Life cycle assessment of distribution vehicles

Battery electric vs diesel driven

SCANIA

Contents

Executive summary

Scania's purpose is to drive the shift towards a sustainable transport system. A holistic view is key both to support our customers' business as well as addressing environmental impacts. Life Cycle Assessment (LCA) is an ISO 14040/44 method to calculate the environmental impacts of products or services over their entire life cycle: in this case the vehicle and battery production, use, maintenance and recovery.

LCA in Scania is used to evaluate the product's environmental impacts and setting internal project targets in product development. Scania has built up in-house capacity and competence to conduct LCA and guides the organisation via LCA as a fact base. With this external LCA publication Scania takes a step further to inform stakeholders of key LCA findings.

Scania is in the middle of a transformation with already connected, more electrified and arising autonomous products and services. For Scania's product development this means more than producing a few electrified vehicles – a complete modular toolbox is needed to offer the great variety of commercial vehicles also as electrified. Scania's first fully serial produced BEV was launched during the autumn of 2020. This made the choice easy to conduct this first publicly available LCA as a comparison between a representative distribution BEV, available in the first launch, with a corresponding ICEV.

The study covers the entire vehicle life cycle from cradle to grave, starting at the extracting and refining of raw materials and ending at the recovery of the vehicles. The chosen functional unit has the aim to reflect and represent a full life of operation for the vehicles. The functional unit is: 500 000 km driven in a representative distribution cycle with an average payload of 6,1 ton.

The vehicle technical properties, besides the drive trains, are kept as similar as possible to make the comparison as fair as possible. The installed battery capacity in the BEV is 300kWh. European grid mix with reference year 2016 is used as the baseline for the carbon intensity in the electricity used in the BEV. Additional grid mixes have been investigated to analyse the impact from future prognosed mixes as well as green electricity.
The fuel used for the ICEV is B7 diesel with 7% RME drop-in, representative for European conditions.

The production of the BEV entails a higher environmental impact, mainly due to energy intensive battery cell manufacturing. GHG emission raises from 27,5 tonnes CO_2eq (ICEV production) to 53,6 tonnes CO_2eq (BEV production). GHG emissions coming from production of battery cells are 74kg CO2eq/kWh of installed battery capacity. Despite the increased production burden, the total life cycle impact on climate change shows a dramatic reduction potential for the BEV, thanks to the much lower impact from the use phase. Depending on the carbon intensity in the EU electrical grid, the life cycle GHG reduction spans from 38% (EU mix 2016) to 63% (prognosed EU mix 2030). Powering the vehicle with green electricity is the way to fully utilise the potential with the BEV. The results show a life cycle GHG reduction of 86%.

"a BEV entering the EU market after 2020 will have more than 50% life cycle GHG reduction compared to the diesel alternative"

Due to the higher GHG emissions from the production, BEV vehicles can be seen as having a carbon debt in comparison to ICEV. The GHG debt will somewhere in time be repaid due to the lower use phase emissions per km. This is usually called the break-even point, the point in time when the BEV starts having a smaller total GHG impact than the ICEV. Depending on the carbon intensity, the break-even occurs between 33 000 km (green electricity) to 68 000 km (baseline 2016). This indicates that the BEV has the potential to have less climate impact than the ICEV already within one or two years of operation, for all investigated electricity mixes in the report.

At the End-of-Life Scania traction batteries are collected, dismantled, shredded and recycled by collection and recycling partners. The exact recycling process depends on geographical location and partner setup. Due to the varying market setups (pilot vs large scale recovery) and limited relevant data, the choice has been to exclude the battery recycling from the recovery model. Further, no second life of the battery is assumed in the LCA model, meaning that the full production burden is attributed to the Scania vehicle's life cycle.

There is also a dramatic reduction potential for other impact categories like fine particle formation, ozone creation and terrestrial acidification. The reduction in these categories lies between 83-97%, mainly due to eliminating tailpipe emissions.
Fossil resource use and eutrophication of marine- and freshwater also decrease significantly (18-48%) for the BEV, even though there are a considerable impact related primarily to coal in the electricity generation. The main reason is that well-to-tank impact from diesel production is higher than the impact coming from electricity generation.

"With sustainable battery production and green electricity, GHG reduction potential for the BEV will be well more than 90%"

This LCA gives a view of the magnitude and relationship between environmental impacts for the BEV and the ICEV distribution trucks. However, the LCA results, especially in absolute terms are not intended to be compared to other OEMs. The choice of functional unit, methodology, scope and access to primary data will have a great influence on the final result.

All facts and figures in this report are third party verified in a background report (Scania internal). The verification was done by IVL Svenska Miljöinstitutet following the ISO 14040/44 standard.

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Abbreviations, terms and definitions

LCA - Life Cycle Assessment.
GHG – Greenhouse Gases
CO_2eq – Carbon dioxide equivalent
WtW – Well to Wheel
WtT – Well to Tank
TtW – Tank to Wheel
ICEV – Internal Combustion Engine Vehicle
BEV – Battery Electric Vehicle
GVW – Gross Vehicle Weight

Life cycle assessment (LCA)

A life cycle assessment is a methodology for assessing the environmental impacts associated with all the stages of the life cycle of a product, from raw materials acquisition through production, use and disposal. It gives a holistic approach to the environmental impacts and avoids shifting of burdens.
The 4 stages of the LCA are: goal and scope definition, life cycle inventory, life cycle impact assessment and interpretation. Goal and scope state the purpose of the study, intended application and audience, system boundaries and functional unit.
Life cycle inventory (LCI) is the process of data collection and calculation of the product model. Life cycle impact assessment (LCIA) is a step of classifying and characterising potential environmental impacts based on the LCI results.
Interpretation is performed based on the impact assessment results and gives an analysis based on the set goal and scope. Results are analysed for each impact category, and differences between product but also life cycle phases are discussed. (ISO 14040:2006, ISO 14044:2006)

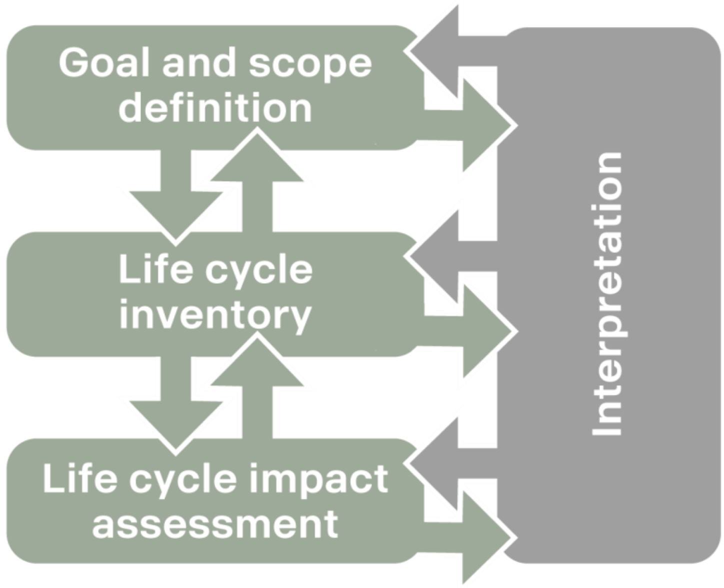


Figure 1. Four stages of the LCA

Functional unit

An LCA is only valid within its defined system boundaries and functional unit. A functional unit is the “quantified performance of a product system for use as a reference unit” (ISO 14044 2006).

