representative of the process should be used for processes under VCC financial control. Secondary data may be used for upstream and downstream processes but fulfilling the requirements above on time-related, geographical and technology coverage.
Precision	Measure of the variability of the data values.	Data that is as representative as possible will be used. Data will be derived from credible sources, and references will be provided.
Completeness	Assessment of whether all relevant input and output data are included for each data set.	Generic data will be derived from credible sources, such as recognised LCI databases. Internal data should cover all relevant inputs and outputs. The data collected from battery module supplier should be verified in close collaboration with the supplier.
Reproducibility	Assessment of the method and data, and whether an independent practitioner will be able to reproduce the results.	Information about the method and data (reference source) should be provided.
Sources of the data	Assessment of the data sources used.	Data will be derived from credible sources, and references will be provided.
Uncertainty of the information	e.g. data, models, assumptions.	Data will be derived from credible sources, and references will be provided.

← Table 2

Data quality requirements used in the study.

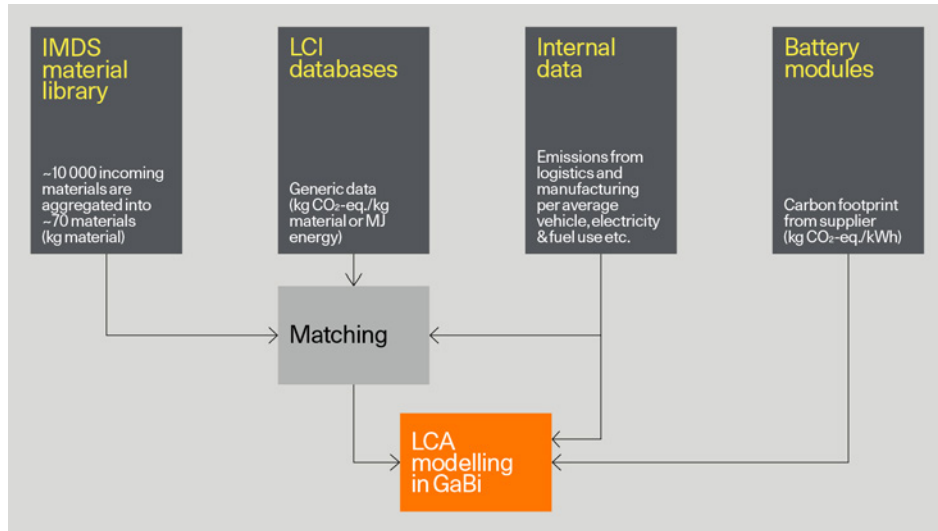
1.7 Data quality requirements

The data quality requirements used in the study are shown in Table 2. The data quality indicators used to assess the data used in the study can be found in Appendix 5, together with the quality assessment itself.

Considering the data quality requirements in Table 2, the data used in this study fulfil the requirements except that a considerable amount of the data-sets used in the material production and refining are more than 10 years old and/or not representing the location of production, and that the technological coverage is insufficient for the EoL stage. This is due to both uncertainty of material origin, uncertainty of waste handling practises globally, and lack of geographical coverage in databases. For more details about the data quality assessment, see Appendix 5.

1.8 Critical review

Compliance with ISO 14067 this study has been critically reviewed by a third party, see Appendix 7.



← Figure 3

Shows a high-level overview of how Polestar works to derive carbon footprints of vehicles.

1.9 Way of working overview

Figure 3 shows a high-level overview of how Polestar works to derive carbon footprints of vehicles.

There are four main ways that data needed for the final carbon footprint are retrieved:

- IMDS⁴ (International Material Data System) datasheets which contain information on material compositions of the components in a vehicle.
- LCI databases from ecoinvent⁵ (version 3.9.1) and Sphera⁶.
- Data from operations controlled by Polestar, such as manufacturing plants and logistics.
- Carbon footprint of Li-ion battery modules, performed by the supplier with guidance and support from Polestar.

1.10 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. However, this BoM cannot be used as direct input to the LCA-model in LCA for Experts but must be processed and aggregated in several steps to 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 LCA for Experts, they are aggregated to more than 70 defined material categories in a material library developed by Volvo Cars (IMDS ML). The "part number BoM" from the product data management system is uploaded to the IMDS ML system iPoint Compliance Agent (iPCA).

In iPCA a "material BoM" is generated that is imported to IMDS ML where all materials are mapped against the 70 defined material categories.

4 IMDS, www.mdssystem.com

5 Ecoinvent, www.ecoinvent.org

6 Sphera LCA databases <https://sphera.com/product-sustainability-gabi-data-search/>

Table 3 →

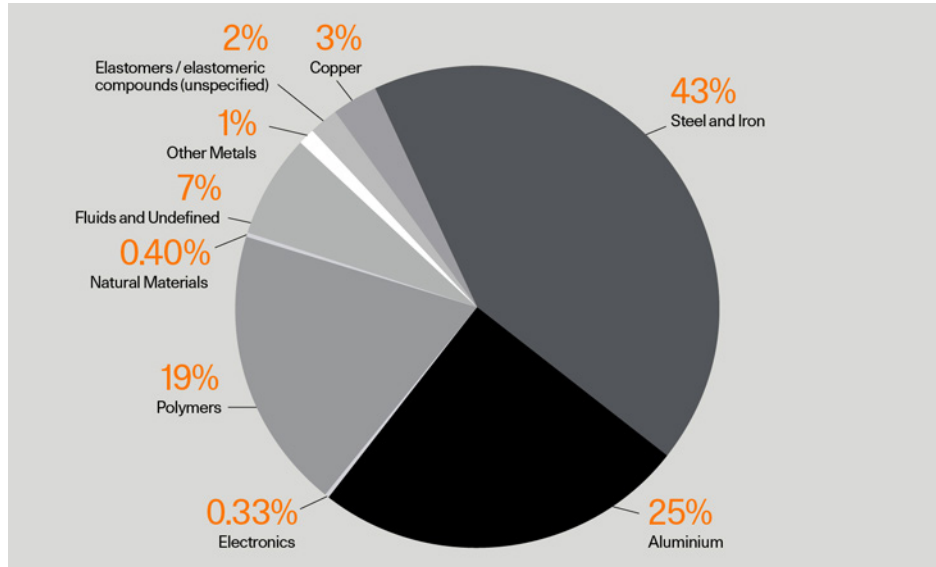
Material categories defined in IMDS ML release 9. Note that Li-ion battery modules are treated separately and therefore not included in the table.

Material type	Number of material categories	Share of total weight of the vehicle
Steel & iron	5	43%
Aluminium	3	25%
Other metals	3	< 1%
Polymers	35	18%
Natural materials	3	< 1%
Elastomers / elastomeric compounds (unspecified)	2	3%
Electronics	1	< 1%
Fluids & undefined	15	7%
Copper	2	3%

In order to have an efficient 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 this carbon footprint study, IMDS ML release 9 is used with the material categories listed in Table 3. For the complete list of material categories, see Appendix 2.

The “material BoM” has been modelled in LCA for Experts with relevant manufacturing process datasets. To follow the ISO 14067 standard, emission factors for the five impact categories have been calculated from the model in LCA for Experts for each material type including processes and refining, and then extracted into a excel document. This is done for both cradle-to-grave emission factors and for EOL emission factors. After this is done, each components emission is calculated by its respective mass.

For the Li-ion battery modules, specific supplier carbon footprint data was used instead of IMDS data. The variety and accuracy of generic datasets for Li-ion batteries is limited, but through the collaboration with the battery module supplier the risk of inaccuracies has been minimised to the best of efforts.



← Figure 4

Shares of material categories of vehicle weight without battery.

This chapter will describe the life cycle inventory of the study.

2.1 Material production and refining

Material production and refining is based on a BoM containing material composition and material weight. The BoM used for modelling in LCA for Experts is specifically developed to be used for the LCA modelling in LCA for Experts and states the composition of the vehicle based on more than 70 material categories. Each material category has an identified mass. The total weight of all material categories is then compared with the total weight of the vehicle. See Figure 4 for share of material categories for the vehicle.

In LCA for Experts 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.

The material production and refining are modelled using datasets from Sphera Professional database and ecoinvent 3.9.1 data. The datasets have been chosen according to the Polestar methodology for choosing generic datasets (described in Appendix 1 in the Polestar 2 carbon footprint report⁷).

The material content corresponding to the entire weight of the vehicle is included in the LCA, but a small amount of materials has been categorised as “fluids & undefined material” in the material library. The share of fluids & undefined material of the total vehicle weight (including battery modules) for Polestar 3 is 6%. 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 78% polymer resin, 14% glass fiber 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 1.

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.

When the materials have been categorised and then modelled in LCA for Experts the emission factor for each material group have been multiplied with the weight corresponding to that material group. This has been done for all five impact categories according to ISO 14067, for manufacturing and for EoL.

⁷ <https://www.polestar.com/dato-assets/11286/1600176185-20200915polestarlcafinala.pdf>

2.2 Aluminium production and refining

The share of aluminium that is cast aluminium and wrought aluminium is assumed to be 65% cast aluminium and 35% wrought aluminium. This is based on the report "Aluminium content in European passenger cars"⁸. 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 losses occurring 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 losses occurring in the production in the factory, the total footprint of the losses is allocated to the vehicle 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 3.

All aluminium is assumed to be produced in China. The assumption is based on an expert judgement by Polestar logistic specialists. The aluminium used in some identified parts in the vehicle comes from renewable electricity smelters. This share has been modeled with a fossil emission factor representing hydropower aluminium smelting in China. The emission factor was obtained through Polestar's own investigations and is a conservative assumption however the other emission factors were not provided (like biogenic emissions, aircraft emissions etc.).

2.3 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:

The steel that is processed and stamped in the factory. The Material Utilisation Degree is according to Volvo Cars data (see Appendix 3). The rest of the steel, which is distributed in various components of the vehicle. The Material Utilisation Degree is according to the chosen database dataset, i.e. literature value.

The losses occurring in the processes of making the steel parts for the vehicle, 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 3.

All steel is assumed to be produced in China. The assumption is based on an expert judgement by Polestar logistic specialists.

2.4 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 3.9.1 has been used. This dataset represents the production of lead-free, mounted PCBs.

2.5 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 3.

30 kg of the plastics in Polestar 3 are recycled plastics. This share has been modelled with a dataset for mechanically recycled plastics.

