Towards a European-wide harmonised transport-specific LCA Approach

TranSensus LCA

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Disclaimer

The information and critical views discussed in this report are those of the authors, based upon their expert knowledge and experience, and aim to serve a basis to facilitate further research. These views are not intended to restrict the further assessment and decision-making process in the subsequent stages of the TranSensus LCA project. Rather, this report, and the critical assessment provided, provides an input to the further work in Work Package 1 Task 1.2 (on needs and gaps), and into Work Package 2, where the individual methodological points will be further discussed in more detail and final methodology recommendations developed.

Executive Summary

Introduction

Zero emissions vehicles (ZEVs) are a promising option for more sustainable mobility services. More serious action needs to be taken in Europe and globally to foster more sustainable road transportation prioritizing climate-neutrality targets. To this end, decision making processes need to be informed via robust methodologies to evaluate and monitor sustainability performance. Life cycle-based methodologies, such as Life Cycle Assessment (LCA), Social Life Cycle Assessment (S-LCA), and Life Cycle Costing (LCC), are the logical choice as these can provide a holistic sustainability perspective. LCA, S-LCA, and LCC are increasingly used within policy making, industry, and science to obtain sustainability information related to products, services, or technologies, as well as systems on a larger scale, including that of ZEVs. However, not all methods are equally mature (e. g. S-LCA being a newer method) and all methods include a number of choices that can lead to variations in results. Currently, there is not enough harmonization on these choices, which leads to variations in results for one and the same product, hinders the comparability of studies, and limits the usefulness of the methods for guiding decision makers.

TranSensus LCA aims at developing a consensus methodology for environmental LCA of ZEVs as a first priority but aims also at casting light on similar issues in S-LCA and LCC. The consortium includes influential European partners in the mobility field.

Methodological Approach

In this report, and as a first step towards the goal of building consensus, a review of current practices from available standards and guidelines, industry, and academia is provided in order to pave the way towards the aspired consensus. The report contains three main chapters that review in detail the current practices and guidelines, one for each methodology: LCA, S-LCA, and LCC. It ends with a discussion and conclusions that highlight key methodological issues for further harmonization.

The review method for this report was based on the following steps: defining the review scope, defining the types of sources to be reviewed, compiling these sources, defining the review criteria, actual review process. Moreover, the desk research was supported by consultation activities in the format of surveys and interviews targeting stakeholders within and outside the consortium. The outcomes from these consultation activities were used to analyse and assess the findings from the desk research. The focus of the review was determined following a consensus on three main scopes for TranSensus LCA which considers the dimensions of time and scale: Retrospective product LCA; Prospective product LCA; and Fleet-level LCA.

Summary of Key Findings for Environmental LCA

Overall, the review on LCA showed that a clear distinction should be considered when evaluating entire vehicles, and when evaluating batteries as a core element of ZEVs. This has implications on the goal and scope definition concerning important aspects such as the functional unit and system boundary. Distance-based functional unit is a typical choice for vehicles (sometimes also incorporating occupancy or loading factors for commercial vehicles), while energy provided by battery in its lifespan is dominating the battery-focused sources. A certain level of consensus on these choices was identified in the literature review, however it was not unanimous since a lot of objections still exist on some of these choices demanding robust assumptions on performance parameters like lifetime span.

Functional unit choice cannot be separated from system boundary. A common choice of cradle-to-grave (a full life cycle) for a vehicle or battery will promote the use stage as the base for defining the functional unit. Conversely, a cradle-to-gate system boundary was found to be the common choice to compare battery chemistries and materials since a lot of focus is given to mitigating the production impacts of batteries.

Data is another important topic in this review and arguably the core of many discussions. The source of data (e. g. databases) as well as assumptions (e. g. battery replacement frequency) differ widely across studies. While LCA practitioners aspire for primary data, this is often not feasible for all parts of the studied product system. This also depends greatly on where the practitioner stands in the supply chain. OEMs, for example, have better chances of obtaining good data through their suppliers of components, whereas this may not be the case for the end-of-life (EoL) of vehicles. LCI databases can fill certain gaps, e. g. for electricity generation or steel-production, but feature only generic and not specific LCI data.

Further, multifunctionality needs to be dealt with in most product systems, but rules have not been sufficiently harmonized. Multifunctionality may arise upstream, e. g., in the context of raw materials acquisition (e. g., due to co-mining). Here, multifunctionality is mostly solved by mass or economic allocation. However, which market price (current or average in a time span) to consider in the case of economic allocation is still an open question. Also, manufacturing processes where in-house services are shared (e. g. electric consumption of climate-controlled rooms shared between various products) is an open issue to solve.

Multifunctionality draws most attention in the EoL phase due to the complexity of re-use, recycling, or treatment options, and the uncertainty of which of these options will become a reality, since they will happen in the future. Despite a plethora of terms and approaches used in the different sources, the two main approaches to deal with recycled materials are the cut-off and the avoided burden approaches. The cut-off approach is the go-to method for most practitioners in the field due to relative simplicity and conservativeness, while the avoided burden approach shows immediate benefits to the same system studied (producer of recyclable materials). Another important approach is the Circular Footprint Formula (CFF) that has been promoted by the Product Environmental Footprint guidelines (PEF). While it lies in between the cut-off and the avoided burdens approach, it is criticized for its complexity and ambiguity in the equation parameters which eventually hampers applicability.

An issue that deserves further harmonization lies within the use stage. Whilst most OEM studies utilise regulatory energy consumption, other studies attempt to better account for the differences in real-world operation (which can be significant) and for different use cases. Electricity supply to battery electric vehicle use stage as well as hydrogen production for fuel-cell electric vehicles are the most impactful factor on the results. The sources reviewed varied from EU average grid mix and country-specific to prospective modelling of future possible mixes. Most of the work done relies on regional and national mixes from LCI databases. Most OEM studies (and also many scientific studies) assume a static electricity (or hydrogen) production mix, rather than a changing mix over the vehicle lifetime (e. g. from current policy projections – e. g., from IEA). Prospective and fleet-level LCA studies tend to utilise a dynamic electricity mix modelling approach, instead. We believe that accounting for future grid mixes in the analysis is of utmost importance when evaluating EVs (e. g. through scenario analyses) given that the decarbonization of grids is progressing rapidly and the electricity mix providing an EV is expected to change substantially during the vehicle's lifetime. Similarly for hydrogen production through electrolysis that is directly influenced by electricity source, or alternative production routes.

Other use-stage-related issues are assumptions of lifetime (very relevant in determining functional unit) which varies substantially in the reviewed work even within the same vehicle segment – in terms of both calendar lifetime (i. e. in years) and lifetime activity (i. e. total km). In terms of operational energy consumption, most studies utilize data based on regulatory testing (particularly OEM studies), however this is known to frequently significantly underestimate real-world consumption; some studies make estimates to account for this in the main modelling or include sensitivities on this aspect. Furthermore, the consideration of maintenance modelling (including potential battery or fuel cell replacement) varies significantly in the literature, between complete neglection, assumptions based on tests and fact sheets, and arbitrary assumptions. Also, direct particulate matter emissions from tire and brake pads wearing were identified as a very difficult flow to estimate (due to lack of empirical data or standardized measurement methods) and often omitted.

Most of the studies focus on climate change given that it is a main driver of road electrification. The prioritization of this impact category was obvious in the reviewed work. This is understandable, but it opens doors for burden shifting to other impact categories. Abiotic resource depletion is an example of a very relevant impact category that does not receive as much attention. More harmonization on mandatory impact categories and on the LCIA method used seems desirable. The Environmental Footprint (EF) method of the PEF seems like the viable option based on our review (to be supplemented at least with a more complete measure of energy efficiency/demand, such as CED due to its policy relevance in the European context). It is important to notice, however, that despite the holistic approach of the LCA, S-LCA, and LCC, only selected impact pathways are included, some of them are not perfect, and others are simply missing. In the context of ZEVs, it would be preferable to also include categories on dissipation and circularity of materials in the future as additional indicators.

Different styles of reporting and interpretation have been pursued by LCA practitioners across the reviewed sources. Variations in interpretations were found to mainly stem from the differences in the goal and scope of study and the nature of the products. Only a few guidelines provide generic recommendations on how to apply uncertainty analysis. Theoretically, uncertainty analyses should take place first to lead to more representative sensitivity analysis. Yet, the review revealed that uncertainty analyses are rarely performed outside the scientific literature, while sensitivity analyses are found more commonly, e. g. in OEM reports to test specific aspects (e. g. electric grid, driving patterns). Verification for data quality, completeness and consistency requires guidance and harmonization since currently third-party verification is often adopted but without clear rules to govern it.

Summary of Key Findings for S-LCA

S-LCA is the most novel methodology among the three methodologies. Some attempts were done in scientific literature to evaluate the social impacts of ZEV value chains or electromobility. However, the immaturity of the original methodology and the availability of very few studies, makes it difficult to extract concrete conclusions for this report particularly for method advancement since it is still applied in a non-harmonized way. The sensitive nature of the data here (if at all available) is a significant issue in S-LCA which hampers its evolvement and recognition, especially in industry. Indeed, no publicly available OEM reports could be found for this review. Therefore, most of the work done is in academia and is dependent on secondary databases like Product Social Impact Life Cycle Assessment database (PSILCA) and The Social Hotspots Database (SHDB) which provide sector-based and country-based data with little primary data usually collected through interviews.

Summary of Key Findings for LCC

The situation for LCC is similar as to that for S-LCA. General standards for LCC do not exist currently and the existing literature regarding LCCs of ZEVs is limited. Several tools use LCC for procurement purposes, most notably for public procurement. For example, the Clean Fleets Life Cycle Cost to determine the monetary value of energy and environmental costs for public vehicle procurement. In reports and scientific literature, LCC's goal tends to be more prospective and comparative, typically comparing the costs of ICEs and EVs over their lifetime. Different LCC approaches exist: Total Cost of Ownership (TCO), Conventional LCC (C-LCC), Environmental LCC (E-LCC), and Societal LCC (S-LCC), each with distinct goals and scopes. Harmonization efforts should seek Clear guidance on LCC type, Monetization of environmental and social impacts, avoiding double counting when addressing LCC with S-LCA, and harmonizing the choice of discount rate which is an important factor affecting LCC inventory and it varies between studies depending on the study's perspective and timeline.

Conclusions to guide harmonization efforts

Proper definition of the goal and scope lays the ground for a consistent meaningful LCA study. The three big scopes defined within TranSensus LCA are thought to be comprehensive for the LCAs conducted nowadays, nonetheless, a clear-cut is sometimes hard to draw between theses scopes. Therefore, the authors suggest clear indication to the scope of LCAs and elaboration on the final intended application. A typical implication of this is defining the modelling approach whether attributional or consequential that better suit the scope and application and point out any deviation from the standard practices of any of the two modelling approaches. Justified deviations are acceptable even if the harmonized methodology of TranSensus LCA is intended to be systematic as much as possible, however adaptability to different technologies of powertrains and core components like batteries should be accounted for.

Functional unit (FU) and system boundaries definition are principal methodological choices in LCA and there are interconnected. It seems that the controversial point here is the service lifetime (from calendar year, mileage and battery charging cycles) whether for full-vehicle studies or battery-focused studies. Since including use phase in the system boundary is typical for a full cradle-to-grave study, service lifetime should be a focal point for harmonization as it heavily affects the functional unit definition. For the functional unit, a distance-based functional unit appear as the most common choice for vehicles, however refining is required on whether to include other factors like passengers carried or goods transported for better representativeness of the function (particularly for commercial vehicles). For batteries, a harmonization is required whether to adopt a capacity-based or throughput based functional unit. Other less harmonized aspects are clear rules for cut-offs/system boundary (e. g. notably for aspects such as maintenance and infrastructure).

Inventory data is perhaps the area that requires the most attention, since harmonization was partly or fully absent in the reviewed work. This starts from the medium of data collection and type of data (primary or secondary) at each stage of the life cycle. Electricity generation modelling (and also hydrogen production for relevant powertrains using this fuel) is arguably the most impactful on the results hence pushing towards clear guidelines on electricity (and hydrogen) supply mix choices should be a priority (i. e. including agreed standardized future projections for these). In particular, there are different views on the treatment of renewable electricity with certificates, and concerns over additionality, and consistency with recent new EU rules for renewable hydrogen. Data and assumptions on operational energy consumption also need reviewing, to ideally find ways to better account for real-world performance (compared to regulatory-testing data). In addition, typical multifunctionality issues in the field (especially co-production of primary materials and EoL of vehicles/batteries) should be dealt with by providing clear rules for allocation and/or substitution. EoL multifunctionality is the area where most unharmonized practices are observed as it is linked to vast immature possibilities especially for batteries when it comes to recycling or giving a second life in other applications. Other minor conflicts were found in how/whether maintenance is modelled, also direct emissions from tires/brake pads wearing in ZEV.

After harmonizing choices made in LCI, the user of TranSensus LCA methodology should be provided with clear LCIA method to follow. From our review, there appears to be some agreement on using EF LCIA method that we observed. The harmonization work can build on these, with further recommendations to be formed on choosing which impact categories to report and in which context. Furthermore, agreement is needed on whether to recommend refined indicators like resources dissipation in the light of the promoted transition towards circular economies. Cumulative and Primary energy demand indicators (which provide a measure of the overall lifecycle energy efficiency) are not part of EF, however they are very relevant for ZEVs to provide comprehensive LCA results, and energy efficiency is a key pillar of Europe's climate and energy framework. Therefore, it seems highly important that an indicator of cumulative primary energy demand should be included; thus, a harmonization is needed on how to consider this.

A partial harmonization has been observed in comparisons and analyses carried out in the last interpretation phase but clear recommendations on what to test on sensitivity analyses are still missing, and also how to/whether to account for uncertainty and reflect that on the sensitivity analysis.

S-LCA and LCC are not yet consolidated methodologies like LCA and not widely applied in ZEV field, so no previous harmonization attempts have been made.

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Glossary

Note:

1) The glossary for Environmental Life Cycle Assessment was primarily adopted from Product Environmental Footprint Guidelines (PEF) (EC-JRC, 2021). Methodological points which are PEF-specific are re-formulated for general applicability. Any new term that did not come from PEF or deviates even slightly from the definition reported in PEF will be written in *Italic*.
2) The terms for Social Life Cycle Assessment were adopted from UNEP guidelines (Benoît et al., 2013)
3) If same term was found to apply for both methodologies, the methodology intended is highlighted between parentheses next to the term.
4) The list of definitions is not limited to the terms appearing in the report since the other terms were thought to be helpful to the reader as well like some basic terms.

***Acidification** –Impact category that addresses impacts due to acidifying substances in the environment. Emissions of NOx, NH3 and SOx lead to releases of hydrogen ions (H+) when the gases are mineralised. The protons contribute to the acidification of soils and water when they are released in areas where the buffering capacity is low, resulting in forest decline and lake acidification.*

Activity data - information which is associated with processes while modelling Life Cycle Inventories (LCI). The aggregated LCI results of the process chains, which represent the activities of a process, are each multiplied by the corresponding activity data1 and then combined to derive the environmental footprint associated with that process. Examples of activity data include quantity of kilowatt-hours of electricity used, quantity of fuel used, output of a process (e. g. waste), number of hours equipment is operated, distance travelled, floor area of a building, etc. Synonym of ‘non-elementary flow’.

Activity variable - An activity variable is a measure of process activity or scale which can be related to process output. Activity variables, scaled by the output of each relevant process, are used to reflect the share of a given activity associated with each unit process. A relevant activity variable is worker-hours. Process-specific coefficients of worker-hours per unit of process output are used to estimate the share of total life cycle worker-hours associated with each unit process. The activity variable is useful to represent the product system in a way that gives an idea of the relative significance of each unit process in the whole system.

***Additional environmental information** – environmental information outside the impact categories that is calculated and communicated alongside LCA results.*

***Additional technical information** – non-environmental information that is calculated and communicated alongside LCA results.*

Aggregated dataset - complete or partial life cycle of a product system that – next to the elementary flows (and possibly not relevant amounts of waste flows and radioactive wastes) – itemises only the product(s) of the process as reference flow(s) in the input/output list, but no other goods or services. Aggregated datasets are also called 'LCI results' datasets. The aggregated dataset may have been aggregated horizontally and/or vertically.

Aggregation - The action of summing or bringing together information (e. g., data, indicator results, etc.) from a smaller scope into a larger scope, e. g., from inventory indicator to sub-category. In S-LCA, aggregation of data may be done at the life cycle inventory or impact assessment phase of the study and should not be done in a way that leads to loss of information about the location of the unit processes.

Allocation – an approach to solving multi-functionality problems. It refers to 'partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems.

Application specific – generic aspect of the specific application in which a material is used. For example, the average recycling rate of PET in bottles.

Area of protection [The term "Damage category" can be used as a synonym] - A state that is desired to be sustained or protected which is of recognizable value to society, in the specific context of sustainability assessment. In the field of S-LCA, one area of protection has been defined and is referred to as human well-being (health and happiness) or simply social well-being. See also Box 17. For environmental LCA areas of protection include human health, natural resources, natural environment, and man-made environment.

Attributes [see "Life cycle attribute assessment"]- Properties or characteristics of a process, which are of interest to stakeholders. These are different from conventional quantitative input/output flows of processes but are of a qualitative nature, e. g. gender discrimination or safety as a whole, and thus also coincide with qualitative parameters of social issues in the context of S-LCA.

Attributional – process-based modelling intended to provide a static representation of average conditions, excluding market-mediated effects.

***Attributional LCA** – a type of LCA focusing on one specific functional unit of the system/product under study, while assuming that the system/product itself does not alter the larger system into which it is embedded/deployed. (e. g., an LCA of one EV, without considering the effects that a large-scale roll-out of EVs may be expected to have on: (i) the demand for LIB metals, and hence on the changing impacts of their supply chains, and (ii) the increased total demand for electricity due to the vehicle's use phase, which may necessitate deployment of new generators and changes in grid mix composition).*

Average Data – production-weighted average of specific data.

Background processes – refers to those processes in the product life cycle for which no direct access to information is possible. For example, most of the upstream life-cycle processes and generally all processes further downstream will be considered part of the background processes.

Benchmark – a standard or point of reference against which any comparison may be made. In the context of PEF, the term ‘benchmark’ refers to the average environmental performance of the representative product sold in the EU market.

Bill of materials *– a bill of materials or product structure (sometimes bill of material, BOM or associated list) is a list of the raw materials, sub-assemblies, intermediate assemblies, sub-components, parts and the quantities of each needed to manufacture the product. In some sectors it is equivalent to the bill of components.*

Business to business (B2B) – describes transactions between businesses, such as between a manufacturer and a wholesaler, or between a wholesaler and a retailer.

Business to consumers (B2C) – describes transactions between business and consumers, such as between retailers and consumers.

Characterization *– calculation of the magnitude of the contribution of each classified input/output to their respective impact categories, and aggregation of contributions within each category. This requires a linear multiplication of the inventory data with characterization factors for each substance and impact category of concern. For example, with respect to the impact category ‘climate change’, the reference substance is* CO_2 *and the reference unit is kg* CO_2*-equivalents.*

Characterization (S-LCA) - In S-LCIA, the characterization models are the formalized, and - not always - “mathematical” operationalization of the social and socio-economic mechanisms. They may be a basic aggregation step, bringing text or qualitative inventory information together into a single summary, or summing quantitative social and economic inventory data within a category. Characterization models may also be more complex, involving the use of additional information such as performance reference points.

Characterization factor *– factor derived from a characterization model which is applied to convert an assigned life cycle inventory result to the common unit of the impact category indicator.*

Characterization factor (S-LCA) - Factor, derived from a characterization model, that is applied to convert an assigned Life Cycle Inventory Analysis result to the common unit of the category and/or subcategory indicator. ISO 14040 (2006).

Classification – assigning the material/energy inputs and outputs tabulated in the life cycle inventory to impact categories, according to each substance's potential to contribute to each of the impact categories considered.

Classification (S-LCA) - The classification step is the step where the Inventory results are assigned to a specific Stakeholder Category and/or Impact (sub)Category.

Climate change – impact category considering all inputs and outputs that result in greenhouse gas (GHG) emissions. The consequences include increased average global temperatures and sudden regional climatic changes.

Co-function - any of two or more functions resulting from the same unit process or product system.

Company-specific data – refers to directly measured or collected data from one or more facilities (site-specific data) that are representative for the activities of the company (company is used as synonym of organisation). It is synonymous to 'primary data'. To determine the level of representativeness a sampling procedure may be applied.

Company-specific dataset – refers to a dataset (disaggregated or aggregated) compiled with company-specific data. In most cases the activity data is company-specific while the underlying sub-processes are datasets derived from background databases.

Comparative assertion – an environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function (including the benchmark of the product category).

Comparison *– a comparison, not including a comparative assertion, (graphic or otherwise) of two or more products based on the results of an LCA study.*

Consequential LCA: *a type of LCA focusing on the changes induced by the deployment of the system/product under study, on the larger system into which it is embedded/deployed (e. g., an LCA explicitly modelling the expected changes in supply-chain impacts for LIB metals due to a large-scale uptake of EVs)*

Consumer – an individual member of the general public purchasing or using goods, property or services for private purposes.

Co-product – any of two or more products resulting from the same unit process or product system.

Cradle to gate – a partial product supply chain, from the extraction of raw materials (cradle) up to the manufacturer's 'gate'. The distribution, storage, use stage and end of life stages of the supply chain are omitted.

Cradle to grave – a product's life cycle that includes raw material extraction, processing, distribution, storage, use, and disposal or recycling stages. All relevant inputs and outputs are considered for all the stages of the life cycle.

Critical review *– process intended to ensure consistency between an LCA study and the principles and requirements of the applied LCA method.*

Cut-off criteria - Specification of the amount of material or energy flow or the level of significance associated with unit processes or product system to be excluded from a study. Adapted from ISO 14040 (2006).

Data quality – characteristics of data that relate to their ability to satisfy stated requirements. Data quality covers various aspects, such as technological, geographical and time-related representativeness, as well as completeness and precision of the inventory data.

Data quality rating (DQR) - semi-quantitative assessment of the quality criteria of a dataset, based on technological representativeness, geographical representativeness, time-related representativeness, and precision. The data quality shall be considered as the quality of the dataset as documented.

Delayed emissions – emissions that are released over time, e. g. through long use or final disposal stages, versus a single emission at time t.

Developing economies -Developing and emerging economies include all countries that are not classified as advanced economies. IMF provides a classification that is revised each year in its World Economic Outlook.

Direct elementary flows (also named elementary flows) – all output emissions and input resource use that arise directly in the context of a process. Examples are emissions from a chemical process, or fugitive emissions from a boiler directly onsite.

Direct land use change (dLUC) – the transformation from one land use type into another, which takes place in a unique land area and does not lead to a change in another system.

Directly attributable – refers to a process, activity or impact occurring within the defined system boundary.

Disaggregation – the process that breaks down an aggregated dataset into smaller unit process datasets (horizontal or vertical). The disaggregation may help make data more specific. The process of disaggregation should never compromise or threaten to compromise the quality and consistency of the original aggregated dataset.

Downstream – occurring along a product supply chain after the point of referral

Due diligence- The process through which organizations identify, consider, and address the potential environmental and social impacts related to their activities and the ones of their business relationships, as an integral part of their decision-making and risk management system. (OECD, 2016)

Ecotoxicity, freshwater – impact category that addresses the toxic impacts on an ecosystem, which damage individual species and change the structure and function of the ecosystem. Ecotoxicity is a result of a variety of different toxicological mechanisms caused by the release of substances with a direct effect on the health of the ecosystem.

EF communication vehicles – all the possible ways that may be used to communicate the results of the EF study to the stakeholders (e. g. labels, environmental product declarations, green claims, websites, infographics, etc.).

EF-compliant dataset – dataset developed in compliance with the EF requirements, regularly updated by DG JRC2.

E-LCA - Environmental Life Cycle Assessment (E-LCA) is a methodology for assessing environmental impacts associated with all the stages of the life cycle of a product, service or organization.

Electricity tracking – the process of assigning electricity generation attributes to electricity consumption.

Elementary flow - Material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation. ISO 14040 (2006)

Elementary flows – *in the life cycle inventory, elementary flows include 'material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material or energy leaving the system being studied that is released into the environment without subsequent human transformation'. Elementary flows include, for example, resources taken from nature or emissions into air, water, soil that are directly linked to the characterization factors of the impact categories.*

Endpoint impact / Endpoint (impact) indicator -Impact at the end of the cause-effect chain for a (social) issue, which can be represented by an endpoint indicator. It captures the impact on an area of protection. For example, impact on health, represented by the DALY indicator.

Environmental aspect (E-LCA) – element of an organisation's activities or products or services that interacts or can interact with the environment.

Environmental aspect (S-LCA) - Element of an organization's activities, products, or services that can interact with the environment. ISO 14040 (2006). The counterpart in S-LCA are social issues.

Impact assessment – *phase of the LCA analysis aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system* *throughout the life cycle of the product. The impact assessment methods provide impact characterization factors for elementary flows, to aggregate the impact so as to obtain a limited number of midpoint indicators.*

***Impact assessment method** – protocol for converting life cycle inventory data into quantitative contributions to an environmental impact of concern.*

***Impact category** – class of resource use or environmental impact to which the life cycle inventory data are related.*

***Impact category indicator** – quantifiable representation of an LCA impact category.*

Environmental impact – any change to the environment, whether adverse or beneficial, that wholly or partially results from an organisation's activities, products or services.

***Environmental mechanism** – system of physical, chemical and biological processes for a given impact category linking the life cycle inventory results to category indicators.*

Environmental mechanism / Social mechanism - System of physical, chemical, and biological or socio-economic processes for a given impact category, linking the Life Cycle Inventory Analysis results to impact (sub)category indicators and to category endpoints.

***Eutrophication** – Impact category related to nutrients (mainly nitrogen and phosphorus) from sewage outfalls and fertilised farmland that accelerate the growth of algae and other vegetation in water. The degradation of organic material consumes oxygen, resulting in oxygen deficiency and, in some cases, fish death. Eutrophication translates the quantity of substances emitted into a common measure, expressed as the oxygen required for the degradation of dead biomass.*

External communication – communication to any interested party other than the commissioner or the practitioner of the study.

Extrapolated data – data from a given process that is used to represent a similar process for which data is not available, on the assumption that it is reasonably representative.

Flow diagram – schematic representation of the flows occurring during one or more process stages within the life cycle of the product being assessed.

Focus group - A focus group is a type of group interview organized to acquire a portrait of combined local perspective on a specific set of issues. What distinguishes the focus group technique from the wider range of group interviews is the explicit use of the group interaction to produce data and insights that would be less accessible without the interaction found in a group. Focus groups with a range of actors can be used to identify relevant stakeholder groups and indicators. Finally, focus groups can also be used in impact assessment when defining the relative importance (weight) of each impact (sub)category.

Foreground elementary flows - direct elementary flows (emissions and resources) for which access to primary data (or company-specific information) is available.

Foreground processes – those processes in the product life cycle for which direct access to information is available. For example, the producer's site and other processes operated by the producer or its contractors (e. g. goods transport, head-office services, etc.).

Functional unit (E-LCA) – defines the qualitative and quantitative aspects of the function(s) and/or service(s) provided by the product being evaluated. The functional unit definition answers the questions 'what?', 'how much?', 'how well?', and 'for how long?'.

Functional unit (S-LCA)- Quantified performance of a product system for use as a reference unit in a life cycle assessment study, and also valid for an S-LCA. ISO 14040 (2006)

Gate to gate – a partial product supply chain that includes only the processes carried out on a product within a specific organisation or site.

Gate to grave – a partial product supply chain that includes only the distribution, storage, use, and disposal or recycling stages.

Generic data - Refers to data that has not been collected for the specific process concerned. If can be data collected from other manufacturers of the same kind of product or in the same country. In other words, it is data with a lower resolution than site-specific data.

Global warming potential (GWP) – An index measuring the radiative forcing of a unit mass of a given substance accumulated over a chosen time horizon. It is expressed in terms of a reference substance (for example, CO2- equivalent units) and specified time horizon (e. g. GWP 20, GWP 100, GWP 500 – for 20, 100 and 500 years respectively). By combining information on both radiative forcing (the energy flux caused by emission of the substance) and on the time it remains in the atmosphere, GWP gives a measure of a substance's capacity to influence the global average surface-air temperature and therefore subsequently influence various climate parameters and their effects, such as storm frequency and intensity, rainfall intensity and frequency of flooding, etc.

Goal and scope -The first phase of an LCA or S-LCA; establishing the aim of the intended study, the functional unit, the reference flow, the product system(s) under study and the breadth and depth of the study in relation to this aim. For S-LCA, a unique aspect in practice is the specification of the stakeholder group(s) of interest and the type of assessment (type I or type II).

Horizontal averaging – the action of aggregating multiple unit process datasets or aggregated process datasets in which each provides the same reference flow, to create a new process dataset.

Human rights due diligence - An ongoing risk management process in order to identify, prevent, mitigate, and account for how [a company] addresses its adverse human rights impacts. It includes four key steps: assessing actual and potential human rights impacts; integrating and acting on the findings; tracking responses; and communicating about how impacts are addressed. (This is brought forward in the “UN Guiding Principles Reporting Framework”)

Human toxicity – cancer – impact category that accounts for adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin – insofar as they are related to cancer.

Human toxicity - non cancer – impact category that accounts for the adverse health effects on human beings caused by the intake of toxic substances through inhalation of air, food/water ingestion, penetration through the skin – insofar as they are related to non-cancer effects that are not caused by particulate matter/respiratory inorganics or ionising radiation.

Impact category - A social impact category is a class that covers certain social issues of interest to stakeholders and decision makers. In practice, impact categories are logical groupings of S-LCA (subcategory) results.

Impact indicator / Impact (sub)category indicator - An indicator that represents a (social) impact, linked to a particular impact category, and in that context, can be called an “impact (sub)category indicator”.

Impact pathway approach / Type II approach / Impact pathway (IP) S-LCIA approach -Impact pathway S-LCIA assesses potential or actual social impacts by using causal or correlation/regression-based directional relationships between the product system/organizations’ activities and the resulting potential social impacts – a process called “characterization”. Here, the analysis focuses on identifying and tracking the consequences of activities possibly to longer-term implications along an impact pathway.

In particular in S-LCIA, aggregation is a way of combining various elements and synthesizing complex phenomena in order to achieve a better understanding and for the communication of results. As such, it may involve the construction of a single, possibly synthetic, score with two or more subcomponents. Single indices or scores are a powerful way to combine and summarize multi-dimensional information.

Independent external expert *– competent person, not employed in a full-time or part-time role by the commissioner of the LCA study or the user of the LCA method, and not involved in defining the scope or conducting the LCA study.*

Indicator - An indicator is a measurement or value which gives you an idea of what something is like.

Indirect land use change (iLUC) – this occurs when a demand for a certain land use leads to changes, outside the system boundary, i. e. in other land use types. These indirect effects may be mainly assessed by means of economic modelling of the demand for land or by modelling the relocation of activities on a global scale. **Input flows** – product, material or energy flow that enters a unit process. Products and materials include raw materials, intermediate products and co-products.

Input - Product, material, or energy flow that enters a unit process. ISO 14040 (2006)

Intermediate product – output form of a unit process that in turn is input to other unit processes which require further transformation within the system. An intermediate product is a product that requires further processing before it is saleable to the final consumer.

Inventory indicator - An inventory indicator is a type of impact indicator that directly relates to the product life cycle, e. g. hours at risk of child labour. An inventory indicator provides the most direct evidence of the condition or result that is measured. They are specific definitions of the data sought. Inventory indicators have characteristics such as type (e. g. qualitative or quantitative) and unit of measurement.

Ionising radiation, human health *– impact category that accounts for the adverse health effects on human health caused by radioactive releases.*

Land use *– impact category related to use (occupation) and conversion (transformation) of land area by activities such as agriculture, forestry, roads, housing, mining, etc. Land occupation considers the effects of the land use, the amount of area involved and the duration of its occupation (changes in soil quality multiplied by area and duration). Land transformation considers the extent of changes in land properties and the area affected (changes in soil quality multiplied by the area).*

Lead verifier – person taking part in a verification team with additional responsibilities, compared to the other verifiers in the team.

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

Life cycle approach – takes into consideration the spectrum of resource flows and environmental interventions associated with a product from a supply-chain perspective, including all stages from raw material acquisition through processing, distribution, use, and end of life processes, and all relevant related environmental impacts (instead of focusing on a single issue).

Life cycle assessment (LCA) – compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle.

Life cycle attribute assessment [see “attribute”] - A method that enables to express the percentage of a supply chain that possesses (or lacks) an attribute of interest. Norris (2006)

Life cycle costing / Environmental life cycle costing - Life cycle costing, or LCC, or more specifically environmental life cycle costing, is a compilation and assessment of all costs related to a product, over its entire life cycle, from production to use, maintenance, and disposal.

Life cycle impact assessment (LCIA) – phase of life cycle assessment that aims to understand and evaluate the magnitude and significance of the potential environmental impacts for a system throughout the life cycle. The LCIA methods used provide impact characterization factors for elementary flows to aggregate the impact, to obtain a limited number of midpoint and/or damage indicators.

Life cycle impact assessment / Social life cycle impact assessment (S-LCIA) - Phase of an S-LCA that aims at understanding and evaluating the magnitude and significance of the impacts for a product system throughout the life cycle of the product. Adapted from ISO 14040 (2006)

Life cycle inventory (LCI) - the combined set of exchanges of elementary, waste and product flows in a LCI dataset.

Life cycle inventory (LCI) dataset - a document or file with life cycle information of a specified product or other reference (e. g., site, process), covering descriptive metadata and quantitative life cycle inventory. A LCI dataset could be a unit process dataset, partially aggregated, or an aggregated dataset.

Life cycle inventory / Social life cycle inventory (S-LCI) - Phase of an S-LCA where data are collected, the systems are modelled, and the LCI results are obtained.

Life cycle thinking - Going beyond the traditional focus on production site and manufacturing processes so to include the environmental, social, and economic impact of a product over its entire life cycle. UNEP-DTIE-Life Cycle Management, a Business Guide to Sustainability.

Loading rate – ratio of actual load to the full load or capacity (e. g. mass or volume) that a vehicle carries per trip.

Materiality assessment - Materiality assessment is a process to select topics that are more important because of their impact on stakeholders and/or on the business. The Global Reporting Initiative consider material issues to be the ones that reflect the organization’s significant social impacts; or that substantively influence the assessments and decisions of stakeholders. This is also recommended by ISO 26000.

Materiality principle - Materiality (principle) constitutes social matter (information, data, performance, impact, stakeholder) that is of such relevance and importance that it could substantially influence the conclusions of the study, and the decisions and actions based on those conclusions. In the Interpretation section, we follow this definition.

Material-specific – a generic aspect of a material. For example, the recycling rate of polyethylene terephthalate (PET).

Method - Specific procedure within a technique.

Methodology - Coherent set of methods.

Midpoint impact / Midpoint (impact) indicator - Impact midway the cause-effect chain of a social issue, which can be represented by a midpoint indicator. It does not imply a fixed point halfway through the cause-effect chain.

***Models**: mathematical description/formula*

Multi-functionality – if a process or facility provides more than one function, i. e. it delivers several goods and/or services ('co-products'), then it is 'multifunctional'. In these situations, all inputs and emissions linked to the process will be partitioned between the product of interest and the other co-products, according to clearly stated procedures.

Non-elementary (or complex) flows – in the life cycle inventory, non-elementary flows include all the inputs (e. g. electricity, materials, transport processes) and outputs (e. g. waste, by-products) in a system that need further modelling efforts to be transformed into elementary flows. Synonym of 'activity data'.

Normalization – after the characterization step, normalization is the step in which the life cycle impact assessment results are divided by normalization factors that represent the overall inventory of a reference unit (e. g. a whole country or an average citizen). Normalised life cycle impact assessment results express the relative shares of the impacts of the analysed system, in terms of the total contributions to each impact category per reference unit. Displaying the normalised life cycle impact assessment results for the different impact topics next to each other shows which impact categories are affected most and least by the analysed system. Normalised life cycle impact assessment results reflect only the contribution of the analysed system to the total impact potential, not the severity/relevance of the respective total impact. Normalised results are dimensionless, but not additive.

Organisation Environmental Footprint Sectorial Rules (OEFSRs) - sector specific, life-cycle based rules that complement general methodological guidance for OEF studies by providing further specification at the level of a specific sector. OEFSRs help to shift the focus of the OEF study towards those aspects and parameters that matter the most, and hence contribute to increased relevance, reproducibility and consistency of the results by reducing costs versus a study based on the comprehensive requirements of the OEF method. Only the OEFSRs developed by or in cooperation with the European Commission, or adopted by the European Commission or as EU acts are recognised as in line with this method.

Organization - Company, corporation, firm, enterprise, authority, or institution, or part or combination thereof, whether incorporated or not, public or private, that has its own functions and administration. ISO 14001 (2004)

Output - Product, material, or energy flow that leaves a unit process. ISO 14040 (2006)

Output flows – product, material or energy flow that leaves a unit process. Products and materials include raw materials, intermediate products, co-products and releases. Output flows are also considered to cover elementary flows.

Ozone depletion *– impact category that accounts for the degradation of stratospheric ozone due to emissions of ozone-depleting substances, for example long-lived chlorine and bromine containing gases (e. g. chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs), halons).*

Partially disaggregated dataset - a dataset with an LCI that contains elementary flows and activity data, and that yields a complete aggregated LCI data set when combined with its complementing underlying datasets.

Particulate matter *– impact category that accounts for the adverse effects on human health caused by emissions of particulate matter (PM) and its precursors (NOx, SOx, NH3).*

Performance reference point (PRP) - Performance reference points (PRPs) are thresholds, targets, or objectives that set different levels of social performance or social risk. PRPs allow to estimate the magnitude and significance of the potential social impacts associated with organizations in the product system. The PRPs are context-dependent and are often based on international standards, local legislation, or industry best practices – Comparing inventory indicator data with PRPs allows to qualify performance on a scale.

Photochemical ozone formation *– impact category that accounts for the formation of ozone at the ground level of the troposphere caused by photochemical oxidation of volatile organic compounds (VOCs) and carbon monoxide (CO) in the presence of nitrogen oxides (NOx) and sunlight. High concentrations of ground-level tropospheric ozone damage vegetation, human respiratory tracts and manmade materials, by reacting with organic materials.*

Population - any finite or infinite aggregation of individuals, not necessarily animate, subject to a statistical study.

Primary data (E-LCA)*– data from specific processes within the supply chain. Such data may take the form of activity data or foreground elementary flows (life cycle inventory). Primary data are site-specific, company-specific (if multiple sites for the same product) or supply chain specific. Primary data may be obtained through meter readings, purchase records, utility bills, engineering models, direct monitoring, material/product balances, stoichiometry, or other methods for obtaining data from specific processes in the value chain. In this report, primary data is a synonym of 'company-specific data' or 'supply chain specific data'.*

Primary data (S-LCA)- Refers to data that has been directly collected by the practitioner, via interview, survey, or participant observation for instance.

Product (S-LCA) - Any good or service offered to members of the public either by sales or otherwise. ISO 26000 WD4.2 (2008)

Product (E-LCA) – any good or service.

Product category – group of products (or services) that can fulfil equivalent functions.

Product category rules (PCRs) – set of specific rules, requirements and guidelines for developing Type III environmental declarations for one or more product categories.

Product environmental footprint category rules (PEFCRs) – product category-specific, life cycle-based rules that complement general methodological guidance for PEF studies by providing further specification for a specific product category. PEFCRs help to shift the focus of the PEF study towards those aspects and parameters that matter most, and hence increase the relevance, reproducibility and consistency of the results by reducing costs, compared to a study based on the comprehensive requirements of the PEF method. Only PEFCRs developed by or in cooperation with the European Commission, or adopted by the Commission or as EU acts, are recognised as being in line with this method.

Product flow – products entering from or leaving to another product system.

Product system – collection of unit processes with elementary and product flows, performing one or more defined functions, which model the life cycle of a product.

Product utility - Product utility refers to the perception of the consumer in regard to what the product provides, besides its function (the capacity of a good to satisfy a need). This appreciation is linked with his/her cultural and social values, as well as his/her desires and satisfaction. Product utility can be identified in technical terms (quality, functionality etc.) or in social terms (convenience, prestige, etc.).

Prospective LCA: *A prospective LCA is conducted in the development stage and aims to estimate environmental impacts before the start of production (several years). The TRL is low (TRL<6) and the BOM is not completely defined.*

Qualitative indicator - Qualitative indicators are nominative; they provide information on a particular issue using words. For instance, text describing the measures taken by an enterprise to manage stress.

Quantitative indicator - A quantitative indicator is a description of the issue assessed using numbers, e. g. number of accidents by unit process.

Raw material – primary or secondary material used to produce a product.

Reference flow (S-LCA) - A reference flow is a quantified amount of product(s), including product parts, necessary for a specific product system to deliver the performance described by the functional unit.

Reference flow (E-LCA) – measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit.

Reference scale - Reference scales are ordinal scales, typically comprised of 1 to 5 levels, each of which corresponds to a performance reference point (PRP).

Reference scale approach / Type I approach / Reference scale (RS) S-LCIA - Reference scale S-LCIA assesses the social performance in the product system. More specifically, it assesses the social performance of activities of organizations in the product system (e. g. the practices implemented to manage social impacts) based on specific reference points of expected activity (called performance reference points - PRPs).

Refurbishment – the process of restoring components to a functional and/or satisfactory state compared to the original specification (providing the same function), using methods such as resurfacing, repainting, etc. Refurbished products may have been tested and verified to function properly.

Releases – emissions to air and discharges to water and soil.

Representative product (model) – this may be a real or virtual (non-existing) product. The virtual product should be calculated based on average European market sales-weighted characteristics for all existing technologies/materials covered by the product category or subcategory. Other weighting sets may be used, if justified – for example weighted average based on mass (ton of material) or weighted average based on product units (pieces).

Representative sample – a representative sample with respect to one or more variables is a sample in which the distribution of these variables is exactly the same (or similar) as in the population of which the sample is a subset.

Resource use, fossil *– impact category that addresses the use of non-renewable fossil natural resources (e. g. natural gas, coal, oil).*

Resource use, minerals and metals *– impact category that addresses the use of non-renewable abiotic natural resources (minerals and metals).*

Retrospective LCA*: A retrospective LCA aims to evaluate environmental impacts slightly before or after the start of production. A nearly finalised bill of materials of all parts is available to the OEM.*

Review *– procedure intended to ensure that the process of developing or revising an LCA study has been carried out in accordance with the requirements provided in a certain document.*

Review panel (in PEF context)– team of experts (reviewers) who will review the PEFCR
Reviewer – independent external expert conducting the review of the PEFCR and possibly taking part in a reviewer panel.

Review report - a documentation of the review process that includes the review statement, all relevant information about the review process, the detailed comments from the reviewer(s) and the corresponding responses, and the outcome. The document shall carry the electronic or handwritten signature of the reviewer (or the lead reviewer, if a reviewer panel is involved)

***Reviewer** – independent external expert conducting the review of the LCA and possibly taking part in a reviewer panel.*

Salient social risks / impacts - Social impact subcategories that account for a greater share of the overall risk/impact. The UN Guiding Principles consider salient risks/impacts to be the ones that affect the most vulnerable stakeholders and that cause irreparable damages.

Sample – a subset containing the characteristics of a larger population. Samples are used in statistical testing when population sizes are too large for the test to include all possible members or observations. A sample should represent the whole population and not reflect bias toward a specific attribute.

Scope of the study -The scope is defined in the first phase of the study. It encompasses issues of depth and breadth of the study. It defines the limits placed on the product life cycle (that can be infinite) and on the detail of information to be collected and analysed. It defines where the data will be coming from, how up to date the study will be, how information will be handled, and where the results will be applicable.

Scoring system - Scoring may use quantitative, semi-quantitative, or qualitative scales, according to the availability of information and the impact (sub)category or impact category under consideration. Scoring systems usually seek to standardize the scores for purpose of comparison.

Secondary data (E-LCA) – data that is not from a specific process within the supply-chain of the company performing a PEF study. This refers to data that is not directly collected, measured or estimated by the company, but rather sourced from a third party LCI database or other sources. Secondary data includes industry average data (e. g., from published production data, government statistics and industry associations), literature studies, engineering studies and patents) and may also be based on financial data and contain proxy and other generic data. Primary data that go through a horizontal aggregation step are considered to be secondary data.

Secondary data (S-LCA)- Refers to data that has been initially collected and manipulated by another person/institution than the practitioner or collected for another purpose than the one being currently considered or, often a mix of the two. For example, a publication, third party audit, or a database.

Semi-quantitative indicator - Semi-quantitative indicators are indicators that have results expressed into a yes/no form or a scale (scoring system): for example, presence of a stress management program (yes-no). Qualitative and quantitative indicator results may be translated into a semi-quantitative form.

***Sensitivity analysis** – systematic procedures for estimating the effects of the choices made regarding methods and data on the results of a LCA study.*

Sensitivity analysis (S-LCA) -Systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study.

***Single overall score** – sum of the weighted LCA results of all environmental impact categories.*

Site-specific data – directly measured or collected data from one facility (production site). A synonym of 'primary data'.

S-LCA - A social and socio-economic Life Cycle Assessment (S-LCA) is a social impact (actual and potential impacts) assessment technique that aims to assess the social and socio-economic aspects of products and their positive and negative impacts along their life cycle encompassing extraction and processing of raw materials, manufacturing, distribution, use, re-use, maintenance, recycling, and final disposal.

Social capital - The social conditions, such as institutions, rule of law, trust, and human networks, that are prerequisites or catalysts for production, but do not enter into the production themselves.

Social endpoint / Social category endpoint - A social attribute or aspect identifying an issue giving cause for concern Adapted from ISO 14040 (2006). It is thus an aspect of an area of protection, e. g. the payment for workers relating to their well-being. They are closely related to endpoint impact categories.

Social footprint - A social footprint refers to the end result of an S-LCA study, in term of adverse effects, overall or by impact category/subcategory (e. g. The total medium risk hours equivalent for labour rights and decent work by purchase category supply chain).

Social handprint - Social handprints are the results of changes to business as usual that create positive outcome or impacts. They can be changes reducing the social footprint, or changes that create additional/unrelated positive social impacts. Those changes can apply to the product or organization value chain, or they may be beyond its scope.

Social hotspots [The term "Bottleneck" can be used as a synonym for negative hotspots] - A social hotspot is a location and/or activity in the life cycle where a social issue (as impact) and/or social risk is likely to occur. It is usually linked to life cycle stages or processes. It needs to contribute significantly to the impact (overall, by impact category or subcategory). In other words, social hotspots are unit processes located in a region where a problem, a risk, or an opportunity may occur in relation to a social issue that is considered to be threatening social well-being or that may contribute to its further development.

Social impact assessment (SIA) - Social Impact Assessment (SIA) is the process of identifying the social consequences or impacts that are likely to follow specific policy actions or project development, to assess the significance of these impacts and to identify measures that may help to avoid or minimize adverse effects.

Social impact pathway [The term “Social mechanism” can be used as a synonym] - An impact pathway that covers the propagation of the cause-effect chain from social LCI results to impact and is specified per social impact (sub)category.