Life Cycle Inventory

The life cycle inventory is a part of the LCA where all necessary data is collected and modelled. It is the process of quantifying raw material use, energy requirements and emissions over the life cycle of the product. It creates an inventory of elementary flows from and to the ecosphere for a product system.

Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) converts the elementary flows from the LCI into potential environmental impacts. It is common to define this in 4 phases: classification, characterisation, normalisation and weighting. The analysis at hand includes classification and characterisation as the obligatory LCIA steps, and excludes normalisation and weighting as they are not recommended for external communication by ISO 14040/44. The classification step assigns the LCI results to specific environmental impact categories (ex CO_2 and CH_4 is assigned to category CCP, Climate Change Potential). The characterisation step converts (via characterisation factors) the LCI results per impact category into impact category indicators (ex CH_4 is converted into CO_2eq).

Operational data

Operational data is data stored in the vehicle control units. Approx. 2000 variables + calculated variables are stored. Read outs are done when the vehicles visit the work shop and the data is stored in an operational data warehouse.
The operational data makes it possible to analyse the performance of the vehicles (fuel consumption as an example) and how the vehicles are operated. The information is used by a broad variety of stakeholders like product development, analysts, workshops, driver services, etc.

BOM

A bill of material (BOM) is a list of all materials and the amount of each material that is used in the vehicle.

GHG Protocol

The Greenhouse Gas (GHG) Protocol is a global framework to standardise accounting of greenhouse gas emissions. To relate the GHG protocol scopes to what is covered in this LCA, the following scopes are fully, or to a great extent covered for the GHG impact category:
Scope 1: Direct greenhouse gas emissions
Scope 2: Indirect greenhouse gas emissions
Scope 3 categories:

1. Purchased goods and services
4. Upstream transportation and distribution
9. Downstream transportation and distribution
11. Use of sold products
12. End-of-life treatment of sold products

Tools and databases

GaBi

LCA software with LCI databases from Sphera Solutions GmbH.

LEAD database

GaBi Professional database including both open source, Gabi specific and VW Group developed datasets.
Service Pack 39 used in this study.

Scania Mapping List

Mapping list is an xml describing each material in a Scania vehicle with the adequate LEAD dataset. It enables automated model generation.

SlimLCI+

The SlimLCI+ application matches LEAD datasets with the BOM, based on Scania Mapping List.

IMDS

International Material Data System (IMDS) is a common automotive material data system where info on material composition of parts are reported by suppliers.

SMART

Scania tool (from by iPoint-systems GmbH) for managing Material Data Sheets (MDS) from IMDS.

VECTO

Vehicle Energy Consumption calculation Tool (VECTO) is developed by the European Commission as the official simulation tool for HDV fuel/energy calculations for declaration of CO_2 emissions.

Goal and scope

The goal of this LCA is to assess the environmental impacts for an electric truck in the distribution segment and to compare it to its diesel driven counterpart. The results are made public with the intention to give increased knowledge of the life cycle environmental impacts of heavy-duty vehicles and the comparison between BEV and ICEV in specific.

The study covers the entire vehicle life cycle from cradle to grave, starting at extracting and refining of raw materials and ending at the recovery of the vehicles.

The functional unit in this study has the aim to reflect and represent a full life of operation for the vehicles. Based on studies of operational data, representative figures for mileage and payload have been derived. Operational data has also been used to adjust VECTO standard drive cycles to closely match real operation. The functional unit is: 500 000 km driven in a representative distribution cycle with an average payload of 6,1 ton.

The assessment is done on midpoint level with ReciPe 2016 v1.1 Hierarchist methodology. The hierarchist perspective is based on scientific consensus with regard to the time frame and plausibility of impact mechanisms. For example, climate change potential is observed over 100 years (Huijbregts et al., 2017). The study shows potential impacts for: climate change, fine particle formation, fossil resource use, freshwater and marine e utrophication, ozone formation (human health and ecosystems) and terrestrial acidificat ion. These impact categories were selected based on impact relevance for transport industry and method maturity (European Commission et al., 2011; Van Loon et al., 2018). Additional impact categories like mineral resource depletion, water use and toxicity that can be considered relevant for Scania products exist but are not included at this point due to the fact that they are still undergoing significant methodological improvements. They are in the meantime monitored internally and will be communicated in the future.

This LCA is attributional as it is based on measured historical data, which fulfills its purpose to correctly capture the emissions coming from a vehicle life cycle, rather than give an estimate of how the production and use of the vehicle affect the global environmental burdens, which would be a consequential approach.

An allocation method is necessary when the environmental impacts of a process should be allocated to more than one product or service. The partition between the products or services can be based on properties like mass, energy or economic values. No specific allocations of environmental impacts besides those already included in the LEAD datasets has been done in this study. LEAD dataset allocations are described in the software documentation (http://www.gabi-software.com/international/databases/gabi-data-search/).

LEAD dataset cut-off criteria, as described in the software documentation (www.gabi-software.com) are used.
Credits for secondary materials during the recovery phase are not taken into account.
Maintenance (except for tyres) is excluded due to the environmental insignificance (0,1-0,3% of life cycle) and the difficulty with defining an average maintenance because of the wide range of operations.
Component production steps of the supply chain activities are excluded for all parts that are not produced within Scania facilities (except for tyres and propulsion batteries).
The reason for this is limited access to data and environmental insignificance (<1% of production phase).
This LCA gives a view of the magnitude and relationship between environmental impacts for the BEV and the ICEV distribution trucks. However, the LCA results, especially in absolute terms are not intended to be compared to other OEMs. The choice of functional unit, methodology, scope and access to primary data will have a great influence on the final result. Scania is welcoming the long-term development of more common LCA guidelines with ISO14040/44 as the fundament, and is committed to contribute to this development.

The vehicles

Scania products are based on the concept of modularity in contrast to a concept of having vehicle models. The modular system enables uniquely adapted vehicles for every sort of transport mission. The specification of the BEV addressed in this LCA is based on sales projections for BEVs that will operate in what can best be called as a mixed distribution segment, where customer operations constitute of a mix of urban and regional distribution.

A comparable diesel driven ICEV is carefully chosen to match the BEV as close as possible while at the same time make sure that it is a good representative for the ICEVs in the segment. This is done based on sales statistics as well as internal knowledge and ensures that the comparison is fair and relevant.

Vehicle	Technical GVW	Cab	Wheel configuration	Power (peak/ continuous)	Traction battery capacity	Transmission
ICEV	28 ton	P17	6x2*4	320 hp Euro 6	N/A	8 speed GR875 Opticruise
BEV	28 ton	P17	6x2*4	295/230 kW	300 kWh	2 speed GE21S21

Table 1. Outline specification of the vehicles.