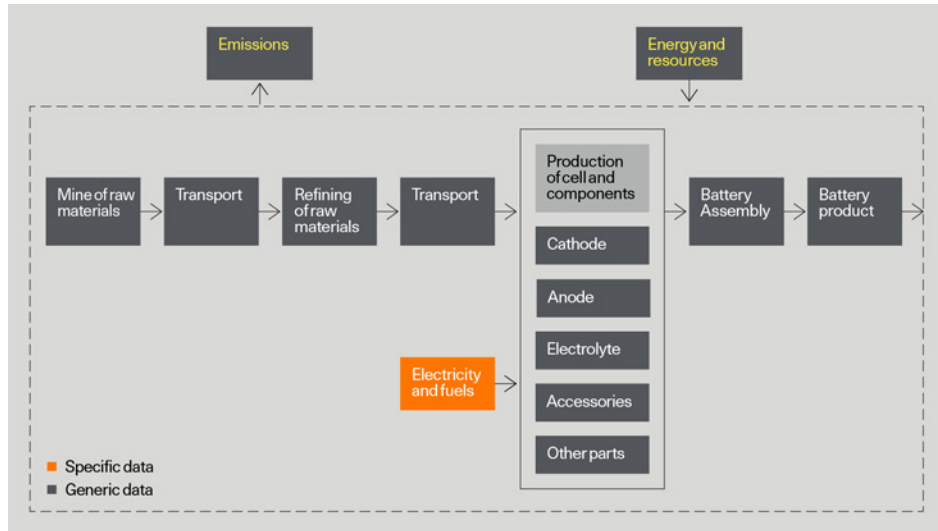
2.6 Minor material categories, production and refining

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).

2.7 Electricity use in materials production and refining

Most of the datasets used for materials production and refining have built-in electricity grid mix corresponding to the region the dataset is compiled for. In the few partially aggregated processes in the Sphera databases where it is possible to add an electricity mix by choice, Chinese electricity grid mix is applied.

⁸ https://european-aluminium.eu/wp-content/uploads/2022/10/aluminum-content-in-european-cars_european-aluminium_public-summary_101019-1.pdf



← Figure 5

Flowchart for battery manufacturing.

2.8 Battery modules

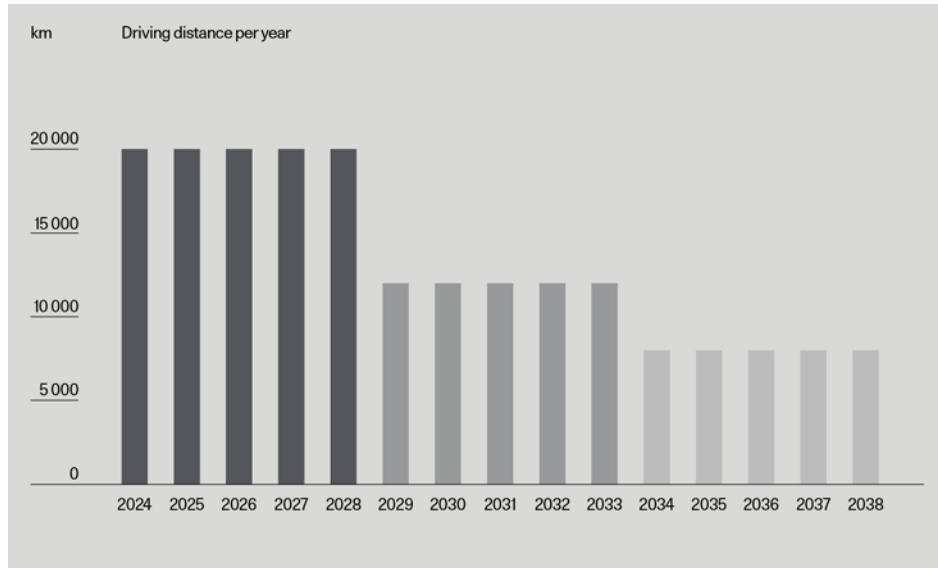
Polestar purchases battery modules from a battery supplier, who, in collaboration with Polestar, performed cradle-to-gate carbon footprint LCAs of their battery module (up until Polestar logistics take over). See Figure 5 for the flowchart of battery manufacturing. The battery modules have therefore 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. The total weight for the battery pack is 663 kg with modules being 474 kg and battery casing 189 kg. The highest weight for the battery pack, excluding the modules are allocated to the aluminum tray and the steel lid.

For the cell production, specifically the production of the anode and cathode, the supplier purchase certificates for renewable energy sources.

The report adheres to LCA standards such as ISO 14044:2006, ISO 14040:2006, and ISO 14067-2018, and the assessment's system boundary extends from cradle-to-gate. The impact categories considered include the Global Warming Potential (GWP) over 100 years, following the IPCC's 6th Assessment Report (AR6), with consideration given to all GHG, not just CO₂. The unit of measurement utilised is kg CO₂-eq. The functional units assessed in the report are the capacity of a finalised battery cell (measured in 1 kWh) and the capacity of a finalised battery module (measured in kWh). The assessment's time boundary was set at 2021, capturing the environmental impact within that specific timeframe. The supplier has used the Sphera tool LCA For Experts to model the impacts of the battery modules. Primary data has been used for energy input at the module supplier and at anode and cathode material suppliers. The cell manufacturing and module assembly uses hydropower as main electricity source and natural gas for heating.

The calculated emissions for the battery module from the manufacturer are based on predictions that will be implemented during summer 2024 in the form of purchase of renewable energy source permits.

The anode and cathode material suppliers will secure renewable electricity for their production, going into effect during summer 2024, some months after start of production. However, since the batteries will be produced for many years, the estimated effect of this improvement has been included in this vehicle study in accordance with Volvo cars specialist. Therefore, the majority of vehicles manufactured will incorporate battery modules produced through the acquisition of certificates for renewable energy sources.



← Figure 6

Assumed driving distances (km) per year during the lifetime of the vehicle.

2.9 Manufacturing and logistics

2.9.1 Logistics

Since Polestar 3 is produced in Volvo Car plants, Volvo Cars has provided data 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 (2022) 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 (2022) has been applied. Emission factors from the Network for Transport Measures (NTM)⁹ has been used as a basis for the calculations. The climate impact is not specified into emission categories, such as biogenic emission or fossil emissions and therefore has conservatively been assumed to only be associated with fossil emissions.

2.9.2 Manufacturing

A forecast of expected electricity (40 % hydro power, 60 % wind power with emission factor 0,01324 kg CO₂ eq./kWh) and natural gas usage in the Chengdu factory was obtained using site-specific input data. The GHG emissions per vehicle were then calculated by dividing the total GHG emissions from the factory by the expected total amount of produced vehicles from that factory during the first year of production.

2.10 Use phase

To be able to calculate the emissions in the use phase of the vehicle, the distance driven is needed together with the energy use, as well as emissions from electricity production. The vehicle lifetime driving distance for Polestar vehicles has been set to 200 000 km, and energy use of the vehicle corresponds to driving according to the WLTP driving cycle 20.1 kWh/100km.

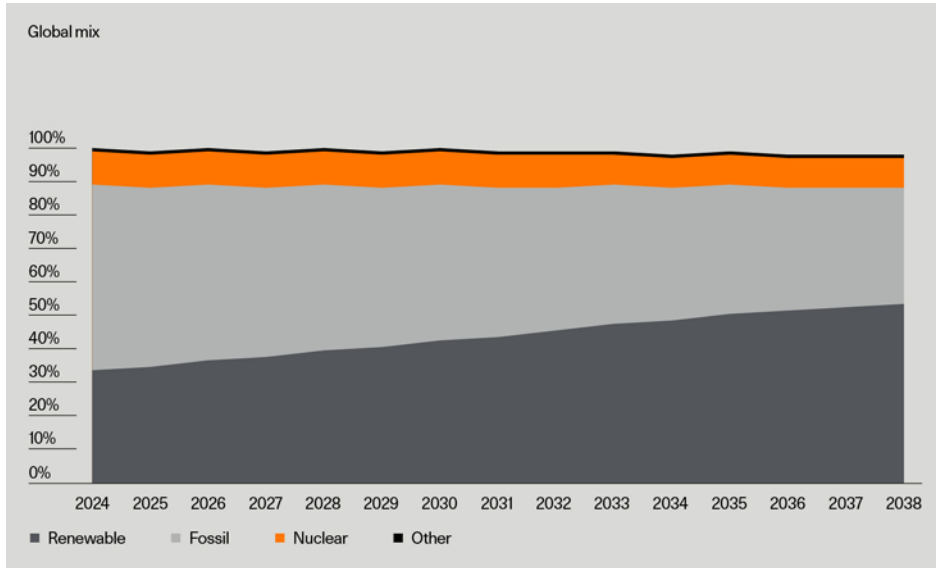
Electricity production is modelled according to three cases: regional (global and EU28) grid mix and as a specific energy source (wind). Current and future global and EU28 electricity generation mixes are based on the World Energy Outlook 2022 Extended Dataset¹⁰ from IEA. Amounts of electricity from different energy sources have in this study been paired with appropriate LCI datasets from Sphera professional database (see Appendix 1) to determine the total climate impacts from different electricity generation mixes, both direct (at the site of electricity generation) and upstream.

The study has correlated electricity quantities from various energy sources with relevant LCI datasets from Sphera (refer to Appendix 1) to assess the overall environmental impacts stemming from diverse electricity generation mixes. This evaluation encompasses both direct impacts (occurring at the electricity generation site) and upstream effects. The analysis assumes that 50% of a vehicle's total lifetime mileage is covered in the initial five years, equivalent to 20 000 kilometers per year, while 30% is driven in the subsequent five years, amounting to 12 000 kilometers annually.

During the last five year of the vehicle's life it is assumed that the yearly distance driven is 8 000 km, illustrated in Figure 6.

⁹ <https://www.transportmeasures.org/en/>

¹⁰ World Energy Outlook 2022 Extended Dataset - Data product - IEA



← Figure 7

Predicted share of energy production sectors in the Stated Policies Scenario STEPS for global energy mix.

IEA uses the Global Energy and Climate (GEC) Model to explore possible future energy related scenarios based on different assumptions. For this study, STEPS has been used to determine the electricity generation mixes used to charge the vehicles in the use phase. STEPS reflects current policy settings based on a sector-by-sector and country by country assessment of the specific policies that are in place, as well as those that have been announced by governments around the world.

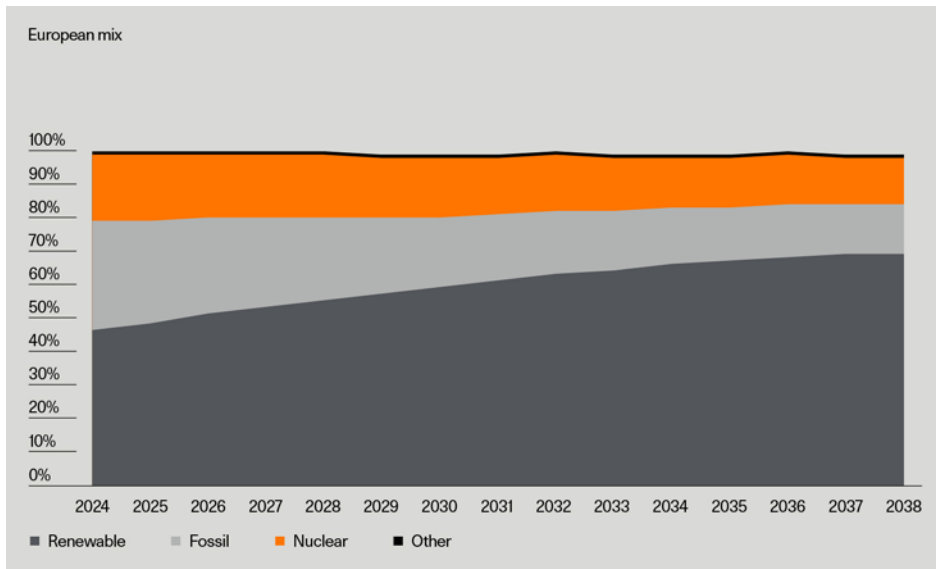
Figure 7 and Figure 8 visually represent the development of electricity sources. It is evident that the production of electricity from fossil sources is expected to diminish, gradually replaced by renewable sources based on the IEA STEPS data.