Social impacts - Social impacts are consequences of positive or negative pressures on social endpoints of area of protection (i. e., well-being of stakeholders).

Social indicators - Social indicators are evidence, subjective or objective, qualitative, quantitative, or semi-quantitative being collected in order to facilitate concise, comprehensive and balanced judgements about the condition of specific social aspects with respect to a set of values and goals. In LCA social indicators are indicators of a social LCI result (inventory indicators) or represent impact per social impact (sub)category.

Social performance - Social performance refers to the principles, practices, and outcomes of businesses’ relationships with people, organizations, institutions, communities, and societies in terms of the deliberate actions of businesses toward these stakeholders as well as the unintended externalities of business activity measured against a known standard (Wood, 2016). Commonly, social performance is measured at the inventory indicator level.

Social significance / significant - Social significance is a judgment on the degree to which a situation or impacts are important. It is highly dependent on context, based on criteria, normative, contingent on values, and entails considering trade-offs.

Social themes / Social issues - Social themes or issues are considered as threatening social well-being or that may contribute to its further development. Social themes of interest include but are not restricted to: human rights, work conditions, cultural heritage, poverty, disease, political conflict, indigenous rights, etc.

Socio-economic - Which involves a combination of social and economic factors or conditions.

Specific data – directly measured or collected data representative of activities at a specific facility or set of facilities. A synonym of ‘primary data’.

Stakeholder category / Stakeholder group - Cluster of stakeholders that are expected to have similar interests due to their similar relationship to the investigated product system.

Stakeholder -Individual or group that has an interest in any activities or decisions of an organization. (ISO 26000, 2008)

Subcategory / Impact subcategory - It is a constituent of an impact category that is assigned to a stakeholder group, for example “Health and Safety” for the stakeholder group “Workers”. Multiple subcategories, possibly across various stakeholder groups, may be part of an overarching impact category.

Subdivision – subdividing involves disaggregating multifunctional processes or facilities to isolate the input flows directly associated with each process or facility output. The process is investigated to see whether it may be subdivided. Where subdivision is possible, inventory data should be collected only for those unit processes directly attributable to the products/services of concern.

Sub-population – any finite or infinite aggregation of individuals, not necessarily animate, subject to a statistical study that constitutes a homogenous sub-set of the whole population. A synonym of 'stratum'.

Sub-processes – processes used to represent the activities of the level 1 processes (=building blocks). Sub-processes may be presented in their (partially) aggregated form.

Sub-sample - a sample of a sub-population.

Supply chain - A supply chain, or logistics network, is the system of organizations, people, technology, activities, information, and resources involved in moving a product or service from supplier to customer. Supply chain activities transform natural resources, raw materials, and components into a finished product that is delivered to the end customer. In sophisticated supply chain systems used products may re-enter the supply chain at any point where residual value is recyclable. Supply chains link value chains. Nagurney (2006).

Supply chain *– all of the upstream and downstream activities associated with the operations of the user of the LCA method, including the use of sold products by consumers and the end-of-life treatment of sold products after consumer use.*

Supply chain-specific – refers to a specific aspect of a company's specific supply chain. For example, the recycled content of aluminium produced by a specific company.

System boundary – *definition of aspects included or excluded from the study. For example, for a 'cradle-to-grave' LCA analysis, the system boundary includes all activities ranging from the extraction of raw materials, through processing, distribution, storage and use, to the disposal or recycling stages.*

System boundary diagram – *graphic representation of the system boundary defined for the LCA study.*

System scope / System boundary - System scope = system boundary: set of criteria specifying which unit processes are part of a product system. ISO 14040 (2006)

Technique - Systematic set of procedures to perform a task.

Temporary carbon storage – this happens when a product reduces the greenhouse gases in the atmosphere or creates negative emissions, by removing and storing carbon for a limited amount of time.

Tool (S-LCA) - Instrument used to perform a procedure.

Tools (E-LCA) *- software or applications supporting the analysis (e. g. LCA software or excel based tool)*

Triangulation - Triangulation implies that different perspectives are brought together when investigating an object or research question. These perspectives can consist of different methods that are applied, in different theoretical approaches that are followed or more frequently in a combination of different types of data or data collection methods. It also refers to the collection of data from different persons or stakeholders or stakeholder groups which are contrasted.

Type III environmental declaration – an environmental declaration providing quantified environmental data using predetermined parameters and, where relevant, additional environmental information.

Uncertainty - Uncertainty refers to the lack of certainty e. g. in the prediction of a certain outcome, in a measurement, or in an assessment's results. It is a general term used to cover any distribution of data caused by either random variation or bias. In LCA and S-LCA, evaluation or measurement of uncertainty is an on-going process and relates to all the elements of data quality as well the aggregation model used and to the general aims of the study as set in the Goal and Scope.

Uncertainty analysis *– procedure for assessing uncertainty in the results of a LCA study due to data variability and choice-related uncertainty.*

Unit process (E-LCA) – smallest element considered in the LCI for which input and output data are quantified.

Unit process (S-LCA) - Smallest portion of a product system for which data are collected when performing a life cycle assessment. ISO14040 (2006)

Unit process, black box – process chain or plant-level unit process. This covers horizontally averaged unit processes across different sites. Also covers multi-functional unit processes where the different co-products undergo different processing steps within the black box, hence causing allocation problems for this dataset4.

Unit process, single operation - unit operation type unit process that cannot be further subdivided. Covers multi-functional processes of the unit operation type5.

Upstream – occurring along the supply chain of purchased goods/ services prior to entering the system boundary.

User of the PEFCR – stakeholder producing a PEF study based on a PEFCR.

Validation *– confirmation – by the environmental footprint verifier – that the information and data in the LCA study, LCA report and communication vehicles are reliable, credible and correct.*

***Value chain** – a synonym of ‘supply chain’*

Verification (in PEF context) – conformity assessment process carried out by an environmental footprint verifier to demonstrate whether the PEF study has been carried out in compliance with Annex I

Verification report – documentation of the verification process and findings, including detailed comments from the verifier(s), as well as the corresponding responses. This document is mandatory, but it may be confidential. The document shall carry the electronic or handwritten signature of the verifier or (where a verification panel is involved) the lead verifier.

Vertical aggregation – technical or engineering-based aggregation refers to vertical aggregation of unit processes that are directly linked within a single facility or process train. Vertical aggregation involves combining unit process datasets (or aggregated process datasets) together, linked by a flow.

Waste – substances or objects which the holder intends (or is required) to dispose of.

***Water use –** LCA impact category that represents the relative available water remaining per area in a watershed, after demand from humans and aquatic ecosystems has been met. It assesses the potential for water deprivation, to either humans or ecosystems, based on the assumption that the less water remaining available per area, the more likely it is that another user will be deprived.*

***Weighting (E-LCA)**– a step that supports the interpretation and communication of the analysis results. LCA results are multiplied by a set of weighting factors (in %), which reflect the perceived relative importance of the impact categories considered. Weighted LCA results may be directly compared across impact categories, and also summed across impact categories to obtain a single overall score.*

Weighting (S-LCA) - Converting and possibly aggregating indicator results across impact categories using numerical factors based on value-choices; data prior to weighting should remain available. ISO 14040 (2006)

Important abbreviations

BEV:	Battery Electric Vehicle
CED:	Cumulative Energy Demand
E-LCA:	Environmental Life Cycle Assessment
E-Mobility:	Electromobility
EoL:	end-of-life
EU:	European Union
EV:	Electric Vehicles
FCEV	Fuel-cell Electric Vehicle
HDV:	Heavy-Duty Vehicle
HEV	Hybrid Electric Vehicle
ICE:	Internal Combustion Engine
ICEV:	Internal Combustion Engine vehicle
kmyr:	kilometre-year
LCC:	Life Cycle Costing
LCP:	lithium cobalt phosphate
LFP:	lithium iron phosphate
LIB:	Lithium-ion battery
LMO:	Lithium manganese oxide
MaaS:	Mobility as a service
MLC:	Managed LCA Content (Former GaBi database)
NCA:	Nickel cobalt aluminium (battery)
Ni-Cd:	Nickel cadmium (battery)
NiMH:	Nickel-metal hydride (battery)
NMC:	Nickel manganese cobalt (battery)
OEM:	Original Equipment Manufacturer
Pb-Ac:	Lead acid (battery)
PED:	Primary Energy Demand

PHEV:	Plug-in Hybrid Electric Vehicle
pkm:	passenger kilometer (a unit of 1 passenger being transported 1 km distance)
REEV	Range-Extended Electric Vehicle
RFNBO:	Renewable Fuels of Non-Biological Origin
S-LCA:	Social Life Cycle Assessment
SotA:	state-of-the-art
TaaS:	Transportation as a service
TCO:	Total Cost of Ownership
tkm:	tonne kilometer (a unit of 1 tonne of freight being transported 1 km distance)
TTW:	tank to wheel
vkm:	vehicle kilometer
WP:	Work Package
WTT:	Well to Tank
WTW:	well to wheel
ZEV:	Zero Emission Vehicle

I. Introduction

I.1 Background and context

Road transportation is a principal driver of multiple environmental problems, among which climate change. Emissions of greenhouse gases (GHGs) from transportation sector accounts for 20% of energy related GHGs globally. If emissions from fuel supply chain are considered, this percentage can be even higher (Dillman et al., 2020). In the European Union (EU), the share of transportation's GHG emissions is around 22% excluding aviation and maritime emissions. Road transport alone emitted 77% of all EU transport GHGs in 2020 (including domestic transport and international bunkers) (European Environment Agency, 2020). Fossil fuels are currently the dominating energy carriers for transportation with around 94% of the total energy carriers (The European Commission, 2016), which puts pressure on the EU to decrease this reliability on fossil fuels in mobility.

From the policy perspective, the European Green Deal, adopted by the Commission in December 2019, has at its core tackling climate change, including more ambitious action in the coming decade, and reaching the objectives of the Paris agreement and other environmental issues. As one of the key elements of the European Green Deal, the European Climate Law enshrines the EU's commitment to reaching climate neutrality by 2050 together with the intermediate target of reducing net GHG emissions by at least 55 percent by 2030, compared to 1990 levels.

Road vehicle electrification and Zero Emission Vehicles (ZEVs) have become one of the most significant climate change mitigation options in Europe, manifested by the rapid growth of ZEVs market in recent years, since they have been associated with promising environmental gains. The EU's Sustainable and Smart Mobility Strategy (European Commission, 2020) calls for an irreversible shift to zero-emission mobility. Given transport's high proportion of total EU GHG emissions, the EU's climate goals will be reached only by introducing more ambitious policies to reduce transport's reliance on fossil fuels without delay.

However, it is acknowledged that focusing only on direct GHG emissions during vehicles use has the potential to lead to burden shifting to other environmental impacts like toxicity and resources depletion or to other life phases of vehicles. A very pronounced example here is the concerns around rechargeable batteries supply chains which is a core element of Electric vehicles (EVs) supply chain. (Xia & Li, 2022)

Methodologies like Life Cycle Assessment (LCA), Social LCA, and Life Cycle Costing (LCC), can play a paramount role in helping assess the sustainability of certain strategic choices in a more holistic way, to help identify options to prevent or mitigate for hotspots. LCA (the most mature methodology among the three aforementioned methodologies) is an established environmental assessment methodology supported by ISO standards (ISO, 2006, 2012, 2020) which takes into account all the life cycle of products and services and a wide spectrum environmental concerns.

A plethora of LCA on ZEVs and batteries have been researched and reported in the literature and applied by automobile manufacturers (for both internal use and public reporting). However, subjectivity in critical modelling choices, such as choosing the functional unit or the electricity grid mix can lead to very diverse results even for the same product. (Bouter & Guichet, 2022; Marmiroli et al., 2018; Nordelöf et al., 2014; Xia & Li, 2022).

This divergence hampers the utilization of these studies in further decision making as it complicates the comparability between results and diminishes the reliability of conclusions for policy making and strategic planning on corporate, country or regional level. In the public-forum, the lack of standardization can at best lead to confusion on the relative performance of different options, or at worst be used as a tool to provide a biased or deliberately misleading picture to support a particular viewpoint or interest. For example, choices could be deliberately made to promote products in a certain way (e. g. a battery manufacturer claiming “zero burdens” when using recycled materials, while an EoL battery treatment company claiming benefits for providing recycled materials).

Therefore, there is a need for a consensus on a single European harmonized approach of applying LCA for zero emission road transport where all stakeholders can calculate, monitor, communicate, and make decisions starting from a common ground. This becomes even more urgent in the light of the increasing adoption of LCA-based requirements in the European regulations. The proposal of batteries and waste batteries is a clear example, where providing a LCA-based carbon footprint declaration will be mandatory for any >2kwh-capacity batteries deployed in the European market (The European Commission, 2020). Similarly, the new life cycle based emissions reporting was proposed in the new regulation on CO_2 emission performance for light duty vehicles. (The European Parliament, 2021)

I.2 Aims of the TranSensus LCA project

The *TranSensus LCA* project (funded under the EU’s Horizon Europe programme) is a promising attempt to achieve such consensus by gathering a wide spectrum of influential European stakeholders in the zero-emission mobility sector ranging from academia and research to industry which covers the whole value chain of ZEVs and batteries. As also indicated above, such a European single LCA approach is seen as a key element in achieving the Green Deal targets, making Europe the first digitally enabled circular, climate-neutral and sustainable economy. By consensus, *TranSensus LCA* aims to enable industry, mobility providers and planners to provide sustainable products and to optimise mobility solutions as needed to combat climate change and prevent burden shifting to other environmental concerns.

The project is structured into six content-related work packages (WPs), plus one work package related to project management as illustrated in Figure 1-1 below. The aim of Work Package 1 (WP1) is to account for the study's context and objectives (e. g., product environmental reporting, possible application for regulatory compliance/assessment, or policy/strategic analysis), and how these influence decisions on scope/boundary, methodology and data, subsequently implying different knowledge gaps and needs. WP1 has been subdivided into an assessment of the current state-of-the art of LCA concepts and approaches (Task 1.1, and the focus of this Deliverable 1.1) and a subsequent assessment of the needs and gaps in the current LCA practice in ZEV field (Task 1.2). S-LCA and LCC are also addressed similarly in this report yet with less emphasis since LCA is the focal point of the project. The identification of needs and gaps should partly build on the outcomes of Task 1.1 and pave the road to WP2 where these needs for harmonization and gaps in current practices will be addressed to eventually achieve a harmonized methodology.

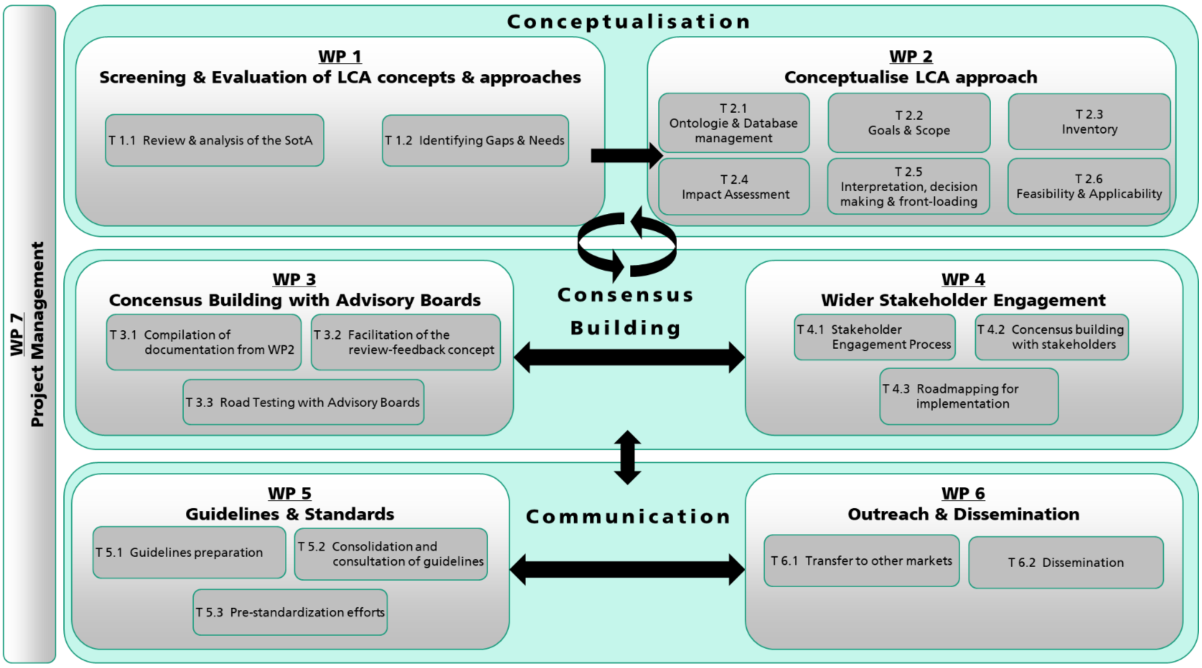


Figure I-1: TranSensus LCA project structure

The review in this deliverable covers all Zero Emission Vehicles, however a strong emphasis is placed on battery electric vehicles (BEVs) and traction batteries for electric powertrain vehicles (which also include Fuel Cell Electric Vehicles – FCEVs) since most of the state of the art (SotA) and guidelines available are related to these topics. Furthermore, the LCA practices are not expected to differ substantially for other powertrain types from a methodological perspective. Any differences that would emerge will be addressed in detail in WP2.

I.3 Aims and structure of this report

In this report, we review the state-of-the-art (SotA) in the field in order to build on it towards the promised methodological harmonization. The report addresses two research questions (RQ):

- RQ1: What is the currently available guidance for LCA, S-LCA, and LCC application in ZEVs?
- RQ2: What are the current practices of LCA, S-LCA, and LCC for ZEVs?

The report starts with an overview of the review method, including how the sources were chosen and reviewed in the light of these research questions and the scopes of the review (Chapter 2). Following this, the review results are reported in a structured manner for LCA, S-LCA, and LCC (Chapter 3, 4 and 5). Each section is structured by the four phases of LCA (ISO, 2006), as illustrated in Figure 1-2 below, which are also the phases in S-LCA and LCC. This is the common structure for contents related to these methodologies and it also facilitates the information flow from WP1 to WP2, which also uses the four phases as a structuring element for its tasks.

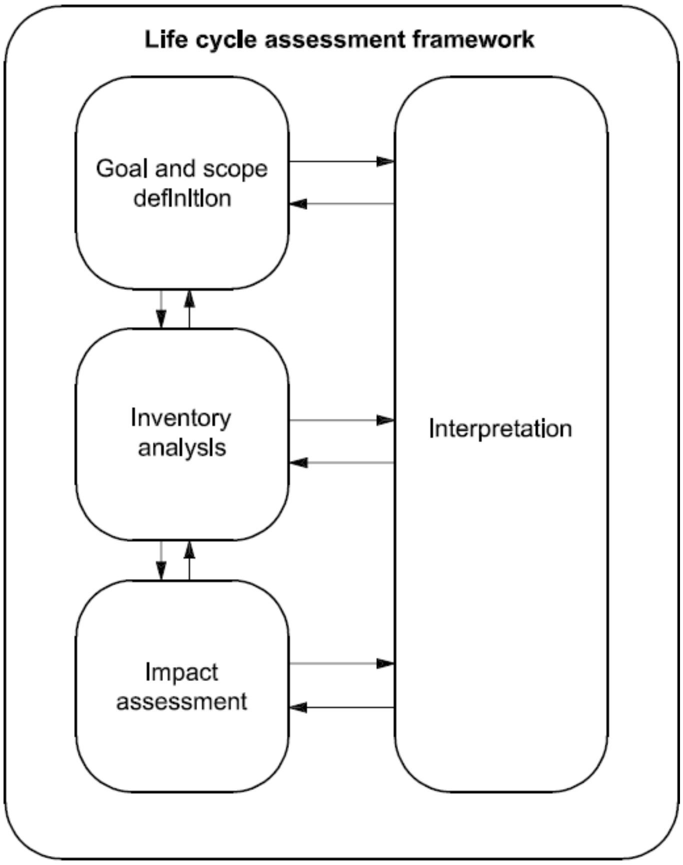


Figure I-2: The four phases of LCA according to ISO 14040

The report sections on the four phases are further subdivided into sections focusing on specific methodologically important topics (more info on how these topics were decided is in Section 2.7). Within each topic section, the information is provided sequentially following the type of the sources reviewed, starting with guidelines and standards then Original Equipment Manufacturers' (OEMs) reports, scientific literature and other documents, then models and databases if relevant. Input from consultation activities is also incorporated to comment and support the discussion of desk research outcomes whenever relevant. These categories of sources are furtherly explained in the review method section.

While the main text dives a bit deeper into details of the reviewed SotA, a blue text box is provided in the beginning of almost each subchapter (as relevant) to provide quick key messages to the reader about the specific topic without the need to read the entire chapter/subchapter.

Finally, the report ends with a general discussion and conclusions in Chapter 6 of this report which tries to underline some areas that need more effort for harmonization based on the review.

II. Review Method

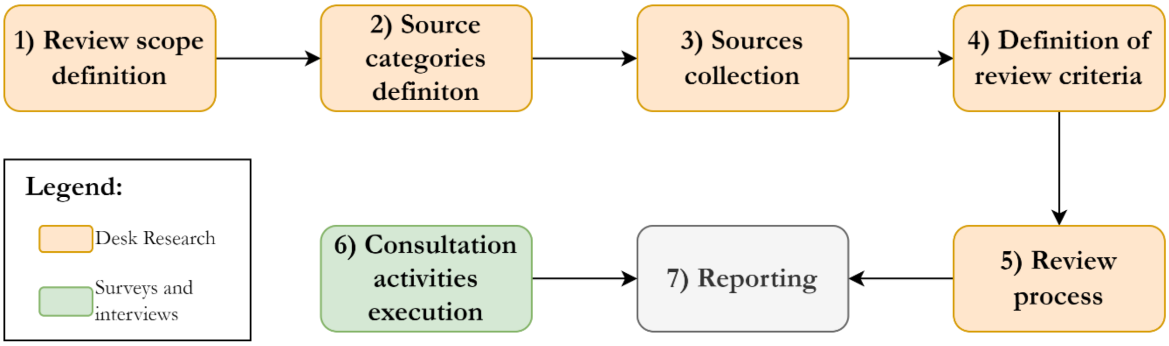


Figure II-1. Overview of the review process

Figure II-1 shows an overview of how the review was conducted for this report. More information on each step is provided under the following headings.

II.1 Review scope definition

To answer the two research questions posed for this Task 1.1 deliverable, the scope of the review had to be defined first. Building on the work package objectives described in the project proposal, an initial survey was conducted to capture the interest and views of the consortium stakeholders. The results helped inform the focus of the research and thus enhance the usefulness of the outcomes of TranSensus LCA. The full survey questions and answers can be seen in Appendix A1.1.

Starting from this survey and through intensive discussions within the consortium, three general scopes were determined to guide the review and can be summarized as follows:

1) LCA of existing products (Retrospective product-scale LCA)
2) LCA of emerging technologies/products (Prospective product-scale LCA)
3) LCA of economy-wide scenarios (Fleet-level LCA).

Since the first scope includes most LCA currently conducted (and is particularly important both to inform customers and from the policy perspective), this area was prioritized as the most urgent scope to address within the project (see survey answers in Appendix 1.1) and therefore deeper review took place for this scope.

II.2 Source categories definition

The following step defined and collected the sources to be reviewed. The sources were categorized as follows (Full list in appendix 1.3):

- Guidelines and standards (see Table II-2)
- Scientific literature
- OEM reports on particular products
- Other studies that could not clearly be categorized under any category in this list (e. g. reports by NGOs, consultancies, other organisations – e. g. to support policy analysis)
- Life Cycle Inventory (LCI) databases, models and tools
- Consultation activities (surveys and interviews)

Although this categorization was meant primarily for environmental LCA, the review for S-LCA and LCC was completed considering a similar categorization of sources.

II.3 Sources collection

The diversity of expertise within the consortium helped recommend, access, collect and screen the different categories of sources. Screening of sources was done according to their potential usefulness to the subsequent project work of methodology development and harmonization.

Scientific literature on environmental LCA is huge and it was not feasible to systematically review all of it given the available time and resources. To tackle this challenge, the previous work led by Ricardo for the European Commission, DG Climate Action (Ricardo et al., 2020) was used as a starting point for this source category since this work included an extensive review of the related scientific literature up to year 2018. Moreover, the study also developed a policymaker-oriented LCA methodology for light- and heavy-duty vehicles covering a selection of major powertrain types and fuel chains for the 2020 to 2050 timeframe (also considered as part of the TranSensus LCA review).

To build upon this previous assessment, the identification of new scientific literature was further divided into three search domains. First, scientific review articles representing the first scope (Retrospective Product-scale LCA) from 2018 until 2023. Second, scientific articles that target the second scope (Prospective product-scale LCA), and third, articles that target the third scope (fleet-level LCA).

A representative list of articles of the most recent and significant research done in the field were compiled and reviewed in three subsequent steps:

1. Systematic search primarily on Web of Science using combination of key words (see Table II-1 below)
2. Initial screening based on relevance.
3. Snowball readings starting from the collected articles whenever deeper analysis were required (e. g. regarding specific methodological aspects)

Table II-1. Search key words used on web of science

Scope	Keywords combination
Retrospective product LCA	(((((TS=((“Life Cycle Assessment” AND “EV”)) OR TS=(“LCA” AND “EV”)) OR TS=(“Life Cycle Assessment” AND “Electric Vehicle”)) OR TS=(“LCA” AND “Electric Vehicle”)) OR TS=(“LCA” AND “Electric Vehicles”)) OR TS=(“Life Cycle Assessment” AND “Electric Vehicles”))
Prospective product LCA	prospective OR ex-ante (Topic) AND life cycle assessment OR LCA (Topic) AND transport OR electric vehicle OR zero-emissions vehicle OR EV or ZEV (Topic)
Fleet-level LCA	“life cycle assessment fleet” AND (“passenger” OR “light”) (Topic)

A flowchart of sources selection process is provided in Figure A1.1, Figure A1.2 and Figure A1.3 in Appendix A1.3 in Appendix A1.3 for LCA, S-LCA and LCC respectively with important notes to consider. The final numbers are as follows: For LCA, 11 guidelines are standards, 16 review articles, 16 prospective LCA articles, 6 for fleet level, and 15 OEM reports and 17 under the category “other”. For S-LCA, 5 guidelines, eight review scientific articles and 38 conventional scientific articles. Lastly LCC, 11 guidelines, three review scientific articles, and 2 under “other”.

LCI databases were also analysed by conducting a high-level assessment on the methodological choices in the most used LCI databases (three databases). In addition to databases, common models used in generating inventories are discussed as well (two). Furthermore, extra section on software and calculators used in the field is provided in Appendix 2.

Table II-2. The list and versions of main guidelines and standards reviewed (E-LCA)*

Name	Abbreviation	Version/date available	Publisher	Reference
GBA battery passport – greenhouse gas rulebook; generic rules	GBA	Version 1.4	Global battery alliance	(Global Battery Alliance (GBA), 2022)
LCA research progress of CATARC	CATARC	October 2022	China Automotive Technology and Research Center	(China Automotive Technology and Research Center (CATARC), 2022)
Catena-X product carbon footprint rulebook	Catena-X	Draft Version 1.0	Catena-X automotive network	(Catena-X Automotive Network, 2023)
PEFCR – product environmental footprint category rules for high specific energy rechargeable batteries for mobile applications	PEFCR-Batteries	Draft Version 2.0 /February 2023	advanced rechargeable & lithium batteries association	(Recharge, 2023)
Pathfinder framework- guidance for the accounting and	PACT	November 2021	World Business Council for Sustainable	Main report: (World Business Council for Sustainable

Name	Abbreviation	Version/date available	Publisher	Reference
exchange of product life cycle emissions			Development (WBCSD)	Devel-opment (WBCSD), 2021; Supplementary material: World Business Council for Sustainable Development (WBCSD), 2021)
Harmonised rules for the calculation of the carbon footprint of electric vehicle batteries (CFB-EV)	CFB-EV	Draft version 2023 (No data on month)	Joint Research Center of the EC (JRC)	(EC-JRC, 2023)
Product category rules public and private buses and coaches	PCR-Buses and coaches	Version 2.0.2/ February 2023	EPD international ab	(The International EPD System, 2022)
eLCAr: guidelines for the LCA of electric vehicles	eLCAr	January 2013	E-Mobility Life Cycle Assessment Recommendations project	(Del Duce et al., 2013)
Life cycle assessment applied to a vehicle or a vehicle equipment – methodological recommendations	PFA	June 2022	Filière automobile & mobilités	(Filière automobile & mobilités (PFA), 2022)
LCA guidelines for electric vehicles	RISE	No version or date found were found	RISE Viktoria	(Loon et al., n.d.)
Guidance for Conducting Life Cycle Assessment Studies of Passenger Cars	VDA-PC	August 2022	German association of automotive industry	(German association of automotive industry (VDA), 2022)

*Note: * Generic guidelines like PEF and ISO are not reported here despite being considered in the report*

II.4 Definition of review criteria

To analyse the sources, a list of review criteria was developed in an iterative approach alternating between testing and refining by the WP partners. The list was hierarchically structured starting with the four phases of LCA according to ISO, then topics often included in each phase. Finally, specific questions were asked in each topic. Topics and questions were defined based on the experience available in the consortium. Specific questions were developed for each source category (guidelines and standards, scientific literature, etc.), to better fit the type of documents being reviewed. A sample of guidelines and standards review criteria is provided in Appendix A1.4. The same approach was followed in LCC and S-LCA, after adjusting the criteria to match the methodologies and their scopes.

II.5 Review process

The desk resources were distributed among the participants to review guided by the review criteria and based on the background of reviewer. Small working groups were formed for each source category to exchange information and monitor the progress. For example, OEM reports were primarily reviewed by partners from consultancies to improve the efficiency of the reviewing process since they have better familiarity with this type of documents and better accessibility. For guidelines and standards further consolidation was needed to ensure that the documents were reviewed by more than one person (two or three) since the interpretation of the content of such documents can significantly vary. Also, because guidelines and standards were prioritized by the WP1 due to its influence on the general LCA practices in the field. The reviews for the same documents were then consolidated into single results (within the review criteria matrix), solving any contradictions in interpretation.

II.6 Consultation activities

For the consultation activities, a more targeted survey was conducted (see Appendix A1.2), in addition to the initial short survey which aimed to determine the scope and the objective of the review. The purpose of this second survey was to collect details on the current practices of industry in the field of LCA, S-LCA and LCC. The survey targeted industrial stakeholders (i. e. mainly automotive OEMs and suppliers) from both within the project consortium and also beyond. Selected outcomes of the survey have been discussed in relevant sections of this report, whenever they were found to enrich the analysis of the desk review of the SotA. The results of this survey are a valuable addition to desk research as they provide first-hand information on current methodological practices in leading industries in the sector. Another consultation activity carried out within WP1 is interviews (Progress in Appendix 1.2.1). Starting from the answers received in the survey, a set of respondents were selected to be interviewed by the WP where they were mainly asked to elaborate on some of their replies to some of the survey questions. The interviews are still ongoing therefore the outcome could not be integrated into this deliverable, and they will be utilized in D1.2 instead.

II.7 Reporting

The review criteria matrix was intentionally very detailed to get the most information from the reviewed document. To move from the matrix to the report, simplification was needed, and the structure of the report had to reflect only the most important methodological topics. An initial structure reflecting these topics was drafted then refined in an iterative approach within WP 1 until a final structure was agreed upon.

Under each subchapter representing a topic, the outcomes from desk research and consultation activities are reported mentioning and analysing the current common practices in the three methodologies in addition to offering some expert critical views at some parts to enrich the usefulness of the document.

III. Environmental LCA (E-LCA)

III.1 Phase I. Goal and Scope Definition

In this chapter we review some of the major points tackled in the goal and scope definition phase of LCA. In section 3.1.1. we describe what goal is usually defined in different types of LCAs for ZEVs and what it entails. Furthermore, we compare the current practise with the recommended best practises outlined in ISO and other guiding documents. This also includes the decision-making context, intended applications and how both of these influences the goal definition. Following the goal definition, scope definition is discussed in section 3.1.2. Topics discussed under this section are technology coverage highlighting the most studied technologies, functional unit reporting and analysing the common and different choices in functional unit, and system boundary used in LCAs for ZEVs.

III.1.1 Goal definition of LCAs for zero emission road transport

Goal definition: Summary of key findings

- OEM reports as well as guidelines and standards focus mainly on retrospective LCA of existing products.
- Scientific literature also addresses prospective and fleet-level LCA.
- Often important elements of goal and applications are not described by scientific literature

The goal definition is the first phase in the LCA and sets the overall context for the study. It mainly answers the “Why” question by clearly defining goals to ensure that aims, methods, results and intended applications are aligned. Despite that goal and scope are seen as one phase, they are quite different in what is to be addressed in each. The decisions made in goal phase affect the elements of scope definition to a far extent, hence the subsequent LCA phases of inventory calculation, impact assessment, and interpretation.

According to (ISO, 2006), the goal definition should state: the intended application, the reasons for carrying out the study, the intended audience, and whether the results are intended to be used in comparative assertions to be disclosed to the public. The Product Environmental Footprint (PEF) (EC-JRC, 2021) adds two more elements to that which are the commissioner of the study and the identity of the verifier.

One important thing to be highlighted here is the distinction between the goal and the application. The application is only a part of goal definition which describes how the LCA results will be used afterwards. In TranSensus LCA, three types of LCA were defined in order to guide the review task and provide a framework to the following phases of the project (i. e. developing the harmonized approach). Figure III-1 illustrates these three types in time and scale dimensions. The retrospective LCA is on the product level and is conducted for already existing products. While the prospective LCA is also on the product level it is performed for future products. This can be emerging technologies or products or also products that do not exist yet. The fleet-level LCA is on a higher system-level and can be performed in the present or in the future.

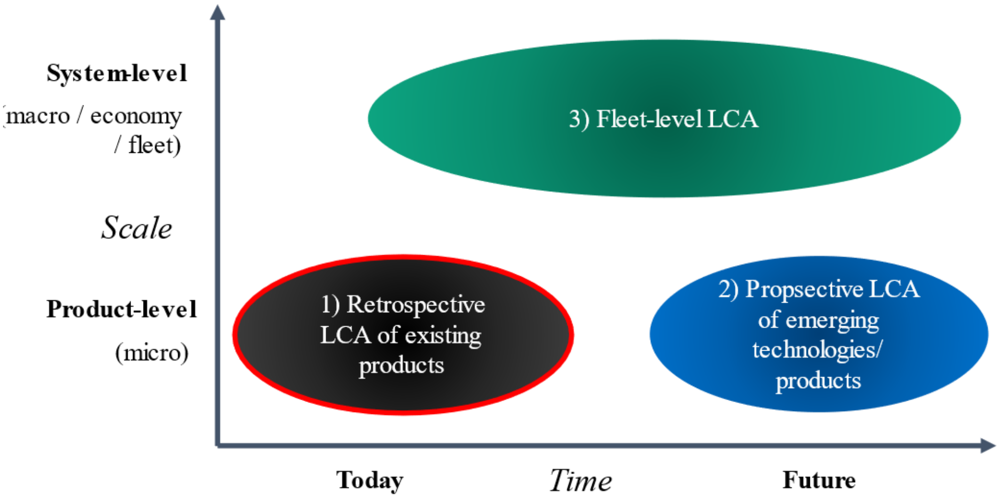


Figure III-1. The three types of LCA of TranSensus LCA considered in the review

A wide range of applications fall under these three scopes. Not all applications can be directly matched with one of the scopes but extend between multiple. For example, policy analysis (e. g. also assessing generic, rather than specific products) can practically be an application emerging from the three scopes depending on the decision-making context.

The review of the available **guidelines & standards** for this study has showed that currently almost all the available guidance is directed towards the first type of LCA (i. e., retrospective LCA for existing products). The one exception was eLCAr (developed under the EC's seventh framework programme), which provides some recommendations for conducting LCAs on the fleet level.

OEM reports cover only the first type of LCA, retrospective LCA of existing products. The goal of these studies is mainly to compare different products (both different drivetrain technologies, predominantly BEVs vs ICEVs and different vehicle models) as well as to assess the environmental impact of specific prototypes. The vast majority of the reviewed reports claim to follow the ISO 14040/14044 standards. For buses, there are a few published EPDs that also follow the ISO 14025 standard and PCR-Buses and coaches. Publicly available OEM reports also included the purpose of these studies to be mainly for public disclosure, while a few studies indicate the need for tracking and evaluating their vehicle's/ model's environmental performance, for internal communication, product optimisation and for corporate reporting. The results from the survey (see Table III-1) highlighted that while OEM reports focus on retrospective LCA for public disclosure and vehicle comparison, OEMs also perform LCAs for internal purpose and also conduct prospective LCAs for the support in development and design of products.

Table III-1. Survey question: What are the main purposes to perform an LCA?

Value	Percent	Count
Product LCA for reporting to stakeholder (EPD, certification, marketing, customer information)	93.8%	15
Support in development and design of products	100.0%	16
Policy analysis to inform decision making (i. e. identification of key hotspots where legislative instruments might be needed to aid mitigation)	50.0%	8
Supporting/ providing a basis for compliance with regulations	62.5%	10
Others:	18.8%	3

Scientific literature on the other hand covers all three types but with varying degrees of emphasis. For example, publications on prospective LCAs are rising substantially. This can be justified by the freedom in exploration which drives the scientific research in general. In addition to science for science, science can also be for informing policy. In their review, (Marmiroli et al., 2018) concluded that most of the studies they reviewed aim to inform policy or decision makers explicitly or implicitly. Nevertheless, the freedom in scientific research studies can be challenging, since most LCA studies are quite ambiguous in reporting their goals as clearly as defined by (ISO, 2006). While most studies report detailed information about the objective of the study (e. g. comparing different power trains of passenger cars), they omit other aspects to be defined like application and intended audience. This was highlighted by (Nordelöf et al., 2014) and later confirmed again by (Marmiroli et al., 2018) who found that only four studies out of 44 studies reviewed clearly abide to (ISO, 2006) when defining the goal. The aspects of goal definition often missing are listed in order below from least reported to the most reported according to 80 scientific articles reviewed by (Arshad et al., 2022):

- Time frame of the study
- Intended audience
- Limitations due to methods, assumptions and impact coverage
- Intended application
- Objective of the study
- Comparative assertion

The goal of product-level prospective LCAs is to assess the environmental performance of a potential future product (which could be emerging technologies or new versions of more mature technologies) under future scenarios, in some cases including a comparison between emerging and mature technologies (e. g., sodium-ion batteries vs. LIBs in Peters et al., (2016)). Goal definition typically incorporates the time dimension, e. g., *“the goal of this LCA is to compare* *the environmental performance of current (production year 2017) and future (production year 2040) electric vehicles (EVs)"* (Cox et al., 2018) , as well as the prospective elements assessed, e. g., *"considering changes in the charging electricity mix over time, battery efficiency fade, vehicle and LIB recycling, and LIB refurbishing"* (Koroma et al., 2022).

In fleet-level studies reviewed in this work, the situation was not different. The objective of the study is usually defined like *"the main goal of this work was to quantify the impacts of several sustainability policies for the road passenger transport sector in Europe"*(Paulino et al., 2018). Nevertheless, the other goal definition aspects such as intended audience or application is not explicitly stated there. The fleet-level studies are very much on the explorative side which usually test different scenarios of big-scale changes to answer the "what if" such as in (Dirnaichner et al., 2022).

III.1.2 Scope definition

Technological coverage

Technological coverage: Summary of key findings

- Technological coverage in the reviewed guidelines and standards was split into: (i) battery packs, and (ii) vehicles. Among the former (i), battery type was either not explicitly mentioned, or several LIB chemistries were included. Among the latter (ii), most focused on passenger vehicles, and a range of ZEV power train options (sometimes also including HEVs and ICEVs for comparative purposes).
- All the reviewed OEM reports focused on vehicles as a whole, and a range of power train options, primarily BEVs, PHEVs and HEVs, often with ICEVs included for comparative purposes. Detailed information on the specific type of LIB was often omitted. Only few OEM reports covered FCEVs.
- Among the reviewed scientific studies, the primary emphasis was on passenger vehicles, with secondary coverage of heavy-duty vehicles, too. In terms of power trains, BEV was the most frequently assessed option, followed by HEV and PHEV then finally FCEV. As for those studies that focused on batteries, several ones explicitly addressed comparing different LIBs chemistries, among which primarily NMCs, NCAs, and LFPs.

Technology coverage defines the vehicle types, powertrains as well as specific power technologies (such as batteries and fuel cells).

Technology coverage in **guidelines & standards** is diverse and not well aligned. Table III-2 provides a summary**.** The GBA, the CFB-EV and the PEFCR-Batteries have a battery focus.

All other analysed guidelines & standards focus on the whole vehicle. Almost all guidelines for vehicles focus on passenger cars. PCR-Buses and coaches focuses on buses and coaches and Catena-X does not specify the vehicle type (as it is designed to be agnostic to this aspect).

Battery types are not specified in most of the guidelines & standards. When specified, different LIB chemistries are included (CATARC, GBA, PEFCR-Batteries). CATARC also includes lead-acid batteries and PEFCR-Batteries also includes NiMH batteries. TranSensus LCA also aims not to be specific to any cell chemistry but to provide a guideline that covers current and future battery types for ZEVs.

The guidelines & standards cover also different powertrains. The GBA and the PFA include all powertrains. RISE and eLCAr focus on BEV, RISE includes ICEV for comparison. The PCR-buses and coaches further includes PHEV and CATARC HEV and PHEV. CATENA-X and the CFB-EV do not specify the power train. With HEVs and PHEVs, the existing guidelines & standards include powertrains which are not emission-free in the use phase and therefore not categorised as ZEV in TranSensus LCA. FCEVs, which are less extensively covered, are classified as ZEV and will be addressed in TranSensus LCA.

Table III-2. Technology coverage as described in the guidelines and standards

Source	Vehicle size	Battery	Powertrain
Battery			
GBA	-	LIB chemistries	All electric powertrains with traction battery (BEV, PHEV, FCEV, FC-REEV, BCEV, …)
CFB-EV	-	Rechargeable industrial batteries with a capacity above 2kWh, light means of transport batteries and EV batteries	Not in scope
PEFCR-Batteries	-	LCO, NCA, NMC, LMO, LFP, LMP, NiMH	-
Whole vehicle			
CATARC	Passenger car (M1, not exceeding 3500kg)	Lithium-ion traction battery and lead-acid battery, specifically mentioned chemistries: LFP, NMC, LMO	ICE, HEV, PHEV, BEV; Other M1 vehicles can refer to this document for implementation
Catena-X	Not specified	Not specified	Not specified
Elgar	Passenger car (Micro/City, Compact, Mid-size)	All types of rechargeable batteries	Focus on BEV, to some extent PHEV is also covered
PCR-Buses and coaches	Buses and coaches	Not specified	All types: ICEV, BEV, PHEV; FCEV not explicitly mentioned

Source	Vehicle size	Battery	Powertrain
RISE	Passenger car	Not specified	BEV and ICE for comparison
VDA-PC	Passenger car	Not specified	ICE, PHEV, BEV, FCEV
PFA	A, B, C, D, E, F, CDV/ Van1-Van2	Not specified	All

All analysed **OEM reports** cover the whole vehicle, which is to say the vehicle and the vehicle battery (BEV, PHEV, HEV) and/or fuel tank/cell (ICEV, PHEV and FCEV). Most reports on BEVs focused on comparison of their newer models/ products with ICEVs and were explicitly stated as comparative LCAs. More than half of the product LCAs reviewed for non-ICEVs omitted details on the chemistry of the battery cells used in the vehicles. Three OEM reports mentioned the battery chemistry and in all three cases it was NMC622. Only a handful of studies focused on non-BEV powertrains each focusing on FCEVs and HEVs, while one other study directly compared two ICEV models (prototype vs existing model). OEM reports that did not include any form of battery-driven powertrain covered either ICEVs only or in three other cases FCEVs and a HEV, with the HEV study considering a vehicle with a high-performance capacitor.

For OEM reports that considered ICEVs, the fuel types included were either diesel or petrol. However, two studies targeting LCA of freight trucks considered the use of different biofuel blends as well. Most of the OEM reports for ICEVs reviewed diesel, as opposed to gasoline fuelled vehicles. This is in part due to the inclusion in the review of buses and trucks, which are usually only diesel driven.

The majority of the OEM reports reviewed were for passenger cars of types including SUVs, saloons, hatchbacks and one study on sports cars. The remaining reports reviewed were for buses (two reports) and trucks (four reports). Due to the modular and tailored nature of products sold, one BEV freight truck LCA report used a vehicle type modelled on BEV trucks sales projections for mixed urban and regional distribution, while another truck LCA report focused on regional distribution and urban construction trucks. This is corroborated by the survey results, reported in Figure III-2.

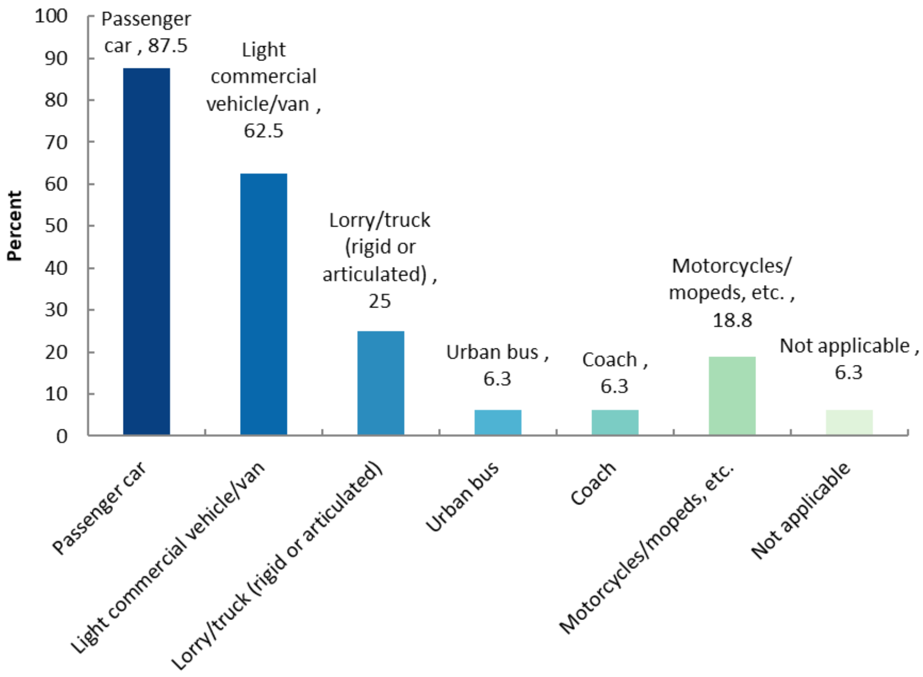
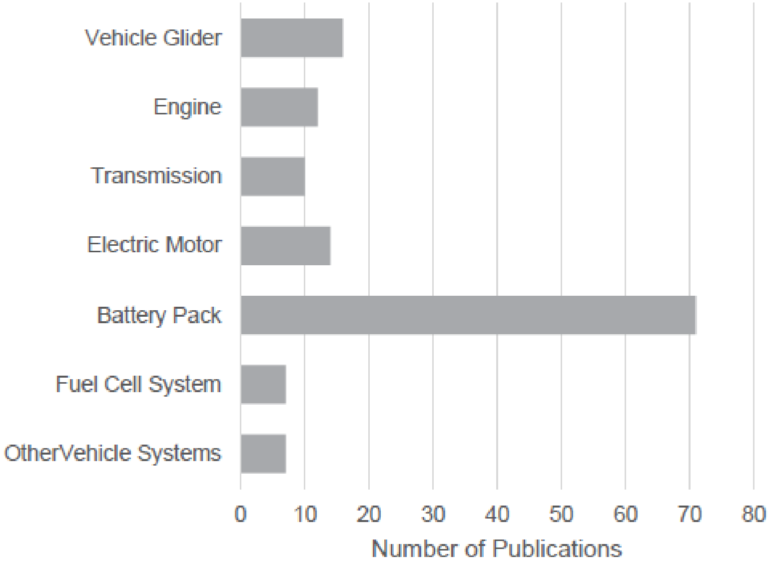


Figure III-2: Survey results on types of vehicles for which LCAs are conducted

In **scientific literature**, the technological coverage presents different levels of detail. Its description ranges from ‘average passenger vehicle’ (Huo et al., 2015) to more detailed vehicle segment (mid-size, compact, sport-utility, etc. . . .), to identification of archetypes (Nissan Leaf as a paradigm of small size EV, Toyota Prius for HEV, etc.) to comparison within specific models with different powertrains: Piaggio Porter (Bartolozzi et al., 2013), Iveco Daily (Giordano et al., 2018), Smart (Helmers et al., 2017; Helmers & Marx, 2012), GM Chevrolet Malibu (Lombardi et al., 2017).