Both vehicles are three axle rigids with steered tag axle. They are equipped with P17 cabs and the chassis are adapted for a box body. Basically, the only thing that differs the vehicles are the drive trains. The differences in powertrain drive train and the battery weight entails that the BEV has a higher curb weight of approx. 1 tonne.

Life cycle inventory

In the Life Cycle Inventory, data is collected for each life cycle phase: production, use, maintenance and recovery.
The process of data collection differs between the life cycle phases. Production phase data is based on the vehicle specification and material composition data from part suppliers via IMDS. The use phase data is based on energy consumption simulations (VECTO) and operational data. The maintenance phase (limited to tyre change) and the recovery phase is based on external LCA studies.

Production phase

Data collection starts with collecting material data for the entire vehicle. Each vehicle has over 10 000 reported materials which are then classified in material groups and finally compose a list of ~45 materials per vehicle.

For visualisation purpose the ~45 materials in the vehicles have been divided into broader material categories and are presented as share of weight for BEV and ICEV.

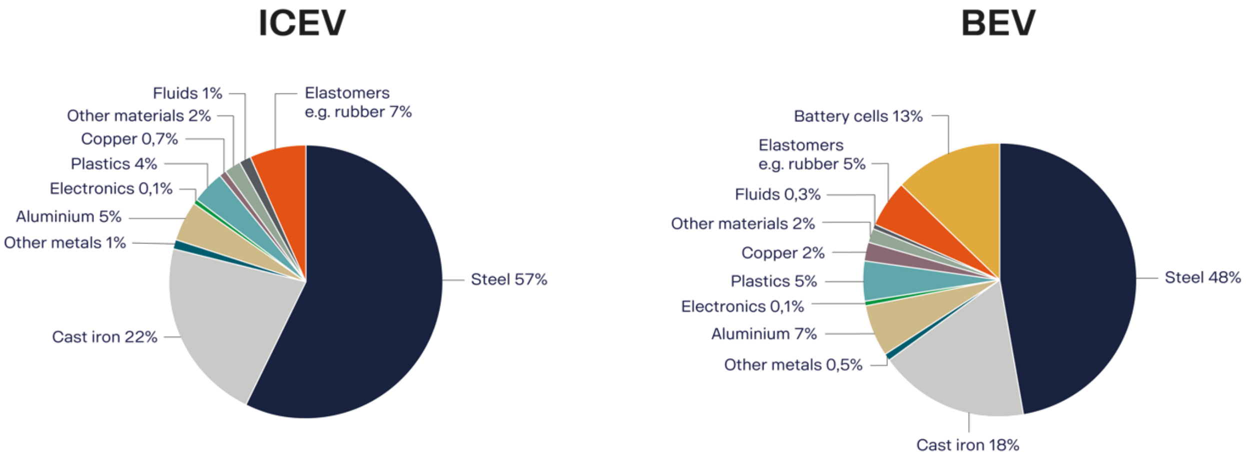


Figure 2. Material composition. Material categories expressed in percent of total vehicle weight.

Material and weight information is compiled in the Bill of Materials (BOM). The BOM is together with Scania Mapping List imported into SlimLCI+ where each material is assigned the best fitting dataset. LEAD datasets describes the environmental burdens for raw material extraction and production of semi-refined products.

Mainly industry average datasets from the LEAD database are used, but for some materials (e.g. large weight materials: steel and aluminium) Scania specific datasets have been developed to accurately represent the steel and aluminium used by Scania. The Scania steel dataset is based on standard LEAD datasets and it includes 82% primary and 18% secondary material. The Scania aluminium dataset is based on standard LEAD datasets and it includes 52% primary and 48% secondary material.

The following step is to add process energy used in component production and vehicle assembly. Following components and assembly steps are covered: powertrain and transmission components, cab, chassis components and final assembly of the complete vehicle. Internal monitoring of direct and indirect emissions (Scope 1 and 2, GHG protocol) enables follow up of greenhouse gas emissions from these activities. Additionally, GHG emissions from logistic operations such as transports from direct suppliers as well as the transport of the produced vehicles to the dealership are included.

For assessing the impact from tyres, cradle-to-gate LCA results are conducted in collaboration with Michelin. This ensures that all environmental impacts from tyre manufacturing are correctly accounted for and that not only material but also process data is considered.

The propulsion battery is made with NMC622 battery cell technology. The installed capacity is 300 kWh. Battery production is a hotspot due to the energy intensive process steps. The largest hotspots of battery cell production are the energy use (electricity and thermal energy) in production of cathode active material (CAM) and the cell manufacturing.
The battery cell manufacturing is done in Europe, while the preceding steps are done in China. This means that cell subcomponents like cathode and anode are produced with

Chinese electricity mix (854 g CO_2eq/kWh), while the cell manufacturing is powered with European electricity mix (424 g CO_2eq/kWh). The model for battery cell production is based on suppliers' data and the modelling is done by VW Group. The LCA model is representative for NMC622 technology.

Use phase

Fuel and energy consumption

An essential part of assessing the impacts from the use phase is to get representative fuel and energy consumption values for the vehicles. A simulation based approach with VECTO as simulation tool is used. VECTO is developed by the European Commission as the official tool for HDV fuel/energy calculations for declaration of CO_2 emissions (European Commission, 2017).

Based on operational data from Scania's connected vehicles, the VECTO *urban delivery* and *regional delivery* cycles have been adapted to better reflect the typical driving conditions for Scania distribution vehicles. The vehicles are simulated in both cycles and afterwards the results from each cycle are weighted into one total result. The consumption values derived with this methodology have been validated against real consumption values from operational data and shows reassuring consistency.

Furthermore, the vehicles are assumed to be equipped with the same body (box) and are thus assigned the same air resistance value, CdxA. Same tyres and same weight distribution between the axles have been used in the simulations. The resulting fuel consumption for the ICEV is 25,5 l/100km and the energy consumption for the BEV is 93,2 kWh/100km (excluding charging losses, *see Well-to-tank*).

Well-to-tank

The ICEV is assumed to run on B7 diesel blend with 7% RME drop-in, representative for European conditions (ACEA, 2013). In addition to the fuel, the AdBlue used in the after-treatment system to reduce tailpipe emissions is also covered for in the analysis.

As a baseline, the BEV is assumed to run on EU electricity mix, reference year 2016 (in text: EU baseline). The reference year is 2016, because that is the available data in LEAD database Service Pack 39 and it is also consistent with the electricity used in the battery cell model. The carbon intensity in this EU baseline is 424 gCO2eq/kWh which is a conservative approach in regards to today's European electricity mix.

Since BEV charging losses are not included in the VECTO consumption results this has to be addressed separately. In this study it is assumed that 80% of the charging is done as overnight charging and 20% is done as fast charging. The charging losses (losses in charging station plus losses in vehicle) for overnight charging are assumed to be 5% and losses for fast charging are assumed to be 10%. This results is a charging loss average of 6% which is added to the BEV energy consumption, resulting in 98,7 kWh/100km.