The well-to-wheel (WTW) emission data for the electricity usage for the vehicle is based on regulatory type-approval testing according to WLTP (Worldwide Harmonised Light Vehicle Test Procedure - used for certification of vehicles in EU). Losses during charging are included in the electricity use of the BEV. The electricity use of the vehicles is 20.1 kWh/100 km.

The energy use in the use phase is modelled based on the WLTP test as that is a global standard. WLTP does not, however, take all driving conditions into account, and, for example, assumes a driving condition where heating or cooling is not necessary and no use of infotainment in use. This could, especially for certain markets, lead to an underestimated energy use figure.

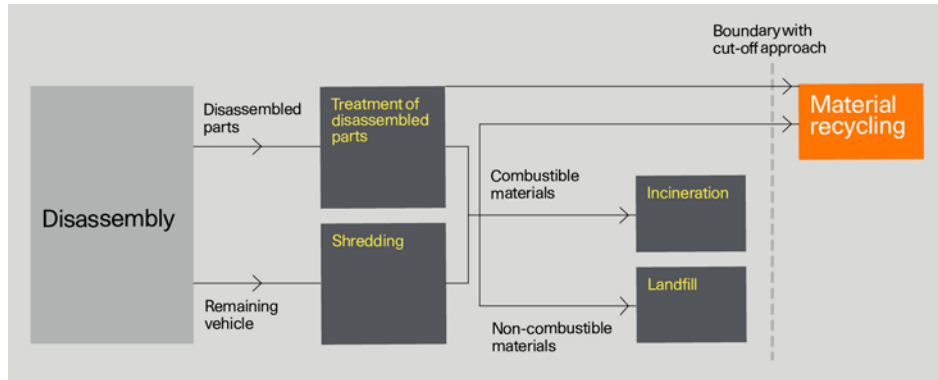
2.11 Maintenance

For 15 years lifespan of the vehicle, it is assumed that some vehicle parts are required to be replaced. The data for maintenance of the vehicle is based on data for maintenance of EX90, this vehicle model was chosen due to the accessibility of the information of its LCA study. The maintenance list is presented in Table 4. It is assumed that the number of items represents groups of items, e.g. one wiper blade represents the entire set of the three wiper blades, i.e. two front and one rear. The vehicle tyres are design to last 40 000 km. It is assumed that the tyres are not changed just before EoL, therefore 16 tyres need to be changed during the lifetime. For each part the corresponding item is found in the BoM and specific material data is used together with the corresponding dataset, in the same way as material production and refining.



← Figure 8

Predicted share of energy production sectors in the Stated Policies Scenario STEPS for European energy mix.



← Figure 9

End-of-life flow chart.

Table 4 →

Maintenance parts changed during the lifetime of the vehicle.

Vehicle part	Unit	
Wiper blades	number of sets	39
Tyres	number of items	16
Brake fluid	liters	2
Brake pads	number of items	24
Brake discs	number of items	4
Lead, battery 12 V	number of items	3
Steering joint	number of items	1
Link arm	number of items	2
Condenser	number of items	1
AC fluid	number of AC container volume	2
Cabin filter	number of items	12

2.12 End-of-life of the vehicle

It is assumed that all vehicles, at their EoL, are collected and sent to EoL treatment.

The same methodology as described in Chapter 1.5 Allocation 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, see Figure 9.

The EoL 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.

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

- batteries, wheels, tyres
- liquids: coolants, antifreeze, brake fluid, air-conditioning gas, shock absorber fluid and windscreen wash
- airbags and seat belt pretensioners removed or set off

From a global perspective, the treatment of coolant generally implies incineration. 55 %¹¹ of the tires are assumed to be salvaged for rubber recovery, and the rest to be incinerated. The lead batteries are assumed to be salvaged for lead recovery. Airbags and seat belt pretensioners, which are disassembled for safety reasons rather than the potential recycling value, are assumed to be incinerated. The Li-ion battery module is assumed to be taken out of the vehicle and sent to recycling. The assumption is that the Li-ion battery will be removed from the vehicle and sent for recycling due to the presence of valuable materials inside the battery module. This comes from the resource-intensive and economically costly processes involved in extracting and refining these materials. Additionally, it is anticipated that recycling legislation will become more stringent, particularly as the vehicle approaches the end of its lifecycle.

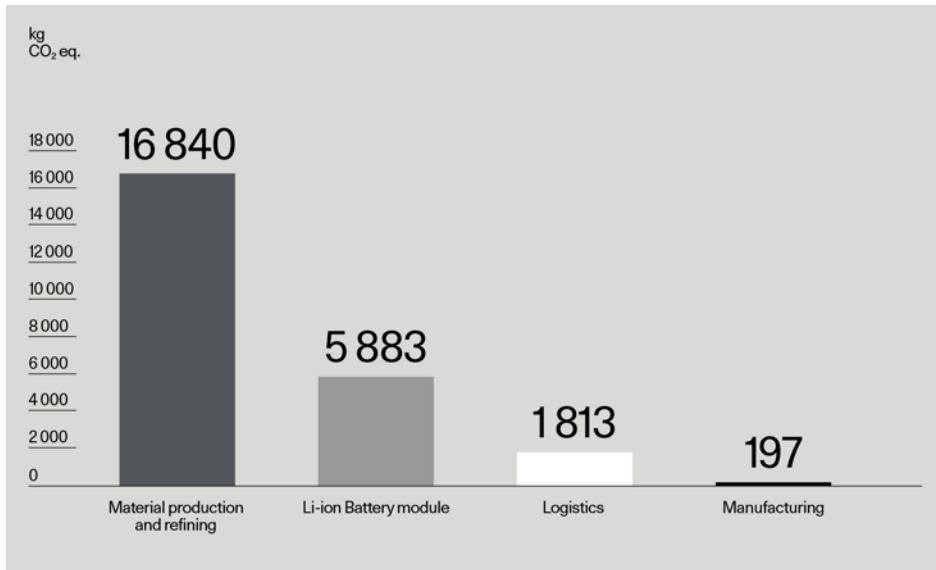
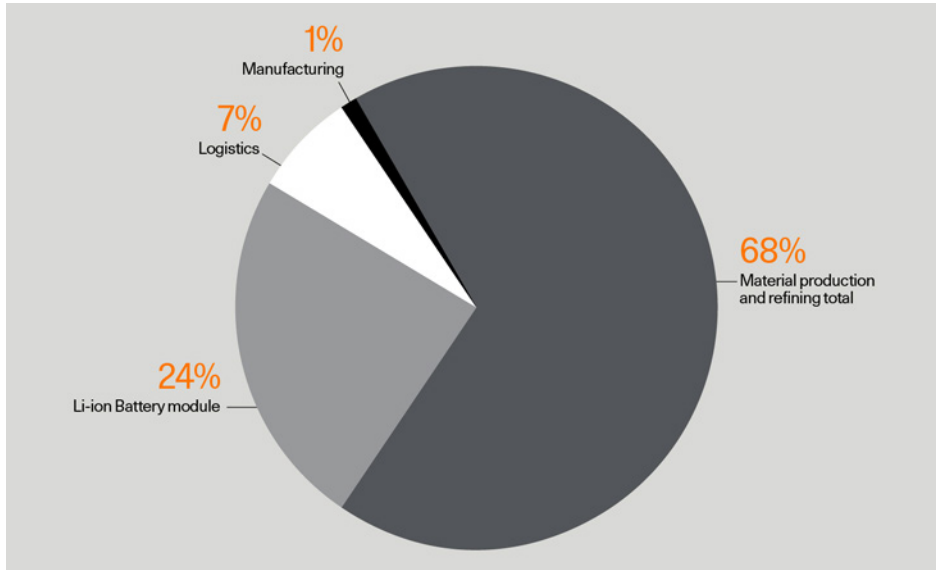
All other parts of the vehicle are sent to shredding. In this process, the materials in the vehicle are shredded and then divided into fractions, depending on different physical and magnetic properties. Typical fractions are:

- ferrous metals (steel, cast iron, etc.)
- non-ferrous metals (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 low 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.

¹¹ <https://weibold.com/europe-collected-and-recycled-94-percent-of-end-of-life-tires-in-2019#:~:text=According%20to%20ETRM%2C%2094%25%20of,between%2092%25%20and%2095%25.>



← Figure 10

Share of cradle-to-gate emissions in kg CO₂-eq. for 1 vehicle.

In the subsequent section, we present the findings of the study. It will start by showing cradle-to-gate results and then cradle-to-grave. It also includes a sensitivity analysis. In accordance with ISO standards, the quantified results within this report have been rounded to three significant digits. This practice serves to improve clarity and maintain consistency throughout the report. Rounding the figures aids in enhancing readability and acknowledges the inherent uncertainties associated with the results.

3.1 Cradle-to-gate

The results showcased in Figure 10 displays the total carbon footprint from cradle-to-gate concerning the production of 1 vehicle with a weight of 2.5 tonnes. As per this assessment, the largest share of impact, constituting 68% of the total, comes from the variety of materials utilised in the vehicle's production, relative from the different parts of the life cycle. Subsequently, the battery modules contribute significantly, accounting for 24% of the cradle-to-gate climate impact, while only a minor 7% of the total footprint is associated with logistics and 1% manufacturing processes.

Table 5 presents the comprehensive climate impact in tonnes CO₂-eq. throughout the cradle-to-gate life cycle of the vehicle. The total climate impact accounts for 24.7 tonnes CO₂-eq. for entire vehicle, being the material production and refining the category with the largest carbon footprint impact. See visualisation of results in Figure 11.