Generally, the most studied vehicle type is by far the passenger car. The rest of publications are almost equally divided between van, bus, small truck, articulated lorry and almost no publications on coaches (i. e. long-distance buses). Regarding powertrain types, BEV was the most mentioned power train within the EV category followed by HEV and PHEV then finally FCEV. (Marmiroli et al., 2018; Ricardo et al., 2020)

For batteries, recent review papers tend to focus on LIBs more than older technologies like Ni-Cd, Pb-Ac, and NiMH batteries which were widely used before the big scale production of LIBs (Xia & Li, 2022). Within LIBs, a lot of work is focused on comparing different LIBs chemistries. (Tolomeo et al., 2020), for example, highlighted that LFP and NMC are the most analysed chemistries in the articles he reviewed followed by LMO and NCA. NMC is also the most diffused cathode chemistry in Europe for EV applications (Dai, Kelly, et al., 2019). In fact, among vehicle components, studies on batteries prevail in the literature (Figure III-3).



Source: (Ricardo et al., 2020)

Figure III-3. Number of publications per vehicle component included as reported by (Ricardo et al., 2020)

Technology coverage in prospective LCA studies includes both batteries and whole vehicles. Battery-oriented prospective LCAs focus either on assessing mature chemistries at a future point in time, such as NMC, NCA and LFP (Xu et al., 2022) or assessing emerging technologies and chemistries, such as all-organic battery (Zhang et al., 2022), lithium cobalt phosphate (LCP) (Raugei & Winfield, 2019), structural battery (Zackrisson et al., 2019), and sodium-ion battery (J. Peters et al., 2016). Vehicle-oriented prospective LCAs typically assess conventional BEVs at a future point in time (e. g.,(Koroma et al., 2022; Zimmermann et al., 2015) or compare different types of passenger vehicles (e. g., ICEVs, BEVs, PHEVs, etc.) considering potential developments of vehicle characteristics, such as battery size, tank-to-well efficiency, driving mass, range, etc. (Bauer et al., 2015; Cox et al., 2020; Sacchi et al., 2021).

Functional unit/reference flow

Functional unit/reference flow: Summary of key findings

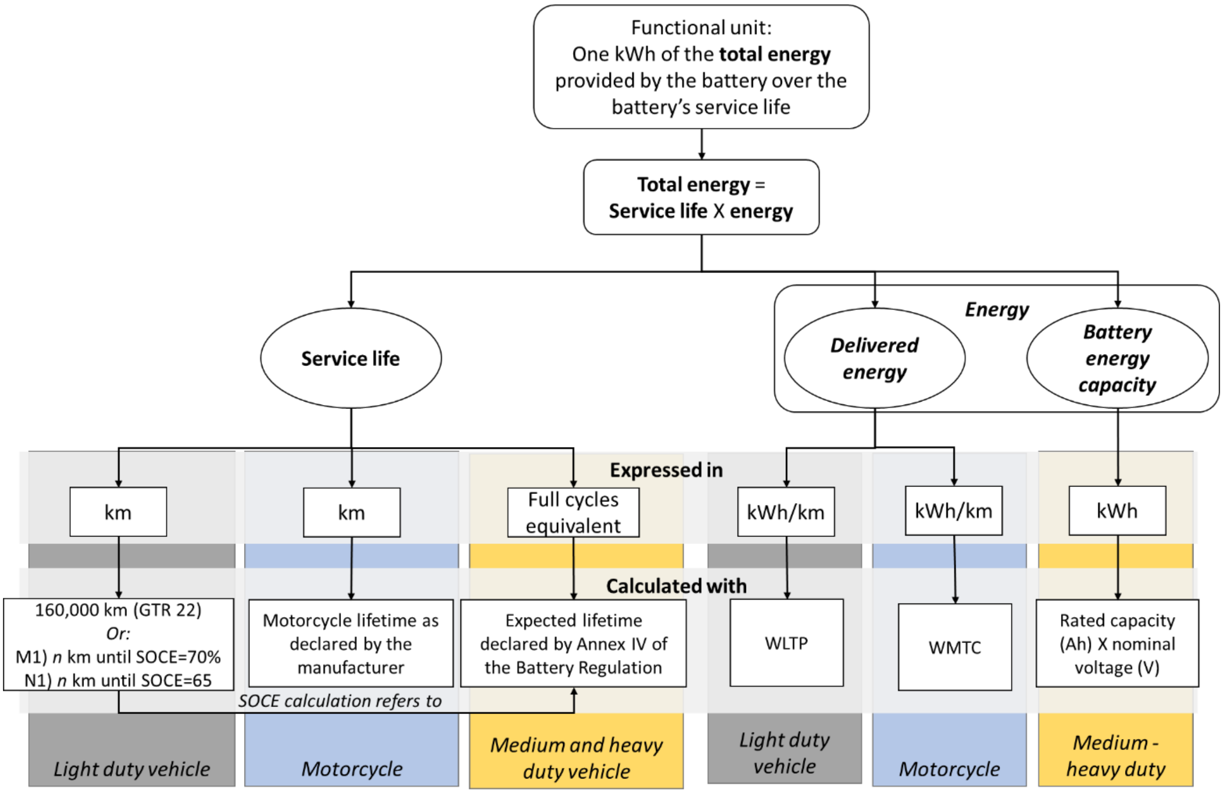
- For all battery focused LCA guidelines and standards the suggested functional unit (FU) is “1 kWh of the total energy provided over the service life by the battery system”. This is also arguably the most meaningful and informative FU, as it implicitly includes considerations of gravimetric energy density and durability/longevity (calendar/cycle ageing).
- Clear guidance on the calculation of the functional unit for batteries is needed because are currently not well defined in the guidelines.
- Battery LCAs in the scientific literature defined the FU commonly as “1kWh (or 1MJ) of battery storage capacity”. This may also be deemed acceptable, but it may lead to inconsistent comparisons across different battery technologies, since it fails to account for durability.
- Lastly, some battery LCAs used “kg of battery” as unit of assessment, which is unacceptable as a FU, since mass is not an intended “function” of the battery.
- The most common FUs for product-level vehicle LCAs (across all reviewed guidelines and standards, and scientific studies) were “passenger*km” (for passenger vehicle), “tonne*km” (for freight vehicles) And “vehicle*km”.
- A majority of OEM reports adopted either “driven distance over the service lifetime of the vehicle (expressed in km)” or more explicitly, “transport of passengers or goods over the vehicle service lifetime (km)” as FU. For buses and trucks either “driven distance over the service lifetime of the vehicle (expressed in km)” or “passenger*km”/ “tonne*km” was used for buses and trucks respectively.
- All these FUs are acceptable, but it is worth pointing out that strictly speaking, the former two (i. e., “passenger*km” and “tonne*km”) would be preferable, since they more directly relate to the intended “function” of the vehicles in question, i. e., respectively “transporting passengers” and “transporting goods”, and they implicitly include considerations of capacity, which may lead to more meaningful comparisons across different vehicle types.
- Finally, in most fleet-level LCAs, the FU was dynamically defined as the set of vehicles that comprise the fleet in any given time period (often 1 year).

Table III-3 shows the suggested definition of the functional unit and reference flow as described in the respective **guidelines & standards**. Looking at, it can be seen that the guidelines & standards for *batteries* prescribe the same functional unit, i. e., 1 kWh of the total energy provided over the service life by the battery system (throughput based). The throughput based functional unit however, received some critique related to the calculation of the total energy and lifetime (number of charging cycles) and the lack of standardised and realistic test cycles for batteries (see also (Peiseler et al., 2022)). Some initial calculation approach for the functional unit are only provided by PEFCR but are not entirely clear or yet finalised yet.

Table III-3. Definition of functional units and reference flows are prescribed in the guidelines and standards reports

Source	**Functional unit**				**Reference flow**	
	1 kWh of total energy provided over the service life by the battery system	**vkm**	**pkm**	kmyr	**Not specified**	Amount of battery (in mass or pieces) needed to provide one kWh
Battery						
GBA	x					Amount of battery (in mass or pieces) needed to provide one kWh
CFB-EV	x					kg of battery per functional unit
PEFCR-Batteries	x					kg of battery per functional unit
Whole vehicle						
CATARC		x				Not specified
Catena-X					The carbon footprint shall be assessed for a declared unit. A functional equivalent is established by the data recipient	1 piece for product; 1 kg for materials
eLCAr					Guidance on how to define a FU is included, note 2	Amount of product or service alternative to fulfil the defined functional unit
PCR-Buses and coaches			x			Not specified
RISE			x or km			Not specified
VDA-PC		x				one vehicle
PFA				x		Not specified

In the most recent draft version of the CFB-EV however (June, 2023, version and not reviewed here), more detailed guidelines to calculate the total energy are provided. The CFB-EV defines the total energy as the multiplication of the service life and the energy. However, different units and calculations to obtain the service life and energy are proposed for different vehicle types, including light duty vehicles (M/N 1), motorcycles (L) and medium and heavy-duty vehicles (see Figure III-4) For M/N1 vehicles for example, service life, expressed in total km, is based on either 1) a default value of 160,000 km based on the UN GTR No. 22 minimum performance requirements for EV batteries or 2) total km driven until the battery reaches a State of Certified Energy (SOCE)[1] of 70% for category M1 or 65% for category N1 vehicles. Due to a lack of battery durability standards for motorcycles or M/HDVs, different methods are proposed to calculate the battery service life. The reference flow is the calculated amount of battery (in mass or pieces) needed to provide 1 kWh, considering battery specifications, like weight, capacity, kWh delivered energy over the service life, etc.



Abbreviations: State of Certified Energy (SOCE); Global Technical Regulation (GTR)

Figure III-4. Overview of the required parameters for different vehicle types to calculate the total energy in the functional unit as defined by the final draft version of the CBF-EV.

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[1] SOCE is defined by the UN GTR No. 22 as "the measured or on-board UBE [usable battery energy] performance at a specific point in its lifetime, expressed as a percentage of the certified usable battery energy".

The guidelines on the definition of the functional unit for whole *vehicles* seem to be less harmonized. Different functional units are prescribed, like person-kilometer (pkm), vehicle-kilometer (vkm), kilometer-year (kmyr); missing from the standards are considerations for freight vehicles, where tonne-km (tkm) is a common unit of utility (also utilised, for example, in HDV CO_2 and fuel consumption certification in the EU,(European Union, 2017)). Some guidelines, like eLCAr, do not suggest a recommended definition of the functional unit. The reasoning is that the definition of the functional unit largely will depend on the goal and scope definition and the interrelationships between compounds of a car and its performance. According to eLCAr, the definition of the functional unit should be detailed to guarantee equal functionality of alternatives. Therefore, detailed provisions (eLCAr: 6.2.1, page 38) are provided for defining the functional unit for E-Mobility applications, taking into consideration:

1. key parameters of vehicles and their components,
2. key links between component and vehicle performance,
3. location and time horizon of the object of study

A majority of **OEM reports** adopted either "driven distance over the service lifetime of the vehicle (km)" or more explicitly, "transport of passengers or goods over the vehicle service lifetime (km)" as FU. Where almost all of the studies adopted a vehicle lifetime figure of 150,000 – 200,000 km among passenger car studies. The truck reports reviewed used vehicle lifetime references that ranged between 500,000 km to 1,600,000 km while the bus reports reviewed used service lifetimes that ranged between 800,000 km to 1,300,000 km. Develop bus-related and in some cases, freight truck-related LCAs used passenger-km (pkm) and tonne-km (tkm) respectively as functional unit, calculated over the above-stated respective service lifetime. Most reviewed product LCAs were observed to not distinguish between reference flow and functional unit. Among half of the cases that did state a reference flow, vehicle and vehicle lifetime were the reference flows used.

Scientific literature clearly shows a big difference in possible choices of functional units. In their papers, (Arshad et al., 2022; de Souza et al., 2018; Dolganova et al., 2020; Tolomeo et al., 2020) compiled tables of earlier LCA studies and their choices on functional unit. The most used functional units for both vehicle and battery LCA are distance-travelled based whether referencing impacts to "per 1 km driven" or using the whole vehicle lifetime directly as a functional unit (Arshad et al., 2022; Ricardo et al., 2020). This is a common choice when comparing the environmental behaviour of different vehicles (e. g. ICEV vs EVs) or when the study focuses on batteries but with transportation as final service provided by system (Temporelli et al., 2020). The second most common FU which is found in battery studies is the battery storage capacity (mostly in kWh). The third most common FU is the mass of the battery pack.

The determination of the vehicle lifetime and lifetime mileage is important for functional units which are defined as "per km driven", since it determines how impacts are scaled to each km driven. Moreover, it determines the importance of the WTW cycle and hence also influences the impact balance between production and use stages. For example, commercial vehicles which have a higher lifetime mileage therefore have a higher proportion of impacts in their use cycle compared to passenger cars (Ricardo et al., 2020). The assumptions on lifetime mileage are however highly debated in the literature. Even within the same segment/type of vehicles, (Dillman et al., 2020) reports that the assumed lifetime in 19 studies on medium-sized passenger vehicles they reviewed varied from 120,000 km and 260,000 km. This is a huge gap which can tremendously affect the results as for example shown by (Hawkins et al., 2013) where a sensitivity analysis on vehicle lifetime activity was carried out. They found out that high mileage assumption (200,000 km, compared to the assumed base-case value of 150,000 km) led to an increase of EVs GWP benefits by more than 25% compared to ICEVs while assuming low mileage (100,000 km) showed a reduction in these benefits up to 9%. Indeed, how challenging it is to select a lifetime assumption was brought up by (Hawkins et al., 2013)

The second most common way to define the functional unit is based on battery storage capacity in kWh (in battery-focused studies) like in (L. A. Ellingsen et al., 2013; Oliveira et al., 2015) or in units of MJ, like in (Majeau-Bettez et al., 2011). In few other studies, energy provided by the battery over its lifetime (e. g. lifetime kWh) was also found. It was found as a common choice when it is necessary to consider the influence of parameters such as lifetime, efficiency, depth of discharge on the output delivered by the batteries. Thus, a clear distinction should be made between the two principles here since one is based on battery capacity and the other on the energy throughput from battery over its lifetime.

The third most common functional unit choice is battery pack mass (e. g. in kg) which is often used when comparing different cathode materials for batteries or when the work mainly relies on battery production phases focusing on raw materials' acquisition, transportation and EOL. However, it should be noted that battery pack mass is not an adequate functional unit in LCA, since the function of the battery is not simply to have mass, but rather to provide and store energy.

In addition to these three most common functional units, other functional units were occasionally found in literature. For example, transportation of one person (/passenger) for 1 km (1 pkm) was found in some studies (Cellura et al., 2016; Choma & Ugaya, 2017). Also, "per vehicle produced" (i. e. the gross impact). See for example (Cimprich et al., 2017) in their cradle-to-gate study. A time-based functional unit was also found in (Ioakimidis et al., 2019) where they chose 4,000 days (given that the scenarios they studied have the factor of time as common reference) to evaluate the repurposing of batteries for a second life in stationary energy storage in buildings. Whatever the choice, the literature repeatedly points out the importance of thoroughly clarifying assumptions on lifetime factors when it is relevant (Arshad et al., 2022).

The type/segment of the vehicle is also to be considered in determining the functional unit. Some vehicles like rigid and articulated lorries are purely intended for big-scale goods transportation which makes the carried load a significant factor in determining the function from the service hence the functional unit. Therefore, this kind of heavy-duty vehicles (HDVs) can have a functional unit of tonne-km (tkm) to represent a full life cycle of a HDV. This can be seen in the work done by (Ricardo et al., 2020).

The unclear definition of the functional unit was also highlighted by (Tolomeo et al., 2020) where they found that 13% of the 59 papers they reviewed did not clearly report the functional unit used.

The definition of the functional unit in prospective LCA case studies is aligned with what has been observed in the scientific literature covering retrospective LCA. For example, the functional unit in battery-oriented prospective LCAs is either “one kWh nominal battery cell capacity” (Xu et al., 2022) or “one kWh of the total energy provided over the service life” (Wei et al., 2023). However, emerging battery technologies and concepts may come with increasing functionality, thereby adding additional challenges to the definition of a relevant functional unit that enables a straightforward comparison with the incumbent technology (Buyle et al., 2019). For example, (Zackrisson et al., 2019) assessed a structural battery that can be used as a car roof in addition to supplying electrical current (Jin et al., 2023)In vehicle-oriented prospective LCAs, the functional unit includes mainly one km driven (Bauer et al., 2015; Cox et al., 2018; Koroma et al., 2020; Sacchi, Bauer, et al., 2022) and driving a specific vehicle over its lifetime (Koroma et al., 2022; Zimmermann et al., 2015).

Using LCA to assess the environmental performance of an entire fleet of vehicles, as opposed to a single individual product (i. e., one vehicle or battery) entails adopting a whole set of different methodological choices and modelling approaches. To follow how the functional unit is defined, the following section will repass and further discuss the goal and scope of the fleet-level LCA.

In most fleet-level studies, the primary goal is to explicitly capture the evolution over time of the environmental impacts of the vehicle fleet, typically starting from the present and extending into the future by a few decades (Garcia & Freire, 2017). This calls for a dynamic modelling approach whereby the Functional Unit itself is dynamically defined as the set of vehicles that comprise the fleet in any given time period (often 1 year) (Garcia & Freire, 2017). The inventory (LCI) and impact assessment (LCIA) stages of the LCA are then carried out iteratively again and again, at multiple points in time, with the total number of iterations depending on both the overall intended time span of the prospective analysis (e. g., 30 years) and the pre-defined time resolution (e. g., 1 year).

In terms of scope, the existing fleet-level LCAs in the scientific literature vary considerably in their comprehensiveness. In the most reduced-scope studies, in each iteration of the calculations, only the use-phase impacts (sometimes including maintenance) are included, for all the vehicles in use in the fleet during the corresponding time period (the length of which is equal to the chosen time resolution) (Reichmuth et al., 2013); (Kromer et al., 2010); (Plotkin et al., 2009); (González Palencia et al., 2012); (Chatzikomis et al., 2014); (He & Chen, 2013); (Ou et al., 2010). The wider-scoped fleet-level studies, instead, also include in the assessment the impacts associated with the manufacturing (including all upstream material and energy supply chains) and EoL treatment (including disposal and recycling) of those vehicles that are respectively added to and retired from the fleet during that same time period (Baptista et al., 2012; Dirnaichner et al., 2022; Garcia et al., 2015; Raugei et al., 2021) Finally, a few studies also include additional elements such as roads and refuelling/recharging infrastructure (which are assumed to depreciate over time and may require replacement, expansion and/or overhaul) (Paulino et al., 2018; Xiong et al., 2021).

Such a dynamic modelling approach is different in several fundamental ways from those which are more typically adopted in product-level LCAs.

Firstly, given that the assessment almost invariably covers a time frame extending into the future, this type of LCA is often intrinsically prospective (even though in principle, retrospective fleet-level studies of the evolution of a fleet over past decades are also possible, and may be of historical interest).

Secondly, this dynamic modelling approach does not entail any steady-state assumptions. This applies both at the level of each individual vehicle within the fleet, since its environmental impacts are taken into account as they occur (within the limitations of the adopted time resolution), and are not artificially “spread out” across the entire life cycle of each vehicle; and at the level of the fleet as a whole, given that the numbers of vehicles respectively being added to and retired from the fleet are allowed to vary independently over time.

Thirdly, the dynamic modelling approach allows capturing the transient effects (both in terms of LCI and LCIA) occurring as older vehicles are gradually replaced by newer ones in the fleet. More specifically, it allows a more realistic estimation of how long it will take for any new technology or material supply chain to make a difference in terms of the overall environmental impacts of the fleet as a whole (Field et al., 2000; Garcia & Freire, 2017), versus what could be inferred using more simplistic extrapolations based on steady-state product-level LCAs (even when the latter are prospective in nature). It also allows explicitly and realistically analysing trade-offs between different fleet-level strategies such as, e. g., extending the service life of in-use vehicles, vs. hastening their decommissioning and replacement with newer, lower-emission vehicles (Garcia & Freire, 2017; Raugei et al., 2021).

Fourthly, it allows incorporating elements of internally-consistent consequentiality in the assessment (i. e., the LCA may be set up to be partially – albeit often not fully – consequential), whereby factors like e. g., the future availability of recycled metals (including e. g., Cu, REEs, Li, Co, etc.) and their uptake in vehicle manufacturing are dynamically co-determined by the EoL treatment of the vehicles that are retired from the fleet and decommissioned over time (Raugei et al., 2021; Stasinopoulos et al., 2012). A further example of consequential modelling is that of some fleet-level LCAs which modelled all new EVs as a net additional load on the electricity grid, and assumed that their use-phase electricity demand will have to be met by ramping up marginal electricity generation (instead of assuming the use of electricity from the average regional grid mix) (Reichmuth et al., 2013).

Finally, a dynamic fleet-level approach allows for explicitly modelling and assessing the environmental consequences of behavioural changes and system-level modal shifts, such as e. g., the increased uptake of shared mobility schemes (TaaS / MaaS) (Raugei et al., 2021).

System boundary

System boundary: Summary of key findings

- The system boundary choice is dependent on the goal of the study and if comparative assessment is intended.
- Cradle to grave and Cradle to gate are the most dominant system boundaries applied and they are the most reported in guidelines.
- Cradle to gate is predominant in battery chemistry comparisons studies which is logical.
- Most OEM studies on vehicles includes a full life cycle (i. e. cradle to grave)
- Most studied life cycle stages in literature are WTT (i. e. the supply chain of energy carrier) followed by the TTW for the use of the vehicle, then the production of vehicle/component
- Infrastructure & maintenance activities are the most subject to exclusion in the reviewed literature.
- Some cut-off processes can be linked to the type of LCA studies (attributional vs consequential) particularly infrastructure which is considered a must-include in consequential work. However, the implications of this type are usually vague. For example, while some OEM studies report attributional approach, they include infrastructure (and use substitution to handle multifunctionality in the EoL)
- Maintenance is usually excluded in guidelines. A reason could be that it is hard to foresee the impacts of that in the real life of the vehicle. Same for scientific literature. Unlike OEMs, who (in considerable number of studies) account for maintenance. This might be due to availability of data from tests and experience which can significantly improve estimations that can be modelled.
- While maintenance exclusion may seem acceptable, it should be emphasized that the magnitude of maintenance should be the reference. For instance, replacing battery or engine is not a minor maintenance to omit.

- Other auxiliary inputs are excluded by some documents like cutting oils, gloves, etc. in production, also car washing in its use stage, and short distance forklift transport of components within the production site. This is somehow acceptable and a good trade-off between reducing complexity and representativeness of the LCA model as long as it is well-known that these excluded parts are (most likely) not environmentally significant.
- Cut-off rules on flows (whenever explicitly stated) are either based on mass (e. g. up to 3% of total weight). Indeed, some OEMs report the inclusion of 98%wt in their studies, or energy, or environmental significance.
- The way the cut-off on flows is identified is very ambiguous and sometimes counterintuitive, since environmental significance of flows should be the benchmark to include/exclude, there is no way to knowing that for sure without including them in the first place.
- Mass-based percentages are very tricky since they can omit very impactful inputs/outputs just because they have low contribution to total weight (e. g. rare metals inputs, dioxins in output). Energy flows on the other hand are much easier to be evaluated for significance, hence fixed values can work better here.
- Catena-X recommendation on conducting screening study before cut-off is a favorable option and in line with PEF which recommends the same.
- Ideally, the rule for cutoff for flows should be “no intentional cut-off” as long as data, computational capacity, and time are available. In any case, proper reporting and transparent documentation are crucial when reporting how cut-off was applied which is also emphasized by the PEF.

Figure III-5 shows the different options for the system boundaries. The main options for system boundaries focusing on the vehicle or a component such as the battery are cradle-to-gate or cradle-to-grave. For the energy carrier (fuel or electricity) life cycle the typical system boundaries are well-to-tank and well-to-wheel.

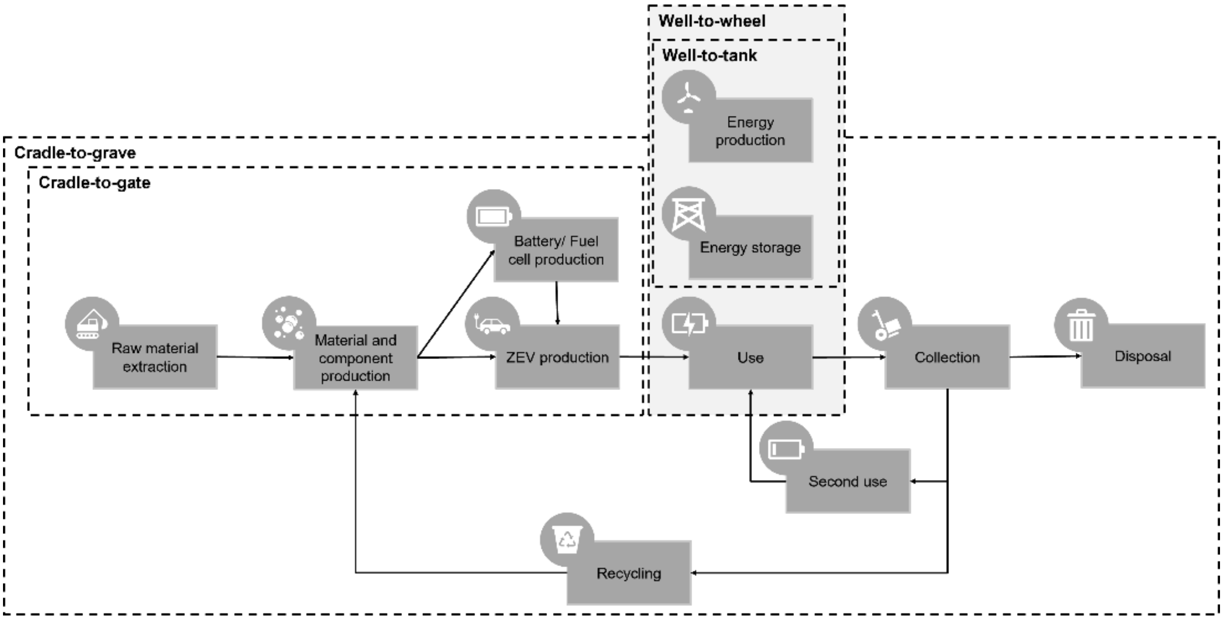

Figure III-5. Commonly applied system boundaries

Table III-4 shows the system boundary **guidelines & standards**. CATARC, GBA and CATENA-X have a cradle-to-gate system boundary. CATARC additionally includes the use phase. All other guidelines and standards analyse the cradle-to-grave system boundary by including the EoL.

The cut off criteria are defined quite differently by the guidelines and standards: eLCAr and RISE do not specify a cut-off rule at all. The GBA rulebook and PEFCR focus on the cut-off of flows and follow the 3% rule of PEF (JRC, 2021) where processes and elementary flows may be excluded up to 3% (cumulatively) based on material and energy flows and the level of environmental significance (single overall score).

The cut-off of flows based on their environmental significance is challenging to adapt in practice. To know what is not significant, the environmental impacts of all flows have to be calculated first. To solve this, previous studies and proxies available can be used. Additionally, what is significant or not can highly depend on the impact category studied. Following mass-based cut-offs of flows brings the risk of excluding impactful flows because of their minor mass. An example for this is rare metals used. Energy-based cut-off might be more reflective of impacts, however, only for impact categories where energy and electricity play a significant role (e. g. Climate Change)

Other guidelines & standards focus on the cut-off of processes. Here, capital goods and infrastructure are often subject to exclusion. Some guidelines provide more details about the specific processes to be excluded. For example, CFB-EV states that battery assembly with other OEM components should be excluded. VDA-PC reports that if the effort for inclusion is far higher than expected significance, exclusion is permitted. They gave an example of short-distance forklift transport. However, some ambiguity was noticed in VDA-PC since they exclude capital goods (infrastructure) in the context of the foreground system only without mentioning explicit guidance for infrastructure in background systems. Maintenance (wear parts, warranty parts, after sales services and washing of cars) is left optional to include according to VDA.

Finally, it seems that PFA provides the clearest cut-off rules in a form of list of items. The most interesting among these is the particulate matter emissions from tire and brake pads wearing. Although PFA declares this as optional to exclude/include, it remains as a challenge. According to industrial partners in the consortium given, this kind of direct emissions are the only expected emissions in the use phase of ZEVs and can be significant.

A summary of cut-off rules and excluded items reported in guidelines are illustrated in Table III-4 where “x” means that the item is explicitly mentioned and “?” means unclear in the guidelines but interpreted by the author (Example: PCR- Buses and coaches reports cleaning agents of facilities to be excluded, the author interpreted this as part of administration).

Table III-4: System boundaries and cut off rules as described in the guidelines and standards

Source	System boundary	Cut-off rules												
		infrastructure (Capital goods)	Environmental Footprint recommendation	Particulate matter (tire wear and brake pads)	Battery use stage	battery assembly with OEM system components	Processes and flows up to fixed %	Based on screening study	transportation of raw materials	transportation of packaging	if unjustified effort (effort>significance)	maintenance	aux materials (cutting oil, gloves)	Administration
Battery														
GBA	Cradle-to-gate + recycling		x											
CFB-EV	Cradle-to-gate+recycling	x			x	x							?	?
PEFCR-Batteries	Cradle-to-grave						x							
Whole vehicle														
CATARC	Cradle-to-gate + use	x												
Catena-X	Cradle-to-gate	?						x						x
eLCAr	Cradle-to-grave	Not really specified												
PCR-Buses and coaches	Cradle-to-grave	x							x	x				?

Source	System boundary	Cut-off rules												
RISE	Cradle-to-grave	Not really specified												
VDA-PC	Cradle-to-grave	x					x				x	x		
PFA	Cradle-to-grave	x		x								x	x	x

All reviewed **OEM reports** use cradle-to-grave system boundaries for the assessments except one simplified LCA that excluded EoL from the study. Raw material production and refining, vehicle manufacturing, distribution, use and end-of-life impacts are included in the studies that considers cradle-to-grave. However, a significant share of the respondents to the survey indicated that a cradle-to-gate system boundary is also used in their LCA modelling, as reported in Figure III-6.

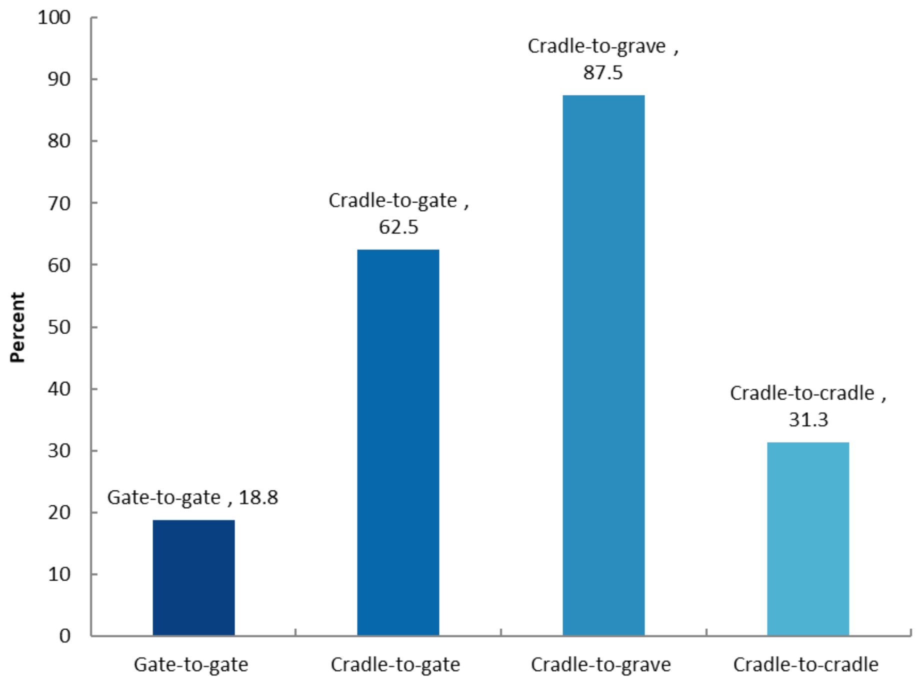

Figure III-6. LCA system boundary as reported by survey respondents (percentages do not add up to 100% because more than one option could be selected simultaneously).

For fuel production, the studies apply a WTT approach and in most cases the studies utilize LCA tools/software and databases for estimating the relevant impact. The inclusion of EoL-treatment steps is commonly included, focusing only on dismantling and shredding, while the impact from recycling is usually excluded. It was not clear from the reports if capital goods (infrastructure) are included or not for WTT chain, however it can be anticipated that when ecoinvent or GaBi databases are used, the infrastructure is considered by default unless it is intentionally excluded by the modeller.

Cut-offs were applied in many of the studies and were consistent with ISO14040/ 14044. Maintenance of the vehicles is for some studies included in the LCAs, while left out for others. Emission attributed to infrastructure such as fuel and charging infrastructure were reported in some studies along with vehicle manufacturing equipment. The review also shows that some of the reports state that more than 98wt% of the mass of the vehicle is included in the calculation.

Geographical considerations are in most cases specifically part of the goal and scope of the OEM reports reviewed. For many, the manufacturing of components and vehicles, the use phase and EoL scenarios have been adapted to reflect certain geographical aspects. For raw materials, components and vehicle assembly the majority of product LCAs consider the European context. Other regions considered include North America, Japan and China, the latter country of which is specifically mentioned in three cases regarding the battery production site. For the use of the vehicles most reviewed product LCAs apply a European perspective, and in some cases also other countries/regions are included as part of the scenario/ sensitivity analysis. Similarly for the EoL-phase, predominantly European scenarios have been applied in the studies and for some Directive 2000/53/CE is referred to as the reference.

All OEM reports except for that of freight truck were based on existing products and therefore classed as ex-post studies. As stated above, the product LCA on freight trucks was conducted for a vehicle composition that was based on projected truck sales. As for temporal considerations, two OEM reports state manufacturing/assembly years. Three state time periods of 2020, 2030 and 2040 considered during the use phase of the vehicle (for different projected electricity generation scenarios). Two OEM reports stated that the use phase of the vehicle occur from the year of the LCA study continuing up to six and ten years after respectively.

The choice of system boundary varies in **scientific literature** since it is very dependent on the focus of the study whether it is vehicle (most inclusive), battery, fuel/energy. However, the mostly studied life stages according to (Ricardo et al., 2020) in descending order are as follows:

1. WTT for Fuel production
2. TTW for Vehicle Use
3. Vehicle/ component production
4. End-of-life
5. Maintenance
6. Infrastructure

This list can give an indication of tendency of including some life stages, nonetheless the study here had a very wide scope which included also conventional ICEV and vehicles running on alternative fuels (e. g. synthetic fuels).

In a more recent review focusing on Li-ion batteries, (Arshad et al., 2022) showed that 38% and 18% of 80 studies they reviewed use cradle-to-gate (often to compare battery chemistries until production) and well-to-wheel system boundary respectively. In 18% of the studies cradle-to-grave was chosen when the primary focus is on the product, process or service being considered. In another review by (Tolomeo et al., 2020) on LCA application to LIBs, it is stated that cradle-to-grave is the most used system boundary. The same was confirmed by (Temporelli et al., 2020). Despite that these reviews declare a focus on batteries for automotive applications, they obviously include full-vehicle studies as well since the battery is a key component of EVs.

The life cycle of fuels and energy can be evaluated separately in well-to-wheel or well-to-tank studies, or as a part of vehicle or battery LCA as the background system of energy provision for the use phase. See for example (Petrauskienė et al., 2020). To a less extend, some studies focus only on EoL for example (Boyden et al., 2016).

Most authors in the reviewed papers recommend a cradle-to-grave approach in any case since it is the only system boundary that represents a full LCA unless the study is solely on electricity or fuel in this case a full LCA would be WTW.

System boundaries in prospective LCA case studies include both cradle-to-gate and cradle-to-grave. A cradle-to-grave scope was found in all the reviewed vehicle-oriented case studies (e. g., (Bauer et al., 2015; Cox et al., 2020)), while battery-oriented case studies include both cradle-to-gate (J. Peters et al., 2016; Xu et al., 2022; Zhang et al., 2022) and cradle-to-grave (Raugei & Winfield, 2019; Zackrisson et al., 2019).

System boundaries in fleet-level LCAs vary in accordance with their intended scope. Where the latter is restricted to the use phase of the vehicles in the fleet at any given point in time, the boundary is usually limited to the Well-to-Wheel life cycle of the fuels and energy carriers used by the vehicles (Chatzikomis et al., 2014; González Palencia et al., 2012; He & Chen, 2013; Kromer et al., 2010; Ou et al., 2010; Plotkin et al., 2009; Reichmuth et al., 2013) . For the wider-scoped studies, the system boundary is extended to include the vehicle manufacturing and EoL (Baptista et al., 2012; Dirnaichner et al., 2022; Garcia et al., 2015; Raugei et al., 2021), and in some cases also additional infrastructure (Paulino et al., 2018; Xiong et al., 2021).

III.2 Phase II. Life Cycle Inventory

Inventory analysis is the second phase in the LCA and involves the compilation and quantification of the inputs and outputs over the life cycle of the studied product (ISO, 2006). Processes' inputs and outputs include elementary flows (e. g., natural resources and emissions), product flows (i. e., goods and services), and waste flows (e. g., wastewater and solid waste) (EC-JRC, 2010). Data quantity and quality required to carry out an LCA is determined by the goal and scope of the study. The LCI phase is critical, first, because it is the most time-consuming phase of an LCA and, secondly, because differences in data sources and inventory modelling assumptions have led to substantial variability in the LCA results of ZEVs (Ricardo et al., 2020). In this section, we review how the different sources have tackled major aspects concerning the LCI phase, namely:

- Data collection and sources across the entire life cycle of ZEVs, from raw materials and component acquisition to manufacturing, use, and EoL
- Data quality requirements
- Multifunctionality issues at the EoL as well as upstream in the value chain
- Electricity modelling.

III.2.1 Data collection and sources

Data collection and sources: Summary of key findings

- There is still a lack of a standardised approach to inventory data collection across different stakeholders throughout the life cycle of ZEVs.
- As a result of this lack of standardisation, discrepancies arise in the literature regarding the treatment of processes as foreground and background and the selection of data sources (e. g., primary vs secondary data).
- Given the current dearth of primary data, secondary data sources (particularly generic LCI databases) play a substantial role in LCAs of ZEVs. Additionally, the reutilization of previously published data (sometimes outdated) is an extended practice.
- The most commonly LCI databases used by academia and industry for conducting LCA of ZEVs are ecoinvent, MLC (former GaBi) databases, and GREET. LCI databases can differ in terms of key methodological aspects, which can have large influence on the final results.
- Prospective LCAs dealing with an emerging technology for which data is still scarce often rely on a combination of data from laboratory and/or pilot-scale experiments, scaling-up assumptions, engineering models, patents, and technical datasheets.
- Fleet-level LCAs, due to their more holistic focus and different goal and scope, heavily depend on secondary data.

The type of data that is collected and compiled in the LCI of a product can be categorised into company-specific (or primary) data and generic (or secondary) data. Processes included within the system boundaries are also typically categorised into foreground and background processes (EC-JRC, 2010). This is a key requirement within the development of system boundaries and setting data quality requirements as a means of ensuring that processes with the most significant impacts are included in the scope, as per the PEF guidance (EC-JRC, 2021). Accordingly, foreground processes are to be treated as core processes in a product's life cycle for which direct site or OEM-specific information is available (Recharge, 2023). Background processes, on the other hand, encompass a set of processes for which direct access to site or OEM specific information may not be available and where the data quality requirements are flexible (secondary data may be sufficient).

Most of the reviewed **guidelines and standards** do not give provisions on a standard way of data collection from different stakeholders throughout the supply chain (see CATARC, eLCAr, PCR-Buses and coaches, RISE, VDA-PC, and PFA). A standardised data collection approach may include, among other aspects, the definition of what processes are considered as foreground or background, what flows should be quantified for each process, what type of data should be used and how to obtain this data, and data quality requirements. It is worth noting that GBA, CFB-EV, PEFCR-Batteries, and Catena-X are specifically aimed at getting to a harmonised structured approach to collect data from suppliers consistently. While these guidelines do provide templates for data collection with varying degrees of details, most of them are restricted to the collection of inventory data relevant to carbon foot printing exclusively (e. g., GBA, CFB-EV, and Catena-X). Only PEFCR-Batteries are aimed to collect data relevant for a broad range of environmental impacts, but its scope is focussed on process data for the production of batteries only. Overall, it is argued that a standard approach for LCI data collection over ZEVs' life cycle would be highly beneficial as it can potentially simplify the time-consuming LCI phase (as the practitioner will know exactly what data to look for) and enhance data exchange, transparency, and reproducibility. The data collection templates provided by some of the guidelines should serve as a basis. Moreover, the standardised data collection approach should be aligned with ongoing developments in traceability systems, especially the digital battery passport.

A review of the **OEM reports** shows compliance with the ISO 14040/44 standards to identify and source the data for processes across the established system boundaries. Some studies were observed to have established these data quality requirements by categorising processes into foreground and background processes. The overall treatment of processes as foreground and background has been mostly identical across the reviewed OEM reports, with some level of discrepancies. These variations may be attributed to the lack of dedicated guidelines, for example, a PCR for passenger cars, which is currently under development and due to be published in 2024 (The International EPD System, 2023). There are five studies encompassing LCAs of

HDVs, mainly urban buses and heavy-duty trucks within the list of reviewed OEM reports. The studies focussing on urban buses are both published EPDs equipped with an LCI that is compliant with the PCR-Buses and coaches (The International EPD System, 2022). Conversely, the **scientific literature** typically does not follow any particular guidelines or recommendations regarding LCI data collection.

Besides the lack of a standardised approach for data collection, the absence of sufficient primary data is also a major gap. For example, Arshad et al., (2022) reviewed 80 case studies on LCA of batteries finding that only 13% obtained primary data. In this context, secondary data plays a substantial role, with some LCA studies relying almost entirely on secondary data (Romare & Dahllöf, 2017; Van Mierlo et al., 2017), while the reutilization of published (sometimes outdated) data is an extended practice (J. F. Peters et al., 2017). Generally, the main source of secondary data is commonly accepted and reviewed **LCI databases** developed by private or public entities. The most commonly LCI databases used by academia and industry to conduct LCA of ZEVs are ecoinvent, Sphera Managed LCA Content (MLC) databases (commonly known as GaBi database), and the Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model (GREET) (Dillman et al., 2020; Ricardo et al., 2020; Tolomeo et al., 2020). The MLC database is mostly used as background database by the automotive industry (e. g., 94% of survey responses state to use MLC, then ecoinvent as second most used). ecoinvent and GREET, on the other hand, are predominantly used in the scientific literature.

An overview of the key criteria for the three most popular LCI databases is presented in Table III-5. ecoinvent is a non-profit association founded by the Swiss Federal Institute of Technology in Zürich and other Swiss institutions. The most recent version of the database when this report was written is ecoinvent v3.9.1. Older versions, like ecoinvent v2, are still widely used in the scientific literature (Marmiroli et al., 2018) (Weidema et al., 2013; Wernet et al., 2016). The MLC database is provided by Sphera, located in Germany. The default database offered by Sphera is called MLC Professional database which covers a wide spectrum of sectors. Sphera also provides specialized databases on demand for specific sectors (Sphera, 2022). GREET is an LCA model and LCI database developed in the US by the Argonne National Laboratory (ANL). Initially born as an Excel datasheet, now it is available also in a graphic user interface. It consists of two sub-models, the GREET fuel cycle model and GREET vehicle cycle. It is widely used to generate data on WTT part of the vehicles life cycle focusing on production of fuels and electricity generation pathways (Argonne National Laboratory, 2019), however much of the material and energy supply-chain information and default factors are US-oriented.

Table III-5. Overview on the three most used LCI databases for LCA of ZEVs within the European context.

Criterion	ecoinvent	MLC database (Former GaBi)	GREET
Organization	Swiss Centre for Life Cycle Inventories	Sphera	Argonne National Laboratory (ANL)
Country of origin	Switzerland	Germany	US
Scope of datasets	Various sectors	Various sectors	Vehicle technologies, fuels, products, and energy systems
Primary data source	- Industrial data - Literature data	- Industrial data - Literature data - Other databases (IBU[a], IEA[b], etc.)	- Literature data - Simulated data - Industrial data
Total LCI datasets	21,238 (Version 3.9.1)	18,500 (MLC)	80**
Type of database	Commercial (LCI)	Commercial (LCI)	Open
Level of aggregation in datasets	Unit process data available	Mostly aggregated (black box) with exceptions of some partially aggregated datasets	Unit process data available
Geographical coverage	- Local (mostly EU countries) - Regional - Global	- Local (mostly EU countries) - Regional - Global	- Regional - Global
Update frequency*	Yearly	Yearly	Frequently (monthly to yearly); when new datasets are available
Technological coverage	Average of current used technology or Best Available Technologies (BAT)	Standard of currently used technology	Standard of current used technology (vehicles + aviation, marine, rail, building module)
Electricity mix	National/regional average mix. Residual grid mixes*** for EU region are also available.	National/regional average mix. Residual grid mixes*** for EU region are also available.	National and US state level
System boundary of datasets	Clearly stated	Clearly stated	Clearly stated
Dealing with multifunctionality	- Allocation[C] - Substitution[d]	Follows ISO hierarchy: - Subdivision - System expansion – (incl. Substitution) - Allocation	- Allocation predominantly[e] - Recycled content & EoL approach in the EoL (Kelly et al., 2022)
CFF application	No	No	No

Criterion	ecoinvent	MLC database (Former GaBi)	GREET
General data quality approach	Data quality is represented by a Pedigree matrix	Six Data quality indicators (DQI) each ranked from 1 (very good) to 5 (very poor)	No specific approach could be identified

*Notes: * Does not mean that all the datasets within the database are updated with each periodic update (usually partial updates of some datasets). [a] Institut Bauen und Umwelt e.V. [b] International Energy Agency. [c] The details of allocation application differ between the three system models of ecoinvent in case of co-production and recyclable content; for further details, see* https://ecoinvent.org/the-ecoinvent-database/system-models/. *[d] "Substitution, consequential, long-term" is the only consequential system model in ecoinvent. [e] Mass, economic, energy, or market-based choice varies; for further details, see* https://greet.es.anl.gov/list.php.