Tank-to-wheel

The tailpipe emissions for the ICEV are based on the simulated fuel consumption and on operational data. The CO2 and N2O emissions are stochiometric and are thus a function of simulated fuel consumption and the AdBlue consumption (taken as an average figure from operational data). Operational data is also used for NOx emissions.

CO, NMHC, NH3 and PM2,5 emissions are calculated using the simulated fuel consumption in combination with the legal limits for these emissions according to the WHTC legislation and are hence conservative figures (European Commission, 2011).

The BEV does not have any TtW emissions (tailpipe emissions).

The use phase is also complemented with particulate emissions (PM2,5) coming from tyre and brake wear (Ntziachristos and Boulter, 2016).

Maintenance

During the lifetime parts like tyres, starter batteries, brake pads, oils etc. will be changed as part of maintenance. However, when investigating the impact from maintenance (tyres excluded) it shows that the environmental impact is insignificant in the whole. The order of magnitude is between 0 and 0,3% of the life cycle emissions for both ICEV and BEV. Therefore, the maintenance phase in this study consist only of tyre change, being the only environmentally significant part of maintenance. Two complete sets of tyres in addition to the tyres mounted in production is assumed. The lithium-ion batteries are assumed to last the entire vehicle lifetime, i.e. no change of batteries are accounted for.

Recovery

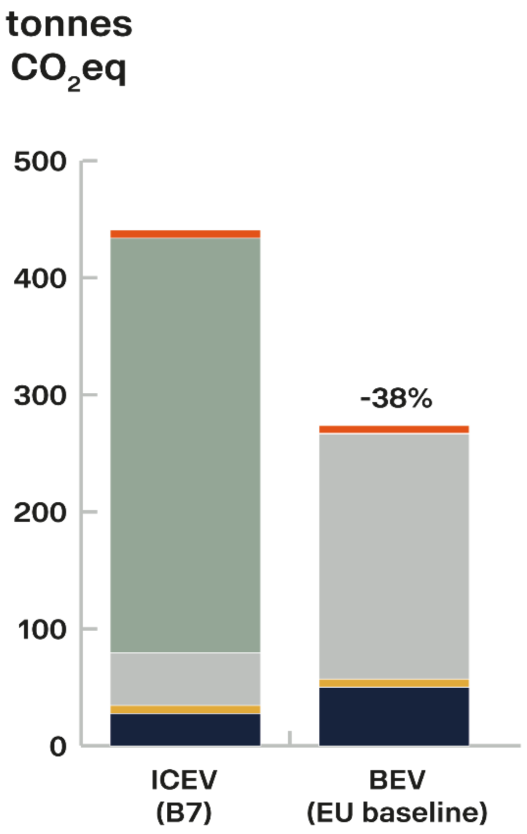
The recovery phase is based on a generic model for the recovery of a heavy-duty vehicle. For the secondary materials emerging from vehicle recovery processes, no credits are taken into account.
No second life of the battery is assumed, meaning that the full production burden is attributed to the vehicle life cycle.
Scania has a well prepared battery recycling setup for all markets. The exact recycling process depends on market and geographical location. The batteries will be collected by partners, dismantled, shredded and recycled by recycling partners at their facilities. Due to the varying market setups (pilot vs large scale recovery) and limited relevant data, the choice has been to exclude the battery recycling from the recovery model. By excluding battery recycling, the burdens of energy used in recycling process are not considered. While this is a definite study limitation, the influence of this step is expected to be low for all used impact categories (based on results of the current recovery impact).

Results

One environmental impact category of particular interest when comparing ICEV with BEV is climate change potential (CCP). In the EU, buses and heavy trucks are responsible for about 6% of the total GHG emissions, and still rising due to increasing freight transport (European Commission, 2016). Climate change potential is by far the most important environmental impact category for Scania due to the fossil energy content in use phase. It remains much in focus for BEVs due to emissions from electricity generation and battery production. The importance of climate change as the major impact category compared to other environmental impacts has been confirmed via Scania internal LCAs and materiality analysis, as well as external studies e.g. RICARDO study (Hill et al., 2020). Hence, the major part of the result chapter is dedicated to climate impact.

Climate change potential

The climate change potential describes the emission of greenhouse gases (GHG), which lead to an increase of heat absorption of solar radiation within the atmosphere and thus can contribute to an increase of global average temperatures. The reference substance for the global warming potential is carbon dioxide. All other greenhouse gases (e.g. CH_4, N_2O, PFCs) are calculated in relation to carbon dioxide (CO_2 equivalents). In figure 4 the total lifetime GHG emissions for the vehicles are presented, aggregated per life cycle phase. The use phase has been divided into well to tank (WtT) and tank to wheel (TtW).



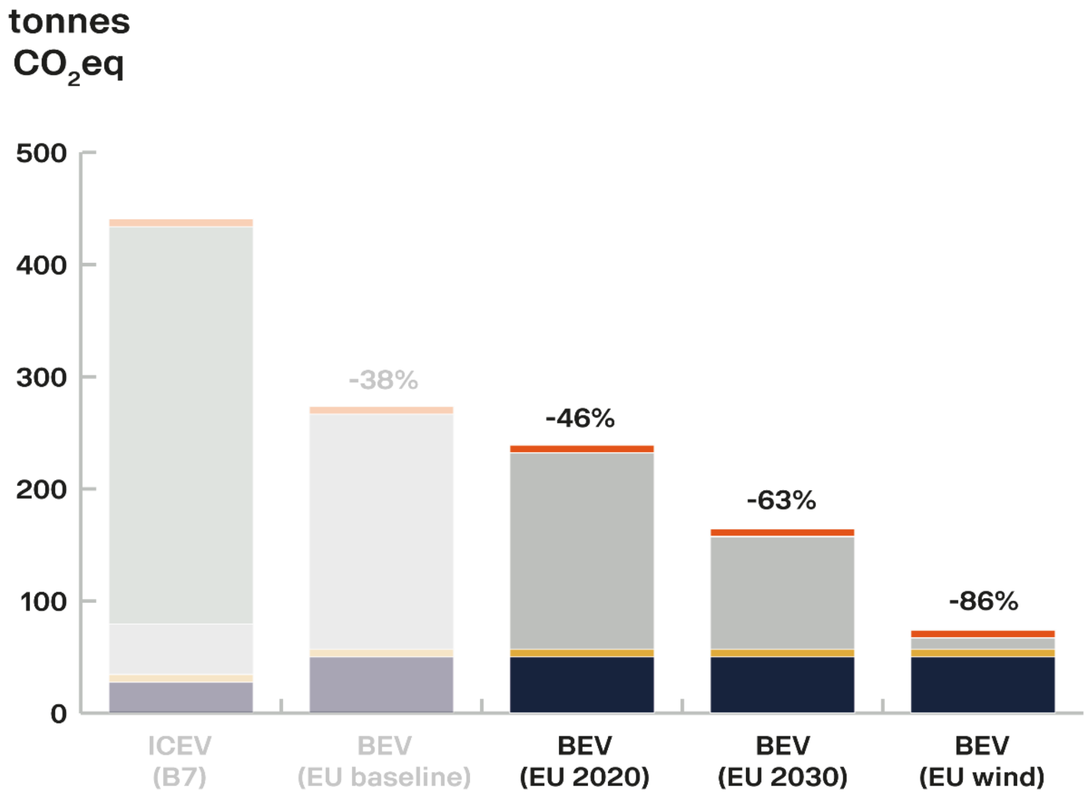
Vehicle	Production	Maintenance	Use WtT	Use TtW	Recovery
ICEV (B7)	27,5	2,4	44,9	354,3	2,1
BEV (EU baseline)	53,6	2,4	209,5	0,0	2,1

Figure 3. Total life cycle GHG emissions presented as tonnes of CO_2eq per life cycle phase. The use phase is divided in well-to-tank and tank-to-wheel.