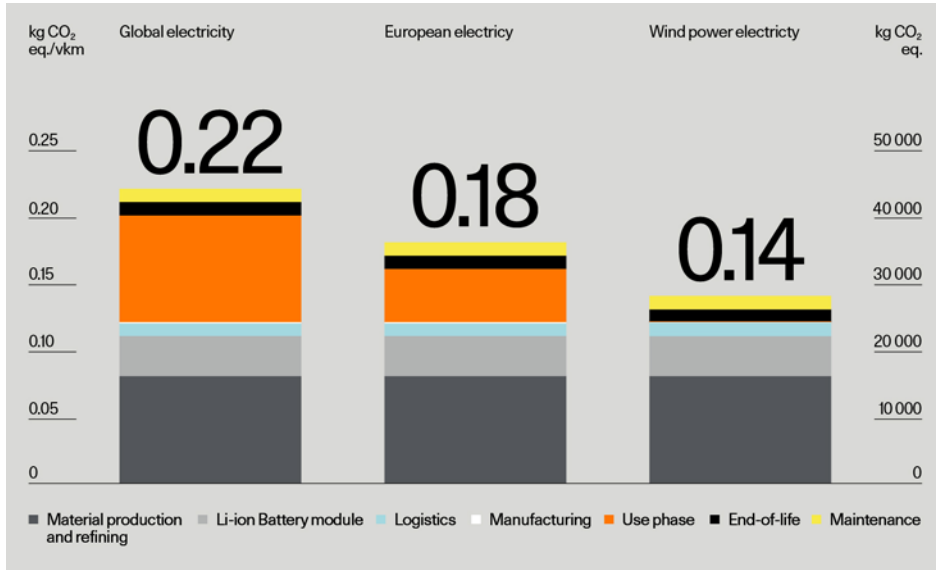
Table 5 →

Cradle-to-gate total climate impact in tonne CO₂-eq. for the life cycle of the vehicle.

Polestar 3	Materials production and refining	Li-ion battery modules	Manu-facturing	Logistics	Total
Tonnes CO ₂ -eq. per vehicle	16.8	5.88	0.20	1.81	24.7

← Figure 11

Cradle-to-gate total climate impact in kg CO₂-eq. for the life cycle of the vehicle.



← Figure 12

Total carbon footprint cradle-to-grave kg CO₂-eq. The axis to the left presents the functional unit of 1 vkm and the axis to the right presents the vehicles lifetime of 200 000km.

	Global electricity		European electricity		Wind power electricity	
	Tonnes CO ₂ -eq. per vehicle	g CO ₂ -eq. per vehicle-km	Tonnes CO ₂ -eq. per vehicle	g CO ₂ -eq. per vehicle-km	Tonnes CO ₂ -eq. per vehicle	g CO ₂ -eq. per vehicle-km
Materials production and refining	16.8	84.2	16.8	84.2	16.8	84.2
Li-ion battery modules	5.88	29.4	5.88	29.4	5.88	29.4
Manufacturing and logistics	2.01	10.1	2.10	10.1	2.10	10.0
Use phase STEPS	16.5	82.7	7.30	36.5	0.55	2.78
End-of-Life	1.17	5.87	1.17	5.87	1.18	5.88
Maintenance	2.05	10.3	2.11	10.3	2.06	10.3
Total	44.5	223	35.3	176	28.5	143

← Table 6

Cradle-to-grave kg CO₂-eq. climate impact with different energy mix during use phase for the functional unit 1 vkm, and for the entire life cycle of 1 vehicle with driving distance 200 000 km.

3.2 Cradle-to-grave

The results of the comprehensive LCA for the vehicle, considering three distinct electricity mixes, are presented in Table 12 for the cradle-to-grave study. Depending on the electricity mixes for the use phase, the climate impacts differ.

The life cycle stages with the most significant climate impact for the global electricity mix are "Materials Production and Refining and the use phase.

During the use phase, large variations are observed based on the electricity sources employed for driving. Wind power electricity exhibits the least climate impact during the use phase, followed by electricity from European sources.

Table 6 presents the climate impact in kg CO₂-eq. throughout the cradle-to-grave life cycle of the vehicle, for different energy mixes during use phase. The total climate impact accounts for 44.5 tonnes CO₂-eq. for entire vehicle with global energy mix, having the material production and refining and use phase being the categories with the largest carbon footprint impact.

For European energy mix and for wind powered electricity the highest climate impacts are seen in material production and refining and the use phase for the different electricity mix scenarios. Total climate impact accounts for 35.3 tonnes CO₂-eq. and 28.5 tonnes CO₂-eq. respectively, for entire vehicle.

Figure 12 displays the same results for both vehicle-kilometers and a lifetime driving distance of 200 000 kilometers for the three electricity scenarios.

3.2.1 Climate impact

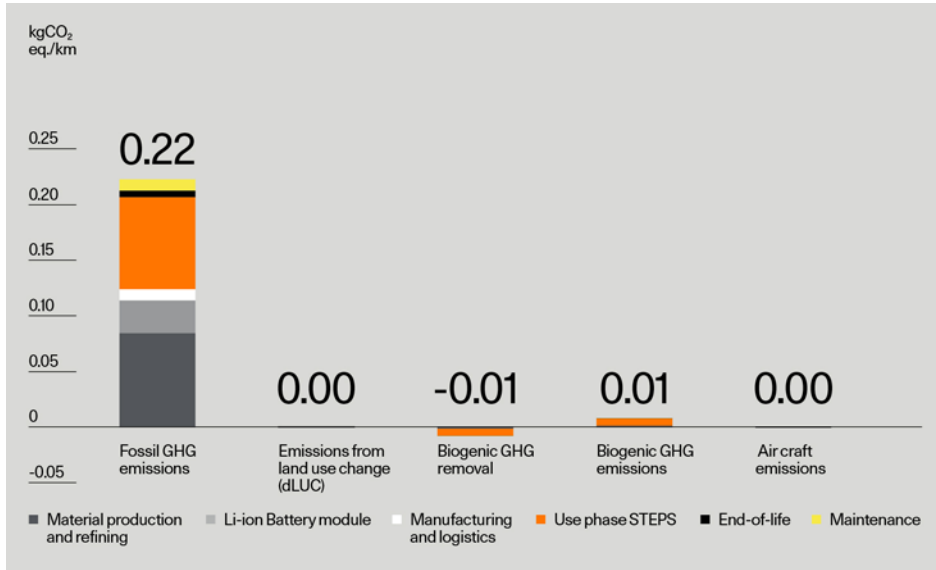
According to ISO 14067 this study includes the five different climate impact categories: fossil GHG emissions, emissions from land use change, biogenic GHG emissions and removal, and aircraft emissions.

The five climate change impact categories are shown in Figure 13. Fossil GHG emissions accounts for the largest portion of the total climate impact, with 96.5% of total GHG emissions followed by biogenic carbon emissions of 3.47%. Land use change emission together with air craft emissions are reported negligible in contrast to the other emissions. Biogenic carbon removal is equal in magnitude as biogenic emissions.

These percentages are based on the global energy mix, due to that mix being the most conservative for GWP. This is represented in Table 7. In Table 8 and Table 9 the two additional energy mixes are represented for each climate impact category.

3.2.2 Climate impact materials production and refining

The primary contributors to GHG emissions from vehicle manufacturing (excluding battery) are aluminium, accounting for than 14% of the total climate impact, followed by steel and iron at 10%. Additionally, the climate impact from polymers 7% and electronics 5% used in vehicles rank as the third and fourth most significant. Other categories such as fluids, copper, other metals, and tires also contribute to the overall emissions but to a lesser degree.



	Fossil GHG emissions g CO ₂ -eq.	Emissions from land use change (dLUC) g CO ₂ -eq.	Biogenic GHG removal g CO ₂ -eq.	Biogenic GHG emissions g CO ₂ -eq.	Air craft emissions g CO ₂ -eq.
Materials production and refining	84.3	0.05	-1.38	1.25	0
Li-ion battery modules	29.4	-	-	-	-
Manufacturing and logistics	10.1	-	-	-	-
Use phase STEPS	82.7	0	-6.33	6.33	0
End-of-Life	5.87	0	-0.07	0.07	0
Maintenance	10.3	0	-0.29	0.35	0

↑ Table 7

Results according to functional unit 1 vkm for the five climate impacts categories according to ISO 14067 with global energy mix in kg CO₂-eq.

← Figure 13

Results cradle-to-grave according to functional unit 1 vkm for the five climate impacts categories according to ISO 14067 with global energy mix in kg CO₂-eq.

↓ Table 8

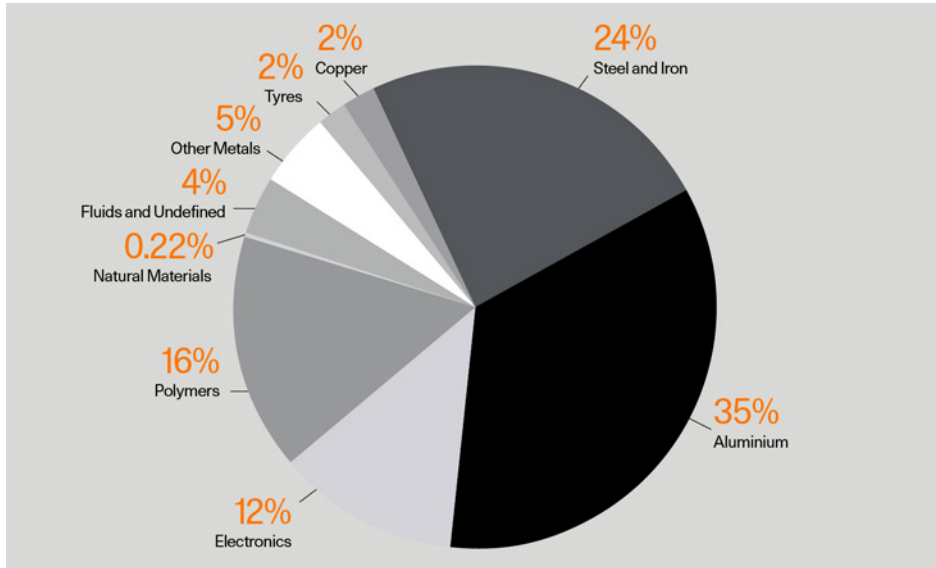
Results according to functional unit 1 vkm for the five climate impacts categories according to ISO 14067 with European energy mix in kg CO₂-eq.

	Fossil GHG emissions g CO ₂ -eq.	Emissions from land use change (dLUC) g CO ₂ -eq.	Biogenic GHG removal g CO ₂ -eq.	Biogenic GHG emissions g CO ₂ -eq.	Air craft emissions g CO ₂ -eq.
Materials production and refining	84.3	0.05	-1.38	1.25	0
Li-ion battery modules	29.4	-	-	-	-
Manufacturing and logistics	10.1	-	-	-	-
Use phase STEPS	36.4	0	-1.18	1.18	0
End-of-Life	5.87	0	-0.07	0.07	0
Maintenance	10.3	0	-0.03	0.03	0

	Fossil GHG emissions g CO ₂ -eq.	Emissions from land use change (dLUC) g CO ₂ -eq.	Biogenic GHG removal g CO ₂ -eq.	Biogenic GHG emissions g CO ₂ -eq.	Air craft emissions g CO ₂ -eq.
Materials production and refining	84.3	0.05	-1.38	1.26	0
Li-ion battery modules	29.4	-	-	-	-
Manufacturing and logistics	10.1	-	-	-	-
Use phase STEPS	2.77	0	-1.18	0	0
End-of-Life	5.87	0	-0.07	0	0
Maintenance	10.3	0.01	-0.03	0	0

↑ Table 9

Results according to functional unit 1 vkm for the five climate impacts categories according to ISO 14067 with wind energy in kg CO₂-eq.