***Reported on GREET website as "80 vehicle/fuel systems". Source: www.ghgprotocol.org/Third-Party-Databases/GREET & https://greet.es.anl.gov/homepage2*

**** Residual mix is used to determine the energy origin of untracked consumption, i. e. consumption, which has not been disclosed with explicit tracking instruments such as Guarantees of Origin. So if all electricity consumption was explicitly tracked to specific generation attributes, residual mix would not be needed* (Klimscheffskij et al., 2015)

Several other LCI databases are available[2] but not as widely used within the European context or relevant for vehicle LCA (i. e., sector or product specific LCI databases). Worth mentioning is the CALCD (China Automotive Life Cycle Database) developed by the China Automotive Technology and Research Center Co., Ltd (CATARC). The CALCD contains vehicle specific LCI datasets that represent the average Chinese market covering the whole life cycle of vehicles (Autmotive Data of China Co., 2022). The CALCD is thereby used as main LCI database within the CATARC vehicle LCA standardisation methodology and feeds into the China Automotive Life Cycle Assessment Model (CALCM). Other more general background databases, such as the JLCA-LCA database (over approx. 250 datasets and established by 54 Japanese industrial associations), are not widely used within the European context and left out of the discussion.

As shown in Table III-5, LCI databases can differ in terms of key methodological aspects, such as modelling approaches (e. g., EoL modelling, electricity modelling, allocation, etc.), data sources and quality, and geographical, temporal, and technological coverage. These variations can yield substantially different LCA results for the same product system when different databases are used for modelling. For example, Sanjuan-Delmás et al., (2022) revealed that some of the impacts associated with copper production can be estimated to be up to 7.5 times higher when using the ecoinvent database (along with the SimaPro software) compared to the MLC Professional database (along with the LCA FE software). Hence, it is highly recommended to consistently employ the same LCI database as the background data source.

Prospective LCAs often assess an emerging technology for which data is still scarce (Cucurachi et al., 2018). Consequently, foreground processes are often modelled based on data from laboratory and/or pilot-scale experiments (van den Oever et al., 2023; Zhang et al., 2022) combined with scaling-up methods to scale up laboratory/pilot scale production to industrial

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[2] See for an overview for example: Life Cycle Databases | GHG Protocol

scale (Tsoy et al., 2020). Other foreground data sources used in prospective LCAs include engineering models (Cox et al., 2020; Raugei & Winfield, 2019; Sacchi, Bauer, et al., 2022; Xu et al., 2022), and patents and technical datasheets (J. Peters et al., 2016). Typically, a combination of the aforementioned data sources is used. For the background processes, there is a growing inclination towards the utilization of a futurized LCI database that considers future energy scenarios based on the output results from an Integrated Assessment Model (IAM) (Koroma et al., 2020; van den Oever et al., 2023; Xu et al., 2022). Recently, changes in the supply chain of key battery raw materials, such as lithium, cobalt, nickel, copper, and steel are being implemented as well (Koroma et al., 2020; van den Oever et al., 2023; Xu et al., 2022).

Finally, due to their more holistic focus and different goal and scope, virtually all **fleet-level LCAs** heavily (and often even exclusively) rely on secondary sources of data, such as industry-average estimates, LCI databases, high-level statistical data, and sometimes even economic input-output tables. This is due to the sheer impracticality of using highly granular primary data sources when attempting to comprehensively cover the entire fleet of vehicles.

In the next subsections, and in order to give more depth to the discussion, the issue of data will be discussed for the different life cycle stages of ZEVs, namely raw material and component acquisition, manufacturing, use and EoL.

Raw materials and component acquisition

Data collection and sources - Raw materials and component acquisition: Summary of key findings

- Standards and guidelines recommendations regarding raw materials data sources vary widely, ranging from site-specific primary data to generic LCI databases (e. g., EF compliant datasets) or default emission factors.
- In OEM reports and scientific literature, raw materials acquisition is predominantly modelled using generic LCI databases and/or other secondary data sources.
- Concerns have been raised about the representativeness of existing LCI datasets for raw materials, which may have so far resulted in underestimated impacts.
- Survey results confirm a large primary data gap when it comes to raw materials acquisition, with less than 20% of the responses declaring access to primary data.
- The lack of dedicated traceability systems is identified as a potential reason for the limited availability of primary data. Current developments in the emerging field of digital product passports can enhance data sharing between mining and refining companies and OEMs.
- A growing number of prospective LCAs explore potential future developments within raw material supply chains, such as changes in ore grade, mining energy efficiency, market shares of primary and secondary production routes, and production sites.

- Regarding traction batteries, based on the review and expert viewpoints, there's a prevailing belief that when it comes to data about raw material acquisition, cathode materials are the primary focus. In contrast, anode materials receive comparatively less attention, and other battery components are almost entirely neglected.

Raw materials and component acquisition are major contributors to the environmental impacts in automotive manufacture due to the demand for energy-intensive materials such as metals and minerals, particularly to produce gliders and EVs powertrains. For traction batteries, a general impression from the review and expert opinions was that cathode materials receive the most attention in the context of data for raw material acquisition, while less attention is given to anode materials and almost no attention is given for other battery components. This tendency might be understandable in the light of the criticality and the social concerns associated with cathode materials acquisition such as cobalt, lithium, and Nickel. Nevertheless, this imbalance in data representation should be kept in mind not to leave something behind when trying to improve data for LCI.

Considering data collection related to raw materials, the literature review performed by (Ricardo et al., 2020) identified two main options depending on the type of the study:

- Full modelling of raw material extraction, processing, refining, and transportation. Mostly practiced in dedicated materials studies or for establishment of generic LCI databases (e. g., ecoinvent, MLC databases, and GREET).
- Use of generic data from LCI databases such as ecoinvent and MLC databases. Practiced in most scientific and OEM studies focussing on the full vehicle cycle.

The provisions given by the different **guidelines and standards** concerning raw materials acquisition are also rather different. Some guidelines and standards only seem to refer to the material composition (i. e., the types and amounts of materials) of a specific (semi) product, as for example the provision or recommendation to use the bill of materials and the International Material Data System (IMDS) in RISE, VDA-PC, and PFA. In this case, it is not clear if these guidelines only refer to materials that finally end up as a component or also includes the auxiliary materials and energy used for materials production. Moreover, it is not clear if guidelines are given for upstream unit process inputs and outputs data, or if default emission factors should be used.

Yet, there are other guidelines that refer to detailed upstream process data collection. As a rule of thumb, they follow a hierarchy of data collection, namely site-specific primary data, generic primary data, data from contractors, or (recommended) LCI databases. GBA, CFB-EV, Catena-X, and PCR-Buses and coaches state that primary data shall be used instead of secondary, if available, and provide detailed templates for data collection. Meanwhile, the PEFCR-Batteries state that data for these upstream processes shall at least be described by EF compliant datasets, but primary data may be optionally provided. Some reports, like CATARC, suggest the use of proxies based on default emission factors per kg of material. Again, it is not clear if this refers to components only or also to auxiliary materials and energy.

Upon review of all the **OEM reports**, it was evident that the data demand for raw materials acquisition were all met with the use of generic or secondary data. The large gap on primary data availability for raw materials extraction is confirmed by our survey, as less than 20% of the responses declare to have primary data for this stage (Figure III-7). This may be due to the lack of dedicated traceability systems or databases for the OEMs to access, especially for critical raw materials upstream of the supply chain.

Conversely, for the pre-processing stage, otherwise referred to as parts and components production or acquisition, most OEM reports have employed company-specific, and sometimes, site-specific information since these processes are either directly under the influence of the vehicle OEMs or have established data sharing ties with their component suppliers. This could include acquiring parts and component specific data through dedicated data collection templates, or vice-versa through processing of data shared by the suppliers themselves. In most cases, material-specific information, for the parts and components, is drawn from material composition and weight of the components/parts. This data is compiled as a bill of materials, which is fed into and retrieved from a global automotive data repository called the IMDS[3] The collected data is then categorised into different material groups and linked with one or several generic LCI datasets pertaining to the extraction and refining of the materials by each category in the library. Where specific (manufacturer) data were unavailable, industry and national average estimates were used from dedicated LCI databases such as MLC databases and ecoinvent (EU), GREET (US) or JLCA-LCA (Japan).

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[3] IMDS is exclusive to automotive manufacturers and suppliers, however, this online global platform has been instrumental in maintaining data consistency and highlighting hazardous controlled substances by supporting the comparison of entered data with regulated list of substances such as REACH (EU Registration, Evaluation, Authorisation and Restriction of Chemicals), ELV (End of Life Vehicle Directive) etc.

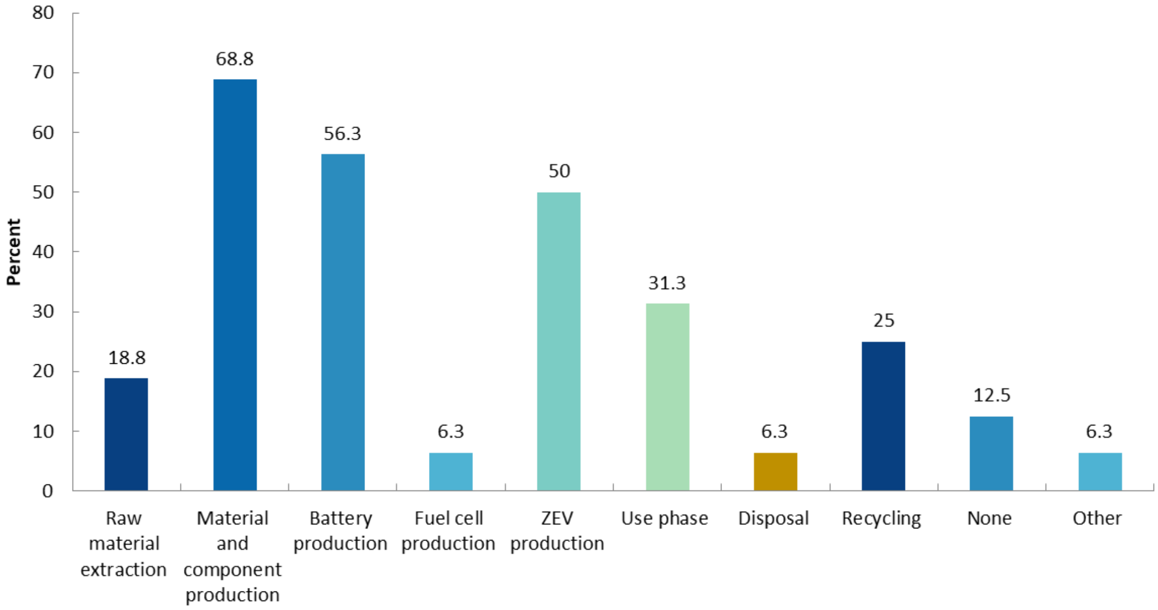

Figure III-7. Survey results for the question: “For which vehicle life cycle stages do you have primary data (i. e., data directly sourced from suppliers)?”.

In **scientific literature**, raw materials’ acquisition is classically modelled considering standard LCI datasets, as in particular observed in the review of LCAs of EVs batteries (Aichberger, 2020; Lai et al., 2022; Temporelli et al., 2020) with ecoinvent as one of the most used background LCI databases (Aichberger, 2020; Tolomeo et al., 2020). Recent scientific literature on the LCA of battery raw materials raised a number of concerns regarding existing LCI datasets, including outdated and non-representative data (e. g., regarding battery-grade graphite and Li_2CO_3 productions; (Engels et al., 2022; Schenker et al., 2022). This may have so far resulted in underestimated carbon footprint of some battery raw materials (Engels et al., 2022; Schenker et al., 2022; Surovtseva et al., 2022). Moreover, LCI modelling of raw materials’ chains, and associated impacts on toxicity and ecotoxicity, are particularly sensitive to the modelling of tailings final disposal, and more specifically to metals mobility (Beylot et al., 2022). These long-term emissions of toxic substances from tailings disposal were identified a hotspot in the LCA literature applied to hybrid, plug-in hybrid, and BEVs (Nordelöf et al., 2014).

Prospective LCAs also rely on secondary data from LCI databases (mainly ecoinvent) to model raw materials acquisition (J. Peters et al., 2016; Raugei & Winfield, 2019; Zackrisson et al., 2019; Zhang et al., 2022). Yet, there is a growing inclination towards the consideration of prospective LCIs for the supply of key battery raw materials (Koroma et al., 2020; van den Oever et al., 2023; Xu et al., 2022). These inventories typically consider possible future changes in terms of ore grade decline, mining energy efficiency improvements, market shares of primary and secondary production routes, and production sites. The development of such LCI datasets is still in its infancy. Prior works have presented prospective LCIs for lithium (Ambrose &

Kendall, 2020; Chordia et al., 2022; Schenker et al., 2022), cobalt (van der Meide et al., 2022), nickel (Harpprecht et al., 2021), and copper (Harpprecht et al., 2021).

All in all, raw materials acquisition is arguably the ZEV life cycle stage for which the most significant efforts are required in terms of data collection and sources. The scarcity of primary data for this life cycle stage is an issue reported in all the reviewed sources. To address this challenge, default emission factors based on a worst case scenario have been suggested elsewhere as a strategy to encourage disclosure of primary data (Peiseler et al., 2022). Moreover, current developments in the emerging field of digital product passports holds promise for enhancing data sharing between mining and refining companies and OEMs, without compromising confidentiality (Adisorn et al., 2021).

Manufacturing

Data collection and sources - Manufacturing: Summary of key findings

- Guidelines and standards generally have specific recommendations and/or obligations concerning data sources for manufacturing processes, of either batteries or vehicles. As a general recommendation, company or site-specific data shall be used.
- OEM reports employ company-specific and/or site-specific data for manufacturing processes, since these are either directly under the control of OEMs, or the latter have established data sharing ties with their component suppliers.
- The results from the survey also highlight a higher availability of primary data for the manufacturing stage compared with other life cycle stages like raw materials acquisition and use.
- The modelling of the manufacturing stage in scientific literature relies on a variety of data sources and modelling approaches.
- Future improvements in manufacturing processes and technologies, the evolution in the electricity grid mix used to power manufacturing, as well as shifts in production locations deserve attention in future LCA studies.

The manufacturing stage is crucial in vehicles and batteries life cycle and it can heavily affect the preferability of ZEVs over ICEVs. The risk of burden shifting from the use to the manufacturing stage in ZEVs is a concern in science and industry. Notably, BEVs generally have higher impacts in the manufacturing stage compared with ICEVs, primarily due to batteries (Lai et al., 2022).

In this context, most of the **guidelines and standards** have specific recommendations/obligations on data sources and modelling of manufacturing processes, of either batteries or vehicles. The general recommendation is that company, or even site-specific, (yearly) data shall be used for manufacturing processes (see GBA, CFB-EV, PEFCR-Batteries, Catena-X, PCR-Buses and coaches, RISE, and VDA-PC). The specific processes mentioned are production of the main parts of the vehicles (i. e., traction battery, electric motor, fuel cell stack), assemblage of the vehicle, and production of the batteries. Some reports give detailed guidelines for the modelling of the electricity and heat used in manufacturing, as in PEFCR-Batteries and VDA-PC. The CATARC guidelines only mention that for vehicle production, on-site data shall be used for energy consumption and carbon emissions, while default emission factors can be used for fuel production and use. The eLCAr guidelines only provide general guidance for data collection, while the PFA technical guidance is rather vaguely stating that data should be informed by available environmental company reports.

To account for manufacture-related energy demand, most **OEM reports** adopted site-specific energy consumption, including a representative regional grid mix. Among these, one specific OEM used default energy consumption values for specific manufacturing processes such as welding, forging, parts assembly, etc., which was then adopted for modelling energy use over the vehicle manufacturing phase. While this is not necessarily site-specific data, the data quality might still be viewed as better than secondary/generic data. Some studies followed an approach where aggregated fuel and electricity use data for manufacturing phase, were split by regions and by the share of cars made in the specific year of study.

Battery production, in the case of EVs manufacturing, is by far the most important component where detailed supplier data should be collected. Some OEM reports were found to source battery data directly from their battery suppliers, while in some cases, vehicle OEMs incorporate data sourced from their own literature review (which may be from a combination of scientific sources or models pre-determined/ developed on LCA software such as LCA FE (former GaBi).

The results from the survey also highlight a higher availability of primary data for the manufacturing stage. More specifically, up to 69%, 56% and 50% of the responses declare to have at least some primary data for components production, battery production, and ZEV production, respectively (Figure III-7). Regarding battery production, about 56% declare to have primary data for battery pack assembly, 50% for cell manufacturing, and 38% for cathode material production (Figure III-8). The latter two stages account for most of the non-raw material impacts in battery manufacturing due to highly energy intensive processes.

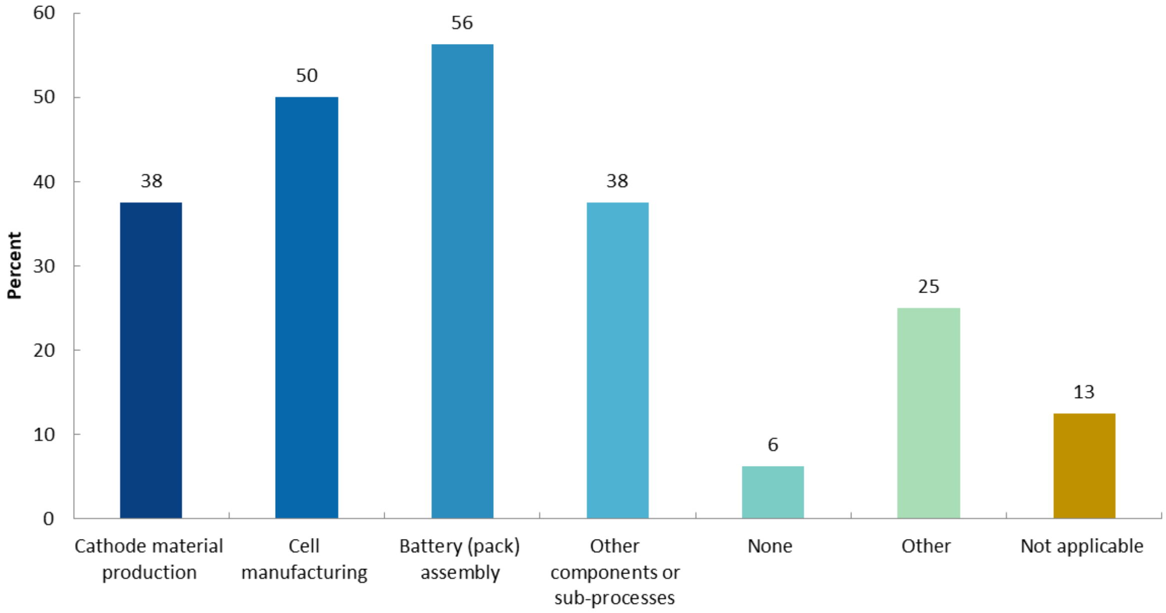

Figure III-8. Survey results for the question: *"For battery production, for which aspects do you have primary data?"*

Modelling the manufacturing stage in **scientific literature** can be summarized in three common approaches regarding data sources (Ricardo et al., 2020):

- Utilizing aggregated data for vehicles/components. This approach is typically employed in comparative overview studies that primarily focus on the use stage of vehicles.
- Employing differentiated material lists along with corresponding energy consumption and auxiliary substances for generic vehicles or components.
- Incorporating highly detailed data provided by manufacturers for specific vehicle models.

In the absence of primary data, **engineering models** are a common resource used in the literature to compile the bill of materials. Notably, BatPaC is a publicly available bottom-up battery design and cost calculation model developed at the Argonne National Laboratory (Knehr et al., 2022). It is widely used by LCA practitioners to obtain the bill of materials and performance for a specific battery design (based on the specified power, energy, and vehicle type). Under its latest version 5.0, BatPaC addresses LIB packs for hybrid, plug-in hybrid, and full-electric vehicles. On the other hand, Carculator is a Python-based open-source library to assess the life cycle environmental impacts of current and future passenger vehicles (Sacchi, Bauer, et al., 2022). Given a time-dependent set of parameters (e. g., battery mass), Carculator estimates the bill of materials of current and future vehicles. It covers nine powertrains (diesel, gasoline, and compressed natural gas ICEs, BEV, diesel and gasoline HEVs and PHEVs, and FCEV), nine vehicle size categories (micro, mini, small, lower, medium, large, medium SUV, large SUV, and van), as well as 50 production years (2000 to 2050).

Regarding manufacture-related energy demand, major differences have been observed in the literature concerning the modelling approach. J. F. Peters et al., (2017) classified these approaches into top-down (in which the gross energy demand of a manufacturing plant is divided by the output) and bottom-up (in which the energy demand of the manufacturing plant is estimated from the specific energy consumption of individual processes). Recently, the bottom-up approach has been combined with information extracted from technical reports of existing and/or planned EV battery cells manufacturing plants to derive more accurate energy consumption data (Chordia et al., 2021; Degen & Schütte, 2022). Overall, the chosen approach heavily influences the final energy demand, as demonstrated for batteries production (J. F. Peters et al., 2017).

Future improvements in manufacturing processes and technologies is something to profoundly consider in future LCA studies which was highlighted by (Raugei, 2022) as somehow overlooked in literature. While this is valid for all powertrain types, some other variables are more specific to ZEVs, like the extremely rapid advancement in batteries technologies and energy density. Not to mention the evolution in electricity grid mix which certainly affects the manufacturing of the different vehicle components as it affects the use phase. The electricity source used to power manufacturing is perhaps the most impactful factor at this stage. This also illustrates the importance of considering the production facility location of the different components in the present and how electric grids would evolve in the future in the production locations (Bouter & Guichet, 2022; Dillman et al., 2020). In this context, **prospective LCAs** often focus on emerging technologies (e. g., a novel battery chemistry or renewable fuel) for which data is still scarce. Manufacturing processes can be modelled based on data from laboratory and/or pilot-scale experiments (e. g., (van den Oever et al., 2023; Zhang et al., 2022) combined with scaling-up methods and assumptions to scale up laboratory/pilot scale production to industrial scale (Tsoy et al., 2020). Other foreground data sources used in prospective LCAs include engineering calculations and models, such as BatPaC (Raugei & Winfield, 2019), EverBatt (e. g., (Xu et al., 2022)), and carculator (Sacchi, Bauer, et al., 2022), and patents and technical datasheets (J. Peters et al., 2016). Typically, a combination of the aforementioned data sources is used. Moreover, prospective LCAs often consider future electricity mixes for the manufacturing stage, as further detailed in Section III.2.4.

Use

Data collection and sources - Use: Summary of key findings

- Existing guidelines and standards generally state that measurements or documented tests shall be used to model vehicle energy consumption for ZEVs.
- There is limited variability in the modelling of vehicle energy consumption within OEM reports, with most of them adopting regulatory values and only a few studies

exploring "real-world" effects (despite well-documented and significant variations in these).

- Some scientific studies adopt data based on simulations for energy consumption (either for regulatory or real-world performance).
- Accounting for battery charging losses is usually included, either as directly in regulatory testing values or indirectly (e. g., based on an assumed battery and charger efficiency).
- Most OEM studies (and also many scientific studies) assume a static electricity (or hydrogen) production mix, rather than a changing mix over the vehicle lifetime (e. g. from current policy projections – e. g., from IEA). Prospective and fleet-level LCA studies tend to utilise a dynamic electricity mix modelling approach, instead.
- Maintenance is frequently excluded from most studies (but addressed in guidelines and standards where these exist), and where it is included, it is usually limited to tyre replacements. Similarly, non-exhaust emissions (including, e. g., PM emissions) are generally not considered.
- Moreover, battery replacements are usually not included, and the methodology/rationale for their inclusion/non-inclusion is usually limited or non-existent, except for a few scientific or other literature sources.

It is worth mentioning that in some of the reviewed documents, the use of the vehicle and/or battery is out of the scope (e. g., the guidelines and standards GBA, CFB-EV, and Catena-X). This is because these documents focus on the cradle-to-gate impacts. Whenever considered, the most outstanding aspects concerning the use of the vehicle and/or battery are the following:

- Amount of electricity (or fuel) consumed in the use of the vehicle and/or battery
- Energy losses from charging the batteries
- The (background) data related to the electricity mix that is consumed
- Maintenance (e. g., replacement of batteries, lead acid batteries, tires, and refrigerants)
- Other non-exhaust emissions such as particulate matter emissions from tires and brakes during use.

In general, there does not seem to be harmonisation between **guidelines and standards** concerning whether and how some of the aforementioned aspects are accounted for. Regarding electricity (or fuel) consumption during the use of the vehicle, CATARC, RISE, PCR-Buses and coaches, PFA, and VDA-PC state that measurements or documented tests (e. g., Worldwide Harmonised Light Vehicle Test Procedure or WLTP) shall be used. In case this information is not available, a calculation method for EVs is provided by RISE, while eLCAr provides equations for the calculation of the electricity consumption for different sub-consumptions (basic driving, heating, etc.) influenced by various factors (drive cycle, distance, vehicle design, etc.). In this case, electricity consumption will depend on several parameters, including 1) type of use of the car (short versus long distance), 2) driving behaviour (drive cycles: Worldwide harmonized Light vehicles Test Cycles (WLTC), Common Artemis Driving Cycle CADC and New European Driving Cycle (NEDC)), 3) climate in which the car is used (regarding heating), and 4) region in which the car is used (production electricity mix). Moreover, the PCR-Buses and coaches mentions that data for the use stage are usually based on scenarios coming from Regulation (EC)595/2009. All in all, real world vehicle-specific data (i. e., energy consumption monitored directly from vehicles driving on the road) may provide more accurate numbers as calculations and simulations are very unlikely to capture variations in conditions linked to real driving. However, for real values to be representative, they need to be based on a large number of tests.

The PEFCR-Batteries focuses exclusively on batteries production and use, stating that the electricity consumed during the use of the battery is defined by the energy losses due to the battery and charger efficiency. Battery charging losses can be quantified based on test cycles of WLTP (VDA) or energy losses due to battery and charger efficiency over battery lifetime (PEFCR-Batteries).

Guidance on the electricity mix that should be considered for the vehicle and/or battery use stage is given by a few guidelines and standards. In general, the consideration of secondary data from a LCI database is recommended, either based on country-specific electricity mixes or following a priority order. Section III.2.4 contains an in-depth discussion on the electricity grid mix that should be considered according to the different standards and guidelines.

Maintenance (e. g., replacement of batteries) is considered in several standards and guidelines based on service intervals (RISE, VDA-PC, CATARC) or the road vehicle preventive maintenance program (PCR-Buses and coaches). The PFA report differentiates between two maintenance needs: i) regular maintenance (e. g., oil, filters, 12V battery, coolant, traction battery, air conditioning gas) and ii) replacement of wear parts (e. g., tires, brake linings, and windscreen wipers). The second type heavily depends on the driving mode (e. g., frequency of tires replacement) and, in consequence, it entails higher challenges to establish a harmonised approach. The recommendation is to assume the theoretical change frequencies as specified in the maintenance book. Moreover, the eLCAr and RISE guidelines state that particulate matter emissions should be included in the use stage.

OEM reports, on the other hand, were observed to conform to a consistent adoption of minimum data criteria for the estimation of vehicle use-impacts. All the studies were observed to account for the vehicle's energy consumptions over regionally relevant drive cycles (such as WLTP and NEDC in the EU, FTP 75[4] and SFTP US06[5] in the US; China light duty vehicle test (CLTC) in China and JC8 in Japan), their modelled vehicle's lifetime, and the regional/national

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[4] Federal Test Procedure, an US EPA implemented city driving cycle
[5] US EPA impelemented Supplementary Federal Test Procedure

electricity mix. LCA studies encompassing freight vehicles used representative urban and regional delivery cycle (i. e. based on European certified values using the VECTO tool (European Commission, 2023). In the vast majority of cases, studies used electricity mix data based on secondary dataset from generic LCI databases, usually assuming a static electricity mix (using the year for which the most current data was available) with a sensitivity on renewable electricity (or similar). Very few studies considered an electricity mix based on the average of how this is projected to change over the lifetime of the vehicle (for further details on electricity modelling, see Section III.2.4).

In terms of vehicle maintenance, most of the OEM reports excluded it, with some studies that include maintenance covering mainly tyre replacement over the vehicle's lifetime, and also sometimes fluid replacements (i. e. screen wash, coolant, lubricants, etc). Most OEM studies assume no replacement traction battery is needed in the typical vehicle lifetime. Moreover, other non-tailpipe emissions, such as emissions from brake pads and tyre wear from contact with road surface, have been predominantly excluded from the scope of the study. Only one OEM report, on heavy duty vehicle for freighting purposes, captures the impacts of non-exhaust emissions as $PM_{2.5}$ emission, following the World Harmonised Transient Cycle (WHTC) legislation, which has now been updated within a 2019 Road tyre and brake wear guidebook (European Environment Agency, 2019).

The review of the **scientific literature** reveals a range of modelling approaches for vehicle use energy consumption, from simple assumptions based on data published in the literature to full vehicle simulations (Ricardo et al., 2020). In battery-oriented LCA studies, energy consumption in the use stage is often accounted for based on an assumed battery energy efficiency, ranging from 85% to 95% (L. A. W. Ellingsen et al., 2017). This assumption, although consistent with the PEFCR-Batteries, often ignores the influence of battery characteristics (e. g., cell format and cathode materials) on energy efficiency, and can have large implications on the impacts of the use stage. Regarding the assumed electricity mix, the predominant choice is a static national or regional (e. g., European) average electricity mix based on secondary data from a LCI database (for further details on electricity modelling, see Section III.2.4).

Maintenance is most often excluded in the scientific literature, generally justified by the low impacts relative to the vehicle life cycle. Among those studies that do include maintenance, there is a lack of detailed information regarding the methodology and data utilized (Ricardo et al., 2020). Typically, generic data sourced from LCI databases is utilized. Battery replacement has been also largely neglected despite its relevance to the life cycle impacts. Although some studies report that they included battery replacement, there is a lack of methodological transparency and data that are not clearly disclosed. This is also reflected in the LCIA results where disaggregation of battery replacement impact hampers the proper interpretation of its impact.

To elaborate on that, (Dillman et al., 2020) indicate that studies deal with the topic of battery replacement in six ways:

- Not discussed and not included (second most common) (Gawron et al., 2018)
- Out of scope—identified as a limitation (Ma et al., 2012)
- Battery life considered longer than or equal to vehicle life (most common) (Burchart-Korol et al., 2018)
- Battery replacement included with unclear methodology (Bauer et al., 2015)
- Included with clear methodology—Ratio of battery lifetime versus EV lifetime (only one of the reviewed studies) (Kawamoto et al., 2019)
- Included with clear methodology—one-time battery replacement (only one of the reviewed studies).

A more comprehensive methodology to account for the frequency of battery replacement has been proposed by (Ricardo et al., 2020) based on a combination of parameters related to battery size and lifetime millage. Under this approach, the number of batteries needed over the vehicle lifetime evolves along with the evolution of the underlying parameters.

Hydrogen for FCEV is also a trending topic in the scientific literature. The most common hydrogen production routes are steam methane reforming (SME), electrolysis, and gasification (Ahmadi & Khoshnevisan, 2022). Possible sources of data are GREET (Argonne National Laboratory, 2019) and JEC WtW (Prussi, 2020), where the production of hydrogen through electrolysis is well documented in a dataset, as well as the subsequent stages of liquefaction, transport, storage and distribution.

In **prospective and fleet-level LCAs**, the electricity consumption in the use of the vehicle and/or battery has been modelled in a similar way as observed so far in the scientific literature. The major difference with respect to retrospective LCAs stems from the consideration of the time dimension for the modelling of the electricity mix. Several prospective LCAs address the changing electricity mix over the lifetime of the vehicle (Sacchi, Bauer, et al., 2022; Zimmermann et al., 2015). However, there are also a substantial number of prospective LCAs that assume a static electricity mix corresponding to the assessed year, typically 2030 or 2050 (Bauer et al., 2015; Cox et al., 2018, 2020). Similarly, fleet-level LCAs also consider a variety of modelling approaches, from prospective static national mixes to more sophisticated dynamic mixes. Further details on electricity modelling in prospective LCA of ZEVs is provided in the corresponding Section III.2.4. Maintenance and other non-exhaust emissions have been either ignored or modelled in a similar way as in retrospective LCAs, i. e., based on secondary data from an LCI database (Koroma et al., 2022) and/or industry reports and handbooks (Sacchi, Bauer, et al., 2022). Typically, these aspects are assumed to remain static and not projected to the future assessed year.

A summary of the key methodological and data choices identified across all sources (where they were documented) is provided in the following Table III-6:

Table III-6: Summary of in-use data collection/sources identified

Use Aspect **Aspect?**	**Basis** **Options / Choices?**	**Source** **Examples**
Energy consumption	1. Regulatory (e. g. WLTP, NEDC, VECTO, etc.) 2. Regulatory plus real-world 3. Simulated (regulatory or real-world)	(1)(2)(3) (3)(4) (3)(4)
Charging losses	1. Included in regulatory test values 2. Separate accounting for charging losses 3. Not included	(1)(3)
Non-exhaust emissions	1. Not included 2. Non-exhaust PM (e. g. tyre/brake wear)	(1)(2) (1)(2)
Data on electricity or hydrogen production mix/emissions	1. Current static regional/national or global mix 2. Current static regional/national or global mix + Sensitivity analysis (e. g., renewable electricity) 3. Prospective static regional/national or global mix 4. Changing electricity mix over vehicle lifetime 5. Other (e. g., national residual mix)	(1)(2)(3) (2)(3) (4)(5) (4)(5) (1)
Battery or fuel cell replacement	1. No replacements 2. 1 battery or fuel cell replacement (simple assumption) 3. Simple methodology to determine battery or fuel cell replacement 4. More sophisticated methodology to determine need for replacement	(3) (3) (3) (3)
Maintenance	1. Not included 2. Replacement tyres only 3. Replacement tyres and fluids 4. *(Also additional maintenance)* 5. *(Fuel cell refurbishment)*	(2)(3) (2)(3) N/A N/A

Notes: (1) = Guidelines/standards; (2) OEM reports, (3) = scientific literature, (4) = prospective LCA, (5) = fleet-level LCA.
Items in *italics and bracketed* = expected but not identified in the reviewed literature

EoL modelling and allocation

Data collection and sources- EoL modelling and allocation: Summary of key findings

- Some of reviewed documents explicitly describe EoL routes of batteries and vehicles (collection, dismantling, etc).
- The focus is primarily on the battery component. Primary data are scarce due to comparatively few batteries having reached their end of life yet
- Some guidelines provide alternative proxy data to be used in case of absence of primary data.
- The methodological choices and assumptions made in the EoL modelling of vehicles and batteries have significant influence on the results.
- The main point of controversy is how to account for recycling burdens and benefits.
- Overall, there are five main options as identified across the different sources: **Circular Footprint Formula (CFF); Cut-off approach; Avoided burden approach (commonly known as EoL approach); 50:50; Allocation at the Point of Substitution (APOS).** Practically all these approaches eventually boil down to the two general LCA concepts of allocation (partitioning) and substitution in ISO.
- The five options either represents a mix of the two concepts or taking an option to its extreme case. Cut-off approach is the extreme opposite of Avoided burden approach. Cut-off approach assumes that the recycled materials inputs are burden-free hence implicitly encourages **using** more recycled content if adopted. Avoided burden, on the other hand, gives credit for the system that **produces** any recycled material that can "substitute" primary material in a downstream system that will use this material.
- 50:50 is a rough estimate that assumes a middle way between "cut-off" and "avoided burden", whereby 50% of the secondary material is modelled as a burden-free input (assuming closed-loop recycling) and 50% is assigned a credit (assuming displacement of primary material downstream).
- CFF is the recommended way in the PEF, and it is a more sophisticated hybrid approach that takes into account the market status, quality of secondary material to divide the burdens and the credits between the producer of secondary material/energy and user of these flows in the following system.
- Although CFF seems to be the wisest choice since it strikes a balance between the extremes, it exhibits some drawbacks at least in its current state in PEF. The drawbacks are mainly due to the complexity in application for each single material (especially in complex inventories), and the coefficients used in the equation which are argued to be arbitrary more than representative of what they are supposed to represent. The complexity issue is reflected in the results of the consultation with industry and OEM reports which showed a preference of using the cut-off method due to simplicity and being the environmentally conservative option.

- Only the guidelines that are based on PEF recommend CFF, while other guidelines are mostly vague about recommending a specific approach. CFF is absent in scientific LCA studies. The approach used for LIB batteries (the most studied) is mainly the EoL (i. e. avoided burden) with fewer studies use the cut-off.
- APOS is a special kind of way of applying allocation and it is one of the system models offered by ecoinventV3 and it is based on economic allocation.
- Choosing the most convenient method is subject to the context including type of study (attributional or consequential). The most important thing is consistency in the method used which should follow the same concept over the entire life cycle. This means that LCA practitioner should be aware of the approaches adopted in the background systems (e. g. LCI databases) as well to maintain this consistency.
- In general, CFF can represent an optimum general approach if: 1) simplified and/or implemented in LCA software to facilitate usage; 2) the coefficients especially the “A” and “B” coefficients are defined as a result of wide consensus; 3) generalized in the commonly used LCI databases like ecoinvent and MLC databases (former GaBi).
- Second life of batteries (i. e. reuse) are also a trending topic with expert and researchers advocating its edge over recycling. Also, more research is needed here, currently there are generally four ways to model this: No accounting; Compare LCIA for second-life of the battery to a specific reference case; credits for substituting new energy storage system; Economic allocation. It is hard to decisively say or prefer one way or another to deal with second life of battery. This is a very new route in the end of life and there are yet few applications of it with few batteries reaching their end of life nowadays. Perhaps until we improve our understanding of the system, it is better to be cautious and omit any benefits in the model.

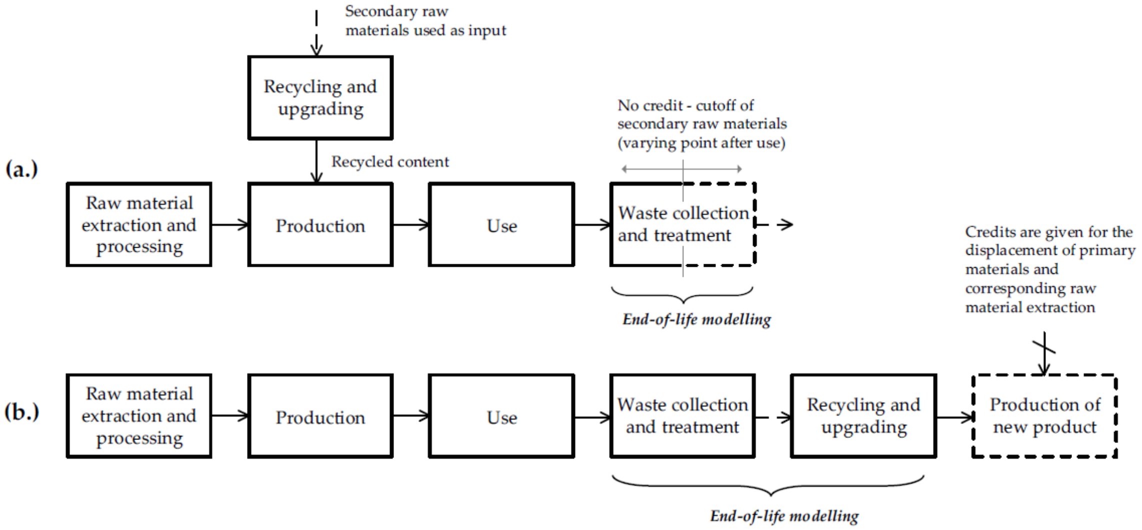
The choice of the EoL modelling approach has a large influence on the environmental impacts associated with the EoL of ZEVs (Ricardo et al., 2020). However, equally important are the considered EoL processes (i. e., different types of recycling, energy recovery, and landfilling) and data sources. Hence, here we review these three aspects related to EoL of ZEVs.

(Ricardo et al., 2020) identified four general options to deal with EoL modelling for vehicles:

- Cut-off approach (100:0), also called recycled content approach: this approach considers the full environmental impacts of the primary material supply chain, while secondary materials come free of burdens. Thus, the producer of waste does not get credits for generating recyclable materials (i. e., polluter pays) but it incentivises using recycled materials upstream by having these materials as burden-free input from other systems (i. e., secondary systems). A graphical representation of the allocation approach is provided in Figure III-9

- EoL approach (0:100), also called avoided burdens: in this approach, secondary materials partly substitute primary materials hence give environmental credits to the producer of the secondary materials. This method encourages recycling and production of secondary materials but does not encourage the usage of these materials in other supply chains. A graphical representation of the EoL approach is provided in Figure III-9
- 50:50 approach: it divides the burdens and benefits of recycling between the producer and user of secondary materials on a 50:50 basis. The two products systems need to be well identified for this method to work.
- Allocation at the point of substitution (APOS): this approach performs economic allocation between the primary and secondary usage of materials. This method is usually associated with the APOS system model used in ecoinvent v3. Hence, this approach is discussed in detail below in the review of EoL modelling in LCI databases.

In addition to these four approaches, there is a fifth one, i. e., the Carbon Footprint Formula (CFF) from PEF which is a formula that tries to allocate burdens and credits between supplier and user of recycled materials and for energy in case of energy recovery. CFF is considered a general approach for which EoL approach and Cut-off are the extreme cases if the right parameters are set. The formula considers the quality of secondary materials as well which is a very important factor. The allocation factors for allocating burdens and credits are the coefficients “A” and “B” for materials and energy (in case of energy recovery) respectively. There is a lot of debate regarding these allocation factors since there are perceived by some experts to be arbitrary numbers rather than based on concrete scientific/dynamic market basis or wider expert consensus.



Notes: Boxes show processes, full arrows show material flows, broken arrows show scrap material flows, the crossed arrows show substituted material flows. In alternative (a), the position of the cut-off point may vary, and as a result, the scope of the upstream “recycling and upgrading” varies correspondingly. Although not shown, upgrading generally requires some blending with primary materials (Nordelöf et al., 2019).

Figure III-9. Illustration of (a) the cut-off approach, and (b) the end-of-life recycling approach.

Some of the **guidelines and standards** do not provide provisions or recommendations on the EoL stage of batteries and/or vehicles, because it is considered outside the scope of the guidelines (see CATARC and Catena-X). Moreover, most of the guidelines reports lack guidance on the EoL routes that should be considered. The guidelines from CFB-EV, and to a less extend PEFCR-Batteries, are more explicit on what EoL processes should be considered. Notably, CFB-EV gives extensive guidance on the EoL of batteries. It states that if no company-specific EoL route is known (to be modelled with company-specific data), a standard recycling model shall be used with provided default values. This generic battery recycling process consists of battery dismantling/disassembly, treatment of the battery cells via the specific recycling process (hydrometallurgical or pyrometallurgical), and the refining of the obtained materials into new battery materials or products that are sold otherwise on the market. The disassembly process shall be modelled based on the specific composition of the battery pack and modules (housing, cooling system and electronics, excluding battery cells) assuming that batteries are completely disassembled to cell level with all materials going to dedicated recycling processes. Other guidelines reports refer to the use of secondary data from LCI databases, such as ecoinvent and MLC databases (see VDA-PC and RISE). Moreover, the eLCAr guidelines do not provide specified guidelines for each phase (e. g., EoL phase), although general guidance for collecting process data is available.

Regarding the multifunctionality of recycling processes, the different guidelines reports provide different provisions or recommendations. Some guidelines reports recommend the use of the CFF, like CFB-EV and PEFCR-Batteries, while others recommend to use the cut-off approach, like PFA. The guidelines of VDA-PC are rather ambiguous and seem to be a mixture of cut-off and substitution. The guidelines report PCR-Buses and coaches states that EoL modelling shall follow ISO 22628:2002 (ISO, 2002). Other guidelines reports do not give any specific recommendations on how to treat multifunctionality of the recycling process (see CATARC, Catena-X, RISE).

All except one of the **OEM reports** reviewed included vehicle EoL modelling and impact estimation. However, the different EoL sub-processes were covered in varying levels of detail. Only one study excluded EoL processing altogether, while all the studies accounted for the dismantling and shredding of vehicles. Ten studies accounted for incineration and landfilling of untreatable EoL fractions. Most of these studies may have quoted recycling as a potential EoL processing route, however, the process itself was mostly excluded from quantitative modelling and analysis within the vehicle's system boundary, due to pursuing cut-off approach. From the perspective of LCA guidance, though a dedicated harmonised passenger car LCA framework is currently under development (due to be published in 2024) (The International EPD System, 2023), an equivalent guidance such as the PCR-Buses and coaches suggests the inclusion of EoL processes (including recycling). The cut-off approach was the most applied

EoL allocation approach both in the US and in the global context. Of the 16 vehicle OEM studies, only two applied the avoided-burden or 0:100 approach.

The higher occurrence of the cut-off approach is also suggested by our survey, showing that 76% of the responses declare to use the cut-off approach and only 12% the CFF (Figure III-10). Companies report some issues related to the complexity in the application of CFF for every single flow especially for very complex inventories. On the other hand, cut-off is simple and environmentally precautious at the same time. Although CFF seems like the wise option thanks to its sophisticated way of employing both credits and burdens and distributing these between the involved system, improvements are certainly needed. The suggested improvements are simplified and/or implemented in LCA software to facilitate usage; the coefficients especially the “A” and “B” coefficients are defined as a result of wider consensus; the application should structurally be implemented in the commonly used LCI databases like ecoinvent and MLC databases.

Question: Which EoL allocation method is used in your LCA?

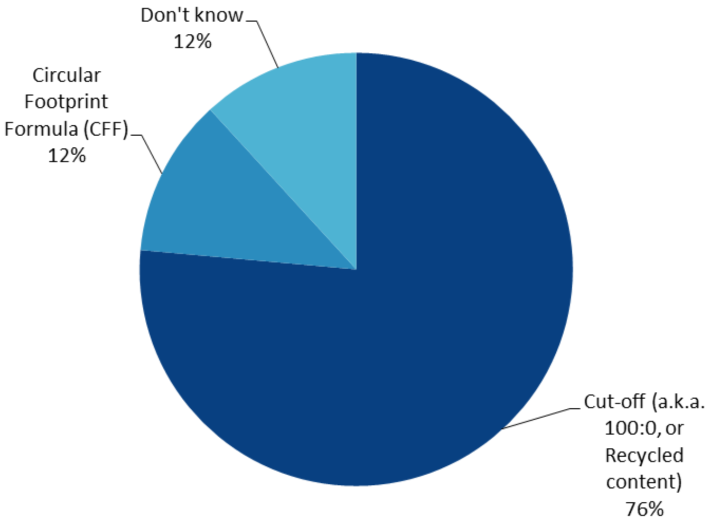


Figure III-10. Answers from Survey on EoL modelling

The EoL of the vehicle is not commonly the focus of the **scientific literature**, although this stage can significantly influence the life cycle impacts. The mass-market EVs have not yet reached EoL is sometimes mentioned as a limiting factor for including EoL (Dillman et al., 2020). Nevertheless, the EoL of EV batteries, particularly LIBs, has recently received a lot of attention in the LCA scientific literature (Xia & Li, 2022).