Even though the impact from production phase is almost doubled for the BEV compared to the ICEV, it is the use phase that is the clearly dominant phase for both ICEV and BEV. In the base line scenario (EU baseline), the BEV can reduce the total life cycle GHG emissions with 38% in comparison to ICEV.

BEV potential with improved electricity mix in use phase

Electricity mix considered for the use phase is the single most important parameter influencing the overall BEV environmental impact. For the baseline, EU electricity mix for the reference year 2016 is used. However, electricity production around the world is continuously improving, which makes it relevant to perform a sensitivity analysis on how different electricity mixes in the use phase calculation is affecting the total lifetime GHG emissions. For this reason, expected EU electricity mix for years 2020 and 2030 has been modelled, based on International Energy Agency publication World Energy Outlook 2019. The environmental burden of electricity production by source is taken from LEAD database and is coupled with electricity shares published in WEO 2019 for Stated Policies scenario (IEA, 2019). As renewables are grouped as one in WEO 2019, breakdown per source is based on RICARDO study (Hill et al., 2020). Distribution and transmission losses of 6,9% are added according to LEAD database resulting in EU electricity mix 2020 (355 gCO_2eq/kWh) and 2030 (203 gCO_2eq/kWh). As an additional alternative, EU Wind (representing green electricity) is investigated. In this sensitivity analysis the electricity mix for all phases (incl. battery cell production) except the use phase is kept unchanged (EU baseline).



Vehicle	Production	Maintenance	Use WtT	Use TtW	Recovery
ICEV (B7)	27,5	2,4	44,9	354,3	2,1
BEV (EU baseline)	53,6	2,4	209,5	0,0	2,1
BEV (EU 2020)	53,6	2,4	175,0	0,0	2,1
BEV (EU 2030)	53,6	2,4	100,2	0,0	2,1
BEV (EU wind)	53,6	2,4	4,7	0,0	2,1

Figure 4. Total life cycle GHG emissions presented as tonnes of CO_2eq per life cycle phase. The use phase is divided in well-to-tank and tank-to-wheel. Four different grid mix scenarios are used for the use phase electricity.

Figure 4 shows the impact from the grid mix on the life cycle GHG emissions. It should be kept in mind that these results are assuming a constant grid mix throughout the vehicle's life cycle from first to last km. This means that figure 4 rather shows the potential effect from grid mix improvements than the real case which would be the aggregated impact of the changing grid mix.

If the BEV in its use phase is powered with an electricity mix that in average corresponds to prognosed EU 2020 mix, the lifetime reduction will be 46% in comparison to ICEV (B7), while a mix corresponding to prognosed EU 2030 mix gives a reduction of 63%. Since it is probable that the grid mix by the end of the vehicle life is closer to the prognosed EU 2030 mix, the expected life cycle reduction will be somewhere between 46-63%.

If using green electricity (as EU Wind), something that is fully possible already today, the life cycle reduction for the BEV can be as much as 86%.

Note that Well-to-wheel for ICEV B7 is assumed to be constant in these comparisons and the result would differ if a biodiesel blend-in higher than the assumed 7% would be the case.

Potential diesel improvements

The focus in this report is to show the potential of a battery electric vehicle in relation to a combustion vehicle running on diesel B7. It should however be made clear that it is possible to significantly improve the GHG emissions from a combustion engine vehicle. The blend-in of biodiesel (primarily HVO) is in many markets already on significant levels and plans for continuous increasing of the blend-in are present on several European markets. Scania diesel engines are possible to run on 100% HVO.

If replacing B7 with waste based (beef tallow) HVO in this study, the life cycle GHG emissions for the ICEV will be reduced with 74% (well-to-wheel reduction 81%).

GHG emissions from vehicle production

As shown in figure 5, the GHG emissions from production are only 6% of the total emissions. For a BEV (EU baseline) the production share increases to 20% of the total. As the transition from ICEV to BEV continues and at the same time the electricity mix improves, the importance of the production phase will continue to increase, to the point of becoming the hotspot of the BEV life cycle.

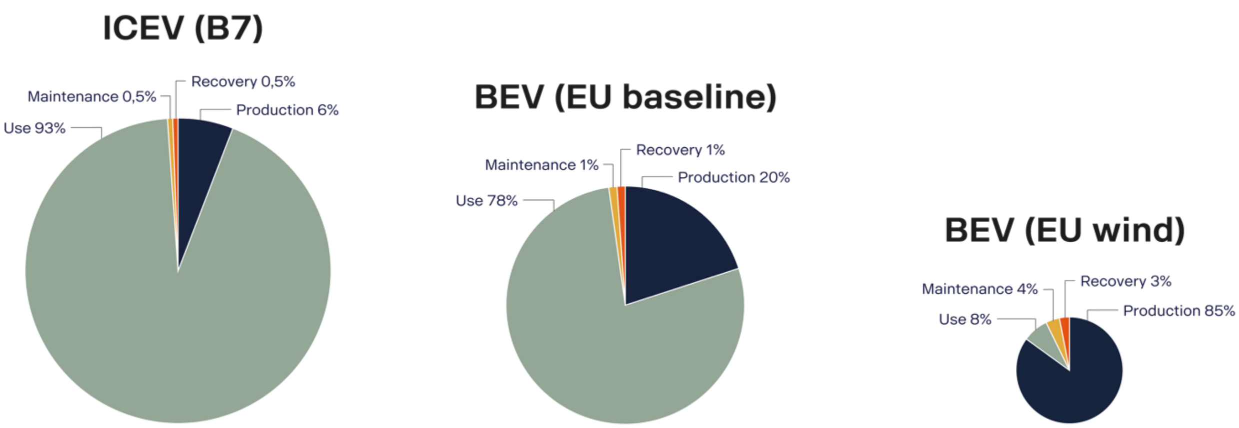


Figure 5. Share from each life cycle phase in % of total life cycle GHG emissions. The sizes of the circles are proportional to total life cycle GHG emissions.

The production phase includes raw material extraction, refining, part production, vehicle assembly and inbound logistics. Part production, vehicle assembly and inbound logistics contribute with roughly 2,5 ton of GHG for both ICEV and BEV.
The greater part of the GHG emissions in production phase thus comes from the process of extracting raw material and refining. Figure 6 shows how extraction and refining of different material categories, logistics and assembly contribute to the production phase emissions for the two vehicles.