← Figure 14

Share of GWP100 results in kg CO₂-eq. for different materials categories.

Table 10 shows the results for GWP100 in kg CO₂-eq. for the different materials used during the manufacturing of the vehicle and Figure 14 share of the results for GWP100 in kg CO₂-eq. of each material category.

	GWP100 Total Tonnes CO ₂ -eq.
Steel and Iron	4.40
Aluminium	6.30
Polymers	3.00
Electronics	2.10
Fluids and Undefined	0.70
Other Metals	0.90
Copper	0.30
Tyres	0.30
Natural Materials	0.04

Table 10 →

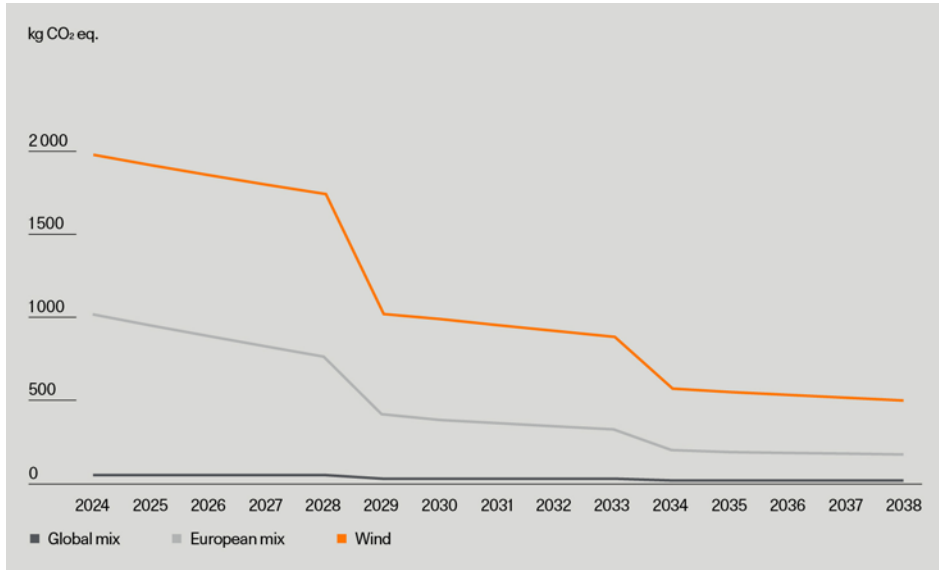
GWP100 results in kg CO₂-eq. for different materials categories.

3.2.3 Climate impact of battery

The results for the battery climate impact were provided by the supplier in a LCA report. The scope includes analysing processes from raw material extraction to the finalised product at the battery company gate. The impact categories focus on GWP over 100 years. Evaluation was based on two functional units: kWh capacity of battery cells, and modules, as explained in chapter 2.2. Data from primary processes managed by the reporting company, while specific data sources include manufacturing plants and contracted suppliers, energy used as electricity comes mainly from hydropower from purchase agreements, and thermal power generated from natural gas. Generic data was based on attributional modeling and represent the process's geographical region and extracted from LCI databases like ecoinvent and Sphera (GaBi professional). The results reveal that the primary sources of greenhouse gas emissions are the anode and cathode of the cell, along with the aluminum casing. Additionally, thermal energy from natural gas plays significant roles as major contributors in the production process but according to the report from the battery module supplier the impact is deemed to be reliable.

3.2.4 Use phase

One of the stages in the vehicle's life cycle with the greatest emissions is the use phase, encompassing the vehicle's entire operational lifespan and the associated electricity usage. The climate impact within this category depends on the origin of electricity production. Notably, for the different scenarios in the use phase electricity sourced from wind power has the least environmental impact during the use phase, followed by electricity generated through the European mix production.



← Figure 15

Climate impact results in kg CO₂-eq. per year during the lifetime of 1 vehicle with driving distance 200 000 km with different electricity mixes during use phase.

Considering the anticipated changes in electricity production—specifically, the reduction in fossil fuel-based electricity and the concurrent increase in renewable electricity forecasted from 2024, it is expected that yearly emissions will decline. The distances driven are then multiplied by the emission factors corresponding to each year, reflecting the changes in global and European electricity. This process yields the graphical representation shown in Figure 15. On average, the emissions throughout the entire lifespan amount to 0.41 kg CO₂-eq./kWh for the global electricity mix scenario and 0.18 kg CO₂-eq./kWh for the European electricity mix scenario.

To be able to calculate the emissions in the use phase of the vehicle, the well-to-wheel emissions from electricity production, are needed. During the lifetime of the vehicle (15 years) it is expected to drive 200 000 km.

The energy-related emissions associated with the actual driving of the vehicle consists of the environmental impact caused during production and distribution of the electricity used.

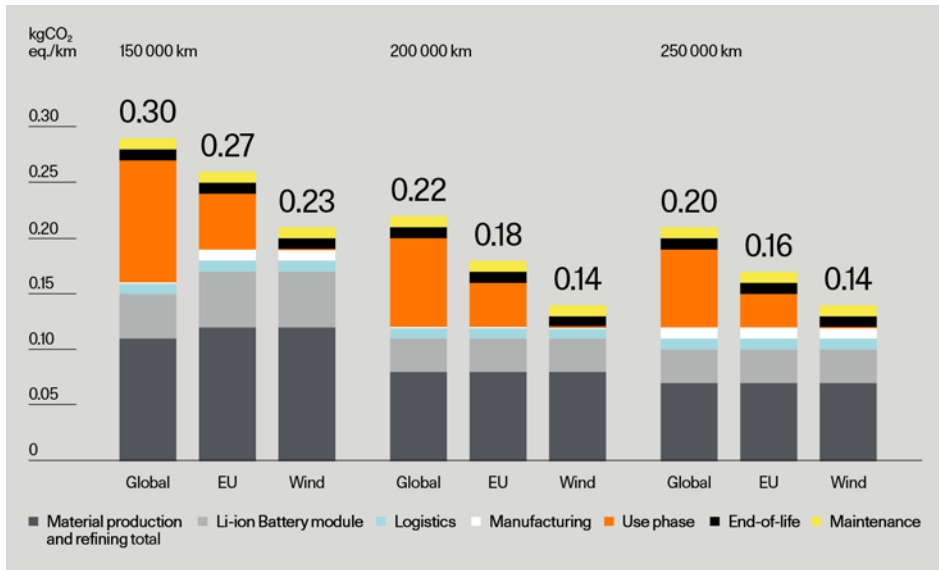
Electricity production is modelled according to three cases: regional (global and EU28) grid mixes and a specific energy source (wind). Current and future global and EU28 electricity generation mixes are based on the World Energy Outlook 2022 Extended Dataset¹² from IEA. Amounts of electricity from different energy sources have in this study been paired with appropriate LCI datasets from Sphera Database (see Appendix 1) to determine the total climate impacts from different electricity generation mixes, both direct (at the site of electricity generation) and upstream.

3.3 Sensitivity analysis

Given the predominantly conservative nature of the data in this study, exploring the climate impact of more probable data on the results is interesting. A sensitivity analysis was carried out to examine the climate impact of lifetime driving distance, and the electricity source during the use phase.

3.3.1 Lifetime driving distance

The current study assumes a lifetime distance driven of 200 000 km, as that is a common distance to use in personal vehicle LCA studies. Larger personal vehicles as the one studied here can, however, be argued to have a longer lifetime distance driven¹³. For that reason, a sensitivity analysis with a 250 000 km lifetime distance driven was carried out. And to explore the effects of a shorter lifetime distance driven, a sensitivity analysis of 150 000 km was also carried out. Figure 16 presents the results for the cradle-to-grave for the different driving distances together with different electricity scenarios.



← Figure 16

Sensitivity analysis lifetime driving distance per 1 vkm (functional unit) for driving distance 150 000 km, 200 000 km and 250 000 km.

12 <https://www.iea.org/data-and-statistics/data-product/world-energy-outlook-2022-extended-dataset>

13 <https://op.europa.eu/en/publication-detail/-/publication/1f494180-bc0e-11ea-811c-01aa75ed71a1>

Table 11 →

Parts changed during maintenance for different driving distances of the vehicle.

3.3.2 Maintenance scenario

Lifetime affects maintenance of the vehicle and Table 11 describes the maintenance for lifetimes included in the sensitivity analysis.

Vehicle part	Unit	150 000km	200 000km	250 000km
Wiper blades	number of sets	39	39	39
Tyres	number of items	12	16	24
Brake fluid	liters	2	2	2
Brake pads	number of items	16	24	32
Brake discs	number of items	4	4	8
Lead, battery 12 V	number of items	3	3	3
Steering joint	number of items	1	1	1
Link arm	number of items	2	2	2
Condenser	number of items	1	1	1
AC fluid	number of AC container volume	2	2	3
Cabin filter	number of items	9	12	15

In conclusion the climate impact of the cradle-to-gate study reveals that 68% is caused by the materials utilised in the vehicle's production, aluminium representing 24% of the emissions, and iron and steel contributing with 17%. Following closely, the production of battery modules emerges as a significant factor, constituting 24% of the cradle-to-gate impact.

The cradle-to-grave study reveals a total carbon footprint for the complete LCA for the vehicle an emission of 44 tonnes CO₂-eq. with global electricity mix in the use phase. 38% of the total climate impact is caused by the material production and refining, with aluminium representing 14% of the material and refining emissions, and iron and steel contributing with 10% in the same category. Following is the use phase contributing 37% of the vehicle's total climate impact, and then the battery modules, constituting 16% of the overall climate impact.

The study categorises the environmental impact into five climate change impact categories, as depicted in Figure 13. Fossil GHG emissions emerge as the predominant contributor, accounting for 96.5% of the total climate impact. Biogenic carbon emission comes on second place with 3.47% which is low in comparison to the fossil emission.

Due to the use phase contributing such a large share of the emissions for the lifetime of the vehicle the emissions connected to the electricity production during this phase is of importance. One can see in Figure 12 that from the different scenario's renewable electricity production such as wind power lowers the emission of the overall lifetime emission of the vehicle. The same goes for European energy mix, however not contributing to the same extent. This is due to the share of production being renewable sources is bigger in those mixes.

When considering emissions linked to battery manufacturing, the emissions might appear relatively low. However, in cell manufacturing 100% renewable electricity is used. For the cathode and anode production 100% renewable electricity will be implemented summer 2024. With electricity use in production being one of the major contributors to emissions in battery module production, this correlates to the presented result.

The results of sensitivity analysis for two different driven lifetime km scenarios, 150 000 km and 250 000 km, demonstrate that the longer distance driven by the vehicle over the lifetime the lower the emissions per km. This suggests that whilst total emissions will be higher, on a per-kilometre basis, the environmental footprint of the vehicle is lower when covering a longer lifetime distance (i.e. fewer vehicles are required to provide the same utility in terms of km driven). As it is strived for more sustainable transportation solutions, these results emphasize the potential benefits of optimizing vehicle usage over its entire lifespan for an eco-friendlier future.