In their exhaustive LCA study of different vehicle impacts, (Ricardo et al., 2020) based their EoL calculation on the CFF since it suits the policymaker’s viewpoint which was the targeted audience from their study. In scientific literature on Li-ion batteries, the two mostly used methods are the cut-off and EoL approaches with the EoL approach (i. e., avoided burden) being the most used (Nordelöf et al., 2019). Some studies also use a hybrid approach between the two which has potential risk of double counting if not applied rigorously; see for example (Richa et al., 2017) which constitutes an example of potential double counting where the upstream raw material input includes recycled content for steel, aluminium and copper. Simultaneously, the recovered materials include aluminium and copper, which are credited for avoiding burden corresponding only to primary material production. Nordelöf et al., (2019) reports that a reason for EoL dominance in the LIB studies could be due to its suitability in evaluating emerging and developing recycling processes for cells, since it allows for a detailed study of these processes themselves. CFF on the other hand is almost not used at all in scientific literature.

The data sources for EoL modelling reported in scientific literature are usually secondary data from databases like GREET (Argonne National Laboratory, 2019) and ecoinvent. In fact, the lack of primary data on battery's EoL was emphasized by (Aichberger, 2020), recommending gathering more data from battery recyclers since available data is very limited and not detailed to components. Within this context, **engineering models** are an alternative source of EoL data. Notably, EverBatt is a publicly available battery recycling cost and environmental impacts model developed at the Argonne National Laboratory (Dai, Spangenberger, et al., 2019). The model allows users to evaluate the cost and environmental impacts of incorporating recycled materials into batteries as well as to benchmark new recycling technologies and processes against existing practices. EverBatt provides default data for pyrometallurgical and hydrometallurgical recycling routes as well as direct cathode recycling routes, considering seven battery cathode chemistries (LCO, LMO, LFP, NMC111, NMC622, NMC811, and NCA) and four geographic regions (California, U.S. national average, China, and Korea).

Reuse of retired batteries when they can no longer meet the traction demand is part of the discussion in scientific community. This option can represent a more appealing alternative to going directly to recycling since the battery can still contain 70%-80% of the initial capacity. However, this aspect is still in the early stage of investigation in literature. In fact, there are relatively few studies available on the potential environmental impacts of the batteries when they are given a second life (Kotak et al., 2021; Lai et al., 2022; Ricardo et al., 2020).

In general, two distinct terms are used when describing a second-life of traction batteries, namely remanufacturing and repurposing, where remanufacturing refers to repairing or refurbishing EV battery packs for redeployments in the original applications (i. e. automotive), while repurposing means that batteries are redirected for other stationary applications like grid-connected storage or peak shaving, backup power, auxiliary services and power tools (DeRousseau et al., 2017; Hua et al., 2021).

Despite the few literature sources, four high-level modelling approaches could be identified to account for second life of batteries (Ricardo et al., 2020):

- Make no accounting in the vehicle life cycle (same concept of cut-off approach): this approach assumes that any environmental benefits are accounted for in the second-life application, rather than in the vehicle lifecycle.
- Compare LCIA for second life of the battery to a specific reference case: an additional LCA is conducted for both the second life of the battery in the chosen energy storage case (e. g. for peak shaving or to enhance home / commercial PV use), and also a reference system (e. g. new Li-ion battery, no battery, alternative storage case).
- Apply a credit based on assumed equivalent displacement of a new energy storage battery (same concept of avoided burden approach): in this case, an assumption is made that the second-life battery is only used to displace the use of an equivalent new battery in an energy storage application (or a fraction of this due to differences in the storage use life-time).
- Economic allocation using the value of the used battery at its end-of-life: when the vehicle battery is replaced, the used battery may still have a certain economic value. Using this value, an economic allocation may be done between the burdens for the primary and secondary use. The issue here is that the data on the economic value of used car batteries are not readily available and may range between the scrap-value and relevant shares of a new battery, depending on the future demand and durability.

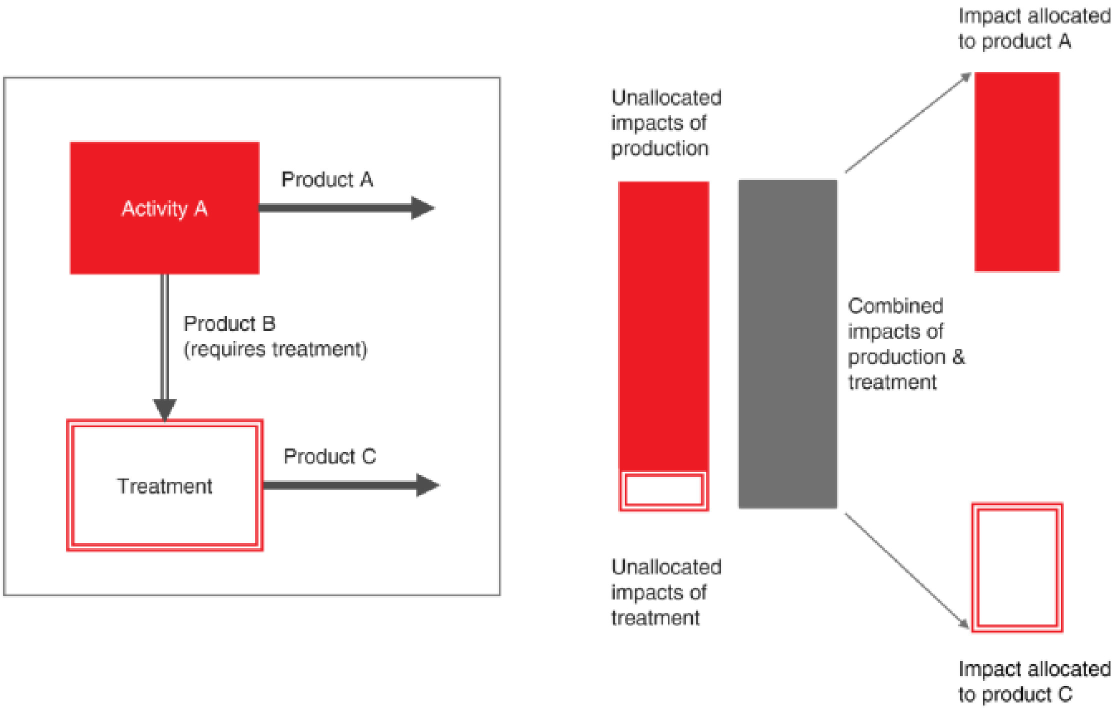
It is hard to decisively say or prefer one way or another to deal with second life of battery. This is a very new route in the end of life and there are yet few applications of it with few batteries reaching their end of life nowadays. Perhaps until we improve our understanding of the system, it is better to be cautions and omit any benefits in the model.

The EoL stage has received rather scarce attention in **prospective LCAs**. If included, EoL has been modelled primarily based on secondary data from a LCI database (i. e., ecoinvent database) (Koroma et al., 2022; Zimmermann et al., 2015). Other data sources include literature and the default data in the PEFCR-batteries (Zackrisson et al., 2019). Only one of the reviewed prospective LCA claims to include primary data for the EoL stage (Raugei & Winfield, 2019). The multifunctionality issue due to energy and materials recovery has been solved using mainly the substitution approach (Koroma et al., 2020; Raugei & Winfield, 2019; Zackrisson et al., 2019) and, to a lesser extent, the cut off approach (to be consistent with the background ecoinvent database) (Koroma et al., 2020). Some prospective LCAs have considered a second use of LIBs at their EoL in stationary applications (Koroma et al., 2022). Here, the substitution approach was adopted to solve the multifunctionality issue, assuming that the refurbished LIBs would displace an equivalent amount of new LIBs in stationary application. It is worth noting that the LIB recycling industry is still in its infancy and recycling technologies can be classified as emerging technologies. Hence, LCA studies focusing specifically on battery recycling technologies are inherently prospective/ex-ante LCAs (Ciez & Whitacre, 2019; Mohr et al., 2020; Rajaeifar et al., 2021).

Since **LCI databases** are widely used to model the waste treatment system, it is worth delving further into how EoL is addressed in the different databases.

In ecoinvent, waste and recyclable content are dealt with differently depending on the system model chosen by the user when conducting the study. The first two system models, namely "allocation cut-off by classification" and "allocation cut-off approach, EN15804", follow the cut-off approach described above. The only difference between the two system models is where the cut-off takes place (i. e., the cut-off point).

Unlike cut-off system models, the APOS system model uses expansion of product systems to avoid allocation within treatment systems. In the APOS system model, products are classified as material for treatment or material not for treatment. A material for treatment (MFT) is a product that requires treatment in general, i. e. waste, or to become valuable for a subsequent processing step, i. e., recyclable material. A material not for treatment (MNFT) is a valuable product that does not require any further processing prior to use. We focus here on MFT. The underlying philosophy of this approach is that allocation within end-of-life, i. e., within treatment activities, should be avoided. To do so, each activity that produces a product that requires further treatment before becoming valuable (e. g., waste) is considered together with all treatment activities required for that product in a single system. The exchanges of the producing activity and those of the treatment activities are then allocated to all the different valuable by-products in the system (from both producing and treatment activities). The point of substitution lies therefore in the first activity in the downstream supply chain after a treatment (or recycling) activity that produces a valuable product. A graphical representation of the APOS approach is provided in Figure III-11.



Notes: The impacts of the production and treatment process are combined and allocated to product A and the treatment by-product C. adapted from (Wernet et al., 2016).

Figure III-11. A visual representation of the expanded allocation system in the APOS system model

Lastly, “substitution, consequential, long-term” which uses a crediting system unlike the above-mentioned system models. Thus, the system uses substitution to deal with multifunctionality in general including the EoL. In other words, producing recyclable materials or useful products from waste treatment phase (e. g., form of energy) is rewarded by credit to the same system which created the waste in the first place. It is worth highlighting that in this system model a consequential LCA approach is ruling the application of substitution (i. e. what is substituted) which in this case is marginal market as consequential LCAs imply (EC-JRC, 2010).

On the other hand, Sphera in MLC (former GaBi) developed their way of EoL multifunctionality modelling based on four possible approaches: (i) cut-off, (ii) substitution (burden/value of scrap)[6], (iii) substitution approach (net scrap), (iv) embodied burden approach[7].

Within the MLC databases, the cradle-to-gate data for materials with recycled contents generally shows any externally supplied scrap or waste inputs (e. g., steel scrap, wastepaper, glass cullet), if known and of significance regarding the overall environmental performance. This

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[6] The “burden/value of scrap” is defined as the difference in LCI of the (theoretical) 100% primary and 100% secondary material production routes, considering the process yield of the recycling step (Sphera, 2022)

[7] *“the net burden that is handed off from one product system to the next would be modeled as the specific upstream burden of the scrap (i.e., burdens per kg of scrap) that enters the product system using the secondary material. As such, it does not matter where in the cascade of product systems a scrap-receiving product system is located”* (Koffler & Finkbeiner, 2018)

allows the user of the dataset to apply the methodological approach of choice to analyse in detail the benefit of recycling contents along the life cycle of a product. Example life cycle models are provided within the MLC databases for user guidance.

Within the models, they have already chosen the most suitable approach to solve the EoL multifunctionality for the specific commodity/material and industry, so they do not structurally provide four versions of the database like ecoinvent. Nevertheless, in many cases they selectively provide different dataset options that consider varying EoL allocation and substitution methods. The approach chosen can be seen by the user within the dataset documentation (Sphera, 2022).

GREET on the other hand has recently implemented the avoided burden approach in addition to the Recycled content (i. e., cut off) one that had previously been the only option (Kelly et al., 2022).

A summary of the key methodological and data choices identified across all sources (where they were documented) is provided in the following Table III-7

Table III-7. Summary of EoL modelling approaches and data collection/sources identified.

Use Aspect **Aspect?**	**Basis** **Options / Choices?**	**Source** **Examples**
Data sources	1. Primary 2. LCI Databases 3. Proxy	(3) (2) (1)
Recycling Modelling	1. Circular Footprint Formula 2. 50:50 3. Cut-off approach 4. EoL approach 5. Allocation at the point of substitution	(1) (3) (2) (3) (6)
Battery second life modelling	1. No accounting 2. Compare LCIA for second life of the battery to a specific reference case 3. substitution (credits) 4. Economic allocation	(3) (3) (3) (3)

Notes: *(1) = Guidelines/standards; (2) OEM reports, (3) = scientific literature, (4) = prospective LCA, (5) = fleet-level LCA (6)= databases.*

III.2.2 Data quality

Data quality: Summary of key findings

- Most of the guidelines and standards include data quality requirements. The specified requirements may include a mass balance check, Data Needs Matrix (DNM), Data Quality Rating (DQR), and Primary Data Share (PDS) at the process level; and completeness, consistency, and appropriateness of methodological choices at the product system level.
- Confidentiality may pose challenges to fulfil data quality requirements for foreground data.
- Qualitative and/or quantitative analyses of data quality is still not common practice in the scientific literature.
- LCI databases often follow their own Data Quality Indicator (DQI) system, which may not necessarily align with existing guidelines and standards.

Most of the **guidelines and standards** reports provide some kind of data quality requirements, except CATARC, PCR-Buses and coaches, and RISE. A distinction can be made between data quality at the unit process level and data accuracy at the product system level (Table III-8). At the unit process level, the mentioned requirements are mass balance check, Data Needs Matrix (DNM), Data Quality Rating (DQR), and Primary Data Share (PDS). The DNM indicates for which processes company-specific data or secondary data shall or may be used, depending on the level of influence the carbon footprint declarant has on the specific process (Recharge, 2023). DQR uses an ordinal scale of data quality related to technological, time, and geographical representativeness, completeness at the process level, and reliability (e. g., Catena-X, pages 31-36). PDS is an indicator that expresses the share of primary data to the total data that is used to define the unit process (e. g., Catena-X, page 28). Some guidelines reports, like eLCAr, refer to the data quality indicators covered in the general ILCD Handbook (EC-JRC, 2010), which includes also the DQR. At the product system level, requirements include a check on completeness, consistency, and appropriateness of methodological choices. These checks at the system level actually are part of the interpretation phase of an LCA (see section 3.4).

Table III-8. General overview of data quality and accuracy checks as covered by available guidelines and standards reports.

		CATARC	GBA	GRB-CFB-EV	PEFCR Batteries	Catena-X	eLCAr	PCR B&C	RISE-LCA	VDA	PFA
System level	Completeness						■				■
	Consistency						■				■
	Methodological choices						■				
Process level	Mass balance		■								
	Data Needs Matrix (DNM)			■	■	■					
	Data Quality Rating (DQR)			■	■	■				■	■
	Primary Data Share (PDS)					■					
	ILCD Handbook						■				

Transparent mass balance is always an issue to enclose and that has received scarce attention in standards and guidelines; only GBA refers to the mass balance issue. Firstly, it is extremely hard to achieve a strict mass balance through all the life cycle stages. This can be time-consuming and/or hardly feasible to achieve due to not knowing every single element circulating in the technosphere. Secondly, mass balance cannot be achieved when economic allocation is applied at any point of the value chain. In consequence, maybe a strict full mass balance should not be a requirement, instead certain materials/elements (e. g., those relevant to further steps of LCIA) should be proven balanced transparently. If even this is hard to achieve, it should be reported explicitly by the LCA practitioner.

OEM reports have been predominantly observed to establish an overall compliance with ISO14040/44, also in terms of data quality requirements. ISO14040/44 provides overall guidance on data quality requirements including time, geographic, technology scope and representativeness, completeness, accuracy, reproducibility, data sources, and uncertainty pertaining to the data used. While almost all OEM reports have consistently adopted minimum criteria for the data sources that is representative of the time, geographic and technological scope of study, the data sources for core-processes or foreground processes are often confidential or drawn from other supply chain members for vehicle components. This may lead to issues pertaining to transparency or reproducibility. As a result, OEM reports seldom provide information on the evidence of data completeness and consistency checks. This may be attributed to their strategies to avoid competitive risks or data confidentiality concerns.

Data quality in the reviewed **scientific literature** is usually mentioned as a problem or limitation concerning primary data availability or in the light of secondary data sources like databases. However, no specific qualitative and/or quantitative approach for assessing data quality was found in the reviewed studies. Overall, data quality requirements, such as those specified in existing standards and guidelines, are still not common practice in scientific literature.

Similarly, data quality remains largely overlooked in **prospective and fleet-level LCAs**, despite that this aspect could be a major concern. Notably, the quality of the data used within future-oriented LCAs decreases substantially while scaling the technology from its current laboratory-scale or low TRL to the future assessed development level (Thonemann et al., 2020). For example, the pedigree matrix approach adopted in some LCI databases (see further details below) gives the lowest quality level to data derived from laboratory-scale (Ciroth et al., 2016). Overall, the use of Data Quality Indicators (DQIs) within the context of prospective LCA has been proposed elsewhere as a good practice to partially reduce the large uncertainties associated with assessing the future (Thonemann et al., 2020).

Data quality in **LCI databases** like MLC databases and ecoinvent is evaluated following a DQI system. MLC, for example, evaluates the overall data quality rating for datasets based on the average of six DQIs, namely technology, time, geography, completeness, methodological consistency, and data origin. Each of this indicator has a qualitative rating ranging from very good to very poor, each associated with a number from one to five, respectively. ecoinvent uses DQI in the form of a pedigree matrix with values ranging from one to five, with one being the best and five the worst quality. The score is given based on a qualitative assessment of five aspects (reliability, completeness, temporal correlation, geographical correlation, further technological correlation) and is attributed to each individual input and output exchange (except the reference products) reported in a dataset. The value in each aspect is transformed into an uncertainty factor, which is added to the basic uncertainty (Weidema et al., 2013). Overall, LCI databases generally implement their own DQI system, which may not necessarily align with the data quality requirements covered by existing guidelines and standards.

III.2.3 Multifunctionality upstream in the value chain

Multifunctionality upstream the value chain: Summary of key findings

- Multifunctionality issues prior to end-of-life is generally not emphasized as in the EoL. This is valid for all sources categories.
- Attention should be given to this issue because it is very relevant to ZEV industry and it can result in misleading results eventually.
- The problem is often mentioned in the context of raw material processing stage and vehicle manufacturing stage. But it can also be seen in the WTT supply chain for the use stage of vehicles.
- In the raw material processing, multiple metals can be produced from the same ore.
- When they discuss multifunctionality, guidelines pay attention to co-production but not to other possible cases like multi-waste treatment processes. Hence, which processes are multifunctional should be clearly highlighted.
- The main debate relies in how to solve multifunctionality issues.
- Theoretically this should be dealt with following the ISO and ILCD hierarchy avoiding allocation. However, substitution or system expansion are very tricky to apply here. The substitutable systems that produce the primary metals (if they exist) can be multifunctional themselves, so the issue won’t be solved due to the cascading of multifunctionality.
- Allocation seems like a more favoured option here as recommended by some guidelines like the CFB-EV. Guidelines often rely on using the ratio of the economic values of co-products to decide between physical or economic allocation. This approach leads to economic allocation for example in the case of precious metals as co-products.
- Only few guidelines recommend details on how to apply economic allocation. E. g., 10-year average global market price or real market where the product is sold. The rest are not providing clear guidance.
- Guidelines provide no or very vague guidance on how to apply substitution (choosing the substituted technology)
- Component and vehicle manufacturing can also exhibit some multifunctionality issues if a machine for example produces multiple products or if facility services are shared among multiple products that are not part of the system under investigation.
- Since databases are the main way to model background systems in LCA studies, they must accurately guide the user on the implemented approach in their datasets.
- ecoinvent in their four system models provides the option of allocation (the base for allocation is decided case by case), and substitution. MLC (former GaBi) on the other hand is not really clear in their approach but they claim that they adhere to ISO hierarchy.

- It is very important for the LCA practitioner to be consistent and transparent in solving multifunctionality issues given the goal and type of the study (attributional or consequential).

In case a process delivers more than one function (e. g., co-production, if more than one product is produced, multi waste treatment, if more than one waste is treated, and recycling, if a waste is treated and a product is produced), the environmental burdens of the non-functional flows (i. e., emissions, natural resources extraction, consumed goods, and produced wastes) must be attributed to the different functional flows (J. Guinée et al., 2021; J. B. Guinée et al., 2004). As multifunctionality at the EoL has been already addressed, here we focus on upstream (other than EoL) multifunctionality issues.

Multifunctionality can exist at the raw material acquisition stage, e. g., due to the co-production of metals from ore processing. The use of the vehicle can result in multifunctionality mainly related to the WTT whether it is electricity or medium for electricity storage like hydrogen. Many of the involved processes in these cycles can exhibit multifunctionality, like in electricity production from CHP plants where electricity is a co-product of heat or vice versa. The manufacturing of vehicle or batteries can also exhibit multifunctionality at any part of the production chain when production lines are shared with other products irrelevant to the system being studied.

There are different methods to solve the multifunctionality issue and attribute the environmental burdens of the non-functional flows to the functional flows. The ISO standards (ISO 14044 (ISO, 2020) and ILCD Handbook (EC-JRC, 2010) prescribe a hierarchy of approaches:

1. Avoid multifunctional processes by breaking down a multifunctional process into its subprocesses, (ideally) based on the causality of the process.
2. System expansion (nearly always) interpreted as substitution (alias avoided burden)), in which a multifunctional process is transformed into a single functional process by subtracting the burdens of an alternative single functional (substitute) system from the multifunctional system.
3. Allocation by partitioning, in which a multifunctional process is transformed into a single functional process by applying allocation factors. Allocation factors attribute the nonfunctional flows to the functional flows. The factors can be based on different principles a) economic allocation by revenues (yield times price), b) physical allocation by mass or energy content or any other physical property c) other flexible partitioning factors (e. g., equal, cut off, or any other factor).

The **guidelines and standards** seem to be rather ambiguous concerning how to consider multifunctionality and how to solve it. Table III-9 shows the recommended approach to deal with multifunctionality of up chain processes. The numbers (1,2,3) in the table refer to the recommended hierarchy in preferred approach. The guidelines of CatenaX and eLCAr seem to follow the above-mentioned hierarchy, i. e., break-down, substitution and partitioning, while the guidelines of CATARC does not mention multifunctionality and allocation at all.

Some guidelines, like GBA introduces some deviations/exceptions to the default ISO hierarchy despite recommending it as the general governing approach. Same for GRB-CBF which claims to follow the PEF hierarchy as a general approach. They set some rules in case of co-production of precious and base metals, and some other rules in case of co-production of other materials. Other exceptions are provided by GRB-CBF for energy and auxiliary inputs in some production line processes, and battery casing/housing.

Partitioning is the recommended approach by GRB-CBF when a process or facility provides several goods and/or services. Three situations are defined in the reviewed draft of this guidelines, first in case of metals (base and precious) where economic allocation was recommended based on 10 years average market price. This distinction was removed in the final draft of the GRB-CBF and not mentioned anymore as a separate point. Instead, it was replaced by a general rule which is *"Economic allocation shall be applied when the price difference between the different outputs is higher than a factor of four. Sixty months global price (or revenues, or costs) averages shall be used as minimum to assess price differences"*.

Second situation is energy and auxiliary inputs of production lines (e. g. dry room) where the following hierarchy is preferred:

1) Mass allocation or other representative physical properties
2) Allocation using the installed capacity or another appropriate criterium

Lastly, the casing/housing of the EV battery. The casing/housing of the EV battery delivers the following functions: A) holding the cells or modules; B) integrating the battery cooling system and / or insulation. In case of battery casing/housing providing additional functions to the electric vehicle (e. g., torsional stiffness, crash resistance, etc) beyond these two main functions. The following hierarchy is provided:

1) physical partitioning: the components of the casing/housing that provide one or more functions to the electric vehicle (and not contributing to functions A) and B) above) shall be excluded from the system boundary.
2) When physical partitioning is not feasible: a virtual casing/housing shall be modelled according to the battery size and reference thickness of each material. Detailed equation to help model that is provided in the guidelines.

Interestingly, System expansion or substitution is totally absent from the default hierarchy provided by GRB-CBF despite being mentioned in the PEF hierarchy which GRB-CBF claims to follow.

The GBA guidelines on the other hand recommends the partitioning by economic allocation only for graphite and metals and by system expansion for products like sulfuric acid (see table 3-9). If system expansion is not possible due to a lack of a well characterised and representative alternative production route, allocation may be used. The last distinction made was for by-products salts and brine processing where mass allocation was recommended. In fact, it was observed that when allocation was recommended, the choice between physical and economic allocation was governed by the price ratio between co-products. So for instance, even if economic allocation is recommended for graphite and metals, it should not be applied if the price ratio is less than four. This is similar to the general rule quoted from GRB-CBF above.

GBA also gives additional recommendations for the partitioning based on economic information. For instance, economic value for metals is to be calculated based on 10-year average global market prices. Also, PCR buses and coaches gives more detailed guidelines for economic partitioning. Reference allocation values should be taken from real market where product is sold and shall be representative of time period and geographical scope for which the EPD is valid (3 years). Many other guidelines reports, like CatenaX, eLCAr, VDA, PFA and RISE, do not provide additional detailed partitioning guidelines. They just mention different possibilities like by pieces, mass, exergy, energy, prices, etc., without providing calculation procedures for the factors.

Regarding the reference system that is used as a substituting system in case of avoided burden, most of the guidelines and standards reports do not give detailed guidance or remain rather vague. The GBA rule book and the VDA-passenger car give no specific rules but require that a justification for the choice of the substituted product system should be made explicit (e. g., is technically appropriate and the by-product is actually used for the intended application). The guidelines of eLCAr only state that for substitution, the subtracted system (preferably) is based on a market mix.

Table III-9. Guidelines and standards reports: Prescribed treatment for multifunctionality in up chain pro-cesses

Guidelines and standards report	**Sub-category**	**Break down**	**Substi-tution**	**Partitioning**		
				Economic	**Physical**	**Other**
Batteries						
GBA	Graphite and metals	2	3	1*	4	4
	Sulfuric acid, ammonium sulfate, sodium sulfate, and chlorine by-products	2	1	4	3	4
	By-product salts from brine processing	2	3	4	1**	4
	Other materials	1	2	4	3	4

Guidelines and standards report	Sub-category	Break down	Substi-tution	Partitioning		
				Economic	Physical	Other
GRB-CFB-EV (final draft released June 2023)	Metals	2	-	1*	3	4
	Other materials	1	-	3***	2	4
PEFCR-Batteries		1	2		3 (mass)	
Vehicles						
CATARC		-	-	-	-	-
Catena-X		1	2	3	3	3
eLCAr		1	2	3	3	3
PCR-B&C		1		3	2	
RISE-LCA				1	1	1
VDA-PC		1		2	2	2
PFA				1	1	1

* Economic allocation is the first option unless price ratio of the co-products is less than or equal to four. In this case theoretically, the user should follow the ISO hierarchy.

** Mass allocation as a first choice unless the price ratio between co-products is greater than 4.

*** Economic allocation becomes the first preferred option when the price ratio is greater than four.

There are two main points in which guidelines might be different:

a) *Which processes are identified as multifunctional?* In all guidelines reports, only co-production is mentioned as a multifunctional process. Nothing is said about multi waste treatment processes, while the modelling of recycling is sometimes mentioned, but not explicitly identified as multifunctional process.

b) *Which approach is prescribed to solve the multifunctionality?* Guidelines differ in the recommended approach, and within one guideline report, sometimes different approaches are prescribed for different processes like in the EoL (see section 3.2.1.4)

Both points a) and b) might lead to large inconsistencies between studies and are therefore a methodological step that might lead to large inconsistencies within and between compared systems. The identification of multifunctionality and how it should be solved therefore seems to be an important issue that needs harmonization.

OEM reports do not explicitly mention the significance or consideration of multifunctional processes as a part of their literature that is publicly available. Nevertheless, these studies have been found to account for multi-output processes, pertaining to the fuel/electricity processes, feeding into a vehicle's system boundary. This is particularly crucial to product LCAs considering ICE vehicles where primary fuels (such as gasoline and diesel), identified to power a vehicle through its use phase, are produced alongside other co-products with energy applications. Product LCAs have been found to consider multi-output processes through the use of secondary data from third-party datasets/databases such as MLC databases and/or ecoinvent, for modelling fuel/electricity production. These databases have their own way of dealing with multifunctionality resulting from multi-output processes (see the introduction to section 3.2.1). It is usually hard to grasp how allocation between outputs is done for example (e. g. in ecoinvent), however some flexibility is sometimes offered to the user when choosing the general approach (e. g. substitution vs allocation in ecoinvent through the different system models)

Multifunctionality in **scientific literature** is mainly discussed within the context of the EoL stage (see Section 0) and not the life cycle stages prior to that. Within the review papers included in this report, no significant mention of multifunctionality issues in raw material acquisition, use, or manufacturing except for some rough recommendations to LCA practitioner to report and discuss their approach to solve multifunctionality in case of co-production. (Tolomeo et al., 2020). It is worth mentioning that in hydrogen literature, it is recommended to deal with co-production using economic allocation in electrolysis and system expansion in case of steam methane reforming (Ricardo et al., 2020)

Given the importance of **LCI databases** for data collection regarding raw material acquisition and WTT phases, a closer look to how the multifunctionality issue is solved in the three most commonly used databases can be useful.

In ecoinvent and before any kind of allocation and substitution is applied, subdivision can come to place. In those activities, more than one reference product is defined, and inputs and emissions are split among products based on various physical characteristics. This is applied for all four system models of ecoinvent. This can be seen compatible with ISO recommendations in that regard. When this is not possible, the approach used depend on the system model chosen by the user of the database. Three system models use allocation where the allocation factor and method (i. e. economic, mass, energy, etc.) vary per dataset but they are reported for the dataset user to see. The last system model (i. e. Substitution, consequential, long-term) uses substitution or “avoided burden” as the name implies and it follows the exchanges with marginal markets given the consequential modelling approach with pre-defined substitution ratios. (ecoinvent, n.d.; Wernet et al., 2016)

While Sphera's MLC databases do not offer distinct system models like ecoinvent, it adheres to the hierarchy outlined by the ISO (ISO, 2020). The hierarchy begins with subdivision as the primary approach. Whenever possible, MLC assumes the utilization of co-products within the same system through looping. Secondly, MLC avoids allocation by substitution whenever feasible. However, caution is exercised to prevent misinterpretation or an increase in the functional unit, as the goal is to provide individual datasets with their respective functional units. In the MLC databases, system expansion is frequently employed for energy by-products resulting from combined or integrated production, where direct use within the same system is not feasible. Lastly, allocation is used, firstly based on physical relations then economically which also goes in line with the ISO recommendations.

Going through the documents available on GREET, it was concluded the tendency to allocation in co-production situations which are primarily based on mass, energy content, or market value. (Wang et al., 2004).

III.2.4 Electricity modelling

Electricity modelling: Summary of key findings

- Guidelines and standards vary in their recommendations about the electricity mix that should be considered for the vehicle and/or battery use stage, ranging from EU grid mix based on background data from LCI databases to country-specific or national residual electricity mixes.
- Most guidelines and standards provide more detailed guidance on electricity modelling in the vehicle and/or battery production stage.
- OEM reports often use regionally representative secondary datasets to model electricity mixes, accounting for geographic grid mix variations.
- There is some debate over the use of certificates/guarantees of origin for renewable electricity, due to additionality concerns, and consistency with new EU rules for renewable hydrogen.
- Consideration of evolving grid decarbonization and future grid mixes is essential for accurate estimation of use-phase emissions, but it is not commonly addressed in OEM reports.
- The scientific literature lacks comprehensive discussions on the electricity mix in the use and/or production phases of batteries and/or vehicles.
- Most articles commonly use national or regional average electricity mixes based on secondary data from LCI databases.
- Future electricity scenarios are integrated into prospective LCAs, sourced from national goals, decarbonization roadmaps, or Integrated Assessment Models (IAMs).
- Modelling the electricity mix in fleet-level LCAs can range from static average grid mixes to dynamic evolving scenarios or marginal grid mixes.
- LCI databases like ecoinvent, MLC (former GaBi) databases, and GREET provide electricity mix data, but differ regarding geographic coverage, reference years and future projections.

This section specifically focuses on the assumptions relating to the use of electricity across all life cycle stages, but with a particular focus on the use stage (due to its obvious significance for electrically powered vehicles).

Only a few **guidelines and standards** give detailed guidance on the electricity mix that should be considered for the vehicle and/or battery use stage but instead focus more on the electricity used in the production stage. The PEFCR Batteries and VDA for example, state that the country/Europe/EU_specific_energy_mix should be used based on EF- compliant datasets. PEFCR provides a hierarchy on what type of electric energy source to be modelled:

1) on-site generated electricity
2) supplier-specific electricity product if electricity is purchased from a supplier
3) the supplier-specific total energy mix
4) country-specific residual consumption grid mix. Country-specific means the country in which the life cycle stage/activity occurs
5) If no country- or grid- specific residual consumption grid mix is available, use the country- or 485 grid- specific average consumption mix

Conversely, the PFA technical guidance prescribes that electricity consumption should be based on the country-specific electricity mix from background LCI datasets. The PCR Buses and coaches states that electricity mix for the region/country where the vehicle is used shall be accounted for according to the following priority: 1) national residual electricity mix[8] or residual mix on the market and 2) national electricity production mix or electricity mix on the market. It should be noted that these assumptions are quite limiting, and do not make any attempt to account for (potentially very significant) change in the electricity mix during the anticipated lifetime of the vehicle (e. g. based on current policy in place).

More detailed guidance on renewable electricity modelling has been included as a criterion for consideration and inclusion by operators that account for renewable energy as a part of energy consumption for battery and/or vehicle production. Guidance such as the Catena-X, PEFCR-Batteries, and CFB-EV suggest emission factors appropriate for renewable energy consumed based on their source and provide a nuanced set of criteria and rules for the identification and quantification of these emission factors. Renewable energy may be sourced through market-mechanisms such as Renewable Energy Certificates (REC) in the US or Guarantee of Origin (GO) in the EU, whereby an economic operator can purchase these certificates from specific issuing bodies for a price and this guarantees that particular amount of electricity is produced from a renewable energy source. Consumption of this REC or GO by the economic operator assures that the specific amount/unit of renewable energy has been consumed by the operator, which is then cancelled by the REC or GO issuing body's registry, in the country of consumption. The effectiveness of this arrangement is very much predicated on the traceability and transparency of the registry and all the stakeholders (suppliers to end-users) in that renewable

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[8] The residual electricity mix is defined by the PCR as the mix when all contract-specific electricity that has been sold to other customers has been subtracted from the total production mix of the electricity supplier

energy supply chain. RECs, in the US, have been categorized as bundled and unbundled RECs where while unbundled RECs operate similar to GO in the EU, purchase of bundled RECs lead to acquiring Power Purchase Agreement (PPA) as a means of demonstrating the purchase of electricity from prospective renewable energy generation plants. This allows economic operators to claim "additionality" as a means of showcasing direct investment into new renewable energy generation plants and its added decarbonization contribution to the overall grid. This is a practice that is currently reaching pace in the EU. As a starting point, recently published LCA guidance are recommending that the economic operators, accounting for renewable energy consumption, consider appropriate emission factors in the order of preference:

1. Own-site generated renewable energy,
2. Renewable energy accounting through unbundled RECs,
3. Location-specific mix, and then,
4. Residual mix.

In addition, a similarly stricter approach with regards to additionality has also been put in place for renewable hydrogen in the EU, as part of new rules for all RFNBOs (Renewable Fuels of Non-Biological Origin)[9].

The review of **OEM reports** demonstrates the use of regionally representative secondary dataset from third-party LCI databases to model electricity chains as a part of the vehicle boundary. This overcomes the complexity of having to accurately model the variations in the electricity production technologies and infrastructure employed across different geographies, which could lead to inaccuracies and modelling complexity. Among the 16 studies, 8 account for the geographic grid mix variations, which nevertheless, depends on the location of the study and its target audience. Besides accounting for the geographic variations, it is also important to account for evolving or steadily decarbonising grid over the lifetime of the vehicle, to ensure a more accurate estimation of use-phase emissions, particularly with the consideration of BEVs. OEM reports are predominantly unclear about whether site-generated or remotely generated renewable energy is accounted for in their studies. Most OEMs claim to not account for them, from the survey responses. Out of the 16 OEM reports, only five account for future grid mixes as a part of either core analysis or sensitivity studies. Recently, there have been further developments in the recommended methodologies for electricity treatment, where GHG reporting guidance by standards, industry alliance and associations are recommending a more nuanced approach to addressing renewable energy utilisation. These guidance provide specific criteria and rules for the consideration of electricity use emission factors, by identifying renewable energy used in vehicle production as either sourced through "market-mechanisms" such as

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[9] https://ec.europa.eu/commission/presscorner/detail/en/IP_23_594

through the purchase of RECs or as "location-based" (demonstrated by most product LCAs) . (Global Battery Alliance (GBA), 2022; IEC, 2022; Recharge, 2023)

The electricity mix used in the use and/or production phases of batteries and/or vehicles has received scarce attention in the **scientific literature**. This is reflected in the lack of a comprehensive discussion of this aspect in published review articles (Dolganova et al., 2020; Lai et al., 2022; Verma et al., 2021; Xia & Li, 2022). In general, the most popular choices are the national or regional (i. e., Europe) average electricity mixes based on secondary data from a LCI database (Lai et al., 2022; Verma et al., 2021). J. F. Peters, (2023) argue that, given the rapid decarbonization of electricity generation, the most recent average electricity mix should be considered, preferably less than two years old. However, it should be noted that this would still be expected to significantly underestimate the likely lifetime average situation based on current policy commitments, and the priority electricity decarbonisation has been placed in national and regional decarbonisation plans. Due to its high influence in the LCA results, the assumption of the electricity mix is typically addressed through sensitivity analysis.

Prospective LCAs generally integrate future electricity scenarios to model the use phase of the vehicle. Studies have been performed considering, e. g., the German electricity mix by 2030 (Zimmermann et al., 2015), the European average mix by 2030 (Bauer et al., 2015), 2040 (Cox et al., 2018)) and 2050 (Koroma et al., 2020), and the global average mix by 2040 (Cox et al., 2018). Future electricity scenarios are typically sourced from national long-term political goals (Zimmermann et al., 2015), regional decarbonisation roadmaps (Koroma et al., 2020), Integrated Assessment Models (IAMs) (Cox et al., 2018, 2020). They represent possible developments of the energy system that are aligned with different climate targets (e. g., limiting global warming to 1.5 or 2 °C above the pre-industrial level). More recently, studies are incorporating future electricity scenarios also in the background system (Cox et al., 2018, 2020; Sacchi et al., 2021; van den Oever et al., 2023). This is achieved by systematically modifying the underlying LCI database (i. e., the ecoinvent database) to adjust the region-specific electricity mixes (as well as other parameters such as power plants efficiency) based on the output results from an IAM (e. g., Cox et al., 2018; van den Oever et al., 2023; Xu et al., 2022). The creation of futurized LCI databases is enabled by the Python-based open-source premise library (Sacchi, Terlouw, et al., 2022). In Ricardo's recent work for the European Commission (Ricardo et al., 2020) and European Parliament (Ricardo, 2023), future average electricity mixes have been based on outputs from recent modelling exercises for the European Commission (e. g. for the Fit-For-55 policy package) and the IEA (e. g. from the World Energy Outlook). In this case these projections were used in assessing future impacts for all lifecycle stages (e. g. also projected changes for EoL).

The approach used to model the electricity mix for the use phase of EVs in **fleet-level LCAs** varies considerably in terms of sophistication, ranging from a single static average grid mix (González Palencia et al., 2012; He & Chen, 2013), to a range of static grid mix scenarios

(Chatzikomis et al., 2014; Garcia et al., 2015; Kromer et al., 2010; Ou et al., 2010). to dynamically evolving average grid mix scenarios (Baptista et al., 2012; Hao et al., 2011), sometimes also with internal consequential feedback loops that account for interactions with the co-evolving vehicle fleet (e. g., through vehicle-to-grid energy storage) (Raugei et al., 2021), to marginal grid mixes that assume that the increased demand for electricity due to EVs will have to be met by ramping up readily dispatchable technologies only (Reichmuth et al., 2013).

The electricity mix is typically retrieved from **LCI databases** like ecoinvent, MLC databases, and GREET (see also Table III-10). The version 3.9 of the ecoinvent database covers electricity supply over 250 geographies, including power generation plants, transformation, transmission, distribution and use, as well as low, medium, and high voltage levels (Wernet et al., 2016). Electricity mixes are provided for both attributional and consequential system models. In the attributional system model, average electricity mixes for the reference year 2019 and 2020 (for US, Canada and Switzerland) are available for 142 countries, with the largest ones (e. g., China, India, and U.S.) split into sub-regions. Electricity markets in ecoinvent consist of domestic production plus imports from other countries (Treyer & Bauer, 2016). In the consequential system model, marginal electricity mixes are provided for 40 countries based on projections of future electricity mixes up to 2030 ((Treyer & Bauer, 2016)). The MLC (former GaBi) database version 2022 provides average electricity production and consumption mixes for the reference year 2018 and contains over 170 geographical locations (including sub-national) (Sphera, 2022). Electricity datasets are highly parameterized, which enable the adaption to country- and technology-specific conditions (Sphera, 2022). Moreover, both ecoinvent and MLC provide residual electricity mixes for the European region in their most recent versions. GREET includes inventories for electricity generation (by source types, technologies, and regions), transmission, distribution and use (Argonne National Laboratory, 2019). It provides electricity mixes for the U.S. national average and >30 countries (reference years between 2017 and 2021). Hence, the geographical coverage of electricity mixes is less comprehensive than in other generic LCI databases.

Table III-10. Overview of electricity grid mix datasets in main LCI databases

	GREET	**ecoinvent 3.9**	**MLC 2022**
Total countries included (for average mixes)	~33	137	84
Sub-national included	Only US	Yes for BR, US, CN, CA, IN	Yes for US, CN, IN, AU, NZ,
Reference year attributional mixes	Differs per country (2017 – 2021)	2019 and 2020 (for BR, CN, US, CA and CH)	2018 and 2019 (US in Extension Module XVII)

	GREET	ecoinvent 3.9	MLC 2022
Future mixes available	No	Yes, only for 2030 and 40 countries	Yes. for 2025, 2030, 2040 and 2050 including different scenarios for 6 geographical regions (EU-27, CN, BR, US, IN and JP)

III.3 Phase III. Life Cycle Impact Assessment

The Life Cycle Impact Assessment (LCIA) phase comprises three mandatory steps: first, the selection of impact categories, category indicators and characterisation models to be used; second, classification, i. e. linking environmental flows to the impact categories they affect; and third, characterisation by multiplying the characterisation factors by the values of the environmental flows from the inventory. In addition, there are two subsequent optional steps which are normalization and weighting of impacts.

Since practically all these steps are already implemented in LCIA methods nowadays which are often utilised as built-in in LCA software, it is beneficial to discuss this first and explore the different existing options. This is done in the first subheading then it is followed by extended discussion on:

- Impact categories: mainly review of current choices on which impact categories to evaluate and report
- Normalization and weighting: a short discussion on how the materials reviewed dealt with these optional steps in ZEV field.

The phases II and III in LCA, respectively Life cycle inventory and life cycle impact assessment, demarcate the system boundary between the economy and the environment. The inventory analysis compiles and quantifies the inputs and outputs of processes within the economy (like goods and wastes) and between the economy and the environment (like extractions of resources and emissions of substances to air, water and soil). The flows of goods and wastes between processes within the economy are called non-elementary (or complex) flows. These non-elementary flows need further human transformation efforts (by processes in the economy) to be transformed into elementary flows. The elementary flows are the extractions from and emissions to the environment (flows from/to the environment that undergoes no further human intervention).

So, the economy-environment system boundary is defined as the boundary across which non elementary flows of goods and wastes (inputs and outputs within the economy) are converted into elementary flows. In accordance with the previous definition, all inflows/outflows connected to the unit processes in the economy can be traced back until they are connected to elementary flows. The elementary flows (emissions to and extractions from the environment) are the starting point for the environmental impact assessment[10]

Now, Life Cycle Impact Assessment (LCIA) is the third phase in LCA in which the results of the inventory (i. e., the inventory table with emissions and extractions) are processed and aggregated into a more limited set of impact scores for one or a set of environmental impact categories. To do this, characterization factors (e. g., Global Warming Potentials (GWPs) in the case of climate change) are used, which are derived using characterization models (e. g., the International Panel of Climate Change (IPCC) model). The characterization factors express the relative contribution of an emission or extraction to the impact category. The calculation of the impact scores is called the characterization step.

There are two additional optional steps in LCIA. The first optional additional step is normalization. This step serves to indicate the relative contribution (share) of the characterized results to a particular reference situation (e. g., the total impact score in the world in the year 2020). The second optional additional step involves weighting: here the impact scores of different impact categories are aggregated into one overall environmental impact score. This involves a purely subjective weighting between impact categories based on societal preferences. The optional steps of normalization and weighting are not recommended for ISO compliant public reporting. However, currently the PEF Guide (EC-JRC, 2021) describes normalization as a recommended step and weighting as an optional step.

There are several different LCIA methods. These methods comprise a particular selection of impact categories and corresponding characterization models and factors. The LCIA methods might be different in the selected impact categories and/or the proposed characterization models. Some of the LCIA methods come with suggested normalization factors (e. g., CML-IA2002) and weighting factors.

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[10] Sometimes primary energy demand and cumulative energy demand are used as proxies to assess environmental problems. However, as will be discussed later, the use of these proxies as impact category is not in compliance with the system boundary between technosphere and environment and thus the demarcation between LCI and LCIA.

III.3.1 LCIA methods

LCIA methods: Summary of key findings

- The focus on the impact assessment in all the sources (guidelines and standards, OEM reports, scientific literature, prospective LCA and fleet-level LCA) seems to be the assessment of climate change using the GWPs as developed by IPCC. However, to avoid problem shifting between environmental problems, it is desirable to do an **encompassing Life Cycle Impact Assessment**, which takes into account more impact categories.
- The review of the guidelines and standards reports tend to suggest that the LCIA set of impact categories and characterization factors by **EF (3.0 and 3.1)** is going to be the recommended standard for Life Cycle Impact Assessment (although importantly this is missing a measure of total cumulative primary energy demand). However, the review of the OEM reports, scientific literature and prospective LCA studies shows that, until now, these studies do not seem to follow the LCIA method of EF as (most often) recommended in the guidelines and standards. The fleet-level LCA in general tends to be focused mainly on impacts on climate change. So, there is a need to harmonize the impact assessment. On the one hand, the guidelines and standards reports should be harmonized. And on the other hand, also the LCA studies should be harmonized with the LCIA method that is recommended in the guidelines and standards.
- Using a mix of impact categories from different LCIA methods (for example from CMLIA 2002 and ReCiPe) was observed as a common practice. In some cases, this was justified by the authors due to either significant impact categories not being available in one other method, or impact categories from different methods judged to be more appropriate (e. g. for the specific application to vehicle LCA) than others.