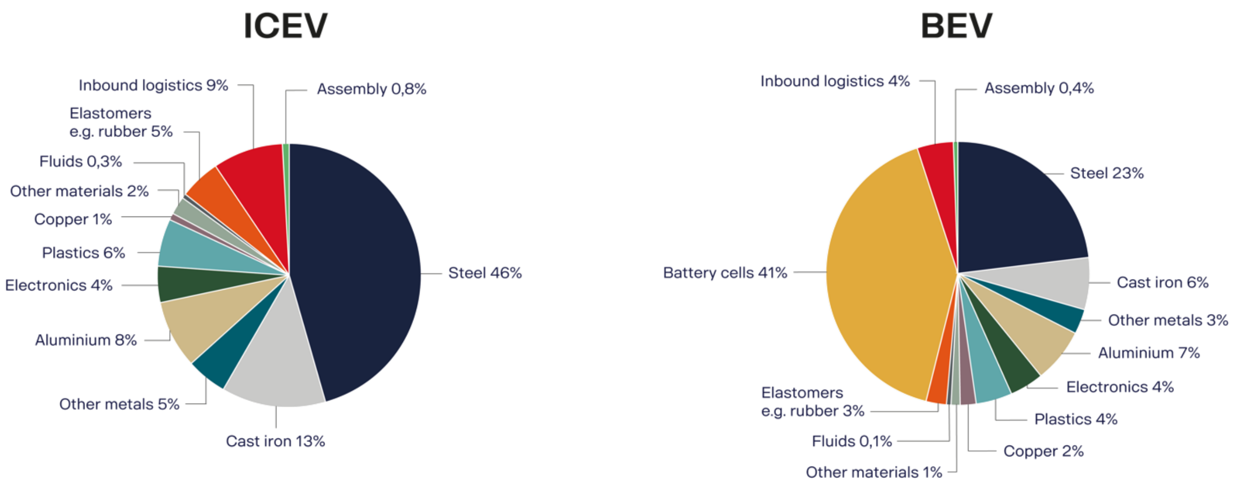


Figure 6. GHG emissions from different material categories in % of total emissions from production phase.

The hotspots in the ICEV production phase are steel production, cast iron production and aluminium production. The same materials are hotspots also for the BEV, but what makes the total GHG emissions from production of BEVs almost doubled is the energy intensive battery cell production. The battery cell impact is 74 kg CO2 eq per installed kWh and the majority of the impact comes from energy intensive process steps in manufacturing of battery sub components, which takes place in China. In figure 7 below, impact coming from f ex cathode includes all the subsequent steps starting with raw material extraction, all the refining processes, transport and energy needed for cathode production. Last step in battery cell production, so called cell manufacturing occurs in Europe and is driven by impacts coming from electricity and thermal energy.

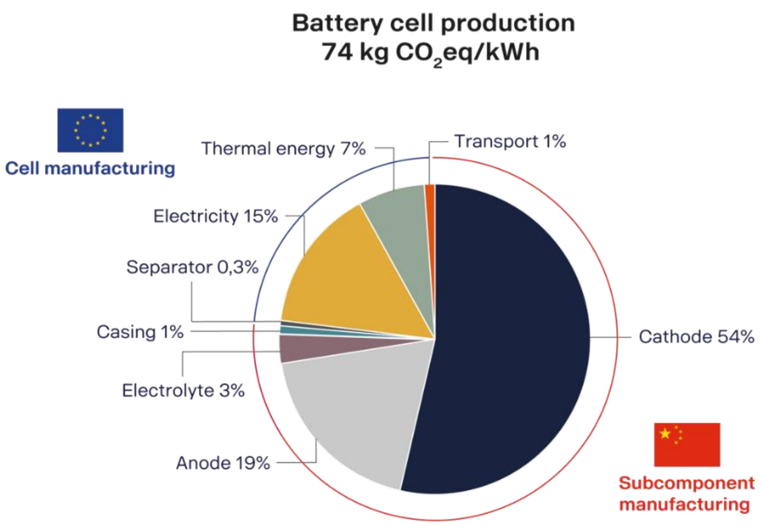


Figure 7. GHG emissions from different steps in battery cell production in % of total impact per kWh installed capacity.

Break-even

The production of BEVs results in higher GHG emissions compared to ICEVs (mainly due to battery cell production) but during the rest of the vehicle life this debt will be paid off since the accumulated GHG emissions from use phase increases more rapidly for the ICEV due to the combustion of diesel. This means that after a certain amount of driven kilometres the total GHG emissions reach a “break-even”. At the break-even point the total GHG emissions are equal for the BEV and the ICEV. After the break-even point, the life cycle GHG emissions for the BEV will be lower than for the ICEV.

Figure 8 shows the total accumulated amount of GHG emissions as a function of total kilometres driven. All life cycle phases except the use phase are summarised and set as the starting point for the curves.

Break-even is reached after approx. 33 000km – 68 000km depending on the electricity mix.

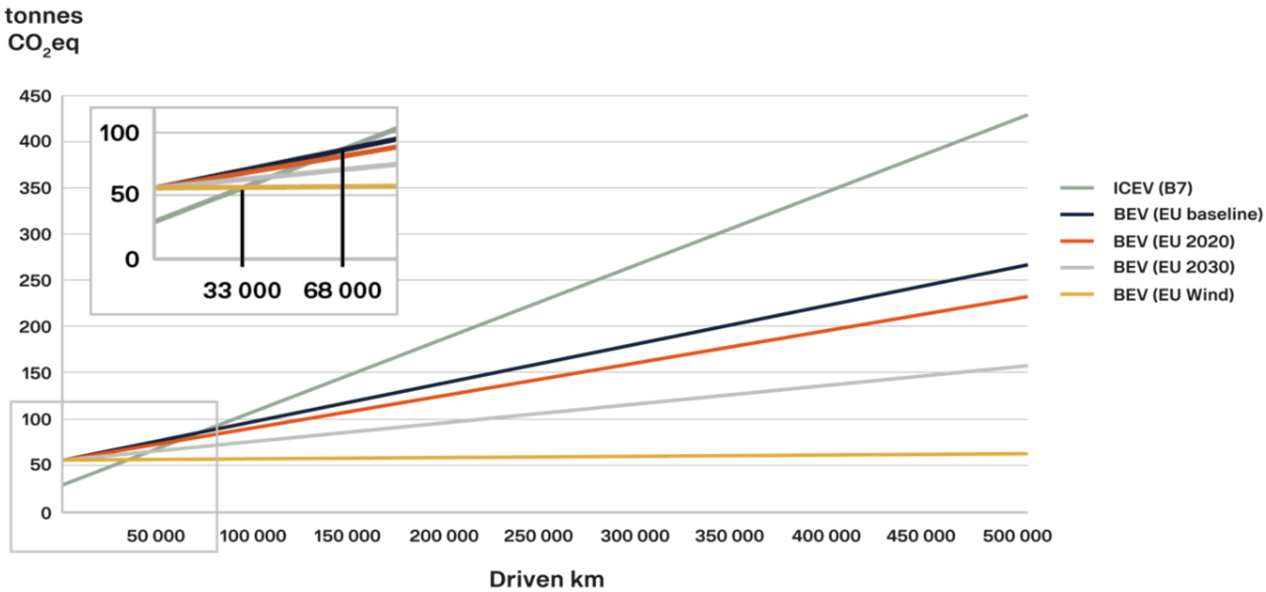


Figure 8. GHG break-even as a function of driven kilometres. The carbon intensity in the grid mix influences when the break-even occurs.