The EU regulation¹⁴ regarding batteries and waste batteries from 2023 outlines the importance for future end of life handling of lithium-ion batteries. The framework emphasizes various crucial elements such as recycled content, collection rates, and end-of-life considerations.

14 REGULATION (EU) 2023/1542 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and repealing Directive 2006/66/EC

The regulation places a strong emphasis on harmonising product and marketing requirements across the life cycle of batteries. To enhance future reports, environmental implications associated with the disposal and recycling of batteries utilised in vehicles would be beneficial. This would give a more comprehensive picture of the impacts and challenges linked to the end-of-life management of batteries in the context of electric vehicles.

Environmental sustainability involves a multifaceted perspective. While the focus of the study has been on carbon emissions following ISO 14 067, future assessments should also aim to broaden the scope by incorporating other significant environmental impact categories such as water consumption, resource depletion, and ecosystem impacts. Expanding the analysis will yield a more holistic evaluation of the vehicle's environmental performance, allowing the possibility to make more informed decisions about its overall sustainability. It could be also interesting involve alternative future energy scenarios in addition to STEPS.

Material and refining is there for identified as one of the hot spots with total climate impact of 38%, when using global energy mix in use phase. It is there for recommended to further evaluate the possibility to lower these emissions.

In the LCA a large number of generic datasets from databases are used. In this appendix the datasets used are listed, see Table 12. Some materials are listed multiple times with different datasets. The reason is that the material carbon footprint is modelled based on a mix of the different datasets corresponding to the material composition.

Table 12 →
Chosen datasets for materials.

Material	Location	Dataset name	Type	Source
ABS	GLO	market for acrylonitrile-butadiene-styrene copolymer	agg	ecoinvent 3.9.1
Aluminium	CN	aluminium ingot mix IAI 2015	agg	IAI/Sphera professional database
Aramid	DE	aramide fiber (para-aramid)	agg	Sphera professional database
Brake fluid	GLO	market for diethylene glycol	agg	ecoinvent 3.9.1
Cast iron	DE	cast iron part (automotive) – open energy inputs	p-agg	Sphera professional database
Catalytic coating	ZA	market for platinum group metal concentrate	agg	ecoinvent 3.9.1
Copper	EU-28	copper Wire Mix (Europe 2015)	agg	DKI/ECI
Copper alloys	GLO	copper mix (99.999% from electrolysis) (65%)	agg	Sphera professional database
Copper alloys	GLO	market for zinc (35%)	agg	ecoinvent 3.9.1
Cotton	GLO	market for textile, woven cotton	agg	ecoinvent 3.9.1
Damper	RER	Polymethylmethacrylate sheet (PMMA) (60%)	agg	PlasticsEurope
Damper	RoW	market for lime (40%)	agg	ecoinvent 3.9.1
E/P	GLO	polyethylene production, low density, granulate	agg	ecoinvent 3.9.1
Electronics	GLO	market for printed wiring board, surface mounted, unspecified, Pb containing	agg	ecoinvent 3.9.1
EPDM	DE	ethylene Propylene Diene Elastomer (EPDM)	agg	Sphera professional database
Epoxy	GLO	market for epoxy resin, liquid	agg	ecoinvent 3.9.1
EVAC	GLO	market for ethylene vinyl acetate copolymer	agg	ecoinvent 3.9.1
Ferrite magnet	GLO	market for ferrite	agg	ecoinvent 3.9.1
Float glass	EU-28	float flat glass	agg	Sphera professional database

Material	Location	Dataset name	Type	Source
Friction	DE	cast iron part (automotive) – open energy inputs (48%)	agg	Sphera professional database
Friction	GLO	market for zirconium oxide (12%)	agg	ecoinvent 3.9.1
Friction	GLO	market for graphite (11%)	agg	ecoinvent 3.9.1
Friction	GLO	market for barium sulfide (10%)	agg	ecoinvent 3.9.1
Friction	GLO	market for barite (7%)	agg	ecoinvent 3.9.1
Friction	GLO	market for aluminium hydroxide (5%)	agg	ecoinvent 3.9.1
Friction	GLO	market for magnesium oxide (4%)	agg	ecoinvent 3.9.1
Friction	GLO	market for expanded vermiculite (2%)	agg	ecoinvent 3.9.1
Friction	EU-28	calcined petroleum (2%)	agg	Sphera professional database
GF-fibre	GLO	market for glass fibre	agg	ecoinvent 3.9.1
Glycol	EU-28	ethylene glycol	agg	PlasticsEurope
Lead, battery	DE	lead (99.995%)	agg	Sphera professional database
Lubricants	EU-28	lubricants at refinery	agg	Sphera professional database
Magnesium	CN	magnesium	agg	Sphera professional database
NdFeB	GLO	market for permanent magnet, electric passenger car motor	agg	ecoinvent 3.9.1
NR	DE	natural rubber (NR)	agg	Sphera professional database
PA	GLO	market for nylon 6	agg	ecoinvent 3.9.1
PBT	DE	polybutylene Terephthalate Granulate (PBT) Mix	agg	Sphera professional database
PC	GLO	market for polycarbonate	agg	ecoinvent 3.9.1
PE	RoW	polyethylene production, low density, granulate	agg	ecoinvent 3.9.1
PET	GLO	market for polyethylene terephthalate, granulate, amorphous	agg	ecoinvent 3.9.1
PMMA	RER	polymethylmethacrylate sheet (PMMA)	agg	PlasticsEurope
Polymer, recycled	EU-28	Plastic granulate secondary (low metal contamination)	agg	Sphera professional database
Polyester	GLO	market for fibre, polyester	agg	ecoinvent 3.9.1

Material	Location	Dataset name	Type	Source
Polyurethane	RoW	market for polyurethane, rigid foam	agg	ecoinvent 3.9.1
POM	EU-28	polyoxymethylene (POM)	agg	PlasticsEurope
PP	GLO	market for polypropylene, granulate	agg	ecoinvent 3.9.1
PS	GLO	market for polystyrene, general purpose	agg	ecoinvent 3.9.1
PVB	DE	polyvinyl butyral granulate (PVB) by-product ethyl acetate	agg	Sphera professional database
PVC	GLO	polyvinylchloride production, suspension polymerisation	agg	ecoinvent 3.9.1
R-1234yf	DE	R-1234yf production (approximation)	agg	Sphera professional database
SBR	DE	styrene-butadiene rubber (S-SBR) mix	agg	Sphera professional database
Silicone rubber	DE	silicone rubber (RTV-2, condensation)	agg	Sphera professional database
Steel, Sintered	Asia	steel hot dip galvanised (1%)	agg	worldsteel
Steel, Stainless, Austenitic	EU-28	stainless steel cold rolled coil (304)	p-agg	Eurofer
Steel, Stainless, Ferritic	EU-28	stainless steel cold rolled coil (430)	p-agg	Eurofer
Steel, Unalloyed	Asia	steel hot dip galvanised (99%)	agg	worldsteel
Sulphuric acid	EU-28	sulphuric acid (96%)	agg	Sphera professional database
Thermoplastic elastomers	DE	polypropylene / Ethylene Propylene Diene Elastomer Granulate (PP/EPDM, TPE-O) Mix	agg	Sphera professional database
Thermoplastics	GLO	market for nylon 6	agg	ecoinvent 3.9.1
Tyre	DE	styrene-butadiene rubber (S-SBR) mix (21%)	agg	Sphera professional database
Tyre	EU-28	water (deionised) (79%)	agg	Sphera professional database
Undefined	GLO	market for nylon 6	agg	ecoinvent 3.9.1
Washer fluid	DE	Ethanol (96%) (hydrogenation with nitric acid)	agg	Sphera professional database
Wood (paper, cellulose...)	EU-28	Laminated veneer lumber (EN15804 A1-A3)	agg	Sphera professional database
Zinc	GLO	Special high-grade zinc	p-agg	IZA

Process	Location	Name	Type	Source
Aluminium manufacturing	DE	aluminium die-cast part	u-so	ts
Aluminium manufacturing	EU-28	aluminium sheet – open input aluminium rolling ingot	p-agg	ts
Aluminium manufacturing	DE	aluminium sheet deep drawing	u-so	ts
Polymers (all categories) manufacturing	DE	Plastic injection moulding part (unspecific)	u-so	ts
Stainless (all categories) manufacturing	DE	Steel sheet deep drawing (multi-level)	u-so	ts
Tyre	GLO	vulcanisation of synthetic rubber (without additives)	u-so	Sphera professional database

Electricity	Location	Name	Year	Type	Source
Electricity grid mix	RER	Electricity grid mix 1kV-60kV	2019	agg	Sphera professional database
Chinese electricity grid mix	CN	Electricity grid mix 1kV-60kV	2019	agg	Sphera professional database
Thermal energy from natural gas	CN	CN Thermal energy from natural gas	2019	agg	Sphera professional database
Natural gas	CN	CN Natural gas mix	2019	agg	Sphera professional database

↑ Table 14

Chosen datasets for energy and electricity for manufacturing.

← Table 13

Chosen datasets for manufacturing processes.

Material category	Location	Name of LCI dataset	Year	Type	LCI database
Use phase					
Electricity from solar power	RER	Electricity from photovoltaic	2019	agg	Sphera professional database
Electricity from wind power	RER	Electricity from wind power	2019	agg	Sphera professional database
Electricity from geothermal	RER	Electricity from geothermal	2019	agg	Sphera professional database
Electricity from hydro power	RER	Electricity from hydro power	2019	agg	Sphera professional database
Electricity from bioenergy	RER	Electricity from biomass (solid)	2019	agg	Sphera professional database
Electricity from nuclear power	RER	Electricity from nuclear	2019	agg	Sphera professional database
Electricity from unabated coal	RER	Electricity from lignite	2019	agg	Sphera professional database
Electricity from unabated gas	RER	Electricity from natural gas	2019	agg	Sphera professional database
Electricity from oil	RER	Electricity from heavy fuel oil (HFO)		agg	Sphera professional database

↑ Table 15

Chosen data sets for electricity for use phase.