Table III-11 below summarizes the LCIA methods, impact categories and normalization and weighting methods used in the references of the guidelines and standards reviewed.

Table III-11. LCIA methods, impacts categories and normalization and weighting methods prescribed in the guidelines and standards reports.

Guidelines and standards report	LCIA methods	Impact Categories (characterisation factors)	Normalization and weighting
Batteries			
GBA	IPCC (EF 3.0)	Climate change (GWP 100 based on the IPCC's AR5)	N.A.
GRB-CFB-EV	IPCC	Climate change	N.A.

Guidelines and standards report	LCIA methods	Impact Categories (characterisation factors)	Normalization and weighting
	(EF 3.1)	(GWP 100 based on IPCC's AR6)	
PEFCR-Batteries	EF 3.0	PEF impact categories Climate change, Ozone layer depletion, Human toxicity cancer, Human toxicity non-cancer, (fresh water) Ecotoxicity, Particulate matter, Ionizing radiation, Photochemical ozone formation, Acidification, Eutrophication terrestrial, Eutrophication marine, Eutrophication freshwater, Land use, Water use, Resource depletion fossil, Resource depletion elements.	Based on EF 3.0, reference situation: Global, 2010
Vehicles			
CATARC	IPCC	Climate change (GWP 100 based on the IPCC's AR5)	N.A.
Catena-X	IPCC	Climate change (GWP 100 based on the IPCC's AR6)	N.A.
eLCAr	ILCD based	Midpoints: Climate change, Ozone layer depletion, Human toxicity, Respiratory inorganics, Ionizing radiation (Ground-level), Photochemical ozone formation, Acidification, Eutrophication Ecotoxicity, Land use, Resource Depletion. Endpoints: Damage to human health, Damage to ecosystem, Depletion of natural resources	Discussed, but not specified
PCR-Buses&Coaches	EF 3.1	Climate change, Acidification, Eutrophication, Ozone layer depletion, Photochemical ozone formation, resource depletion (fossil), resource depletion (elements), Water Deprivation	Not specified

Guidelines and standards report	LCIA methods	Impact Categories (characterisation factors)	Normalization and weighting
RISE-LCA	Not specified	Climate change, Damage to human health (or human toxicity), Resource depletion, Acidification, Eutrophication, Ecotoxicity, Photochemical Ozone formation, Water consumption	Not specified
VDA-PC	CML-IA2002	Primary Energy demand, Climate change, Acidification, Eutrophication, Photochemical ozone creation. The evaluation of additional categories is encouraged.	Normalization, grouping and weighting shall not be conducted due to their subjective nature.
PFA	Mix of CML-IA 2002-2016, ReCiPe 2016 and an additional Impact Category, PED.	CML 2002: Acidification, Eutrophication, Climate change, Photochemical ozone formation, Abiotic Resource Depletion ReCiPe 2016: Metal depletion Primary Energy Demand (PED) (flow indicator) EF 3.1 will be evaluated for possible future recommendation.	Not specified

Four different LCIA methods are explicitly recommended in the **guidelines and standards** that are reviewed (see Table III-11): EF (3.0, 3.1), IPCC, CMLIA2002 and Recipe. The results of the **consultation activities** of survey amongst sectors in the industry seem to reflect these recommendations. According to the result of this survey 69% of the respondents used the CML-IA2002 method, 38% the EF 3.0 (PEFCR), 25% ReCiPe and 19% IPCC. The LCIA set of impact categories by EF (3.0 and 3.1) seems to become the standard method. It is recommended, or under study (PFA), in half of the documents. This probably is due to the initiative of the European Union to harmonize Life Cycle Impact Assessment methods for LCA (ILCD[11]) in combination with the European origin of the guidelines and standards reports. A more global sample would probably change this observation. The Global Warming Potentials (GWPs), as developed by IPCC, are the standard characterization factors to access climate change. It should

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[11] https://eplca.jrc.ec.europa.eu/ilcd.html

be noted that the PFA document is the only one to recommend a mix of two methods: CML2002 and ReCiPe 2016.

The EF (initially based on ILCD) recommended set of impact categories and characterization models are a result of a consensus initiative by EU-JRC to harmonize LCIA for Environmental Footprints of products and companies in Europe. Hence, the EF method seems like the right starting point for building a consensus over this aspect given the accreditation of it. (However, it may be optimal to supplement this with additional indicators currently missing, particularly for cumulative energy demand – discussed further in the next section III.3.2). Impact-assessment-specific references can be found on the European Platform on LCA | EPLCA[12].

In the case of **OEM reports**, a variety of LCIA methodologies were observed to have been adopted, while some specific studies have adopted two different methodologies to address geographical representativeness. For example, these studies have adopted CML-IA2002 method for interpretation of results for the European market and LIME 2 (based on ReCiPe, including weighting) method for the audience from Japan. Out of the 16 studies, only two adopted ReCiPe method and three studies have not clearly specified the choice of the LCIA method. Two studies, which are vehicle EPDs, were observed to have adopted a mix of impact categories and characterization factors from CMLIA2002 and ReCiPe, as prescribed by the guidance in the PCR for buses and coaches[13]

When it comes to the assessment of the impacts on Climate change the review of **scientific literature** shows that all studies use the characterization factors as developed by IPCC. However, for the assessment of additional impact categories, different LCIA methods are used. Mostly used are the LCIA methods ReCiPe, CML-IA2002, and Ecoindicator 99 (a predecessor of ReCiPe) (Arshad et al., 2022; Dolganova et al., 2020). Other methods are IMPACT 2002+ and GREET. However, these are rarely used. It is striking that some studies do not clearly indicate the impact assessment method used as reported by (Tolomeo et al., 2020). See for example (Nordelöf et al., 2014). Furthermore, most scientific articles and other reports use midpoint indicators (Ricardo et al., 2020).

Some studies do not use the full selection of impact categories and characterization models as suggested by an LCIA method. Rather a mix is used of different Impact categories and characterization models from different LCIA methods. This was the case, for example, by (Ricardo et al., 2020) and explained in their methodology description (i. e. also accounting for European policy and regulatory considerations). Usually, this deviation is justified within the studies.

Since resource use is a major concern in ZEVs, the most used methods that include the impact of resources use are CML-IA2002 (ADP_elements; with its different versions regarding the

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[12] https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml

[13] The PCR has been updated since the reviewed EPDs are published and now it is recommended to use EF3.1.

CFs), ReCiPe (mineral depletion), and Ecoindicator99 (mineral resources). However, it should be noted that the impact category on resource use based on depletion of resources is debated. There is a tendency to develop new LCIA models for resource use which are based on the dissipation of resources instead of depletion. Unfortunately, no fully operational assessment model for dissipation of resources is available, yet.

The most common LCIA methods in **prospective LCA studies** are the IPCC 2013 and ReCiPe methods. Other methods include EF 3.0 (van den Oever et al., 2023), ILCD 2011 (Zhang et al., 2022), and CML 2002 (Zimmermann et al., 2015). The official IPCC global warming potentials are typically updated in prospective LCAs in order to properly account for biogenic carbon flows (e. g., van den Oever et al., (2023); Cox et al., (2020); Sacchi et al., (2021); Sacchi, Terlouw, et al., (2022)). Notably, a GWP of +1 is assigned to biogenic CO_2 emissions and a GWP of -1 to CO_2 uptake from air[14].This is needed in order to guarantee that negative emission technologies (NETs) such as bioenergy with carbon capture and storage (BECCS) and direct air capture (DAC), which acquires higher relevance under future energy scenario, results in net negative CO_2 emissions (Mendoza Beltran et al., 2018). In general, the LCIA methods and characterization factors are not modelled prospectively in existing studies.

III.3.2 Impact categories

Impact categories: Summary of key findings

- Midpoint impact categories are the default choice in almost all the reviewed work.
- Overall, **Climate change** is by far the most studied impact category using the characterization factors developed by IPCC (i. e., GWPs)
- Other commonly reported impact categories across scientific articles and OEM reports are acidification, eutrophication, and photochemical ozone formation.
- Despite its relevance at least for traction batteries, the mineral resources depletion indicators are not given enough attention.
- Next, in the context of ZEVs, **alternative or additional impact categories/indicators** might be considered relevant, like dissipation of abiotic resources (instead of depletion), circularity of resources, criticality of abiotic resources.
- An interesting alternative for the impact category 'abiotic resource depletion of elements' might be **resource dissipation**. A dissipation model also might address better **circularity** issues, since it identifies at which process in the process chain resources are not recycled. However, methods to assess dissipation of resources are in development and not operational, yet.

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[14] Please note that the beneficial or detrimental effect of respectively an extraction or emission of CO2 also could be modelled differently. That is, GWP could be defined +1 for CO2, both fossil and biogenic CO2. However, the sign of the elementary flow in the Inventory is opposite, that is positive (+) for an emission of CO2 and negative (-) for an extraction of CO2.

- Another important indicator as a proxy for environmental assessment of ZEVs is **Cumulative Energy Demand**[15] **(considered by VDA and PFA guidelines)**. This indicator is highly relevant for vehicle LCA, as it provides a measure of the overall energy efficiency across the entire lifecycle. This is one of the areas of high/critical technical importance to meeting climate change mitigation objectives, and a central pillar of the EU's overall climate and energy framework. However, it should be noted that CED is not in compliance with the system boundary between technosphere and environment in the LCIA, and thus not a classical impact category in the LCA framework.
- An additional interesting indicator might be **criticality**, i. e., a hamper in the supply of resources due to geopolitical factors. However, it should be noted that in LCIA the effect of the product system on the environment is assessed, while in criticality assessment the effect of the (geopolitical) 'environment' on the product system is assessed.
- Related to LCI and LCIA software and databases, the **coupling between results of the LCI to the LCIA** not always is complete or sound and thus might need harmonization.

This section provides further discussion on the relevant impact categories. All the **guidelines and standards** reviewed are based on mid-point impact categories except for eLCAr which mentions also damage to human health, damage to ecosystem and depletion of natural resources, as end-point impact categories. For the impact category climate change the characterization factors GWP 100 are considered in all the documents. For half of them climate change is the only impact category considered. For categories other than climate change, the list considered is associated to the method recommended. Primary energy demand and cumulative energy demand are considered as an additional indicator by VDA and PFA. However, it should be noted that PED and CED are not in compliance with the system boundary between technosphere and environment. This will be discussed later in this section.

For the evaluation of the impact categories adopted as a part of the industry practice, **OEM reports** were consulted. All OEM reports adopted mid-point impact categories. For the assessment of Climate change the characterization factors developed by IPCC (i. e., GWPs) are by far the most used in all vehicle LCAs. A majority of LCA studies were observed to have adopted few other impact categories as presented in Figure III-12, while only four other studies also included the consideration of ADP- metals and minerals, a crucial mid-point impact category for BEVs (although with its own limitations). One notable omission from the figure below are indicators relating to particulate emissions – which have a very high policy and regulatory importance for road transport in particular. Similarly, measures of cumulative primary energy

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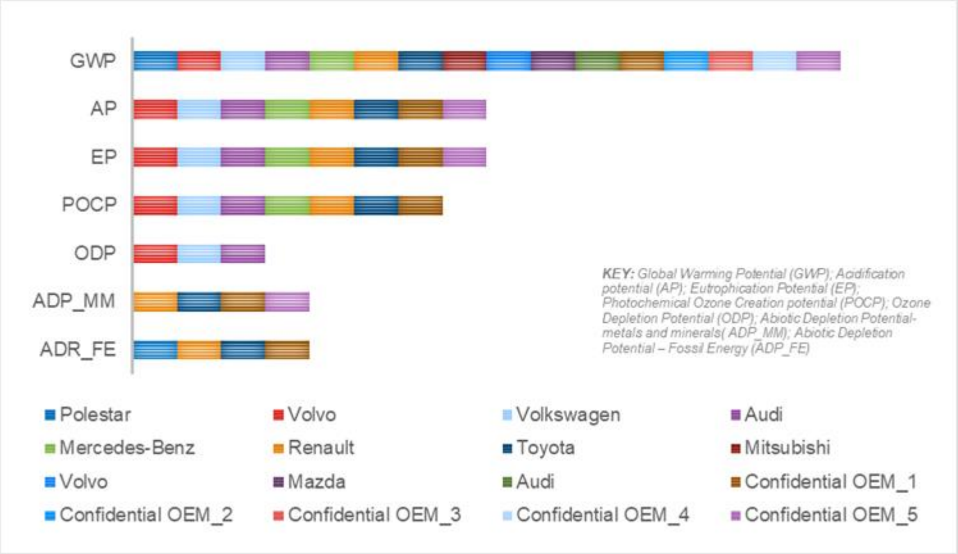
[15] Although Cumulative Energy Demand and Primary Energy Demand are very important for ZEV field as complementary LCI indicators, it has to be highlighted that they should not be labelled as impact categories according to LCA framework because they are not in compliance with the system boundary between technosphere and environment in the LCIA. Despite that, it was observed from the review that they are often reported together with other impact categories without distinction which is not a good practice.

demand are also absent (with fossil energy demand only providing a partial picture), which is inconsistent also with the importance of energy efficiency as a key pillar of Europe's strategy, policy and initiatives for climate change mitigation.



KEY: Global Warming Potential (GWP); Acidification potential (AP); Eutrophication Potential (EP); Photochemical Ozone Creation potential (POCP); Ozone Depletion Potential (ODP); Abiotic Depletion Potential-metals and minerals(ADP_MM); Abiotic Depletion Potential – Fossil Energy (ADP_FE)

Figure III-12. Environmental impact categories adopted and reported within OEM reports

The **consultation activities** results do confirm the findings for the industry. Table III-12 shows the results of the survey amongst sectors in the industry. The table presents the percentage of responding companies that state to consider a particular impact category in the calculations and reporting. It shows that all responding companies calculate and report on climate change. Other impact categories that are frequently taken into account in the calculations are resource depletion, acidification, eutrophication, photochemical ozone creation and cumulative energy demand. However, results of these impact categories are not always reported.

Table III-12. Percentage of responding companies that state to consider impact categories (IC) in their calculations and reporting on LCA (result of consultation activities survey amongst sectors in industry)

	Calculated ICs		**Reported ICs**	
Value	Percentage	Count	Percentage	Count
Climate change	100.0%	16	100.0%	16
Cumulative energy demand	56.3%	9	25.0%	4
Human toxicity	37.5%	6	6.3%	1
Resource scarcity/ resource depletion	62.5%	10	31.3%	5
Acidification	62.5%	10	31.3%	5

	Calculated ICs		**Reported ICs**	
Eutrophication	62.5%	10	37.5%	6
Ecotoxicity	37.5%	6	6.3%	1
Stratospheric ozone depletion	37.5%	6	12.5%	2
Photochemical oxidation/ tropospheric ozone formation	62.5%	10	37.5%	6
Water consumption	50.0%	8	18.8%	3
Others*	25.0%	4	12.5%	2

Notes: Others included metal depletion, primary energy demand and particulate matter.

The most studied impact category in **scientific and other literature** is by far climate change or global warming, followed by energy consumption indicators (e. g., cumulative energy demand), acidification, particulate matter formation and photochemical ozone formation (i. e., air quality related impact categories), and toxicity related impact categories (human and ecotoxicity), and eutrophication. The impact category abiotic resource depletion is used as well for the assessment of resource use, however to a lesser extent. (Ricardo et al., 2020; Temporelli et al., 2020; Tolomeo et al., 2020).

Although resource use is a major concern particularly for batteries used in EVs, (Dolganova et al., 2020) found that only 25 out of 103 studies they reviewed on EV considered resource-use-related impacts. It was also surprising to find that even in studies focusing on batteries the resource consumption part is widely omitted despite being a major issue in batteries' life cycle.

Overall, few LCA studies provide an explicit justification for the chosen impact categories. The main motive behind the choices (explicitly justified or not) seem to be 1) comparability with previous studies, so same impact categories are chosen and/or 2) opinions of experts on areas of environmental concern of ZEVs. Other studies, such as that by Ricardo et al., (2020), have provided justifications also supported by how relatable they are to policy and regulatory situation (particularly for road transport). For example, the particular matter formation indicator (PMF, in PM2.5 equivalents – covering both primary and secondary particles) was chosen due to clearer alignment with transport impacts, policy and regulation air pollutant emissions than the default indicator in PEF (i. e. 'particulate matter' in units of 'disease incidence'). However, the disadvantage of the PMF indicator is that it is based on simple pollutant weighting, and does not take into account location type also (as is possible for the EF particulate matter indicator).

All the prospective LCA studies address climate change impacts, with some studies presenting results for ReCiPe midpoint indicators (e. g., Bauer et al., 2015; Cox et al., 2020; Koroma et al., 2020).

The main focus of all of the reviewed **fleet-level LCAs** was on climate change. Several studies also considered fossil energy consumption (Baptista et al., 2012; Hao et al., 2011; He & Chen, 2013; Kromer et al., 2010; Ou et al., 2010; Reichmuth et al., 2013), and some additionally reported a range of tailpipe emissions (including NOx, PM10, etc.) at the LCI stage (Baptista et al., 2012; He & Chen, 2013). Only very few fleet-level studies included other impact categories at the LCIA stage; where this was done, the authors' choice of impact categories was based on perceived relevance for the system being assessed, such as: photochemical ozone creation, abiotic resource depletion, and human toxicity (Raugei et al., 2021).

In conclusion, to harmonize impact assessment between LCA studies, the PEF set of impact categories and models is recommendable as a starting point, to be complemented by a measure of total cumulative primary energy demand (e. g. CED) as a minimum (i. e. due to its relevance and significance to assess contribution to meeting key policy objectives). Moreover, in the context of ZEVs, alternative or additional impact categories/indicators might be considered relevant, like dissipation of abiotic resources (instead of depletion), circularity of resources, criticality of abiotic resources, noise and probably other environmental problems. In addition, the particular matter formation indicator (PMF) might also be considered further, due to its clearer alignment with vehicle emissions regulation in the EU versus the PEF default (as noted above).

However, these impact categories are not part of the PEF recommended set of impact categories and characterization models. So, there is no consensus on, whether these indicators should be part of the environmental assessment, and if so, which characterization models should be used for this assessment in most cases. Development of such methods and reaching consensus between different stakeholders in industry and science, is probably beyond the scope of TranSensus. However, an overview of promising possible future developments can be given.

During the review, the impact category '**resource dissipation**' pops up as a relevant and interesting alternative for the presently recommended impact category based on depletion of resources. The transition to new electricity production systems, based on wind and solar energy in combination with storage of electricity in batteries, will lead to an increasing demand for minerals and metals. This increase in demand, together with the limited amount of resources that is at present accessible, given the present technological and economic conditions, will reduce the accessibility for resources for future generations. The impact assessment of resource use that is at present recommended in the EF is based on extraction of resources (J. B. Guinée & Heijungs, 1995; Van Oers et al., 2016; van Oers, Guinée, & Heijungs, 2020). However, this impact assessment method, based depletion of resources in the earth crust due to extractions, is much debated nowadays. One of the reasons is that after extraction the resources are not lost (i. e., depleted) but might be still available for future use, if they are recycled. Furthermore, an assessment method based on extraction does not identify where in the process chain the resources are actually lost, in case they can't be recycled (given the present technological and economic conditions). So, the dissipation indicator could better identify **resource circularity**[16] issues. An impact assessment model that is focused on dissipation instead of depletion of resources could solve these problems. At present, there are several methods in development (Beylot et al., 2020, 2021; Poncelet, 2022; van Oers, Guinée, Heijungs, et al., 2020)). However, many of these methods are not fully operational, yet.

On top of this come the geopolitical factors that also might hamper the supply of resources in the short-term (Schrijvers et al., 2020). These supply risks are assessed in so-called **criticality assessments**, like for example the criticality studies for the EU (EU, 2023). These are normally not part of the (environmental) impact assessment in LCA. There is a difference between impact assessment in LCA and criticality assessment. In the LC impact assessment, one tries to assess the impacts of the product system on the environment. In the supply risk indicators, one tries to assess what external factors (mostly geopolitical and economic constrains, like monopolization, stability of regions etcetera) might hamper the supply of resources to the product system. So, in short, in LCIA the effect of the product system on the environment is assessed, while in criticality assessment the effect of the (geopolitical) ‘environment’ on the product system is assessed.

To conclude on this, dissipation of resources in the process chain, circularity to overcome dissipation and criticality issues, all seem to justify a revisit of the problem of resource use in LCA.

An additional impact category for the assessment of ZEVs that is also mentioned in the sources is **cumulative energy demand**. However, it should be noted that CED is not fully in compliance with the system boundary between technosphere and environment in the LCIA and thus the definition of elementary flows in the LCI and the characterization of these flows in the LCIA (see also the introduction of in section 3.3). Produced energy or consumed energy are non-elementary flows, i. e., the flow remains within the technosphere. That means, (produced or consumed) energy does not cross the system boundary between the technosphere and the environment. However, the production and consumption of energy can be traced back to their elementary flows, i. e. the extraction of fossil fuels, which contributes to the impact category “abiotic resource depletion of fossil energy”, respectively the emission of carbon dioxide which contributes to the impact category “climate change” (Next to climate change, combustion emissions also do contribute to other impact categories, like acidification and toxicity.) So, caution should be given when additional (environmental proxy) indicators like PED and CED are

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[16] An additional impact category next to dissipation, to assess circularity is disputable. Circularity or non-circularity is not an environmental problem as such. (e. g. system boundary issues: It refers to economic flows that still should be processes by technosphere, for example comparable to waste incineration and land fill). Thus, one might argue that circularity should be solved in the LCI and NOT in LCIA. In LCI there are different methods to deal with this: a) solving recycling as a MF process (using allocation by partitioning or substitution), or b) using the CFF. For example, when using the present ADP method, if EoL a product system uses recycling the benefit of recycling is that no down chain processes (incineration or land fill) are attributed to the product system. If a product system uses secondary materials, the benefit is that no primary mining and refinery processes are attributed to the product system. (please note that the dissipation methods already take into account dissipative flows, for example defined as flows that are NOT recycled given the present economic and technological conditions. So, if there is recycling and no landfill or incineration, the system avoids dissipative flows).

presented next to the recommended conventional impact categories. By presenting proxy environmental indicators next to impact categories, there is the potential to introduce some overlap in counting of environmental issues (e. g. where another indicator, such as abiotic resource depletion – fossil energy, contains a subset of the coverage of PED or CED indicators). However, this remains a mainly presentational issue when they are provided separately, except in cases where normalisation and weighting are applied and accounting for this overlap would need to be addressed.

Related to **bioenergy and biogenic carbon dioxide** the following issue might need attention. Considering Biogenic CO_2 sometimes emissions and extractions of Biogenic CO_2 are not taken into account in the LC Impact Assessment. A priori, it is assumed that Biogenic CO_2 will not contribute to Climate Change. This is because 'in the real world' the CO_2 that is emitted due to the combustion of biomass is (a short term before) fixated by the biomass. So, over all the net contribution of biogenic CO_2 to climate change might be considered neutral. However, in LCA, due to allocation of multi-functional processes, the biogenic CO_2 extraction and emission along the process chain might no longer be in balance. For this reason, it is strongly recommended to clearly label biogenic CO_2 and fossil CO_2, for both extractions and emissions. It is also necessary to clearly state whether the biogenic CO_2 has a characterization factor for both the extraction of carbon dioxide due to fixation by biomass and the emission of carbon dioxide due to the combustion of the fuels that is sourced from the biomass.

Finally, related to the existing impact categories it should be noted that the **coupling between results of the LCI to the LCIA** not always is complete or sound. There are several reasons for this. For example, the Life Cycle Inventory (LCI) may report on emissions of a substance-group (e. g., VOCs) while the Life Cycle Impact Assessment (LCIA) method only has characterization factors for individual substances. In this case additional characterization factors should be defined for substance group emissions (or vice versa), for example based on a weighted average based on some kind of emission profile of a particular reference (e. g., a process or country). Furthermore, for some impact categories, particularly toxicity related impact categories, the completeness of available characterization factors sometimes is limited, although these substances or elements might be very relevant to ZEV supply chains. So, it might be recommendable to check the elementary flows of emissions and extractions between LCI and LCIA, both on completeness and soundness, particularly to the automotive industry.

III.3.3 Normalization and weighting

Normalization and weighting: Summary of key findings

- **Normalization** might be a useful step for the interpretation of results (e. g., soundness of results). However, choice of the reference situation is debated in present scientific literature. Thus, harmonization of this step needs attention.
- **Weighting** is subjective, and thus can't be harmonized as such. However, the procedure to get to weighting factors can be standardized and be made more transparent.

As mentioned in the ISO 14044 standard, normalization and weighting are optional elements of LCIA. They are never explicitly mentioned in the **standards and guidelines** reviewed apart from the VDA guidelines which state that they should not be taken into account due to their subjective nature. Indeed, the ranking of indicators through weighting is certainly a subjective step, and therefore difficult to specify in a guideline, as it may depend on the context of the analysis and the perspective of the stakeholders.

While normalization and weighting are optional sub-steps for classification and characterization of impacts, to aid the interpretation of results, no **OEM reports** have applied these steps due to the potential uncertainties associated and implications of the subjective judgements in the results reported.

Normalization and weighting are rarely considered in **scientific literature**. The results are often presented as characterised impact category impact scores. Therefore, it was not a topic discussed in the considered review articles. While normalization is a common practice overall, weighting is very controversial due to the weighting value subjectivity. In fact, it is not ISO compliant that is why it should not be included in comparative studies intended for public.

Nevertheless, attempts are made to create a formalised procedure for the weighting step in LCIA. A significant piece of work in that field was completed by JRC (Sala et al., 2018) which is the weighting approach used in PEF. In this approach a robustness factor was given to each impact category based on:

- Coverage completeness (based on the extent to which the inventory data is available)
- Robustness of data for normalization (e. g., statistical quality)
- Robustness of impact assessment method

Impact categories with perceived robustness in all three parameters would have an overall robustness factor of 1. The final weighting factors then already consider this robustness and reflect the importance which should be given to the impact; they are scaled to total 100 when all impact categories listed are considered (see Table III-13).

Table III-13. Robustness factors and final weighting factors suggested by (Sala et al., 2018)

Impact category	Robustness factor	Final weighting factors including robustness
Climate change	0.87	21.1
Eutrophication	0.56	9.5
Particulate matter	0.87	9.0
Water use	0.47	8.5
Resources use, fossil fuels	0.6	8.3
Land use	0.47	7.9
Resource use, minerals and metals	0.6	7.6
Ozone layer depletion	0.6	6.3
Acidification	0.67	6.2
Ionizing radiation	0.47	5.0
Photochemical ozone formation	0.53	4.8
Human toxicity, cancer and non-cancer	0.17	4.0
Ecotoxicity, freshwater	0.17	1.9

However, it is debatable if this procedure of applying robustness factors to impact categories will help to make the weighting more transparent, let alone less subjective. What is described here is not the weighting step. It is flagging impact categories with some robustness factors, based on completeness of characterisation factors in relation to inventory, uncertainty in normalisation factors and soundness of the characterisation model. In that sense it belongs to the section interpretation on uncertainty analysis and completeness and consistency check.

The actual weighting factors are based on panel weighting, and this is a subjective step. Please note that when applying weights to impact categories (some of) the panel members might already have taken into consideration some kind of uncertainty/robustness issues, next to the subjective political choices. So, the described procedure and the resulting factors in Table III-13 might lead to double counting of the uncertainty and robustness issue.

Furthermore, it is highly debatable whether a lack of robustness should lead to reduced consideration/weighting for any impact category. E. g., one type of impact may be highly uncertain and yet still extremely important and deserving the utmost consideration. In fact, some of the panel members in a weighting session might argue that the lack of certainty could be a further reason for applying the precautionary principle and giving such impact category a higher (not lower) weighting factor. In other words, the weighting step is subjective. The subjectivity applies to both, how the robustness will influence the consideration of the impact category, as also the relative importance between the different impact categories.

None of the reviewed **prospective** and **fleet-level LCAs** used normalization and weighting.

In conclusion, normalization and weighting are optional steps in the impact assessment. Normalization might be a useful step for the interpretation of results (e. g., soundness of results, facilitate comparison). However, the choice of the reference situation is debated in present scientific literature (e. g. Cucurachi et al., 2017; Pizzol et al., 2017)

Considering normalization, guidelines to harmonize LCA studies seem to be desirable. What are the new developments and insights in normalization in LCA? Is normalization desirable, or sometimes even, necessary, and for what? Can a best method be suggested, and for which conditions? At least, the (geographical) scope of the characterization model and normalization reference should be the same (e. g., world scope for depletion of abiotic resources).

Weighting is subjective, and thus cannot be harmonized as such. However, the procedure to get to weighting factors can be standardized and be made more transparent.

III.4 Phase VI. Interpretation

Interpretation takes into the LCI and LCIA results and try to comprehend the meaning of these numbers to land on meaningful conclusions and robust understanding of the studied system to help achieve the defined goal in the first phase. This section discusses the most important topics that are usually tackled under this phase:

- Results reporting
- Hotspots and contribution analysis
- Uncertainty analysis & Sensitivity analysis
- Completeness and consistency checks
- Verification processes

Interpretation is the final step of life cycle assessment. ISO 14044 provides general guidance on what should be covered in the interpretation study of an LCA. This namely involves: Addressing significant issues; Evaluation, Conclusions, limitations, and recommendations. In this stage the environmental burden quantified for a product, in the previous step of life cycle impact assessment, is systematically translated into perceivable impacts, in line with the goal and scope of study. This key step helps:

- Identify, quantify and link the impacts to their contributors across the life cycle of the product or process (via contribution analysis); evaluate the sensitivity of the reported results to those contributing factors and any other assumptions, like functional unit used, allocation method used, assumed electricity mix etcetera, and uncertainty in data (via sensitivity analyses of relevant parameters);

- Analyse the quality and completeness of data to ensure that the results reported are reliable and consistent. This may also require accounting for any underlying uncertainties stemming from the data used which could also be interpreted through appropriate uncertainty analyses;
- Analyse trade-offs in environmental impacts across a set of parameters applicable to the product or process. Identify the shift of environmental burdens across impact categories when tweaking these parameters via dedicated scenario analyses;
- Translate these findings into easily comprehensible take away messages and make recommendations for the environmental optimisation of the products and processes.

III.4.1 Results reporting styles

Results reporting styles: Summary of key findings

- **Generic LCA standards and guidance** were predominantly found to provide **generic recommendations** on result reporting and interpretation approaches. Dedicated LCA guidance, particularly Catena-X and GBA, provided relevant recommendations emphasising only on product carbon footprint.
  - Product LCAs have consistently adopted the recommendations within **ISO14040/44**, while product LCAs from specific geographies have adopted their regional vehicle LCA guidance such as **VDA (Germany), PFA (France)** [which again draw their recommendations from the ISO standards] and **LIME method** (Japan). A harmonised approach to reporting or results and interpretations, which is **consistent with the current needs and anticipated regulatory requirements** for vehicles and batteries, is therefore, required.
- **Different styles of reporting and interpretation** have been pursued by LCA practitioners in the various sources of reviewed literature. They could be comparative LCAs, single product LCAs or environmental product declarations (EPDs), or simply LCAs for hotspot analysis and optimisations, design-related decisions and to evaluate tech. changes or upgrades. Specific categories of reporting and interpretation styles need to be first identified and harmonised.

Some **guidelines & standards** only focus on requirements for reporting of results, like PEFCR-Batteries and PFA. PEFCR-Batteries describes requirements for the reporting of results, including full life cycle inventory, characterised results, normalised results, weighted results, all in absolute values for all impact categories and the aggregated single overall score in absolute values. The standards and guidance provide general (less-specific) recommendations on attributes or types of analyses to be covered as a part of the results reported which can be challenging for the wider community of LCA practitioners to interpret in a harmonised way. For example, PEFCR-Batteries does not provide clear instructions on the parameters to be considered for undertaking sensitivity and scenario analyse, pertaining to a battery's life cycle.

There are other guidelines and standards, including the eLCAr (that follows the ILCD reporting template), PCR-Buses and coaches (which follows Environmental Product Declarations (EPD) reporting template) and VDA (which adheres to ISO 14044) that provide precise recommendations for comprehensive reporting of the product LCA, pertaining to all phases of the ISO-LCA framework.

Catena-X Ver 2.0 only prescribes required elements for Product Carbon Footprint data exchange (Catena-X Automotive Network , 2023), while GBA and RISE do not provide any recommendations for reporting of results. CATARC is yet to be developed, nevertheless, the current version of the guidance does not discuss much about how results are to be interpreted.

Interpretation approaches often vary with the goal and scope of study. For example, in the case of **OEM reports**, the environmental impacts associated with the target vehicle, operating on specific zero-emission powertrains, have been presented predominantly through a comparison of its performance against that of conventional powertrains (for example, BEVs and/or PHEVs, have been predominantly compared with ICEVs, in the case of passenger cars). One freight truck LCA conducted a comparison of BEV vs FCEV analysis. To emphasise, through these comparisons (for example, when showcasing climate change), most OEM studies can showcase how relatively higher environmental burden is observed upstream of the manufacturing phase for BEVs and PHEVs, while the opposite is the case for ICEVs. Such an approach to comparison of results shows how the environmental impacts of BEVs and PHEVs 'break-even' with that of the lifecycle impacts of a comparative standard ICEV.

For OEM reports focussing on ICEVs only, comparisons seemed to centre around variations in vehicle model along the lines of construction and/or year of operation, or with other ICEV models. Approaches to product comparison in the case of one bus related LCA and one freight truck LCA differed from the rest of the studies along the lines of different use scenarios. One bus LCA study communicates applying different mileage scenarios, and another modelled impacts based on vehicle usage in different European countries. Likewise, one freight truck LCA modelled short haul and long-haul usage scenarios as well as extended product lifetimes which included battery exchanges. Some studies highlighted that additional modelling scenarios were conducted but omitted from the report and could be accessed upon request by the publishing organisation. Most of the product LCAs were observed to have provided inventory details sufficient for public disclosure. In some cases, more detailed inventory and impacts assessment details are stated to be available upon request and held for internal communication and environmental monitoring purposes. Key information may be withheld from detailed reporting to avoid competitive risks or due to data confidentiality concerns.

The reporting styles of **scientific literature** in general including prospective and fleet-level LCAs varied considerably, with each study adopting a bespoke style and none adhering to any specific standard.

III.4.2 Hotspot/contribution analysis

Hotspot/contribution analysis: Summary of key findings

- **Variations in interpretations** were found to mainly stem from the **differences in the goal and scope of study and the nature of the products** (vehicle types and vehicle + powertrain combinations) analysed; However, all the reviewed literature adopt **contribution/ hotspot analysis** to make these comparisons;
    - More often, LCA focussing on **newer models** or fuel-efficient prototypes of ICEVs are often evaluated through **comparison with an existing or an older model**; **Zero-emission vehicles** are often subjected to a **comparison with ICEVs**, in general. Environmental Product Declarations (EPD) mainly emphasise on the reporting of results on performance of a single product.

There are different ways that are suggested by ISO 14044 on how to structure results in order to identify hotspots. Results can be categorised by life cycle phase (e. g., contribution of processes grouped in mining, production, use and waste treatment to climate change), processes, elementary flows (e. g., contribution of GHG emissions (CO_2, CH_4 and so on) to climate change), process-elementary-flow-combinations (e. g., contribution of GHG in electricity production to climate change), or by differentiating between processes under different levels of management influence. This categorization could and should be done for each individual impact category, to provide further insight. Once results have been categorised in such a way, further analysis should be carried out to determine the relevance of various inventory data to the total impact score of the key impact categories.

Most of the **guidelines & standards** do not include recommendations or provisions on performing a contribution analysis. Only eLCAr recommends providing a contribution analysis on different levels (most relevant stages, processes, and elementary flows contributing to impact category scores). The PFA prescribes that the contribution analysis should be based on the life cycle stages.

All **OEM reports** reviewed adopted a LCA stage-based contribution analysis, particularly attributing the impacts to the main system processes. From a life cycle perspective, some (3 reports) of the product LCA reports produced by the vehicle OEMs were observed to attribute the quantified environmental impact to material composition and energy intensity of the parts and components feeding into the vehicle construction. Reminder of the product LCAs and EPDs, alternatively, highlight the key impact hot spots such as a list of material inputs or energy intensity attributed to the various life cycle processes. For example, impacts from the product stages are usually attributed to the metals and minerals used in vehicle and components (e. g., battery) production, while in the use case, environmental impacts were found to stem from fuelling and tail-pipe emissions for ICEVs and electricity use for low/ zero emissions vehicles. The purpose of this stage is to identify those core factors contributing to these impacts, which is then are then subjected to a sensitivity study or aggregated for a scenario analysis.

In the case of BEVs, choice of a varying geographical static grid mix is a common for sensitivity study, while and EPD on full-electric freight trucks combines future grid mix with long-haul and short-haul applications, suitable for a scenario analysis. More details will be included in the upcoming segments.

In addition to this, in some studies, impacts were disaggregated by material type or a comparative vehicle. The same trend was found in **scientific literature**. One freight truck LCA study visualised material hotspots in addition to conducting an LCA-stage based study.

III.4.3 Sensitivity analysis

Sensitivity analysis: Summary of key findings

- Results reported for passenger cars often adopted a **sensitivity study that vary by vehicle segments and their use cases**. For example, the use case for **passenger cars** if often centred around transport of passengers, adopting the impacts of geographically relevant fuel/ electricity mix consumed over the vehicle's service life.
    - A **dynamic grid-mix model,** following the World Energy Outlook (WEO) scenarios**,** is found to be adopted only by some studies to provide a representative reporting of use-phase results. This data was not necessarily available for most geographies.
    - Some **consistent recommendations on the most representative choice of grid-mix scenarios**, suited for general use and for specific geographies need to be identified and harmonised.
    - In the case of **larger vehicle segments**, such as buses and trucks, a **long-haul and** short-haul transportation of goods or passengers are often adopted, alongside the use of geographically relevant fuel and electricity use, over the vehicle's service life. In the case of **fleet-level LCAs**, **further complexities** are introduced into use-case analysis including powertrain efficiency improvements, rate of penetration of new tech., EV charging patterns, deployment of V2G etc., in addition to dynamic electricity mix.

Sensitivity analysis is the procedure in which the robustness of results of the Life Cycle Impact Assessment are analysed due to changes made in the methodological assumptions (definition of the Functional Unit, chosen allocation method, chosen electricity mix and so on) and uncertainty of data.

Reviewed **guidance and standards** predominantly provide overarching recommendations to check how results are impacted by possible variations to the underlying assumptions. Beyond this, this guidance recommends that the sensitivities of the report results to a given set of parameters be evaluated based on the goal and scope of study.

Many **OEM reports** have also employed sensitivity studies for the comparisons of impacts from different electricity mixes modelled, particularly over the product (mainly BEVs and PHEVs) use phases. Within this comparison criteria for BEVs, variations appeared along the lines of electricity mix baseline projections and specific electricity generation scenarios. Most studies compare at least one or more electricity grid mixes (national and/or regional) to electricity produced from renewable sources, such as wind or hydropower.

Two studies covering ICEVs also included comparisons of performance with diesel against biodiesel (HVO) and biomethane. Five studies explored future electricity grid mix scenarios and the effect on the results and conclusions. Four OEM studies were observed to have adopted the future dynamic grid mix scenarios published by the World Energy Outlook from the International Energy Agency (IEA) (International Energy Agency (IEA), 2023). The study that covers an FCEV also explores the impact of the hydrogen source and thus compares hydrogen produced from natural gas, to hydrogen produced from electrolysis using renewable electricity. Three studies explore different lifetime mileage for the vehicle. Two studies from the same OEM also include the sensitivity of hydrocarbon emissions due to fuel evaporation and the impact of including the manufacturing plant in the assessment. Two OEMs briefly discuss the sensitivity of the supply chain and therefore compare global averages for material production and refining to European ones for selected materials. One OEM includes the potential impact of introducing “fossil free steel” as an alternative to conventionally produced steel.

In general, within **scientific literature**, due to the lack of primary and reliable data from industry, many assumptions must be made. Therefore, sensitivity analysis has an important role, especially in a traction battery LCA, where some data are hard to find or to access due to confidentiality issues. Although in comparative LCAs sensitivity analysis is requested by the ISO 14040 standard, it was noticed that it is not always there, see for example (Petrauskienė et al., 2020). In fact, no sensitivity analysis was reported in eight out of seventeen studies reviewed by (Temporelli et al., 2020) and the same trend can be seen in (Arshad et al., 2022) as well.

The most tested parameters can be organized under three big umbrellas in traction-battery studies: Energy, distance driven, and lastly battery components materials and their recycling rate. The first umbrella usually refers to the energy mix in the use phase and in the battery manufacturing (L. A. Ellingsen et al., 2013; Majeau-Bettez et al., 2011). For example, marginal mixes are used along with average mixes. Some of these consider alternatively one mix or the other as a matter of sensitivity analysis, others for testing results with the mix of higher GHG intensity, others use different mixes for different time horizon, due to difficulties in determining the marginal mix in future energy systems (Marmiroli et al., 2018).

The second category addresses the total distance driven or the lifespan of EVs (L. A. Ellingsen et al., 2013; Faria et al., 2014). Different mileages can be considered to verify the robustness of the results. The third tested parameter is about the battery component materials and their recycling rate in the EoL (Anna et al., 2019). The sensitivity analysis related to this parameter could help to identify the materials with higher environmental impacts and if material recovery can help to decrease environmental impacts or if recycling operations cause further impacts than the disposal of these components. These three main umbrellas are dominating the sensitivity and uncertainty analysis due to its big influence on the results hence conclusions as discussed in the other sections of this report (Aichberger, 2020).

All of the **fleet-level LCAs** included at least some sensitivity analysis. This ranged from relatively simple grid mix scenarios for the vehicle use phase, to more elaborate and sophisticated multi-parametric sensitivity analyses addressing multiple factors at once, among which: power train efficiency improvements, penetration rates of new technologies, battery technology evolution, fuel mixes (including biofuels), vehicle lightweighting, hydrogen production routes, EV charging patterns, vehicle lifetime activity, deployment of V2G storage, and adoption of shared mobility (TaaS).

III.4.4 Uncertainty analysis

Uncertainty analysis: Summary of key findings

- Guidelines and standards provide only generic recommendations in procedures for **uncertainty analysis**. **Peer-reviewed scientific literature** was found to often employ dedicated approach, such as **Monte Carlo analysis** to investigate the uncertainties in data employed, while **product OEMs** do not explicitly employ or declare any uncertainty analysis. Instead, **sensitivity analyses** are used to address data quality concerns.
- **Prospective LCAs** which are often burdened by uncertainties due to modelling of future complexities. These studies overcome such significant hurdles through **scenario analysis** with multiple possible future developments. However, the parameters adopted, assumptions applied, datasets used and their relevance to the study is usually high complex. Some level of standardisation can be achieved, following an investigation of potential goal and scope and the intended audience of the study

Uncertainties can arise in the form of the data quality and completeness issues in the inventory data, assumptions applied, allocation method used, etc. Most of the **guidelines & standards** only provide overarching recommendations, while only eLCAr guidance recommends that uncertainty calculations shall be used to support the comparison of systems, especially to identify whether differences can be considered significant or too small to justify the superiority of one system over the other (EC Joint Research Centre, 2010). VDA states that uncertainties shall be discussed in a qualitative way and quantified by means of sensitivity analyses if possible. RISE-LCA mentions Monte Carlo Simulation. GBA recommends a sensitivity analysis in case a new data gap is closed from secondary sources to see its influence on the overall GHG footprint of the respective step in the battery value chain.

Most **OEM reports** do not explicitly discuss how the analyses were used to support the conclusions of the study but some report that the inclusion of different current and future electricity mixes gave insight into the importance of electricity mix during use and the key contributors to environmental impact. No other uncertainty analysis (such as Monte Carlo) was reported by any OEM. Instead, some OEM reports have been observed to provide technical annex to the OEM report detailing assumptions made, providing a data quality matrix, raw data used etc. However, this annex is rarely publicly disclosed and predominantly used for internal circulation.

In the case of **scientific analysis**, it is common that sensitivity analyses are used to address uncertainty which results in these two terms (i. e., uncertainty and sensitivity) being used interchangeably. Whenever uncertainty analysis is provided in the studies as a standalone analysis, it is usually done using Monte-Carlo analysis (Arshad et al., 2022). Some studies explicitly distinguish between uncertainty and sensitivity analysis by applying both depending on the required output and available input, see for example (Vandepaer et al., 2017). Although the study is on stationary applications of Li-ion batteries, it is worth highlighting the common practice of mixing up the two terms.

Prospective LCAs assess unknown future situations, resulting in additional sources of uncertainties compared with standard LCA studies (Buyle et al., 2019). A major source of uncertainty inherent to prospective LCA is linked to the assumptions to model the future situation (i. e., how the world could look like at a certain point in time). Scenario analysis has been proposed as a suitable approach to deal with these uncertainties by considering multiple possible future developments (van der Giesen et al., 2020). For example, Sacchi, Bauer, et al., (2022) assessed the carbon footprint of ZEVs by 2050 under a baseline scenario, representing a situation without any specific climate policy, and a more stringent scenario aligned with the 2°C climate target. The baseline and the stringent scenarios serve as the upper and lower bound in their analysis. A similar scenario analysis approach can be found in other prospective LCAs, such as Cox et al., (2020); van den Oever et al., (2023); Xu et al., (2022). Moreover, additional uncertainties are linked to the rather limited knowledge of emerging technologies at low TRLs (Buyle et al., 2019; Cooper & Gutowski, 2020) or how mature technologies will evolve into the future. This has been addressed in prior works by defining probability distributions for key technology parameters (e. g., Cox et al., 2018, 2020; Sacchi, Terlouw, et al., 2022).

III.4.5 Completeness and consistency check reporting

Completeness and consistency check reporting: Summary of key findings

- **Guidelines and standards**, like PEFCR-Batteries, GBA in addition to GRB-CFB-EV provide varying set of prescriptive instructions on **data quality checks and verifications** for LCA of batteries. There appears to be **a need for a single standardised set of instructions on integrating and reporting data quality checks and third-party verifications,** that the product OEMs and other relevant stakeholders could benefit from.
- Most **OEM reports** employ their **own data quality checks** following instructions from ISO standards and often include **a record of modelled datasets and assumptions in the technical annex** of their reports. Their studies are also predominantly **verified by third-party**.
- Other literature such as **scientific literature, prospective LCAs and fleet-level LCA seldom declare consistency and completeness checks** in their reporting. These studies may be peer-reviewed but are **not necessarily third-party verified**, with exceptions in literature published by product OEMs themselves.

Completeness checks provide information regarding the percentage of flows that are measured, estimated or recorded, as well as unreported emissions (i. e., cut-off). Consistency on the other hand is meant to represent the uniformity of the data, methodology and procedure used in the data set-up and database maintenance and additions (Sphera, 2022).

Most of the **guidelines & standards** do not include recommendations or provisions on the completeness and/or consistency check of the analysis. Only eLCAr has extensive requirements. Separate provisions are given for the completeness check, mainly related to LCI modelling (eLCAr, provisions in section 9.3.2) and the consistency check (eLCAr, provisions in section 9.3.4 (Del Duce, Egede, Öhlschläger, & et al. , 2013). GBA only prescribes a completeness check on the process level, particularly related to mass balances. In Catena-X the completeness check is restricted to the cradle-to-gate GHG emissions that are collected. In GBA and Catena-X nothing is said about completeness and consistency check on the system level (flow charts, elementary flows, characterization factors etc.).