Other environmental impacts

Figure 9 shows the relation between ICEV and BEV for the other impact categories investigated in this study. ICEV is set as the reference value (100%) and BEV values are presented as reduction in relation to ICEV. No absolute values are presented and no assumptions nor statements are done regarding the importance of one impact category in comparison to the others. The intention is to show the reduction potential for the BEV. There is a distinct reduction potential in all categories, especially for the ones driven by tailpipe, which is the case for fine particle formation, photochemical ozone creation and terrestrial acidification. In these categories, the BEV is showing steep reduction potential. Fine particle formation shows impact on human health from primary and secondary aerosols, expressed in PM2,5 equivalents. Important to mention is that only a fraction of this impact category comes from direct PM2,5. The direct PM2,5 comes from: tailpipe (20%), tyre and brake wear (50%) and road wear (30%). However, the major part of the emissions in the category comes from secondary aerosols like NO_x and NH_3.

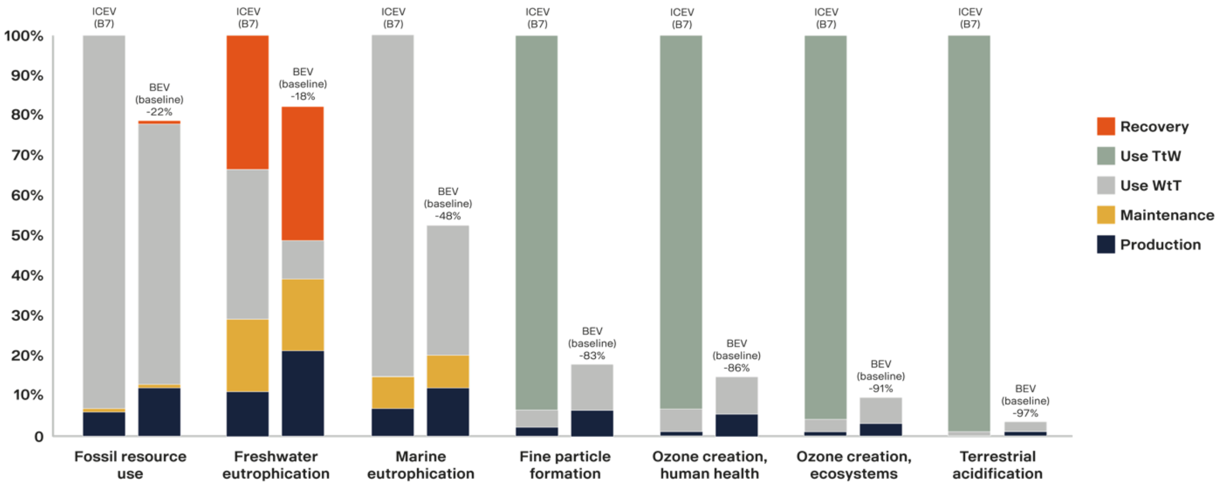


Figure 9. BEV reduction potential for other impact categories. BEV reduction values presented in relation to ICEV emissions.

The impact in the categories fossil resource use, marine- and freshwater eutrophication also decreases for the BEV in comparison to the ICEV, however not as dramatic as in the previous mentioned categories.

The biggest driver behind fossil resource use and marine eutrophication is well-to-tank, i.e. diesel production for the ICEV and electricity generation for the BEV. As the electrical grid decarbonises, these impact categories are expected to lower subsequently for the BEV and the reduction in comparison to ICEV will increase.

When looking specifically on freshwater eutrophication, contribution from use phase (well-to-tank) is still the major part for the ICEV, while for the BEV that part is reduced by 4 times. This is due to bigger impact from diesel production in comparison with electricity generation.

Another hotspot in freshwater eutrophication is vehicle recovery, with impact coming from metal recycling. Since recovery is based on a generic model in this study, the impact from ICEV and BEV are the same.

In the categories marine- and freshwater eutrophication, the relative importance of the maintenance phase is bigger than in the other categories. The impact in the maintenance phase comes from the production of the tyres that are changed on the vehicles during their life cycle. The size of the maintenance impact is therefore the same for BEV and ICEV.

Discussion

Tonne-km as functional unit

Tonne-kilometre (tkm) is a common functional unit in LCA studies within the transport sector and fits well if the aim is to compare the impacts for two possible alternatives for a transport mission. However, the intention with this study is not only to compare the two vehicles but also to transparently show the total lifetime environmental impacts from the products. In that case the functional unit of 1 tkm is not the adequate for the study goal, since results are not straight away scalable in regards to the functional unit. Scaling is not impossible but needs to be done with great care and each life cycle phase needs to be handled separately. Instead of 1 tkm, the chosen functional unit is total mileage with an average payload, which is expected to be a good reflection of a representative full life of operation.

Real-life energy/fuel consumption

It is a challenging task to find representative assumptions for fuel and energy consumption. Operational data is a very valuable and in many cases the best source of information, but it requires big populations to minimise the risk for misleading conclusions and impact from outliers. Since the BEV in this study is a brand new product the available operational data on energy consumption is very limited and hence not a good source for representative values. By using a simulation based approach it is assured that both vehicles are given the same prerequisites for the assumed fuel/energy consumptions. The choice of VECTO as the simulation tool is based on its transparency and the fact that it is a well-known and established tool for fuel and energy calculations.

The relevant VECTO drive cycles for vehicles in the distribution segment are the Regional delivery and Urban delivery cycles. To derive the most representative results possible, the VECTO default drive cycles has been modified. By using operational data from a reference fleet of distribution vehicles with specifications similar to the vehicles in this study, factors such as stop frequency, road gradients and standing time have been analysed. Based on this data, the VECTO cycles have been adapted to better represent the foreseen driving conditions for the vehicles in the study.

Life cycle impact assessment – methods and categories

There are two key terms when talking about Life Cycle Impact Assessment: LCIA methodology and impact category.

LCIA methodology is a comprehensive sum of methods to calculate an array of impacts (also called impact categories). An impact is the consequence of the LCI emissions to the environment, human health and resource availability. There are different methodologies to calculate the same impact (category). These complex calculations aim to best represent even more complex natural flows of emissions. In the LCA, it is important to choose a methodology that is recognised by academia and industry experts as robust and applicable (among other criteria), and that is why ReCiPe 2016 v1.1. Hierachist is chosen for this study.