Table 16 →
IMDS 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	Steel and iron
Aluminium	Aluminium
Low carbon aluminium	Aluminium
Recycled aluminium	Aluminium
Copper alloys	Copper
Magnesium	Other Metals
Zinc	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

Material name	Material group
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
Thermoplastics	Polymers
Thermoplastic elastomers	Polymers
Elastomer	Polymers
EPDM	Polymers
NR	Polymers
SBR	Polymers
Silicone rubber	Polymers

Material name	Material group
Epoxy	Polymers
Polyurethane	Polymers
Damper	Polymers
Polyester	Polymers
Aramid	Polymers
Tyre	Elastomer
Recycled Tyre	Elastomer
Lubricants (matcat)	Fluids & Undefined
Brake fluid	Fluids & Undefined
Catalytic coating	Fluids & Undefined
Ceramic	Fluids & Undefined
Damper	Fluids & Undefined
Ferrite magnet	Fluids & Undefined
Float glass	Fluids & Undefined
Friction	Fluids & Undefined
GF-Fibre	Fluids & Undefined
Glycol	Fluids & Undefined
Lead, battery	Fluids & Undefined
Sulphuric acid	Fluids & Undefined
Cotton	Natural Materials
Wood (paper, cellulose...)	Natural Materials
Washer fluid	Fluids & Undefined
Undefined	Fluids & Undefined
R-1234yf	Fluids & Undefined
NR	Natural Materials

Table 17 →

Summary of data choices and assumptions for component manufacturing.

Material	Assumption on component manufacturing	Comment	Material utilisation 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).	
Tyres	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 4: End-of-life assumptions and method

Transport

Transportation of materials sent to material recycling is included and is conservatively assumed to be transported 100 km by truck.

Disassembly

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

Pre-treatment

Pre-treatment was included for the following disassembled components:

- Lead acid battery
- Tyres
- Li-ion batteries

For the lead acid batteries and tyres, ecoinvent datasets were used for the pre-treatment stage. The Li-ion battery is conservatively assumed to be transported 1500 km by truck to the recycling facility according to Polestar logistics specialist. 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 that are incinerated likewise do not go through any pre-treatment.

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 usage per kg in the dataset "treatment of used glider", passenger car, shredding from ecoinvent 3.9.1 was used. The electricity used for this process was modelled as a 2038 global electricity mix, based on the IEA STEPS scenario and Sphera professional database data. 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.

Material recycling

This is the fate of the flows of metals from the shredding, as well as for the materials in the pretreated 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.

Final disposal – incineration and landfill

The disassembled fluids 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 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 Sphera 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 Sphera.

Transportation of materials which are separated in the shredding processes and which are assumed to be recycled is conservatively estimated to be 100 km by truck.

Data collection

This section provides an overview of the data collection activities relating to each life cycle stage, see Table 12.

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

Table 18 →

Data collection activities.

Disassembly stage	Pre-processing stage	Final disposal
Batteries	Separated handling. Lead recovery from lead acid and designated Li-ion battery dismantling	According to material category*
Tyres	Pre-treatment for tyre recycling	None (sent to material recycling)
Liquids (coolants, brake fluid etc)		Incineration
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 materials to incineration (mainly plastics) and residue to landfill		

Table 19 lists the data quality indicators used to assess the data used in this study. Each datapoint has received a score from 1 (best) to 5 (worst) according to five different correlation aspects. Table 20 lists the scores for the data used for materials production and refining in the study. Table 21 summarises the findings.

For the temporal and geographical correlation, the scores vary widely. The datasets from ecoinvent are generally more than 10 years old, while Sphera professional database datasets tend to be less than three years old. The most important reason why the geographical correlation varies widely is that the origin of many materials is unknown. The origin of the materials that are used in the largest quantity and with the largest overall climate impact, however, score 1-2 on geographical coverage: aluminium, steel and battery modules. Another material group with high climate impact is electronics. Electronics scores poorly on both time, geographical and technological correlation, which should be considered when interpreting the results. Overall, technological correlation also has a large variation in scores, however, the majority of the data has 2 as score. Representativeness and precision have good scores, as the data is from databases or supplier specific.

Car manufacturing and logistics receive overall good scores as the data is collected from own production facilities and controlled processes. The use phase also scores well, as electricity usage data is based on vehicle specific measurements, and climate impact calculations are based on fairly new emission factors from the professional database (2021) and current and forecasted electricity mix data from IEA. The End-of-Life treatment receives fewer good scores as data from the current state is used, and it is highly uncertain how well it correlates to the conditions in 15 years. It is also highly uncertain how the waste handling will be (and in some cases currently is) performed in different markets.

Based on the comprehensive assessment of data quality, it is indicated that the data quality requirements outlined in section 1.7 are met.

Table 19 →

Data quality indicator matrix used to assess the data used in the study.

Aspect	1	2	3	4	5
Temporal correlation (time related coverage)	Less than three years of difference to year of study (dataset from 2020-2023)	Less than six years of difference (dataset from 2017-2019)	Less than 10 years of difference (dataset from 2013-2016)	Less than 15 years of difference (dataset from 2008-2012)	Age of data unknown or more than 15 years of difference (dataset age unknown or before 2007)
Geographical correlation	Data from area of process origin (it is likely that our material comes from this country and we are using a dataset from that country, e.g. Al produced in China, and we use a dataset for China production)	Average data from larger area in which area of process origin is included (it is likely that our material comes from this country and we are using a dataset from that continent, e.g. Al produced in China, and we use a dataset for Asia)	Data from area with similar production conditions (it is likely that our material comes from this continent/country and we are using a dataset for a continent/country with similar production conditions (e.g. plastic produced in Europe, and we use a dataset for Germany)	Data from specified area used for process in unknown area (we don't know where the material comes from, and use a global dataset, e.g. we don't know where the plastics comes from and use a global dataset)	Data from area with very different production conditions (we know the material is produced in China, but we use a dataset for Europe, unknown production location of plastic we use data for production in Germany)
Technological correlation	Data from enterprises, processes and materials under study (data from actual site, for example VCC data for vehicle manufacturing)	Data from processes and materials under study but from different enterprise or group of enterprises (use of data for production of aluminium for production of aluminium)	Data from processes and materials under study but from different technology (use of data for production of copper wire for production of all copper that is not copper alloy)	Data on related processes or materials but same technology (using data for ceramic glass to represent production of MICA)	Data on related processes or materials but different technology (we don't know the global technological match to our EoL model, e.g. recycling share etc)
Representative	Representative data from sufficient sample over an adequate period to even out normal fluctuations (this includes future projection if necessary) (using data for VCC annual production for vehicle manufacturing, generic data from a database)	Representative data from a small sample but for adequate periods (only one out of two factories, but for full year)	Representative data from sufficient sample but from shorter periods (primary data for only two months)	Representative data but from a small sample and shorter periods or incomplete data from sufficient sample and periods (maintenance)	Representativeness unknown or incomplete data from a small sample and/or shorter periods (maintenance)
Precision	Verified data based on measurements (primary data from our own sites but also generic data from databases such as Sphera andecoinvent, third party verified data form supplier)	Verified data partly based on assumptions or non-verified data based on measurements (battery supplier data)	Non-verified data partly based on assumptions (share of cast and wrought aluminium)	Qualified estimate (e.g. by industrial expert) (maintenance, where material comes from)	Non-qualified estimate (share of recycled plastic split on different types of plastic)

Table 20 →

Quality assessment of data used for materials and processes in the study.

Material/process	Location	Dataset name	Year	Source	Correlation score				
					Temporal	Geographical	Technological	Representative	Precision
ABS	GLO	market for acrylonitrile-butadiene-styrene copolymer	2023	ecoinvent 3.9.1	1	4	2	1	1
Aluminium	CN	aluminium ingot mix IAI 2015	2015	IAI/Sphera professional database	3	1	2	1	1
Aluminium from hydropower	CN		2022	Polestar's own investigations	1	1	1	1	2
Aramid	DE	aramide fiber (para aramid)	2021	Sphera professional database	1	5	2	1	1
Battery modules	CN		2022	Battery module supplier	1	1	1	1	2
Brake fluid	GLO	market for diethylene glycol	2023	Ecoinvent 3.9.1	1	4	2	1	1
Cast iron	DE	cast iron part (automotive) - open energy inputs	2021	Sphera professional database	1	5	2	1	1
Catalytic coating	ZA	market for platinum group metal concentrate	2015	ecoinvent 3.9.1	3	5	2	1	1
Copper	EU-28	copper Wire Mix (Europe 2015)	2015	DKI/ECI	3	5	3	1	1
Copper alloys	GLO	copper mix (99.999% from electrolysis)	2021	Sphera professional database	1	4	2	1	1
Copper alloys	GLO	market for zinc	2011	ecoinvent 3.9.1	4	4	2	1	1
Copper alloys	GLO	tin	2021	Sphera professional database	1	4	2	1	1
Cotton	GLO	market for textile, woven cotton	2011	ecoinvent 3.9.1	4	4	2	1	1
Damper	RER	Polymethylmethacrylate sheet (PMMA)	2005	PlasticsEurope	5	5	2	1	1
Damper	RoW	market for lime	2011	Ecoinvent 3.9.1	5	5	2	1	1
E/P	GLO	polyethylene production, low density, granulate	2011-2016	ecoinvent 3.9.1	3	4	3	1	1

Material/process	Location	Dataset name	Year	Source	Correlation score				
					Temporal	Geographical	Technological	Representative	Precision
Electronics	GLO	market for printed wiring board, surface mounted, unspecified, Pb containing	2011	Ecoinvent 3.9.1	4	4	3	1	1
EPDM	DE	ethylene Propylene Diene Elastomer (EPDM)	2021	Sphera professional database	1	5	2	1	1
Epoxy	GLO	market for epoxy resin, liquid	2011	ecoinvent 3.9.1	4	4	2	1	1
EVAC	GLO	market for ethylene vinyl acetate copolymer	2011	Ecoinvent 3.9.1	4	4	2	1	1
Ferrite magnet	GLO	market for ferrite	2011	ecoinvent 3.9.1	4	4	3	1	1
Float glass	EU-28	float flat glass	2021	Sphera professional database	1	5	2	1	1
Friction	DE	cast iron part (automotive) - open energy inputs	2021	Sphera professional database	1	5	4	1	1
Friction	GLO	market for zirconium oxide	2011	ecoinvent 3.9.1	4	4	4	1	1
Friction	GLO	market for graphite	2011	ecoinvent 3.9.1	4	4	4	1	1
Friction	GLO	market for barium sulfide	2015-2020	ecoinvent 3.9.1	1	4	4	1	1
Friction	GLO	market for barite	2011	ecoinvent 3.9.1	4	4	4	1	1
Friction	GLO	market for aluminium hydroxide	2011	ecoinvent 3.9.1	4	4	4	1	1
Friction	GLO	market for magnesium oxide	2011	Ecoinvent 3.9.1	4	4	4	1	1
Friction	GLO	market for expanded vermiculite	2011	ecoinvent 3.9.1	4	4	4	1	1
Friction	EU-28	calcined petroleum	2021	Sphera professional database	1	5	4	1	1
GF-fibre	GLO	market for glass fibre	2011	ecoinvent 3.9.1	4	4	2	1	1
Glycol	EU-28	ethylene glycol	2008	PlasticsEurope	4	5	2	1	1