In terms of the **OEM reports**, some studies may inherently implement their own data quality checks in adherence with the ISO14040/44 standards. However, details pertaining to exclusive consistency or completeness check are seldom disclosed as a part of the public LCA reporting. Besides their declared compliance with the ISO 14040/44, only a selection of industry reports encloses scientific annexes on the raw data and their sources. However, these studies are mostly never supplemented by documentation on completeness, consistency checks, except the direct inclusion of sensitivity in some cases. The same applies to the **scientific literature** in general including prospective and fleet-level LCAs. Or at least no such checks were explicitly declared in the documents.

Completeness and consistency are relevant to **LCA databases** developers which is usually discussed under the verification process (which might include third party verifiers) or discussed as an indicator for datasets quality. Completeness checks provide information regarding the percentage of flows that are measured, estimated or recorded, as well as unreported emissions (i. e., cut-off). Consistency on the other hand is meant to represent the uniformity of the data, methodology and procedure used in the data set-up and database maintenance and additions (Sphera, 2022).

Completeness and consistency are two of the DQI that Sphera employs which contributes to the overall score of the dataset quality. Completeness is rated as follows:

- *"all flows recorded":* The entire process is covered by complete access to process data or the process was modelled in a very detailed form. Processes in which the cut-off rules were applied and checked can also be considered complete.
- *"all relevant flows recorded":* The relevant flows of the process are covered. When not all flows can be recorded, this is the next option, which still enables good quality of results in terms of evaluation.
- *"individual relevant flows recorded":* Only particular flows are recorded. It must be clear that in this case some important flows can have been omitted, so only medium quality of data can be achieved. If possible, further research should be performed.
- *"some relevant flows not recorded"*: If good quality is desired, this case should not occur. In the case that no data is available, reasons for using this kind of data should be documented.

The setting for consistency is simpler and it relates the uniformity of the data, methodology and procedure used in the dataset up to a benchmark. This benchmark can be GaBi modelling principles itself (rated as good) or ISO 14040.

Completeness represents a criterion in the pedigree matrix used by ecoinvent to determine what is called "additional uncertainty" (see section III.2.2). According to ecoinvent, all datasets are as complete as the knowledge of the data providers allows and no cut-off is structurally done. This is ensured by means of stoichiometric, mass balances, energy balances etc. in case of missing data on some flows. Consistency on the other hand is only mentioned by ecoinvent in a general context stating that ensuring consistency was taken into account but it was not discussed separately in detail. In fact, consistency is not one of the criteria in the pedigree matrix. (Weidema et al., 2013)

III.4.6 Verification

Verification: Summary of key findings

- Most guidelines propose procedures for verification of data.
- A considerable number of OEM reports declares a verification done by third party against ISO 14040/44 and PCRs.
- Peer-reviewing is the only verification process for scientific publications (scientific LCA studies).
- Normally, databases providers have their datasets verified by a third party either a LCA expert or industry.

Most of the **guidelines & standards** propose procedures for the verification of data. However, it is not clear if these requirements cover verification on the same level of completeness and/or detail.

According GBA, the GHG calculation from each member along the value chain needs to be reviewed and verified in accordance with the GBA scheme for Battery Passport data verification (Global Battery Alliance , 2022). The auditor will at least verify the

1) primary data collected,
2) the selection of GHG emission factors,
3) the calculation method and documentation of the result,
4) recycled content (calculation and documentation of recycled content from supplier).

According to GRB-CFB, the verification of the CFB shall be carried out in compliance with the general requirements included in the Battery Regulation Proposal and EC Recommendation 2021/2279 (Annex I – Section 8). In particular:

i. The verification shall cover at least the points as specified in the EF Recommendations 2021/2279 (Annex II – Section 8.4).
ii. Additional details of the verification are specified in the Carbon Footprint calculation rules document, including regarding Application for verification and technical documentation.

PEFCR-Batteries requires that the verification of an EF study/report shall be done according to all the general requirements included in Section 8 of the PEFCR Guidance 6.3 and the requirements list in chapter 8. The eLCAr requirements for verification are defined in chapter 11, based on ILCD requirements. PCR Buses and coaches requires a third-party review by an approved reviewer within the EPD International system. VDA requires that vehicle LCAs that are published shall be critically reviewed by an external reviewer or review panel according to ISO 14071.

Five of the 16 reviewed **OEM reports** were third party verified. Three were verified against the ISO 14040/14044 standards and two were verified against the PCR for buses.

Except the peer-reviewing process often adopted in scientific literature, none of the reviewed articles were verified by third parties. Same for prospective and fleet-level LCAs, no additional verification activity has been declared except the peer-reviewing for scientific publications. Lastly for **databases,** they are usually verified (on the dataset level) by third party like industry or LCA expert.

IV. Social Life Cycle Assessment (S-LCA)

IV.1 Introduction to S-LCA

S-LCA and Automotive Sector: Summary of key findings from the review

- Social Life Cycle Assessment (S-LCA) assesses the social impacts of products and services throughout their life cycle.
- S-LCA is the most commonly used approach for assessing social impacts, informing choices, and showing the potential for improvement in social conditions.
- S-LCA contributes to the understanding of social impacts and the ability of the automotive industry to make responsible choices.
- Challenges in conducting S-LCA for automobiles include complex supply chains, data sharing concerns, lack of standardization, and stakeholder engagement.
- The S-LCA methodology consists of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.
- Goal and scope phase defines objectives, stakeholders, and improvement opportunities.
- Inventory analysis collects relevant data for hotspot assessment and impact evaluation.
- Impact assessment evaluates the magnitude and significance of potential social impacts.
- Interpretation includes checks, conclusions, and recommendations based on the assessment.

Social life cycle assessment is a methodology to assess the social impacts of products and services across their life cycle, from the extraction of raw materials to the end-of-life phase. (UNEP/SETAC, 2020). It is the best available approach to collecting and reporting data about negative and positive social impacts, therefore S-LCA is the best technique used for increasing the knowledge about social issues, informing choices, and promoting the improvement of social conditions in product life cycles. S-LCA can also be used to identify, learn, communicate, and report the social impacts, set up strategies and action plans, and inform management policies and purchasing practices (Benoît et al., 2010). According to the UNEP/SETAC guideline, the uses of S-LCA are to support companies to develop a strategy for future development and policies, to support a decision-making process that involves a variety of stakeholders from different knowledge and background, to manage social risks, to provide structure, credibility, and consistency to supply chain materiality assessment and to support the disclosure of non-financial information.

Various S-LCA methods are discussed in different peer-reviewed articles, case studies, and guidelines. According to the article "Addressing the Effects of Social Life Cycle Assessment," there are three types of S-LCA techniques: consequential S-LCA, educational S-LCA, and lead firm S-LCA. (Jørgensen et al., 2012)

The consequential S-LCA focuses on the social impacts that arise because of the life cycle of a product or service. It analyses the social consequences resulting from changes in the system caused by the product's life cycle activities. This approach considers indirect effects and potential cascading impacts that occur throughout the supply chain and broader society. Consequential S-LCA helps assess the overall social sustainability of a product by considering its long-term social implications. (Jørgensen et al., 2012)

Educative S-LCA emphasizes the role of raising awareness and improving knowledge about social impacts among stakeholders. It aims to educate and inform stakeholders about the social dimensions of a product's life cycle. Educative S-LCA focuses on providing information, guidelines, and tools to support decision-making processes that prioritize social sustainability. It helps foster learning and capacity-building to enhance social responsibility within organizations and society. (Jørgensen et al., 2012)

Firm-led S-LCA involves conducting social life cycle assessments from the perspective of a specific organization or firm. It focuses on assessing and managing the social impacts associated with the firm's activities, products, or services throughout their life cycle. Firm-led S-LCA helps companies identify social hotspots, improve social performance, and implement strategies for social responsibility. It enables organizations to understand their social footprint, engage with stakeholders, and develop targeted actions to address social challenges. (Jørgensen et al., 2012)

There are three other S-LCA methodologies mentioned in the review paper ‘Social consideration in the product life cycle for product social sustainability’. These include the S-LCA methodologies developed by Dreyer, Hunkeler, and Weidema. The Dreyer S-LCA methodology set a group of multicriteria indicators for evaluation, they are the establishment of the impact category, evaluating management effort in terms of human respect, and well-being. Dreyer and Hauschild suggested a S-LCA approach for evaluation that incorporates real-world social environments, and regional cultures (Kalvani et al., 2021). A relative value of the social impact assessment based on the data is more reliable and realistic, according to the Hunkeler S-LCA approach. In this method, the quantification of data for the impact assessment is done in five stages, including gathering data on material handling and emissions over the course of a product's life cycle, estimating the number of worker hours from raw material extraction to emission management, estimating the number of working hours for each nation over the course of a product's life cycle, and estimating the purchasing power of the person and nation (Kalvani et al., 2021). Weidema's S-LCA technique acknowledges the protection areas such as people, the biotic environment, and the abiotic environment and uses human life years lost over a product's life cycle to assess the social impact. (Kalvani et al., 2021)

IV.1.1 S-LCA and Automotive Sector

The S-LCA is essential for the automobile sector as it provides valuable insights into the social impacts associated with the entire life cycle of vehicles. While environmental assessments like LCA have been more common in the past, there is growing recognition that social impacts are equally critical to consider in sustainability evaluations.

By conducting S-LCA, automobile manufacturers and stakeholders can gain a comprehensive understanding of the social implications of their products. This knowledge empowers them to make more informed decisions and take proactive measures to address any negative social aspects that may arise throughout the vehicle's life cycle. For instance, S-LCA helps to identify potential human rights issues in the supply chain, ensuring that raw materials and components are sourced ethically, and workers' rights are upheld. It can also shed light on labour conditions, worker health and safety, and fair wages during the production phase. By addressing these concerns, automobile companies can enhance the overall well-being of their employees and communities, leading to increased social acceptance and improved reputation. This information aids in developing safer and more sustainable transportation solutions and policies, ultimately benefiting society as a whole. Furthermore, an S-LCA approach highlights the importance of end-of-life management for automobiles. Proper recycling and waste disposal practices can reduce the burden on landfills and minimize potential negative impacts on waste pickers and local communities. This contributes to the creation of a circular economy and fosters a more sustainable approach to automobile manufacturing and consumption. In conclusion, the social life cycle assessment is crucial for the automobile sector because it facilitates a comprehensive evaluation of the social impacts associated with vehicles throughout their life cycle. By identifying and addressing social challenges, automobile manufacturers can enhance their social performance, build stronger relationships with stakeholders, and contribute to a more sustainable and socially responsible automotive industry.

One of the main challenges to carry out S-LCA for automobile is the complexity and global nature of the automotive supply chain. Automobile manufacturers source components and raw materials from numerous suppliers across different countries, making it challenging to trace and assess the social impacts at each stage of the supply chain. Furthermore, the privacy and confidentiality concerns of data shared by various stakeholders in the automotive industry can hinder the availability of relevant social data for assessment. Companies may be reluctant to disclose sensitive information related to labour conditions, supplier relationships, and community engagement, limiting the depth and accuracy of S-LCA studies. Another crucial issue is the lack of standardized methodologies and impact assessment indicators for S-LCA in the automotive sector. Different studies may use varying criteria and metrics to assess social impacts, making it difficult to compare results and draw meaningful conclusions.

Additionally, conducting an S-LCA for automobiles requires collaboration and engagement with a wide range of stakeholders, including government agencies, non-governmental organizations, labour unions, and local communities. Building these partnerships can be time-consuming and resource-intensive, making it challenging for some companies to fully embrace the S-LCA approach.

In conclusion, while Social Life Cycle Assessment offers valuable insights into the social impacts of automobiles, the automotive sector faces several challenges in conducting such assessments. These include complexities in the supply chain, data sharing concerns, lack of standardization, and the need for broad stakeholder engagement. Addressing these challenges is essential to promote sustainable and socially responsible practices in the automobile industry.

IV.1.2 Survey Findings

A survey was also conducted on 14 partner companies of the project aimed to evaluate their knowledge of social life cycle assessment associated with their company as well as social topics throughout their life cycle along with the Environmental LCA. The survey employed various types of questions which includes multiple-choice questions and open questions. First of all, 78.6% (11) of organizations participated in the survey anonymously i. e., without mentioning the company name, among which 6 companies showed a willingness to respond to the social responsibility section and 3 companies on social LCA.

Out of the total of 6 responses, 3 companies often discuss their social issues frequently. The main methods or tools used to tackle social issues are “social risk assessment” (6 responses) and a code of conduct for suppliers (6) followed by reporting (5) and audit (2). The feedback on which social issues the companies collected data for were even for almost all choices except for “corruption” as only 1 company collected data for it. Also, all 6 participating companies disclosed that they publish sustainability reports annually. Coming to the social issues related to suppliers, companies mainly ask sustainability-related questions to the suppliers only to a limited extent and this is also the same with respect to the companies that handle the waste or by-product of the respective organization. In terms of measuring S-LCA in the future, 3 out of 6 companies don’t have an exact answer whereas 2 of them responded that they will measure to a large extent.

3 companies came forward to participate in the S-LCA survey from which only 1 was familiar with it and the UNEP/SETAC guideline and has used it. In addition, 2 companies felt that such a method is necessary for them and hence for using it, training is something very important followed by access to data. Also, 1 company expressed a clear need to implement S-LCA in their firm.

According to the Goal and Scope, currently, the Handbook for Product Social Impact Assessment by Pre-Sustainability is the methodology used by 1 company for S-LCA. The main motivation to perform S-LCA was to identify the social risks and hotspots. However, according to one response, lack of data and complexity in the supply chain are the main challenges faced while performing S-LCA. Also, 1 company responded that they have a dedicated team to conduct such studies.

The rest of the questions of the survey which comes under the inventory, impact assessment, and interpretation phases were unanswered by the participants.

IV.1.3 Phases of the S-LCA

The S-LCA methodology typically consists of four phases, namely goal and scope definition, inventory analysis, impact assessment, and interpretation. These phases provide a structured approach to understanding and evaluating the social implications of a product or service.

Goal & scope phase of a S-LCA focuses on clearly defining the objectives and purpose of the study. This step aims to answer critical questions such as: Why is the study being conducted? What are its goals? How will the findings be utilized? Who is the intended audience? What aspects do we intend to assess? Is the study intended to support decision-making processes? If so, in what specific area? Furthermore, this phase considers the potential improvement opportunities that can be derived from the knowledge generated through the study. Which areas can be enhanced? How can social sustainability be improved? It also identifies the stakeholders who are directly or indirectly affected by the product, service, or organization being assessed (UNEP/SETAC, 2020).

The scope should define – what to analyse and how, it should define functional unit, reference unit &flow, product system, activity variable, cut-off criteria, system boundaries, approaches, and impact categories and subcategories (João et al., 2016).

Life cycle inventory involves identifying the data for collection, collecting the data for hot spot assessment, collecting data for the selected/relevant stakeholders and subcategories, collecting complementary data for the impact assessment, collecting site-specific and generic data for unit processes, and activity variables and finally collecting data for scoring or weighting. (UNEP/SETAC, 2020).

Life cycle impact assessment includes Calculating, understanding, and evaluating the magnitude and significance of the potential social impacts of a product system throughout the life cycle of the product. Interpretation mainly consists of a completeness check, consistency check, sensitivity and data quality check, materiality assessment, conclusions, limitations, and recommendations regarding the earlier phases (UNEP/SETAC, 2020)

By following these four phases, S-LCA provides a comprehensive understanding of the social implications associated with a product or service, enabling stakeholders to make informed decisions and take appropriate actions to improve social sustainability throughout the life cycle.

It helps identify areas for improvement, fosters stakeholder engagement and contributes to the development of socially responsible practices.

IV.2 Phase I. Goal and Scope Definition

Summary of key findings from the review

- The goal and scope definition phase are crucial in S-LCA, like LCA.
- Goal definition involves defining the purpose of the study, its intended use, target audience, and what aspects will be assessed.
- Clear definition of the goal is important for successful outcomes in S-LCA.
- Examples of goals include identifying social hotspots in the supply chain of lithium-ion batteries and determining the social performance of a freight service in a developing country and its supply chain.
- Activity variables measure process activity and can be used to determine the impact share of a process.
- Primary data can be collected from the study site, while secondary data can be obtained from databases.
- Primary and secondary data are often used together in S-LCA studies.
- Allocation methods and communication strategies are not mentioned in the reviewed studies.
- Stakeholder categories include workers, local communities, value chain actors, consumers, society, and children.
- Impact sub-categories vary depending on the database used.

Like LCA, “goal and scope definition” is the most important phase in S-LCA since the assessment is carried out based on what is defined in this first phase. This phase is investigated in two parts below: Goal definition and scope definition.

IV.2.1 Goal definition

The UNEP Guideline (2022) state that during the goal definition phase, the purpose of the study will be defined with questions like, "What is its goal? What is its intended use? Who are the target audience? What do we want to assess? For an S-LCA to be successful, the goal must be clearly stated.

Below are a few goal examples from publications that have been reviewed.:

“To identify the social hotspots in the supply chain of lithium-ion batteries used in electric vehicles.”(Thies et al., 2019)

"The goal of the case study was determining the social performance of the freight service offered by a company in a developing country such as Malaysia and in its supply chain."(Osorio-Tejada et al., 2020)

"The goal of the implementation of S-LCA framework in this work is to evaluate the social risks associated with electric vehicle transportation technologies in comparison with the conventional ones." (Bouillass et al., 2021)

In the reviewed articles the intended use of the results is described as methods to compare different scenarios, create evaluation tools and provide indicators for social risk assessments. Insight from the studies can be used to inform decisions-makers as well as trigger actions and collaborations among stakeholders to mitigate negative impact and reduce social risks throughout the life of a product or service.

The target audience in the reviewed articles were mostly stated as manufacturers along the supply chain. S-LCA practitioners, researchers and public were the other mentioned target audiences. However, there might be other audiences like trade unions and workers' representatives, governments, NGOs to be targeted. The limited target audience might be related to the limited number of the studies that were reviewed and/or that they were published in scientific journals.

Some of the reviewed articles also include the application timeframe of the study as well as the databases that are used to conduct the study. The potential improvement opportunities based on the S-LCA results is also defined in the goal definition. The opportunities listed in the reviewed articles are improvement of working conditions, human rights etc. (Shi et al., 2023), to reduce social risks in the production value chain (Baumann et al., 2013; Koese et al., 2023), to start collaborations between stakeholders to decrease negative social impacts (Thies et al., 2019), to develop more sustainable mobility strategies (Gompf et al., 2020).

If the study intends to support decision making this can be also defined in the goal definition. In Koese et al., (2023)informing decision-makers while choosing from different alternatives is mentioned and, in the paper, related to S-LCA of mobility services (Gompf et al., 2020), city planners are mentioned to be supported for decision making.

IV.2.2 Scope definition

The scope definition of S-LCA is similar to LCA, clarifying the object of the study and determine the methodological framework related to the goal of the study. The scope definition covers the definition of the function of the object and its functional unit or service, determining the reference flow, activities in the product system and identifying the system boundaries, choice of impact assessment method, data collection strategies, data quality requirements, allocation, limitations, interpretation, and communication strategies. However, there is an additional feature in the S-LCA which is related to stakeholders.

According to the UNEP/SETAC guideline for S-LCA the functional unit defines quantitatively the object of a study. The functional unit in the studies examined for this research has included, for example., an instrument panel for a vehicle, a battery, an airbag system, 1 km of vehicle travel, a unitary freight service between different cities, mobility services in urban context etc. The reference flow represents the quantity of materials or resources needed to produce the product or output being studied. The functional unit helps quantify the object of study and provides a basis for determining the reference flow. It allows for the comparison of different products or services based on social impacts. It could be the annual production of airbags systems and the lives and injuries that are saved and lost annually, or the mass of material needed per battery pack.

According to UNEP/SETAC guideline, the product system is the definition of what steps, activities and organizations are needed to comply with the functional unit. The system boundaries are the identification of which parts of the assessment. The system boundary can be identified as cradle-to-grave, cradle-to-gate or gate-to-gate. In Koese et al., (2023) although the system boundary is defined as cradle-to-use, the social impacts that can raise during end-of-life stage is discussed separately. Cradle-to-grave, cradle-to-gate, cradle-to-use, or merely use phase are all referred to as system boundaries in the evaluated publications.

The concept "activity variable" is also an additional feature in S-LCA. According to the Guideline "The activity variable is a measure of process activity which can be related to process output." and "The activity variable may be used to represent the impact share of a process compared to that of the product system (e. g., working injuries can be partitioned among processes based on worker hour(s) per process". However, it is not compulsory to use activity variable, so it is not used in all studies. In SHDB and PSILCA databases the activity variable is worker hours, therefore the reviewed studies that used SHDB or PSILCA (for example Shi et al., (2023 and Thies et al., (2019) used worker hours as activity variable) (for more information on databases, please refer to section 4.3.1). The chosen variables will determine the importance of different activities in the product system. Worker-hours is the most used activity variable.

Data collection strategies and data quality requirements are also defined in the scope definition. Primary data can be collected from the study site or secondary data can be collected from databases and these can be used together in the study. In most of the reviewed studies primary and secondary data is used as complementary to each other. However, data quality is not mentioned in most of the studies or only mentioned briefly related to the data quality of the database used.

Allocation method can be also defined in the scope definition; however, allocation was not mentioned in any of the reviewed studies. This is also the same for the communication strategies for the results (selection of results to be communicated, communication format and specifications, type and format of report, other communication) that can be defined in the scope definition. Limitations of the study needs to be explained in the scope definition in a similar manner to LCA. For example, indicators being measured country-based and not sector-based is mentioned as a limitation in (Koese et al., 2023), and the limited number of interviews that were used to collect data for qualitative indicators (Gompf et al., 2020) are listed as limitations. It is advised to adhere to the critical review type described in ISO 14040–14044. Since the work was published in peer-reviewed publications, the critical review is not done separately in any of the considered studies.

IV.2.3 Impact assessment method

During the goal and scope definition phase, the impact assessment method should be chosen. There are two methods: the Reference Scale S-LCIA and Impact Pathway S-LCIA. To what extent these methods will be applied should be determined through the weighing approach, i. e.:

1. Equal weighting
2. Most robust indicators prioritized
3. Expert or stakeholder values
4. Worse performance prioritized

More information on the impact assessment methods as well as how they are applied in the reviewed articles is presented in section 4.4.

IV.2.4 Stakeholders, impact categories and indicators

Based on the selected impact assessment method, the social topic of interest should be identified by selecting stakeholders, impact categories, and subcategories if relevant. Referring to the UNEP/SETAC Guideline, the impact categories that can be affected are human rights, working conditions, health and safety, cultural heritage, Governance, and Socio-economic repercussions.

Definition of affected stakeholder categories is an important S-LCA step which does not exist in LCA since stakeholders are not relevant in environmental LCA. However, in the S-LCA, stakeholder categories and impact (sub)categories are the core of the assessment. In the Guideline there are six stakeholder categories which are Worker, Local community, Value chain actors, Consumer, Society and Children, and 40 impact sub-categories are classified according to the stakeholder categories. The stakeholder categories and impact sub-categories in the Guideline are listed in Table IV-1.

Table IV-1.Stakeholder categories and impact categories in the UNEP guideline

Stakeholder category	Impact subcategory
Worker	1. Freedom of association and collective bargaining
	2. Child labour
	3. Fair salary
	4. Working hours
	5. Forced labour
	6. Equal opportunities/ discrimination
	7. Health and safety
	8. Social benefits / social security
	9. Employment relationship
	10. Sexual harassment
	11. Smallholders Including farmers
Local community	1. Access to material resources
	2. Access to immaterial resources
	3. Delocalization and migration
	4. Cultural heritage
	5. Safe and healthy living conditions
	6. Respect of indigenous rights
	7. Community engagement
	8. Local employment
	9. Secure living conditions
Value chain actors (not including consumers)	1. Fair competition
	2. Promoting social responsibility
	3. Supplier relationships
	4. Respect of intellectual property rights
	5. Wealth distribution
Consumer	1. Health and safety
	2. Feedback mechanism
	3. Consumer privacy
	4. Transparency
	5. End-of-life responsibility
Society	1. Public commitments to sustainability issues
	2. Contribution to economic development
	3. Prevention and mitigation of armed conflicts
	4. Technology development
	5. Corruption
	6. Ethical treatment of animals

Stakeholder category	Impact subcategory
	7. Poverty alleviation
Children	1. Education provided in the local community
	2. Health issues for children as consumers
	3. Children concerns regarding marketing practices

In the social databases like SHDB and PSILCA not all 40 subcategories that are listed above are assessed. The impact sub-categories in SHDB and PSILCA are given in Table IV-2 and Table IV-3 respectively. As a result, even while all the sub-categories available in the database are covered in the study, only some of the impact sub-categories from the Guideline are evaluated if the S-LCA study is based on a database. In the SHDB, unlike the Guideline and PSILCA, the impact sub-categories are categorized under impact categories and not stakeholder categories (Table IV-2).

Table IV-2. Impact categories and impact subcategories in SHDB

Impact category	Impact subcategory
1 Labour Rights & Decent Work	1A Wage
	1B Poverty
	1D Child Labour
	1E Forced Labour
	1F Excessive Work Time
	1G Freedom of Association
	1H Migrant Labour
	1I Social Benefits
	1J Labour Laws/Conventions
	1K Discrimination
	1L Unemployment
2 Health & Safety	2A Occupational Toxicity & Hazards
	2B Injuries & Fatalities
3 Human Rights	3A Indigenous Rights
	3B Gender Equity
	3C High Conflict Zones
	3D Non-Communicable Diseases
	3E Communicable Diseases
4 Governance	4A Legal System
	4B Corruption
5 Community	5A Access to Drinking Water
	5B Access to Sanitation
	5C Children out of School

Impact category	Impact subcategory
	5D Access to Hospital Beds
	5E Smallholder versus Commercial Farms

Table IV-3. Stakeholder categories and impact subcategories in PSILCA. (Maister et al., 2020)

Stakeholder category	Impact subcategory
Worker	1. Child labour
	2. Forced labour
	3. Fair salary
	4. Working time
	5. Discrimination
	6. Health and safety
	7. Social benefits, legal issues
	8. Worker`s rights
Local community	1. Access to material resources
	2. Respect of indigenous rights
	3. Safe and healthy living conditions
	4. Local employment
	5. Migration
	6. GHG footprints
	7. Environmental footprints
	8. Labor footprints
Value chain actors (not including consumers)	1. Fair competition
	2. Corruption
	3. Promoting social responsibility
Society	1. Contribution to economic development
	2. Health and safety
	3. Prevention and mitigation of conflicts

The evaluated stakeholder categories are listed in the S-LCA case studies that have been studied. Typically, the most affected stakeholder categories are determined during the study's scope defining phase, and the decision is justified. For example, Koese et al., (2023) mentioned "*The workers, local communities, and society stakeholder groups are chosen because the supply chain is expected to mainly affect these stakeholders and these categories are covered most comprehensively in the PSILCA database*". It was noted that the choice of stakeholder categories is also related to the availability of the assessed stakeholder categories in the used database.

To assess the impact on the (sub)categories, relevant indicators should be selected in this phase. Table IV-4 presents examples of some of the indicators used throughout the reviewed scientific studies.

Table IV-4. List of Indicators used throughout the reviewed studies

Category	Indicator	Type of indicator	Calculation Formula description
Safety	Number of passengers	Quantitative	Accessibility= total number of passengers per mobility mode
	Fatal and non-fatal traffic accidents	Quantitative	Safety = No. of fatal and non-fatal traffic accidents/total no of trips
Affordability	Trip fare	Quantitative	Trip fare = Fare of 5 km trip within study area/average income
Privacy	Data privacy	Qualitative	Measures the extent to which a company respects and protects users' data privacy
Child labour	Prevention of child labour	Qualitative	Measures the extent to which a company works to eradicate child labour and pro-actively raising awareness of issues associated with child labour
Fair salary	Remuneration	Qualitative	Measures the extent to which management compensates workers. The indicator measures a combination of wages and social benefits received by workers
	Minimum wage paid	Quantitative	Minimum wage paid= number of workers with at least minimum wage/total number of employees * 100

Source: (Gompf et al., 2022).

IV.3 Phase II. Inventory Analysis

Summary of key findings from the review

- The inventory analysis phase in S-LCA involves collecting data for all relevant processes within the defined system boundary.
- Data collection includes both physical flows for unit processes and social inventory data based on chosen stakeholders and subcategories.
- Social databases like SHDB and PSILCA are most used and can be used to model the system and connect sectors with a specified currency.
- Best way to of data collection is site-specific data collection, using S-LCA dedicated databases, or through input-output or other databases.
- Indicators for social inventory data can be qualitative, semi-quantitative, or quantitative.
- The suggested sources for inventory indicators include interviews, company reports, websites, governmental agencies, and NGOs.
- Main Challenges during data collection include data availability and data quality.
- S-LCA can be conducted with an attributional or consequential approach, with most studies using an attributional approach.
- Dedicated databases for S-LCA include SHDB and PSILCA, providing access to social data on the country-specific sector level and not site specific or product level.
- SHDB and PSILCA databases are based on input-output models and worker-hour models, but with different underlying methodologies for example, assigning risk levels.
- SHDB is frequently used for social hotspot analysis.

The social life cycle inventory phase covers the data collection for all relevant processes that are defined in system boundary in the scope definition step. In the inventory phase both physical flows for all unit processes and social inventory data needs to be collected. Social inventory data is collected based on the stakeholder and subcategories chosen in the goal and definition phase. Social databases can be used to model the assessed system as a sector-based model where the sectors are connected to each other with a specified currency. According to the Guideline, sector-based and process-based models can be used together in a hybrid model.

The Guideline states that data collecting needs to be prioritised because it takes the most time, much like the LCA stage did, particularly when site-specific data is gathered from organisations. To do that, it is necessary to first conduct a literature review to determine whether the system under investigation has any documented social issues. However, it is also possible to argue that all impact categories must be , as stated in Koese et al., (2023). Finding the most intensive activities and locating system hotspots are the second and third methods for prioritising data (UNEP/SETAC, 2020). The analysis of social hotspots typically uses SHDB.

Data can be collected using the three approaches below (UNEP, 2020):
1. Through site-specific data collection.
2. Use of an S-LCA dedicated database (SHDB or PSILCA).
3. Through input-output or other databases.

These approaches can be combined or used alone where needed. To evaluate social impacts of mobility services in Berlin, Gompf et al., (2020) collected public transportation and population density information from geographic information system. They used company sustainability reports and their code of conduct and used SHDB. Besides this publicly available data sources, they conducted interviews to collect data related to the chosen indicators. On the other hand, some of the reviewed studies (e. g., Koese et al., (2023)) are based on input/outputs of the studies processes and conversion of this data into economic sectors using PSILCA database.

During the foreground and background systems data collection, data about the social flows and indicators are collected, e. g., salary or number of accidents. In the studies where the databases are used, the data for the indicators are already in the database therefore in these studies it is mentioned that the indicators are used as in the database (e. g. Koese et al., (2023)). In most of the studies one of the widely used databases (SHDB or PSILCA) is used. The databases can be used with different software however in all reviewed studies that use databases, OpenLCA was chosen as the software. The only challenge mentioned for using a database is that the data is country and sector specific. Different countries and sectors may have different approaches to data collection and reporting. This can result in inconsistencies in the data, making it challenging to compare social impacts between regions or industries accurately. Country and sector-specific databases may not cover all relevant social indicators for a comprehensive S-LCA. As a result, the assessment may not capture the full range of social impacts associated with a product's life cycle.

While collecting the data, the system can be subdivided process-based, sector-based or hybrid. All three are applied in different reviewed studies.

According to the Guideline there are three approaches to prioritize data collection:

1. Does the literature review of the studied system identify key social issues not to miss in the S-LCA?
2. Which are the most active or intensive activities/unit processes in the studied system, e. g. based on an activity variable?
3. Identify the hotspots in the product’s life cycle.

In the reviewed studies data prioritization is only mentioned in Koese et al., (2023), as they didn`t prioritize any data according to their literature research.

Life cycle inventory data is collected mainly based on chosen social inventory indicators specific to impact sub-categories. According to the Guideline, "*indicators can be of qualitative, semi-quantitative, or quantitative nature*". In the methodological sheets (2021), several indicators are suggested for all impact sub-categories. In Table IV-5, as an example, the indicators suggested for Health and Safety subcategory under Worker stakeholder category are listed.

Table IV-5. Suggested indicators for Health and Safety sub-category (Traverso et al., 2021)

Indicators
- Number/percentage of injuries or fatal accidents in the organization by job qualification inside the company
- Hours of injuries per level of employees
- Presence of a formal policy concerning health and safety
- Adequate general occupational safety measures
- Preventive measures and emergency protocols exist regarding accidents and injuries
- Preventive measures and emergency protocols exist regarding pesticide and chemical exposure
- Appropriate protective gear required in all applicable Situations
- Number of (serious/non-serious) Occupational Safety and Health Administration (OSHA) violations reported within the past 3 years and status of violations
- GRI LA8 - Education, training, counselling, prevention, and risk control programs in place to assist workforce members, their families, or community members regarding serious diseases

The suggested data sources for the inventory indicators in Table IV-5 are; interviews with management and human resources, company reports (audits or sustainability reports) and websites, interviews with workers and unions, governmental agencies and non-governmental organizations (NGOs). (UNEP, 2021)

Some interview questions are listed in Table IV-6. These interview questions were used to collect data to assess the Freedom of Association subcategory by Gompf et al., (2022).

Table IV-6. Interview questions related to inventory indicators of Freedom of association impact sub-category

Interview questions
Is there a general regulation/company policy that gives employees the freedom to join labour unions or private organizations?
Can you estimate approximately how many employees in your company have joined a union?
Does your company have a workers' council that represents the interests of the employees to the Board of Management? - If not, is a foundation planned? - If not, would you find the introduction of a workers ‘council critical? If so, what is the cooperation between the workers' council and the employer like? Is the workers' council accepted?
Does your company accept its workers' council and unions as negotiating partners in collective bargaining, etc.?
Are you aware of cases where employees have been directly or indirectly prohibited from joining a labour union or forming a workers’ council/standing for election? If so, was any action taken as a result?

The challenges during data collection are mentioned as data availability and data quality in some of the studies. This availability issue leads to exclusion of some stakeholders as in Koese et al., (2023).

Multifunctionality of the systems and allocation method to be used to handle division of the social impacts into different functions are not mentioned.

Like LCA, S-LCA can be conducted with an attributional or consequential approach. Only one of the studies (Pastor et al., 2018) mentions that their study is conducted using a consequential approach and the rest of the studies are conducted with an attributional approach.

IV.3.1 Database

Dedicated databases currently available for S-LCA on the market are Social Hotspot Database (SHDB)[17] and Product Social Impact Life Cycle Assessment (PSILCA) database[18]. The SHDB and PSILCA databases provide access to large amounts of social data on the country-specific sector (CSS) level, which enables practitioners to assess social risks associated with certain sectors and product systems. The two main functions of these databases are to complete a study

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[17] https://nexus.openlca.org/ws/files/23286

[18] https://psilca.net/wp-content/uploads/2020/06/PSILCA_documentation_v3.pdf,

or provide screening of social risks prior to an in-depth study i. e., identify hotspots that will be studied further. SHDB and PSILCA databases are based on three main building blocks: An Input-Output model, a Worker-Hours model, and a database on social aspects. However, it`s important to be aware of the differences. The Input-Output models underlying both social LCA databases differ: SHDB is based on the GTAP Input-Output model, but PSILCA is based on EORA/MIRO Input-Output model. Both databases have applied different methodologies for calculating the worker-hour model. The main social data sources used to create social risk tables are shared among the databases, however, methodologies used to assign risk levels may differ.

The GTAP (Global Trade Analysis Project) Input-Output model and the EORA/MIRO (Economic Input-Output and Resource Accounting/Multi-Regional Input-Output) model are both widely used frameworks for analysing economic interdependencies and trade relationships between different sectors and regions. While they share similarities in their general structure as input-output models, there are notable differences in their data sources, coverage, and applications. The GTAP Input-Output model is developed and maintained by the Global Trade Analysis Project, a collaborative effort among numerous institutions and researchers worldwide. It provides a global database of input-output tables and bilateral trade data, covering a wide range of economic activities and countries. The GTAP model is particularly known for its focus on trade and international economic relationships, making it well-suited for analysing the impacts of trade policies, regional economic integration, and global supply chain linkages. On the other hand, the EORA/MIRO Input-Output model is a product of the EORA project, which focuses on environmental and resource accounting aspects in addition to traditional economic analysis. The EORA model incorporates satellite data on environmental accounts and resource consumption, enabling the assessment of economic-environmental linkages and the estimation of environmental footprints associated with different industries and regions. The differences between the two models lie in their data coverage and intended applications. While the GTAP model emphasizes global trade and economic interdependencies, the EORA/MIRO model extends its focus to encompass environmental considerations. Thus, the EORA/MIRO model is more suitable for analysing the environmental impacts of economic activities and consumption patterns, making it useful for studies related to sustainability and natural resource management.

IV.4 Phase III. Impact Assessment

Summary of key findings from the review

- Impact assessment is a process to evaluate the positive or negative effects of policies, projects, and activities using predetermined criteria.
- Social impact assessment in social life cycle assessment (S-LCA) evaluates the potential social impacts of a product or product system throughout its lifecycle.
- Two methods used in S-LCA are the reference scale approach (RS S-LCIA) and the impact pathway approach (IP S-LCIA).
- The reference scale approach uses a predefined benchmark or set of criteria to assess social performance and social risks.
- The impact pathway approach focuses on cause-effect relationships between activities and social impacts, using midpoint and endpoint indicators.
- Other approaches in impact assessment include the checklist method, scoring method, database method, empirical method, environmental life cycle inventory database method, and PLAN-DO-CHECK-ACT method.
- A review of 27 articles found that the Performance Reference Points/Reference Scale approach was the most commonly used method, followed by the Impact Pathway approach.
- All stakeholder categories except Children were addressed.
- Worker' stakeholder category is identified as having high negative impacts and low performance and 'Local community' is the stakeholder category with a high-performance rate or the stakeholder group with very low risk.
- The assessment results indicate both positive and negative impacts in various categories, with workers and local communities often experiencing negative impacts.

Impact assessment is a process that systematically determines the positive or negative effects or impacts of policies, projects, and activities and evaluates them using a set of predetermined criteria. (Remer, 2018). The main three applications of the impact assessment are Economic impact assessment to conduct a cost-benefit analysis, Environmental impact assessment, and finally the social impact assessment in the form of a social impact analysis or a health impact assessment. (Remer, 2018). In the context of social life cycle assessment, the definition of life cycle impact assessment (LCIA) is more specific. UNEP guideline state that the social impact assessment phase in S-LCA is the process of evaluating the potential magnitude and significance of the potential social impacts of a product or product system throughout its lifecycle. (UNEP/SETAC, 2020). It can be used for analysing past, current, and future impact assessments of a product system. Terms such as ‘’impact indicators, impact categories, and impact subcategories’ are always associated with the process of social life cycle impact assessment. The main aim of S-LCIA is to assess social performance, social risk, and social impacts by characterizing the cause-and-effect chain. There are many methods and approaches available for SLCIA and the selection of each method depends on what we want to assess. (UNEP/SETAC, 2020)

IV.4.1 Characterization Models /Types

The social life cycle impact assessment is conducted using one of two techniques, as per the UNEP/SETAC guideline for S-LCA:

- Reference scale (Type 1) – social life cycle impact assessment method (RS S-LCIA)
- Impact pathway (Type 2) – social life cycle impact assessment method (IP S-LCIA)

These two methods are also known as the characterization models.

Reference scale approach

A reference scale is an ordinal scale that typically consists of grades 1 through 5, with each grade corresponding to a performance reference point (PRP). PRPs are thresholds, goals, and objectives that set different levels of social performance or social risk and assess the magnitude and significance of potential social impacts associated with organizations and products within production systems. PRPs are contextual and often based on international standards, local laws, or industry best practices. It can also be based on comparing relevant stock index data to these values, it is possible to identify whether the collected data indicate negative or positive developments. RS S-LCIA methods are selected when the impact assessment aims to find out the social risk or social performance of the product system. According to UNEP/SETAC, (2020), social performance refers to the evaluation of business activities against established benchmarks or standards. It involves measuring the company's performance using specific data relevant to that particular organization. This approach recognizes the unique context and characteristics of each company. On the other hand, social risks are assessed by considering the extent of social impacts experienced by stakeholders due to a company's activities throughout its life cycle and business relationships. These risks can also arise because of unexpected incidents or events. Social risk evaluations typically incorporate generic or sector- and country-level data to assess the potential social effects and their significance. In summary, social performance assessment involves measuring a company's activities against specific standards, utilizing company-specific data. In contrast, social risk evaluations consider the rate of social impacts on stakeholders throughout the life cycle and business relationships, and they often rely on more general data at the sector or country level. RS S-LCIA also known as the Type-1 model doesn’t consider any causal relationships (cause-effect) and summarizes each model according to the scoring system such as multi-level scores for indicators or two levels of score. (Social life cycle assessment revisited). There are two types of reference scales as shown in Table IV-7 and Table IV-8:

Table IV-7. Generic ascending reference scale which is used for social performance evaluation

+2	Ideal performance best in class
+1	Beyond compliance
0	Compliance with local & international laws/basic societal expectations
-1	Slightly below compliance level
-2	Starkly below compliance level

Table IV-8. Generic descending scale which is used for social risk assessment

🟥	Very High Risk
🟧	High Risk
🟨	Medium Risk
🟩	Low Risk

Ascending reference scales range from negative to positive social performance and it is normally used for performance evaluation, if it is descending, it ranges from low risk to very high risk of potential impacts and it is used for the social risk evaluation. (UNEP/SETAC, 2020). In the reference scale approach, the first step is to develop performance indicators that serve as both quantitative and qualitative markers of performance. These indicators are designed to measure various aspects of a system or process being assessed, such as social impacts, sustainability, or specific performance criteria. They provide a standardized way to evaluate and compare performance across different entities or time periods. Once the performance indicators are established, the next step involves assessing the inventory data and performance indicators against reference scales. A reference scale is a predefined benchmark or set of criteria against which the performance is evaluated. It can be based on established standards, industry best practices, regulatory requirements, or other relevant frameworks.

Impact pathway approach

The main target of the impact pathway approach is to assess and develop a model which consists of the relations between the cause and effect. The impact pathway assessment is based on the social mechanisms, and it belongs to certain impact subcategories. IP S-LCIA approaches do not strongly focus on the stakeholder groups but will give the impact results of a social issue through midpoint and endpoint indicators. Midpoint Indicators: Midpoint indicators are used to measure intermediate social impacts that occur as a result of a product's life cycle activities. These indicators focus on specific cause-effect relationships within the impact pathway. They are often based on quantitative data and can provide insights into the magnitude or intensity of the social impacts. Endpoint indicators could include measures like overall social well-being, social contribution to society, or the level of social sustainability achieved throughout the life cycle. These indicators are useful for comparing different products or services, identifying hotspots or areas of concern, and supporting decision-making processes (UNEP/SETAC, 2020). According to the UNEP/SETAC guideline, there are two types of impact pathways, those are qualitative pathways and quantitative pathways. Qualitative pathways usually identify social topics of interest or concern such as fair wages and child labour and it is described and combines different disciplines of natural and social sciences. The quantitative pathway approach is more focused on measurable numbers and target explanations of one or more phenomena. The quantitative approach is further divided into two, pathways following a mechanistic modelling approach oriented on E-LCA and pathways following a regression-based modelling approach (UNEP/SETAC, 2020). According to a review paper on Social Life Cycle Assessment (S-LCA), impact pathway models are employed as empirical relationship pathways. These pathways can be classified into two main categories: the Preston pathway and the Wikinston pathway (Pollok et al., 2021). The Preston pathway and Wikinston pathway represent different approaches or frameworks for establishing and understanding the relationships between life cycle activities and their social impacts. These methods are mainly quantitative, experimental, or statistical and try to predict consequences based on quantifiable cause-effects or regression-based directional relationships between the product/organization and the resulting potential/actual social impacts (Pollok et al., 2021). The Preston pathway is the approach to set or determinate more causal relations between the process, one example described by the Preston pathway for the empirical relation is: “increasing economic activity(income) leads to better human health and then a better life expectancy” (Pollok et al., 2021). Increased economic activity can be described as the midpoint indicator and better life expectancy is known as the endpoint indicator. It is clear in the example that it is a cause-effect or consequential type of assessment. The Wikinston pathway describes the causal relationship between income and health. It describes that unequal distribution of income is harmful to health and more equally distributed income makes better health conditions. Both pathways are approaches to finding endpoint indicators or results by finding the cause and effects (Louisa Pollok, 2021). The major challenge of the impact pathways model is the model requires quantitative data which is not easily accessible or available and therefore difficult to understand the inter/consequential relation for each social topic considered (Louisa Pollok, 2021).

Other Approaches

The other main assessment methods mentioned in the studies are listed below (Wu & Su, 2020):

1. Checklist method

This method uses two signs to indicate the presence of an impact. This tick sign (√) uses to indicate the presence of an impact in other words, if the subcategory affects the impact category, they are marked with the tick sign. If the subcategory doesn’t affect the impact categories, then impact categories are marked by the sign ‘— ‘. The impact category will be shown as blank if there is no effect between the subcategory and the impact category. The impact assessment column is marked with five different colours. The impact category raw with most of the tick signs will be marked with dark colour and the impact category with a smaller number of tick signs will be marked with light colour. Moreover, this is not an impact evaluation method, but it can conclude whether the evaluated impact from the PRP method exists or not.

2. Scoring method

In this method, scores are used to assess an impact. A questionnaire is used to collect shreds of evidence according to the subcategories and its indicators and the collected data and information are then converted into numerical or quantitative figures by applying the standard scores. The example given in the study for the scoring method is: The number of workers saying YES to the question of wage satisfaction in the survey represents the fraction of sampled population of workers satisfied with their wages and marks the percentage of each subcategory based on the established scoring standard. The other type of scoring method indicates positive and negative impact with a score ranging from 1 to 6. ‘1’ represents positive impact and ‘6’ represents very negative impact.

3. Database method

SHDB and PSILCA are the two main databases available for the S-LCIA. Both of the databases contain data, categories, and indicators framework from the methodological sheets and the UNEP guideline. It uses global government, organizational and statistical data as the main sources. It contains data about the impacts of each subcategory of different nations, sectors, and regions.

4. Empirical method

The empirical formulas or rules used to assess the social impacts, there are mainly two empirical methods, they are QALYs (quality-adjusted life years) and DALYs (Disability-adjusted life years). Perston’s pathway is also a kind of empirical method that is used to assess the health, education, and employment impacts.

The calculation procedures of the DALY indicator are obtained from a case study about the social impact assessment of airbags.:

Therefore DALY=YLL+YLD

YLL= years of life lost
YLD= years of life disabled
YLD=w*D, where w is a severity factor between complete health and complete disability

Here, if the DALY result is 0 it indicates complete health and if DALY is 1 it indicates complete disability measured in years.