It is common to use a single LCIA methodology when conducting an LCA. However, this means some impacts can be more or less developed, something that can hinder their communication. To achieve full transparency and avoid shifting of the burden, optimally, all relevant impacts for transport industry should be assessed and communicated. However, practitioners' choice in this study was to leave out some of the impact categories where the methods are still under development and are hence not considered mature (ex. mineral resource depletion, water use and toxicity).

Communicating results from immature methods, which are expected to develop significantly, could in worst case be misinformative and lead to wrong conclusions.

The goal of the study is considered to be fulfilled by studying eight environmental impacts of highest relevance for transport industry and with currently mature methods. LCIA methodology and impact choice will continue to be closely monitored as methods and impacts undergo further development.

Conclusions

HDV's are in general characterised by high utilisation rate which makes the use phase the by far most important life cycle phase in terms of environmental impact. It is also in this phase that big, radical improvements will be achieved with the transition to fully electrified vehicles. Considering the climate impact reduction potentials with prognosed electricity mixes EU 2020 (46%) and EU 2030 (63%) and since it is probable that the grid mix by the end of the vehicle life is closer to the prognosed EU 2030 mix it can be concluded that a BEV entering the EU market after 2020 will have more than 50% life cycle GHG reduction compared to the diesel alternative.

This study shows that by using green electricity in the use phase, there is a potential reduction of 86% for the total life cycle GHG emissions for the BEV. This reduction is despite the fact that the production of the BEV emits the double amount of GHG compared to the ICEV.

Within the production phase, the Li-ion-battery is a major contributor. For the BEV investigated in this study the battery cells stands for a bit over 40% of the GHG emissions coming from production. There is however a big potential for improved emission values from the production of BEV's as the battery industry continuously decarbonises and the use of green electricity continuously increases.
It is therefore reasonable to assume that with sustainable battery production and green electricity, GHG reduction potential for the BEV will be well more than 90%.

The BEV has a "production debt" in terms of GHG emissions. However, another consequence of the HDV high utilisation rate is that the GHG break-even occurs early in the life span. The calculations in this study shows that the GHG break-even occurs already between 33 000 to 68 000 km depending on the carbon intensity in the electricity mix. This indicates that the BEV has the potential to be better than the ICEV already within one or two years of operation, for all presented electricity mixes.

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Appendix – datasets

Production phase (excluding battery cell and tyres)

Material	Country	Dataset name	Type	Origin
Steel	EU-28	Steel-coil worldsteel, cold-rolled	agg	worldsteel
Steel	EU-28	Steel-coil worldsteel, hot-rolled	agg	worldsteel
Steel	EU-28	Steel galvanized	agg	worldsteel
Steel	EU-28	Wire rod worldsteel	agg	worldsteel
Steel	EU-28	Stainless steel (EN15804 A1-A3)	agg	worldsteel
Cast iron	EU-28	Cast iron component (automotive)	p-agg	ts
Aluminium	EU-28	Aluminium sheet mix	agg	ts
Aluminium	EU-28	Aluminium ingot mix	agg	ts
Aluminium	EU-28	Aluminium ingot (AlCu4MgTi) secondary	p-agg	ts
Magnesium	CN	Magnesium	agg	ts
Copper	EU-28	Copper wire mix (Europa 2015)	agg	Internal/ECI
Zinc	DE	Zinc mix	agg	ts
Nickel	GLO	Nickel mix	agg	ts
Lead	EU-28	Lead primary and secondary mix	p-agg	ILA
Praseodymium	CN	Praseodymium	agg	ts
Neodymium	CN	Neodymium	agg	ts
Tin	GLO	Tin	agg	ts
Gold	GLO	Gold mix (primary, copper and recycling route)	p-agg	ts
Silver	GLO	Silver mix	agg	ts
Chromium	DE	Ferrochrome mix	agg	ts
PE	EU-28	Polyethylene pipe (PE-HD)	agg	PlasticsEurope
PE	EU-28	Polyethylene film (PE-LD)	agg	PlasticsEurope
PE	EU-28	Polyethylene low density granulate (PE-LD)	p-agg	ELCD/PlasticsEurope
PE	EU-28	Polyethylene high density granulate (PE-HD)	p-agg	ELCD/PlasticsEurope
PP	EU-28	Polypropylene fibers (PP)	agg	ts
PC	EU-28	Polycarbonate	agg	PlasticsEurope
PA6.6	EU-28	Polyamide 6.6 fibers (PA 6.6)	agg	ts
PBT	DE	Polybutylene terephthalate granules (PBT) mix	agg	ts
PET	EU-28	Polyethylene terephthalate fibers (PET)	agg	ts
PVC	DE	Polyvinyl chloride granules (Suspension, S-PVC) mix	agg	ts
ABS	EU-28	Acrylonitrile butadiene styrene (ABS)	agg	PlasticsEurope
POM	DE	Polyoxymethylene granules (POM) mix	agg	ts
NR	DE	Natural rubber (NR)	agg	ts
EPDM	DE	Ethylene propylene diene elastomer (EPDM)	agg	ts
VMQ	DE	Silicone rubber (RTV-1, moisture-curing)	agg	ts
UP	DE	Unsaturated polyester resin (UP)	agg	ts
PU	DE	Rigid polyurethane foam (PU)	u-so	ts
Electrics	GLO	Printed circuit boards assembled (standard average, LEAD)	agg	internal
Cotton	GLO	Textile manufacture - fabrics	p-agg	CottonInc
Paint	DE	Water-based painting (industry; black)	agg	ts
Resin	DE	2-component epoxy resin adhesive (simple)	agg	ts
Cardboard	EU-28	Corrugated cardboard excl. papermaking 2015	p-agg	ts/FEFCO
Paper	EU-25	Graphic paper	agg	Euro-graph/ELCD
Glasswool	EU-28	Glass wool	agg	ts
Glass	DE	Window glass	agg	ts
Barium carbonate	DE	Barium carbonate via barium sulfide and CO2	agg	ts
Calcium carbonate	EU-28	Calcium carbonate >63µ	agg	IMA-Europe/ELCD
Lubricant	EU-28	Lubricants, from the refinery	agg	ts

Phosphate	GLO	Phosphate mix (32,4 % P2O5)	agg	ts
Perlite	EU-28	Perlite (grain 0/3) (EN15804 A1-A3)	agg	ts
R134a	DE	Tetrafluoroethane (R134a)	agg	ts
Platinum	GLO	Platinum mix	agg	ts
Sulphuric acid	EU-28	Sulfuric acid (100% H2SO4)	agg	Fertilizers Europe
Process water	EU-28	Process water	agg	ts

Use phase

Energy/Fuel	Country	Dataset name	Type	Origin
EU baseline	EU-28	Electricity mix	agg	ts
EU wind	EU-28	Electricity wind	agg	ts
Diesel	EU-28	Diesel mix, at the gas station (100% fossil)	agg	ts
RME	EU-28	Biodiesel made from rape seeds (RME)	agg	ts
AdBlue	DE	Urea (Stami carbon process)	agg	ts
HVO	FI	Hydrotreated Vegetable oil (HVO) from beef tallow (tallow production burden free)	agg	ts