Lead, battery	DE	lead (99.995%)	2021	Sphera professional database	1	5	2	1	1
Leather	CN		2022	Bridge of Weir	1	1	1	1	2
Lubricants	EU-28	lubricants at refinery	2018	Sphera professional database	2	5	2	1	1
Magnesium	CN	magnesium	2021	Sphera professional database	1	5	2	1	1
NdFeB	GLO	market for permanent magnet, electric passenger car motor	1995-2002	Ecoinvent 3.9.1	5	4	2	1	1
NR	DE	natural rubber (NR)	2021	Sphera professional database	1	5	2	1	1
PA	GLO	market for nylon 6	2011	ecoinvent 3.9.1	4	4	2	1	1
PBT	DE	polybutylene Terephthalate Granulate (PBT) Mix	2021	Sphera professional database	1	5	2	1	1
PC	GLO	market for polycarbonate	2011	ecoinvent 3.9.1	4	4	2	1	1
PE	RoW	polyethylene production, low density, granulate	2011-2016	ecoinvent 3.9.1	3	5	2	1	1
PET	GLO	market for polyethylene terephthalate, granulate, amorphous	2011	Ecoinvent 3.9.1	4	4	2	1	1
PMMA	RER	polymethylmethacrylate sheet (PMMA)	2005	PlasticsEurope	5	5	2	1	1
Polymer, recycled	EU-28	Plastic granulate secondary (low metal contamination)	2021	Sphera professional database	1	5	3	1	1
Polyester	GLO	market for fibre, polyester	2007-2022	Ecoinvent 3.9.1	1	4	2	1	1
Polyurethane	RoW	market for polyurethane, rigid foam	2011	Ecoinvent 3.9.1	4	5	2	1	1
POM	EU-28	polyoxymethylene (POM)	2010	PlasticsEurope	4	5	2	1	1
PP	GLO	market for polypropylene, granulate	2011	ecoinvent 3.9.1	4	4	2	1	1
PS	GLO	market for polystyrene, general purpose	2011	Ecoinvent 3.9.1	4	4	2	1	1

Material/process	Location	Dataset name	Year	Source	Correlation score				
					Temporal	Geographical	Technological	Representative	Precision
PVB	DE	polyvinyl butyral granulate (PVB) by-product ethyl acetate	2021	Sphera professional database	1	5	2	1	1
PVC	GLO	polyvinylchloride production, suspension polymerisation	2013-2018	Ecoinvent 3.9.1	2	4	2	1	1
R-1234yf	DE	R-1234yf production (approximation)	2021	Sphera professional database	1	5	3	1	1
SBR	DE	styrene-butadiene rubber (S-SBR) mix	2021	Sphera professional database	1	5	2	1	1
Silicone rubber	DE	silicone rubber (RTV-2, condensation)	2021	Sphera professional database	1	5	2	1	1
Steel, Sintered	Asia	steel hot dip galvanised	2020	worldsteel	1	2	3	1	1
Steel, Stainless, Austenitic	EU-28	stainless steel cold rolled coil (304)	2014	Eurofer	3	5	2	1	1
Steel, Stainless, Ferritic	EU-28	stainless steel cold rolled coil (430)	2014	Eurofer	3	5	2	1	1
Steel, Unalloyed	Asia	steel hot dip galvanised	2020	worldsteel	1	2	2	1	1
Sulphuric acid	EU-28	sulphuric acid (96%)	2021	Sphera professional database	1	5	2	1	1
Thermoplastic elastomers	DE	polypropylene / Ethylene Propylene Diene Elastomer Granulate (PP/EPDM, TPE-O) Mix	2021	Sphera professional database	1	5	3	1	1
Thermoplastics	GLO	market for nylon 6	2011	Ecoinvent 3.9.1	1	4	3	1	1
Tyre	DE	styrene-butadiene rubber (S-SBR) mix	2021	Sphera professional database	1	5	2	1	1
Tyre	EU-28	water (deionised)	2021	Sphera professional database	1	5	2	1	1
Tyre	GLO	vulcanisation of synthetic rubber (without additives)	2021	Sphera professional database	1	4	2	1	1
Undefined	GLO	market for nylon 6	2011	ecoinvent 3.9.1	1	4	5	1	1

Washer fluid	DE	Ethanol (96%) (hydrogenation with nitric acid)	2021	Sphera professional database	1	5	3	1	1
Wood (paper, cellulose ...)	EU-28	Laminated veneer lumber (EN15804 A1-A3)	2021	Sphera professional database	1	5	3	1	1
Zinc	GLO	Special high grade zinc	2018	IZA	2	4	3	1	1
Aluminium manufacturing	DE	aluminium die-cast part	2021	ts	1	5	3	1	1
Aluminium manufacturing	EU-28	aluminium sheet – open input aluminium rolling ingot	2021	ts	1	5	3	1	1
Aluminium manufacturing	DE	aluminium sheet deep drawing	2021	ts	1	5	3	1	1
Polymers (all categories) manufacturing	DE	Plastic injection moulding part (unspecific)	2021	ts	1	5	2	1	1
Steel (all categories) manufacturing	DE	Steel sheet deep drawing (multi-level)	2021	ts	1	5	3	1	1

Data points	Material production and refining	Car manufacturing, inbound and outbound logistics	Use of vehicle	End-of-life treatment
Temporal correlation (time related coverage)	1-5	1	1	3
Geographical correlation	1-5	1	2	3
Technological correlation	1-5	1	1	3
Representative	1	1-2	1-2	5
Precision	1-2	2	2	4

↑ Table 21

Summarized quality assessment of data used in the study (based on matrix in table).

Table 22 →

Characterisation factors according to IPCC Intergovernmental Panel on Climate Change by the United Nations¹⁵.

Species	GWP-100	Unit
Carbon dioxide	1	CO ₂ -eq
Nitrous oxide (laughing gas)	273	CO ₂ -eq
R 116 (hexafluoroethane)	12400	CO ₂ -eq
Tetrafluoromethane	7380	CO ₂ -eq
Sulphur hexafluoride	25200	CO ₂ -eq
Methane	29	CO ₂ -eq
Carbon dioxide, fossil	1	CO ₂ -eq
R 23 (trifluoromethane)	14600	CO ₂ -eq
R 113 (trichlorotrifluoroethane)	6520	CO ₂ -eq
Carbon tetrachloride (tetrachloromethane)	2200	CO ₂ -eq
R 22 (chlorodifluoromethane)	1960	CO ₂ -eq
R 12 (dichlorodifluoromethane)	11200	CO ₂ -eq
R 134a (tetrafluoroethane)	1530	CO ₂ -eq
Ethane	0,437	CO ₂ -eq
Halon (1301)	7200	CO ₂ -eq
R 152a (difluoroethane)	164	CO ₂ -eq
R 124 (chlorotetrafluoroethane)	597	CO ₂ -eq
Trichloromethane (chloroform)	20,6	CO ₂ -eq
Dichloromethane (methylene chloride)	11,2	CO ₂ -eq
R 11 (trichlorofluoromethane)	5560	CO ₂ -eq
Propane	0,02	CO ₂ -eq
Methyl bromide	2,43	CO ₂ -eq
Dichloroethane (ethylene dichloride)	1,3	CO ₂ -eq
R 245fa (1,1,1,3,3-Pentafluoropropane)	962	CO ₂ -eq
Halon (1211)	1930	CO ₂ -eq

¹⁵ https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter07.pdf

Species	GWP-100	Unit
1,1,1-Trichloroethane	161	CO ₂ -eq
R 125 (pentafluoroethane)	3740	CO ₂ -eq
Butane (n-butane)	0,006	CO ₂ -eq
Nitrogen trifluoride	17400	CO ₂ -eq
R 21 (Dichlorofluoromethane)	160	CO ₂ -eq
R 141b (dichloro-1-fluoroethane)	860	CO ₂ -eq
R 143 (trifluoroethane)	364	CO ₂ -eq
Ethyl chloride	0,481	CO ₂ -eq
R 32 (difluoromethane)	771	CO ₂ -eq
R E245fa2 (2-(Difluoromethoxy)-1,1,1-trifluoroethane)	878	CO ₂ -eq
Trichloroethene (isomers)	0,044	CO ₂ -eq
R 142b (chlorodifluoroethane)	2300	CO ₂ -eq
Tetrachloroethene (perchloroethylene)	6,34	CO ₂ -eq
Chloromethane (methyl chloride)	5,54	CO ₂ -eq
Perfluoropentane	9220	CO ₂ -eq
Bromoform	0,25	CO ₂ -eq
1,2-Dibromoethane	1,02	CO ₂ -eq
R 143a (trifluoroethane)	5810	CO ₂ -eq



POLESTAR 3 LCA - INDEPENDENT CRITICAL REVIEW STATEMENT

Ricardo confirms that a critical review was performed of the following carbon footprint study of the Polestar 3.

Table 1: Details of Carbon Footprint Study

Aspect	Details
Title of study	Critical review of the carbon footprint assessment prepared by Polestar to calculate the potential carbon footprint of the new electric Polestar 3.
Standard the study was conducted to	Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification (ISO 14067:2018)
Commissioner of the LCA study	Polestar
Practitioner of the LCA study	AFRY Management Consulting
Version of report to which the critical review belongs	Version 1.0 / 29th February 2024
Assurance type	Third party assurance via critical review panel based on UNI CEN ISO/TS 14071:2016 (ref. par. 4.2). Additional requirements and guideline to ISO 14044:2006), verifying the conformity of the carbon footprint study with the requirement of ISO 14067:2018 All reviewers are employed by Ricardo-AEA Ltd and are independent of the CFP study.
Critical review date	March 2023 to March 2024

The review panel included:

Nikolas Hill – Nikolas is a Technical Director and the Head of Vehicle Technologies and Fuels in Ricardo's Sustainable Transport team of the Policy, Strategy and Economics (PSE) practice area. Nik has over 24 years experience, in environmental analysis and is the lead on vehicle LCA for the sustainable transport team.

Marco Rauegi – Marco is a Senior Consultant in Ricardo's Sustainable Transport team on a part-time basis as an LCA expert, while also retaining his role as Senior Research Fellow at Oxford Brookes University.

Kim Allbury – Kim is a Principle Consultant in the Ricardo's LCA team and has over twenty years' experience in the field of life cycle assessment and has an in-depth understanding of relevant ISO standards and other methodologies relating to LCA, (such as product category rules).

1.1 CONCLUSIONS

The independent critical review process focused on the Carbon Footprint assessment of the Polestar 3 vehicle. It is considered that the critically reviewed CFP study, as documented:

- is substantially correct, representing, on the basis of the available data, a reasonable identification of the potential GHG emissions and removals related to the product under study, within the limits of the assumptions and limitations highlighted in the CFP study report;
- has been prepared in accordance with the principles and requirements of ISO 14067:2018 - Greenhouse gases - Carbon footprint of products - Requirements and guidelines for quantification.

Full details on the Critical Review Statement can be found within the Critical Review Statement Report that is available upon request from Polestar.

1.2 DISCLAIMER

Polestar retains sole liability for the content of the LCA study. Ricardo was commissioned to provide a critical review of the LCA study for compliance with the methodical requirements, and to assess the adequacy, correctness and consistency of information included in the study.