5. Environmental life cycle inventory database method

An environmental database or life cycle inventory database is used for estimating social impact assessment; therefore, the functional unit system boundary is kept constant as an environmental life cycle impact assessment. It is not possible to assess all the social impacts but to assess impacts related to health and employment. (Marzia Traverso, 2020)

6. PLAN-DO-CHECK-ACT

Plan-do-check-act is one of the social life cycle assessment methods used in a case study “A practical approach for social life cycle assessment in the automobile industry”. It has a strong focus on the characterization and standardization of indicators of mining, production, and disposal processes and the interrelations with activity variables. The four steps are described below.

Firstly, a survey of all possible stakeholders will be conducted, and development indicators used to characterize the social aspects. The categorized indicators assess against the PLAN-DO-CHECK-ACT

Plan – Analyse whether a company has defined or written policies for the respective social aspect.

DO- develop measures/systems to implement the principles.
Check- Introduced control measures to monitor the implementation.
Act- Established a process to react to violations. (Wu & Su, 2020)

IV.4.2 Reviewed Article Findings on Social Life Cycle Impact Assessment Methods

This compilation of reviewed case studies, research articles, and review papers offers valuable insights into impact assessment methods within S-LCA. With a total of 27 articles analysed, the aim is to identify the most utilized method and explore its procedural implementation.

The articles cover topics including automobile/mobility/transportation (11 articles), general S-LCA (8 articles), and production/manufacturing sectors (remaining articles). Through this examination, we aim to uncover prevailing methodologies and facilitate informed decision-making for sustainable practices in S-LCA.

Table IV-9. Research articles, author, sector, Impact assessment method, and details

Sl.no	Research article/review/case study	Author	Sector	Impact assessment method used or discussed	Details about impact assessment methods
1	Social life cycle assessment: A review of past development, advances, and methodological challenges	Louis Pollok, Sebastian Sperling.	General	Performance reference points, PLAN-DO-CHECK-ACT, Impact pathway, Scoring method, Checklist method, Database method.	General descriptions
2	Towards social life cycle assessment of mobility services: systematic literature review and the way forward	Katharina Gompf, Marzia Traverso, Jorg Hetterich	Mobility	Reference scale and impact pathway	colour coding, scoring, and weighting methods are used for aggregating the inventory indicator data to impact categories. Inventory data--inventory indicators-subcategory indicators-impact category indicators Assess the social impacts by means of impact pathways as characterization models (midpoint and endpoint indicators used)
3	A practical approach for social life cycle assessment in the automobile industry	Hannah Karlewski, Annekatrin Lehmann, Klaus Ruhland, Matthias Finkbeiner	Automobile	PLAN-DO-CHECK-ACT	Non scoring types, positive impacts displayed as '+' and negative impacts displayed as '-'
4	Social aspects of water consumption: risk of access to unimproved drinking water and to unimproved sanitation facilities an example from the automobile industry	Miriam Moreno Pastor, Thomas Schatz, Marzia Traverso, Volmar Wagner, Olaf Hinrichsen	Automobile	Reference scale/Scoring type	risk assessment though inventory indicators result assess against each step in the system boundary of the study. Scoring risk-level, low 0.01, medium 0.5, high 0.75, and very high 1.0

Sl.no	Research article/review/case study	Author	Sector	Impact assessment method used or discussed	Details about impact assessment methods
5	An integrated social life cycle assessment of freight transport systems and social organizational life cycle assessment of transport services: case studies in Columbia, Spain and Malaysia	Jose Luis Osorio-Tejada, Eval Llera Sastresa, Ahmed Hariza Hashim	Transportation	Performance reference points/ reference scale	1.inventory analysis characterization (Level 1): Linguistic labels based on data source, shows the performance of the sector/country in each social impact subcategory (A numerical value then defined on colour scale) 5-very positive- Green 4-positive- Blue 3-Neutral - Gray 2-Negative-Orange 1-Very negative- Red 2.inventory analysis characterization (level 2): A scoring system ranges from 0-10, Here 5 is the basic requirement that company should meet.
6	Social life cycle assessment of lithium iron phosphate battery production in China, Japan and south Korea based on external supply materials.	Yi Shi, Xintong Chen, Tinting Jiang, Qiang Jin	Li-ion battery Automobile	Social hotspot index SHDB	Characterization model is done by social hotspot index in each subcategory then it aggregated towards the subcategory, correspondingly characterization factors are equal to 0.1,1.5 and 10 respectively provided by SHDB. Three risk levels are determined based on data distribution, expert judgement and literature
7	A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage	Maarten Koese, Carlose F. Blanco, Vincente B. Vert, Martina G. Vijver	Li-ion battery Automobile	Performance reference points	Performance assessment is performed to find the impact of the categories with standard performance reference points. If score 1 - Dark green- Very good performance if score 6-Dark red- very poor performance inventory data of each impact categories assess against performance reference points.

Sl.no	Research article/review/case study	Author	Sector	Impact assessment method used or discussed	Details about impact assessment methods
8	Development of a social life cycle assessment framework for manufacturing organizations	Ben Ruben R, Prasanth Mrnon, Raja Sreedharan	Manufacturing	performance reference points and impact pathway	in performance reference point method If score 1 - Dark green- Very good performance if score 6-Dark red- very poor performance
9	Step by step SLCA assessment framework: a participatory approach for the identification and prioritization of impact subcategories applied to mobility	Ghada Bouillass, Isabelle Blanc, Paula Perez-Lopez	Mobility	reference scale approach	
10	Does the production of an airbag injure more people than the airbag saves in traffic? (Opting for an empirically based approach to SLCA)	Henrike Baumann, Rickard Arvidson, Hui tong, Ying Wang	Automobile	Empirical Methods (DALY)	calculations already explained
11	Assessment of social sustainability hotspots in the supply chain of lithium-ion batteries	Christian Theis, Karsten Kieckhafer, Thomas s Spengler, Manbir S Sodhi	Li-ion battery Automobile	Reference scale Performance reference points	Different risk categories are expressed relative to the medium risk level by multiplying them with respective characterization factors.
12	Cornell digiciation, SLCA of electric vehicles compared to conventional vehicles	Kyle Morgan	Automobile	Reference scale Colour coding	Green-positive effect red-very negative effect
13	Social life cycle assessment in Indian steel sector: a case study	Rajesh Kumar Singh	Steel	Reference scale Scoring method	reference scale range 1-4 low risk to high risk
14	social life cycle assessment for material selection: a case study of building materials	Seyed Abbas Hosseinijou	construction	site-specific analysis/Analytic hierarchy process	Rating and ranking alternatives by site specific data

Sl.no	Research article/review/case study	Author	Sector	Impact assessment method used or discussed	Details about impact assessment methods
15	Social impact improving model based on a novel social life cycle assessment for raw rubber production: A case of Sri Lankan rubber estate	Passan Dunuwila, Vhl Rodrigo	Rubber	Reference scale and impact pathway approach	Reference scale ranges from1-6 Impact pathway with midpoint and endpoint indicator
16	SLCA: organic cotton sweater	Marie Loubert, Green delta	cotton	PSILCA	
17	Calculation of fair wage potentials along products life cycle introduction of a new midpoint impact category for social life cycle assessment	Sabrina Neugebauer, Yasmine Emara, Christine Hellerstrom, Mathias Finkbeiner	General SLCA	Impact pathway	Inventory indicators--midpoint categories--endpoint categories
18	Towards social life cycle assessment	Marzia Traverso, Lynn bell, Peter Saling, Joao Fontes	General SLCA	Reference scale/reference value	
19	Addressing the effect of social life cycle assessments	Andreas Jorgensen, Louise C, Arne Wangel	General SLCA	Consequential SLCA/Educative SLCA/Lead firm SLCA	
20	Applying social life cycle assessment in the early stages of a product development -an example from the mining sector	Stephanie muller, Antoine Beylot	Mining sector	PSILCA Database/reference scale	
21	Social organizational life cycle assessment and social life cycle assessment: different twins? Correlations from a case study	Manuela D Eusanio	General SLCA	Impact pathway and reference scale	General definitions
22	social life cycle assessment revisited	Ruqun Wu, Dan yang	General SLCA	impact pathway and reference scale	

Sl.no	Research article/review/case study	Author	Sector	Impact assessment method used or discussed	Details about impact assessment methods
23	The Guidelines for social life cycle assessment of products: just in time	Catherina Benoit, Gregory A. Norris	General SLCA	reference scale/performance reference scale approach	
24	Assessment of social sustainability hotspots	Grogory A, Norris	General SLCA	SHDB	
25	Life cycle sustainability assessment of sport utility vehicles: the case for Qatar	Nour NM Aboushsgrah, Nuri Cihat Onat	Automobile	life cycle cost impact assessment	
26	Additive manufacturing: exploring the social changes and impacts	Florinda Matos, Radu Godina	Manufacturing	Impact pathway	shows cause effect relationships.
27	Guidelines for social life cycle assessment of product and organizations	UNEP/SETAC	Guideline	reference scale and impact pathway	detailed description of methods

In Table IV-9, which summarizes the findings from the review of 27 articles, a comprehensive analysis of the impact assessment methods used or discussed in each article has been presented. The results reveal distinct patterns and preferences among researchers in the field of S-LCA. Out of the 27 articles reviewed, it was found that 9 of them exclusively focused on or utilized the Performance Reference Points method or the Reference Scale approach for impact assessment. These methods involve establishing benchmarks or scales to evaluate and compare the social impacts of different products, processes, or systems. In contrast, 2 articles (out of the 27) discussed or employed the Impact Pathway method. This approach involves identifying and analysing the cause-effect relationships between activities, intermediate outcomes, and final social impacts. Interestingly, 7 articles delved into both the Reference Scale and Impact Pathway approaches, recognizing the value in combining these methods to gain a comprehensive understanding of social impacts. Furthermore, 1 article out of the 27 adopted the PDCA (Plan-Do-Check-Act) method, which entails a continuous improvement cycle through systematic planning, implementation, monitoring, and adjustment of activities. Another article utilized an empirical method, indicating the use of empirical data and observations to assess social impacts directly. In the case of 4 articles, a database method was employed, suggesting the utilization of existing databases or data sources to quantify and evaluate social impacts. Two articles were classified under "Other Methods," suggesting the adoption of alternative or specialized methodologies not explicitly mentioned. Lastly, one article provided a comprehensive discussion encompassing all the aforementioned methods, offering an overview and critical evaluation of different approaches. These findings highlight the diversity and range of impact assessment methods utilized in S-LCA research. The predominance of the Performance Reference Points/Reference Scale approach indicates its popularity and effectiveness in evaluating social impacts. However, it is noteworthy that a significant portion of the reviewed articles recognized the value of combining different methods to enhance the comprehensiveness of impact assessments. By understanding the prevalence and utilization of these different methods, researchers and practitioners in the field of S-LCA can make informed decisions regarding the appropriate methodological approaches for their own studies. Additionally, the identified gaps and potential areas for further research can guide future investigations to refine and expand the toolkit of impact assessment methods in S-LCA.

IV.4.3 Impact evaluation: Stakeholders, impact categories, sub-categories

The 7 scientific studies (Ben Ruben et al., 2018; Dunuwila et al., 2022; Hosseinijou et al., 2014; Koese et al., 2023; Osorio-Tejada et al., 2020; Singh & Gupta, 2018; Vivoda & Fulcher, 2017) have adequate information about the considered stakeholders, subcategories, and impact categories. From these 7 studies, the stakeholders, impact categories, and impact subcategories are arranged in Table IV-10.

Table IV-10. Stakeholders, impact categories and subcategories

Stakeholders	Impact categories	Impact Subcategories
Workers Consumer (User) Local community Society Value Chain actors	Human rights	Child labour, Forced labour, Equal opportunities and discrimination
	Working Conditions and Health and Safety	Freedom of association, Fair salary, Fair workhours, Health and safety at work, Social benefits/social security, Discrimination
	Cultural Heritage	Delocalization and migration, Respect for local traditions and cultural heritage, Respect for the rights of the indigenous community, Community involvement, Healthy and safe living conditions, Access to material resources, Access to intangible resources, Transparency in social and environmental issues
	Socio-economic repercussions	Creation of local employment, Contribution to the national economy, Prevention and mitigation of armed conflicts, Technological development, Suppliers' relationships, Confidentiality with customer information, Feedback mechanism
	Governance	Public commitment to sustainability issues, Corruption, Unfair competition

IV.4.4 Impact assessment results

Based on the literature review of 7 case studies (Ben Ruben et al., 2018; Dunuwila et al., 2022; Hosseinijou et al., 2014; Koese et al., 2023; Osorio-Tejada et al., 2020; Singh & Gupta, 2018; Vivoda & Fulcher, 2017) it is evident that the 'Worker' stakeholder category is identified as having high negative impacts and low performance in 6 out of the 7 cases. This indicates that workers are significantly affected by the assessed systems or products. The subcategories associated with workers that are impacted include freedom of association and collective bargaining, fair work hours, health and safety at work, child labour, lost time injury frequency, discrimination in wages, social benefits, and social security. In one of the 7 cases, the 'Local community' is reported as the worst affected category, while in 2 out of the 7 cases, the 'local community' is indicated to have high negative impacts following the 'Worker' stakeholder group. The subcategories affected within the local community include respect for local traditions and cultural heritage, access to intangible resources, unemployment, safe and healthy living conditions, mortality, and infrastructure. In one of the 7 cases, negative impacts are observed for the 'Society' category. Specifically, the subcategories of contribution to economic development and public commitment to sustainable issues demonstrate negative outcomes. Out of the 7 case studies, the results of five studies indicate that the 'Local community' is the stakeholder category with a high-performance rate or the stakeholder group with very low risk. The main impact subcategories that yield positive results in these cases include a contribution to the creation of local employment, contribution to the national economy, technological development, and supplier relationships. In 3 out of the 7 cases, the 'Society' stakeholder group follows the 'Local community' category and demonstrates positive impacts. The subcategories identified in these cases are technological development and supplier relationships.

IV.5 Phase IV. Interpretation

Summary of key findings from the review

- Interpretation is the final phase of the social life cycle assessment (S-LCA), where all other phases are analysed.
- The interpretation phase consists of five main steps: completeness check, consistency check, uncertainty sensitivity and data quality check, materiality assessment, and aggregation, conclusion, limitations, and recommendations.
- Completeness check ensures that the problems and issues from the goal and scope phase are integrated into the S-LCA.
- A two-stage approach is used in the study for the completeness check process, those are hotspot analysis and site-specific analysis.
- Consistency check ensures that the methods and data used in the inventory and impact assessment are consistently applied and aligned with the study's goal and scope.
- Uncertainty sensitivity and data quality check involves analysing and evaluating the uncertainty and sensitivity of data used in the assessment.

- The results of sensitivity analysis indicated a slight increase in the human rights performance index, reflecting an improvement in human rights considerations, child labour and rate of corruption.
- Materiality assessment determines the significance of selected issues and identifies key social performances, impacts, risks, stakeholders, and life cycle phases.
- No materiality assessment was performed on any of the reviewed articles.
- Aggregation combines indicators within subcategories and stakeholders, aiming to generate a single score for enhanced comprehension.
- The aggregation is performed across the indicators as well as across the stakeholders in order to determine the hotspots throughout the value chain.
- The interpretation phase concludes by addressing limitations and providing recommendations for improvement actions to decision-makers.
- Critical review is recommended for S-LCA studies to enhance quality, credibility, and learning, like environmental life cycle assessments.

Interpretation is the final phase of the social life cycle assessment, and this is the phase in which all other phases are reviewed. This review and discussion of the S-LCA phase provide sufficient information for developing the conclusion, recommendations, and decision-making by the goal and scope definition (UNEP/SETAC, 2020). The interpretation phase consists of mainly five steps namely, Completeness check, Consistency check, Uncertainty Sensitivity and data quality check, Materiality assessment, Aggregation, Conclusion, limitations, and recommendations. From the review articles and case studies, explanations about these five steps are not that much available, The UNEP guideline are used as the main resource for the explanation for these five steps, and almost 7 case studies/review papers as the supporting documents.

IV.5.1 Completeness check

A completeness check is a process that ensures the problems or issues explained in the goal and scope phase are sufficiently integrated into the life cycle inventory and impact assessment phase. It ensures that relevant data are collected and sufficiently used for the entire S-LCA cycle. A completeness check also finds out the unsolved questions described in the goal and scope of the study and figures out the reason behind the issues. The completeness check is an iterative process, it can be used to fill the gaps in the other phase by proper review, if the gaps are not filled by the iterative process, the lack of completeness will be remarked at the completeness check phase (UNEP/SETAC, 2020). Completeness aims to assess if all relevant issues have been addressed in the study and all necessary data are collected. A two-stage approach is used in the study for the completeness check process, those are hotspot analysis and site-specific analysis. In both phases, check whether all relevant data collected was sufficient and addressed issues were solved (Hosseinijou et al., 2014). In one case study (Osorio-Tejada et al., 2020) about freight transport, the completeness check process was done on 2- levels, the first level completeness check in the areas of auto parts, oil production, and road material, and the second level analysis in vehicle manufacturing, fuel refining, and distribution, and road construction. The site-specific data and the data from the newspapers were used for the completeness check (Osorio-Tejada et al., 2020). The UNEP/SETAC guideline have a detailed checklist method for the completeness check process.

IV.5.2 Consistency check

A consistency check ensures that the methods used in the inventory and impact assessment and data collected are consistently applied throughout the study and check whether is it aligned with the goal and scope of the study (UNEP/SETAC, 2020). A consistency check ensures the applied procedures are not contradicting the choice of indicators, the impact assessment method chosen to process them, and the typology of results. In other words, a consistency check ensures the robustness of choices or verifies the appropriateness of modelling and the methodological choices according to the defined goal and scope. (Hosseinijou et al., 2014)

IV.5.3 Uncertainty, Sensitivity, and data quality check

Uncertainty analysis can be performed in two ways: quantitatively or qualitatively, depending on the data and information at hand. This analysis is necessary when comparing two products. In the context of S-LCA, quantitative analysis can be employed to evaluate the uncertainty associated with scoring factors and the aggregation of impact subcategory indicators based on stakeholder types. The resulting uncertainty ranges can provide insights into whether the two systems being studied are statistically distinct. (UNEP/SETAC, 2020)

Sensitivity analysis is a procedure that evaluates the impact of choices and assumptions on the results. It is essential to conduct a sensitivity analysis on several key factors, including Choice of the activity variable (working hours or value added), Referencing system selection, Aggregation criteria used during the social impact S-LCIA phase, Weighting criteria applied, Allocation methods utilized, Assumptions made about the data, and Scenario analysis considerations.

To perform a sensitivity analysis, the identified variable, assumption, or choice within the S-LCA model should be varied in the scope definition, inventory, and/or impact assessment. The assessment should be run, and any resulting changes in the results should be critically analysed and documented. It's important to note that conducting a sensitivity analysis should follow an uncertainty analysis. However, certain key factors may require a complete reassessment. If resource limitations exist, quantifying the effects of changes may not be feasible. Nevertheless, even in such cases, the effects of choices should be discussed qualitatively whenever relevant. (UNEP/SETAC, 2020).

A review paper based on social life cycle assessment defines that, the comparability and transparency of Social Life Cycle Assessment (S-LCA) are currently lacking (Pollok et al., 2021). Each phase of S-LCA is tailored to specific cases, and the rationale behind choices and procedures is not adequately explained. As a result, there is a wide diversity of approaches, and there is no standardized framework for all S-LCA phases. This lack of standardization poses a significant obstacle when using or sharing S-LCA results, as it becomes challenging to interpret and compare processes, companies, and social impacts in a clear and unambiguous manner. The use of different data sources, such as qualitative or site-specific data, often includes confidential information. On the other hand, relying solely on generic macro-level data or risk classifications is deemed insufficient for supporting meaningful and robust decision-making. Comparing two similar studies in this context can lead to unreliable results and potentially misguide decision-making processes. The broader field of Life Cycle Assessment (LCA) also faces uncertainties and lacks transparency due to the multitude and variety of approaches influencing the selection of impact categories, indicators, stakeholder categories, characterization, normalization, and data interpretation (Pollok et al., 2021). Among the reviewed case studies, only one study conducted a sensitivity analysis specifically focused on freight transport within the context of S-LCA. The results of this sensitivity analysis indicated a slight increase in the human rights performance index, reflecting an improvement in human rights considerations. Furthermore, the analysis revealed highly positive variations in relation to child labour, suggesting a significant reduction or mitigation of child labour practices. Additionally, the sensitivity analysis provided insights into the impact on other social aspects. It showed a slightly slower rate of corruption, indicating a potential decrease or better control of corrupt practices. Similarly, the analysis revealed positive variations regarding unfair competition, implying that measures were implemented to reduce or mitigate unfair competitive behaviours (Osorio-Tejada et al., 2020).

IV.5.4 Materiality Assessment

The obtained results need to be further interpreted to determine the significance of the selected issues. This interpretation phase aims to identify significant social performances or impacts, risks, stakeholder categories, and life cycle phases of processes, in line with the study's goal and scope. In S-LCA, significance is closely linked to the concept of materiality. Materiality refers to the relevance and importance of a social matter, such as information, data, performance, impact, or stakeholder. If a social matter has the potential to substantially influence the study's conclusions, as well as the decisions and actions based on those conclusions, it is considered material. Materiality is independent of the level of influence an organization may have on different phases of the product system being studied. To assess materiality, a contribution analysis can be employed. This analysis involves determining the proportion of social performances/impacts attributed to life cycle phases, processes, and/or stakeholders. The contribution can be expressed either as a percentage contribution or through qualitative ranking (UNEP/SETAC, 2020).

IV.5.5 Aggregation

Aggregation is a key aspect of S-LCIA, occurring in various stages where indicators are combined within subcategories. This process involves defining weighting criteria that assign relative importance to impact subcategories or stakeholder category results. The aggregation steps, including the weighting, aim to generate a single score and are integral to the S-LCIA phase. In the Interpretation phase, additional aggregation is conducted to present the results in a manner that enhances comprehension. The choice of aggregation method should align with the study's Goal and Scope and consider the intended audience of the study. However, it's important to recognize that aggregation inherently simplifies and obscures details, and it is influenced by personal perspectives and values. The study’s results should always be complemented with disaggregated data to ensure a comprehensive understanding. Furthermore, practitioners must transparently report and justify the criteria used for aggregation to prevent misinterpretation of the results (UNEP/SETAC, 2020). The aggregation procedure consists of an arithmetic average for all indicators in each stakeholder group (UNEP/SETAC, 2020). The aggregation is performed across the indicators as well as across the stakeholders in order to determine the hotspots throughout the value chain. Aggregation of all the responses against the indicators for a single life cycle stage gives the scores on a scale of 0 to 1. The minimum value possible is 0.25 which is obtained if all the respondents give a rating of 1 representing a highly negative impact. The cut-off has been set at 0.5 which represents a score of 2.5 or less by the respondents, representing a rating of negative or highly negative impact while ratings of neutral or positive impact would result in scores above the cut-off (Singh & Gupta, 2018). The maximum possible score is 1 if all the responses are given a rating of 4 against the impact indicators indicating a positive impact. For the first step, (identification of the significant issues) it is recommended to calculate aggregated scores for each impact category, subcategory, stakeholder category, and life cycle stage. Based on these aggregated scores, one may identify significant issues, key concerns, and where the issues of concern may be the most significant in the product’s life cycle. It also enables the identification of stakeholders that are the subject of key concerns (Hosseinijou et al., 2014).

IV.5.6 Conclusion, limitation, and Recommendations

Once the results have been thoroughly analysed for completeness and consistency, and the material aspects of the study have been identified, it becomes possible to conclude. This involves addressing limitations and providing recommendations for improvement actions to the decision-maker. Limitations may pertain to the type and quality of data used, the referencing system employed, the scoring system applied, or the weighting criteria utilized (particularly relevant for aggregating reference scale results into impact subcategory results). Involving stakeholders in this final step can be crucial, as it broadens the representation of those who may be affected by the study's outcomes. This is where the main questions raised during the goal and scope of the study find answers, contributing to a more inclusive and comprehensive decision-making process.

Some conclusions and recommendations from different case studies are listed below as a reference.

The S-LCA studies need a universal and replicable method. S-LCA only provides a snapshot of how companies and their products affect the social chain. S-LCA possesses the capability to adapt to evolving conditions by converting impact subcategories and regularly updating performance references, such as international standards. S-LCA must maintain a certain level of flexibility that enables it to adjust to these changing conditions. Additionally, S-LCA should effectively demonstrate how organizations influence various factors such as technological advancements, education levels, and the environment. This demonstrates the importance of capturing and analysing the dynamic interplay between organizations and the social conditions they operate within (Pollok et al., 2021). The case study about S-LCA of freight transportation concludes that the salary offered by the transport company may not be high, but it is balanced by the benefits of flexible workdays and reduced work hours. Unfortunately, stakeholders fail to prioritize safety concerns, particularly regarding accidents in road construction, despite the transport sector experiencing relatively fewer accidents. To enhance the social performance of transport companies, it is advisable to invest in technological advancements, environmental and social studies, and promote transparency by publishing these efforts on their websites (Osorio-Tejada et al., 2020). The case study related to the S-LCA of a manufacturing organization concludes that the firm must focus on CSR & communal development and be less dependent on the system and more on the intelligence and opportunism of employees (Ben Ruben et al., 2018). The S-LCA of material selection for building construction defines that conclusions may be about the final ranking of the alternatives regarding all considerations. Recommendations are a means to formulate options for actions and may be about future public and private policies regarding key stakeholders and key impact categories that are identified in step 1 of the current phase (Hosseinijou et al., 2014).

IV.5.7 Critical Review

Conducting an independent and critical review has been shown to significantly enhance the quality and credibility of the Social Life Cycle Assessment (S-LCA), similar to its impact on the Environmental Life Cycle Assessment (E-LCA). Additionally, critical reviews play a vital role in promoting continuous learning and professional development among life cycle practitioners. Therefore, it is highly recommended to include a comprehensive critical review process when planning an S-LCA study. According to the ISO standards for Life Cycle Assessment (LCA), an independent critical review is mandatory for studies that aim to make "comparative assertions," such as claims about the superiority of one product's life cycle over another. The critical review process outlined in ISO 14044 is considered suitable for S-LCA as well. However, as experience in S-LCA accumulates, there may be opportunities to develop specific guidelines or refinements to the critical review process tailored to the unique aspects of S-LCA. By incorporating a robust critical review, S-LCA studies can ensure greater reliability, validity, and transparency in their methodologies, data sources, and interpretation of results. This not only strengthens the credibility of the assessment but also facilitates more informed decision-making, fosters sustainability improvements, and contributes to the ongoing development of S-LCA as a valuable tool in the field of life cycle assessment (UNEP/SETAC, 2020). The critical review plays a crucial role in the Interpretation phase of the Social Life Cycle Assessment (S-LCA) as it helps ensure the reliability and robustness of the study's findings. It involves a comprehensive evaluation and analysis of the S-LCA methodology, data sources, assumptions, limitations, and overall credibility of the results. Overall, the critical review in the Interpretation phase of S-LCA should aim to provide an unbiased assessment of the study's strengths, weaknesses, and overall credibility. It should offer constructive feedback and recommendations for improving the study's methodology, data quality, and interpretation of results. By conducting a thorough and rigorous critical review, the reliability and usefulness of the S-LCA study can be enhanced, enabling informed decision-making and promoting sustainability improvements in the assessed systems (Pollok et al., 2021).

V. Life Cycle Costing (LCC)

V.1 Introduction and review focus

The product life cycle costing (LCC) concept emerged in the 1960s and 70s, primarily for use in public procurement. It aims to provide a comprehensive understanding of a product's total cost over its entire life cycle, including acquisition of raw materials, manufacturing, transportation, use, and disposal. LCC is thereby often praised as the logical economic counterpart of LCA in the move to more comprehensive life cycle sustainability assessments (Clift & Druckman, 2015; Kloepffer, 2008). Despite this, LCC is not as well discussed and applied as compared to LCA[19]. Several guidance and standards on LCC have been developed for specific technologies (see also Table V-1). ISO 15663:2021, for example, provides guidance on applying LCC within the context of drilling, exploitation, processing and transport of petroleum, petrochemical and natural gas resources. However, general standards (i. e. non-technology specific standards such as ISO 14040) currently do not exist. Furthermore, as pointed out by the responses of the TranSensus LCA survey, vehicle related LCC is currently not often implemented or linked to LCA by industry.

Considering the above, LCC literature on ZEVs is not as widespread as compared to LCA. The LCC review in this report thereby focuses on not only literature specifically targeting ZEVs (scientific literature, reports and tools), but also LCC more generally (i. e. standards and guidelines).

V.2 Phase I. Goal and scope definition

Goal and scope: Summary of key findings from the review

- The Life-Cycle Cost (LCC) goal is similar to Life-Cycle Assessment (LCA) - it defines the intended application, study purpose, intended audience, and whether the results will be used for comparative assertions.
- Current LCC standards are technology (e. g. water treatment technologies) or sector-specific (e. g. petrochemical industry) with no universal standards for vehicles or batteries.
- Several tools use LCC for procurement purposes, most notably for public procurement. For example, the Clean Fleets Life Cycle Cost to determine the monetary value of energy and environmental costs for public vehicle procurement.
- In reports and scientific literature, LCC's goal tends to be more prospective and comparative, typically comparing the costs of ICEs and EVs over their lifetime.

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[19] For example, a Web of Science search for "Life Cycle Cost" results in 6,996 articles as compared to 36,809 articles for "Life Cycle Assessment"

- Different LCC approaches exist: Total Cost of Ownership (TCO), Conventional LCC (C-LCC), Environmental LCC (E-LCC), and Societal LCC (S-LCC), each with distinct goals and scopes.
- TCO focuses on costs from the perspective of a single owner or stakeholder, while C-LCC includes additional expenses related to product development, design, transportation, installation, and disposal.
- E-LCC is conducted in parallel with LCA and monetizes only externalities that are part of the cash flow, while S-LCC monetizes externalities that do not directly affect cash flow (e. g. monetisation of environmental pollutants) to provide an assessment of the societal costs

V.2.1 Goal and applications

The goal definition of an LCC in general is similar to that of an LCA and should generally state the intended application, the reason for carrying out the study, the intended audience and whether the results are intended to be used for comparative assertations. (Swarr et al., 2011)

As highlighted in Table V-1, existing LCC standards are currently not general but instead always technology or sector specific. To date, no LCC standards for vehicles or batteries exist. LCC as used in technology specific standards is typically used for planning purposes and to provide support to procurement decisions.

A strong focus of several of the reviewed tools targeting vehicles specifically is the use of LCC for procurement purposes using a retrospective perspective (see Table V-1). Most notably is the use of LCC for public procurement and the identification of the most economically advantageous tender (MEAT). For example, the Clean Fleet Directive (2019/1161) advises contracting authorities and contracting entities to use LCC as a tool to determine the monetary value of energy and environmental costs in the support of public procurement of vehicles. Several LCC calculation tools have been established to support such vehicle procurement decisions by public authorities (e. g. LCC calculators by the Norwegian Agency for Public and Financial Management (DFØ), Swedish National Agency for Public Procurement or the European Commission (Clean Fleets tool)).

The goal of LCC in reports and scientific literature on the other hand, tends to be more prospective and of comparative nature. Most typically, the costs of ICEs are compared to EVs over their entire lifetime to understand the cost competitiveness of EVs, see for example (Ayodele & Mustapa, 2020) or (Roosen et al., 2015).

Table V-1. Overview of reviewed standards, guidelines and tools for LCC

Name	Type	Goal	Technology scope	Approach
ISO 15663:2021	Standard	To support decision making processes by evaluating alternative options and performing trade-off studies.	Petroleum, petrochemical and natural gas industries	C-LCC
ISO 15686-5:2017	Standard	To provide a clear terminology and a common methodology for life cycle costing that can be used by public procurers for decision-making processes and for comparing alternatives.	Buildings and constructed assets	E-LCC
ISO 20468-8:2022	Standard	Planning and performance evaluation.	Treatment technologies for water reuse systems	C-LCC
ASTM E917 – 15	Standard	To expand the perspective of initial investment costs by adding future operational costs so that decision makers and investors can make comprehensive, long-term decisions between similar alternatives.	Buildings and building systems	C-LCC
ASTM E2453	Standard	To provide a property owner with the life-cycle cost of the corresponding asset whilst being consistent with accounting principles.	Property assets	C-LCC
EC life cycle costing and green public procurement	Guideline	To provide decision support to public procurers and scientific guidance regarding LCC, highlighting environmental aspects.	General	S-LCC
Clean Fleets Directive (2019/1161 + 2009/33)	Guideline	Purpose of LCC is to support public procurement decisions.	Vehicles	S-LCC (2009/33)
Environmental LCC – code of practise	Guideline	To provide practitioners of LCC with a consistent framework for conducting a LCC analysis, that ultimately contributes to an international standard paralleling the ISO 14040 standard for LCA.	General	E-LCC
Berechnungshilfe Lebenszykluskosten Fahrzeuge	Tool	Assessing which alternative has the smallest life cycle cost and environmental burdens to make a science-based decision.	Vehicles	S-LCC
Clean Fleets LCC tool	Tool	To provide guidance for purchasing clean and energy efficient vehicles and comply with the Clean Vehicles Directive.	Vehicles	S-LCC
Lifecycle Cost Tool for Fleet Managers	Tool	To take economic and purchase information and provide an analysis of the lifecycle cost of your vehicle.	Vehicles	TCO (C-LCC minus EoL)

Name	Type	Goal	Technology scope	Approach
LCC-KALKYL FÖR PERSONBILAR	Tool	To support public procurement decisions.	Vehicles	TCO (C-LCC minus EoL)
Effektkalkulator for personbiler	Tool	To support public procurement decisions.	Vehicles	TCO (C-LCC minus EoL)
IEA – EV TCO	Tool	To compare the costs of owning and operating fossil fuel and electrified vehicles and to help users understand the trade-offs in order to make more informed decisions when purchasing a vehicle.	Vehicles	TCO
AFLEET - ANL	Tool	Tool for Clean Cities stakeholders to support procurement decisions about costs and environmental impacts.	Vehicles	Stated TCO but really S-LCC

V.2.2 LCC approach

There are several related LCC concepts that sound similar but have a different goal and scope. Which LCC approach is used, however, is almost never stated and a wide variety of concepts are used. Among the frequently used concepts and the ones adapted here are total cost of ownership (TCO), conventional LCC (C-LCC), environmental LCC (E-LCC) and societal LCC (S-LCC). In the reviewed documents, the type of LCC used is not commonly stated and the different concepts and definitions are not always used consistently. One common way to differentiate between these types is based on the perspective they take, the sustainability dimension covered, and the way externalities are monetized [20] (see Figure V-1).

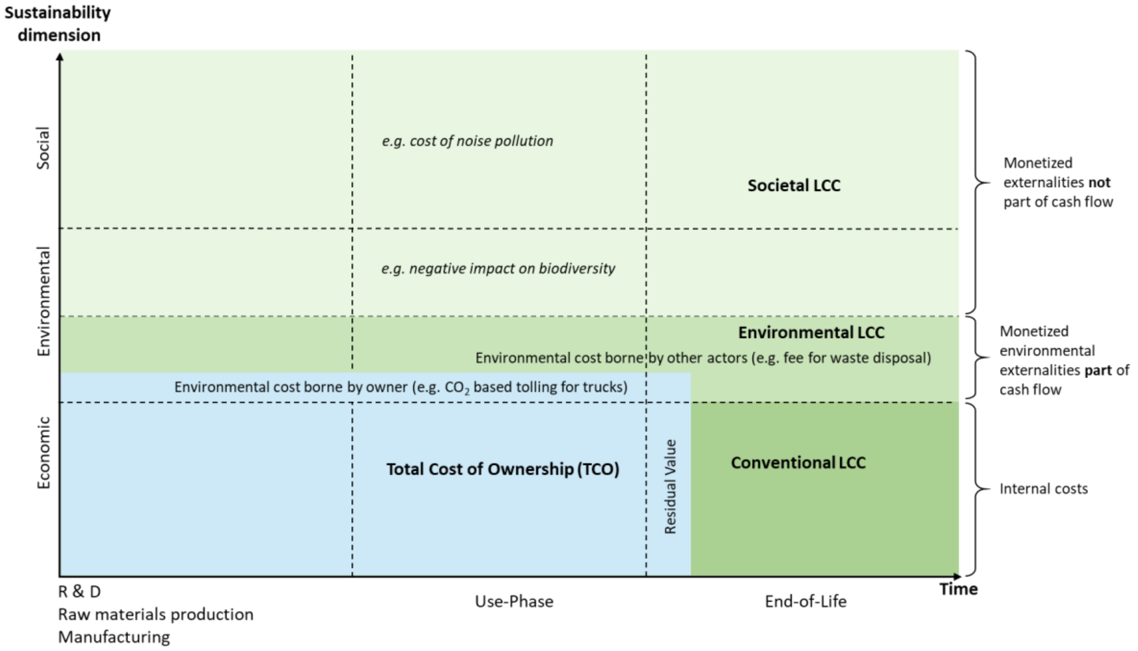

Figure V-1. Overview of different types of LCC and TCO (adapted from (OECD, 2022)

TCO quantifies the costs associated with the ownership starting with its purchase/leasing. It typically assesses the cost from the perspective of a single owner or stakeholder such as a vehicle owner or manufacturer. A commonly chosen (economic) timeframe is thereby five years and can be extended to multiple subsequent ownership periods (although TCO for the complete vehicle lifetime is also typically reported). The end-of-life phase is typically left out and a residual value included after the vehicle use. The TCO approach is widely applied in scientific literature and in some tools. The IEA EV TCO calculator, for example, provides (potential) vehicle owners with a tool to compare the economic cost of owning and operating an electric vehicle. TCO provided from the perspective of the end-user/owner can also be complimented

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[20] Monetizing externalities refers to the process of assigning a financial value to the positive or negative effects that certain activities or events impose on the broader society or the environment (e. g. 0.087 EUR/g particulate matter, Directive 2009/33/EC).

by the TCO from the societal perspective in policy impact assessments for road vehicles (e. g. as for those relating to the car and van CO_2 regulations conducted by Ricardo for DG CLIMA, (Ricardo et al., 2018). In this case, the assessments are always done on the lifetime of the vehicle, and will exclude all taxes, but often include externalities for certain environmental impacts (typically GHG and air pollutants), but also sometimes other social costs (such as noise and accidents).

Following from TCO, **conventional LCC**, also referred to as financial LCC (Hoogmartens et al., 2014), can be regarded as a synonymous concept to TCO but typically also includes expenses associated with the development, design, transportation, installation, and disposal of products. Similar to TCO, it typically takes the perspective of a single user. As TCO and C-LCC usually take the perspective of a single stakeholder or end-user, externalities might be included if they form part of the cash-flow of the end-user. An example of this is the IEA EV TCO calculator whereby a CO_2 taxation can be included to the total cost.

Environmental LCC breaks with the single user focus of TCO and C-LCC and instead covers all costs associated with the life cycle of a product that are directly covered by all stakeholders in that life cycle (Kloepffer, 2008). E-LCC is thereby designed to be conducted in parallel to LCA as is reflected in the adjective “environmental”, referring to the fact that the economic analysis is largely consistent with that of LCA following ISO 14040 (Heijungs et al., 2013).

Similar to C-LCC, monetization of environmental externalities in E-LCC only includes externalities that are currently or soon to be expected as a part of the cash flow. ISO15586:5 (life-cycle cost of buildings and constructed assets) refers to these costs as “environmental cash flows” and form part of the LCC cost components. As E-LCC was designed to be conducted in parallel to LCA, non-monetized external costs are typically recommended to be excluded from E-LCC. This is because they can be conceptually regarded as double counting of environmental impacts in both the economic and environmental impact assessment, i. e., the same environmental emission is measured in LCIA and also converted to a monetary measure (Swarr et al., 2011).

S-LCC refers to cases where externalities are monetized but do not form of the actual cash-flow. Another synonymous concept such as used by ISO 15686-5 (ISO, 2017) is whole life cycle cost (OECD, 2022). In S-LCC, the societal perspective is taken, and different cost elements are included. For example, externalities are converted to monetary values (e. g. EUR/g NOx) used to reflect on the cost to society, taxes are typically excluded and discount rates are lower (see Section V.3 below). An explicit reference to S-LCC however is not commonly made. For example, as noted above, (Ricardo et al., 2018) refers to TCO from a societal perspective to reflect on the cost of a passenger car when non-cash flow related external costs are internalised (e. g. GHG, air pollution, noise). Similar, the former EU Clean Fleet Directive (2009/33) (European Union, 2009) provides a methodology to convert environmental emissions of vehicles to monetary units to be taking into the cost of public procurement of vehicles. However, by monetizing non-internalised externalities, S-LCC is typically regarded as not consistent with LCA due to the issue of double counting when integrating LCA and LCC results (Rödger et al., 2018, Chapter 15; Swarr et al., 2011)

It is worth mentioning that monetisation of external costs as in the case for S-LCC remains a highly discussed topic. Especially emissions affecting both environment and human health require attributing a monetary value to human lives if they need to be expressed in monetary terms themselves. This is commonly done either by market data (e. g. the cost of medicines and care) or by contingent valuations (surveys assessing the willingness to pay to maintain the existence of an attribute such as human health). Monetary costs of externalities, such as those stated in the Clean Vehicles Directive, are typically derived from mathematical models which also account for dispersion, exposure and dose-response correlations (Bickel et al., 2005; European Union, 2009)

V.3 Phase II. Inventory

Inventory: Summary of key findings from the review

- The inventory of economic costs related to vehicles is categorized into private, external, and other costs.
- Private costs include costs borne by vehicle owners such as the purchase or lease price, fuel/electricity, maintenance, insurance, taxes, and residual value. These costs vary based on the study and have different levels of detail (e. g. vehicle purchase price based on retail price versus built from specific component prices). The lack of official projections / standardization on future energy costs is particularly problematic, as this is a highly influential component.
- External costs represent societal costs such as greenhouse gas emissions that do not form part of the cash flow. These costs are therefore only included in S-LCC studies. These are often not monetized in the scientific literature, but when they are, various conversion factors from different sources are used.
- Another factor influencing Life Cycle Cost (LCC) results include the discount rate, which varies between studies depending on the study's perspective and timeline.

The inventory phase for LCC is similar to LCA but additional economic information needs to be collected. The inventory of economic costs related to vehicles is categorized into private and external costs. Following is a discussion of these.

V.3.1 Private cost categories

Private vehicle costs refer to the cost elements that are borne by the vehicle owner. Typically included private cost categories for LCC of vehicles include:

- Vehicle/battery purchase or lease price, subsidies/tax breaks (related to *raw materials and manufacturing)*
- Fuel or electricity cost, (private) charging infrastructure, maintenance/repair, insurance, taxes (related to *use-phase)*
- Residual value (related to *end-of-life phase)*

Vehicle acquisition and fuel/electricity costs are the most commonly considered categories included (see e. g. Roosen et al., (2015)). Additional cost categories are highly depended on the goal of the study. For example, many comparative studies between similar vehicle types assume equal costs for different elements (e. g. insurance, vehicle taxes) and therefore exclude them from calculations (see for example (Tol et al., 2022)). Studies with a prospective element (e. g. comparison of EVs and ICEs in the future) typically break down the vehicle price in several components. The level of aggregation varies significantly ranging from very detailed price information (e. g. battery coolant, brake callipers, brake fluid etc. in the AFLEET model) to aggregated information (e. g. batteries as a separate price component of vehicle by (Messagie et al., 2013)). Cost for private charging infrastructure was rarely considered in the studies (e. g. 4 out of 44 studies according to (Roosen et al., 2015) but is included in most tools reviewed.

Finally, future costs for fuel and electricity during the operational lifetime of vehicles are subject to market mechanisms and exposed to fluctuations. Short-term fluctuations are difficult to predict and rarely included in LCC studies whereas the long-term evolution of prices is sometimes considered. Some use generic future price forecasts based on third party estimations (e. g. future electricity prices-based projections by the US Energy Administration as in the Clean Fleets LCC Tool) or linear interpolation of fuel prices (e. g. sensitivity analysis of the impact of variable diesel fuel and electricity prices between 2020 and 2030 for TCO analysis of battery electric and diesel trucks (Basma et al., 2021)). As mentioned earlier, for analyses from the societal perspective, all taxes/incentives will typically be excluded.

Overall, there are a wide variety of assumptions made on the current and future projections of energy costs between studies, which significantly hampers comparability. In some instances, there are official projections available (e. g. for policy analysis in the UK), however there is generally a significant lack of information and standardisation.

V.3.2 External costs

External costs refer to the costs that are imposed on third parties or society without a direct compensation. These are typically only included in S-LCC studies.

Externalities are not often monetized in the scientific literature. According to (Roosen et al., 2015), out of 44 studies, only 12 monetize externalities. These studies primarily focus on greenhouse gas (GHG) emissions from vehicle exhausts, fuel production, and electricity production.

In certain cases, externalities are monetized through environmental legislation (only for TCO, C-LCC and E-LCC studies). ISO 15686-5 (LCC for buildings and constructed assets) refers to this also as "environmental costs". Through governmental regulation, these external costs are somewhat internalized and already incorporated into the consumer price. This approach can be observed in various examples in the reviewed documents, including carbon taxes (indirectly included through fuel prices), congestion charges (aiming to reduce environmental impacts caused by congestion), toll roads (with tolls based on vehicle emissions), and vehicle registration fees that incentivize low-emission vehicles.

Some of the reviewed documents do monetize one or several externalities by using different monetary conversion factors (see Table V-2). In the older EU Clean Fleets Directive (Directive 2009/33/EC), a calculation method to monetize environmental externalities was included in Article 6, "Methodology for the calculation of operational lifetime costs". A conversion factor was included in the Annex to multiply the vehicle pollutant emissions with the cost of emissions per g (NO_x, NMHC, particulate matter) or kg (CO_2) and adopted by several tools. The sources of such conversion factors in general are typically derived from scientific literature or impact assessment handbooks (see e. g. the EC handbook on the external costs of transport (European Union, 2020).

Table V-2. Monetization of external cost.

Review item	Review category	Externalities	Assumption or source for cost factor
Berechnungshilfe Lebenszykluskosten Fahrzeuge	Tool	NO_x, PM, NMHC, CO_2	Directive 2009/33/EC - Annex
Clean Fleets Life Cycle Cost (LCC) Tool	Tool	Optional and according to CVD: NO_x, PM, NMHC, CO_2	Directive 2009/33/EC - Annex
IEA - Electric vehicles: total cost of ownership tool	Tool	CO_2	Only as percentage of total vehicle cost
Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool	Tool	CO_2, NO_x, PM_{10}, $PM_{2.5}$, VOC, SO_x, GHGs (CO_2, CH_4, N_2O)	Wide range of literature sources
Ricardo 2018	Report	Air pollution (PM, NO_x), CO_2, noise, congestion, accidents	PRIMES-TREMOVES model
EC 2016 - Life cycle costing and Green Public Procurement	Guideline	Environmental	Provides an example of Directive 2009/33/EC

V.3.3 General assumptions

In addition to private and external cost categories, there are other (often region-specific) aspects influencing the LCC-results (e. g. distance travelled per year, charging behaviour, discount rates). One of the most frequently discussed aspects in the LCC literature is the discount rate. The discount rate converts future costs to equivalent costs in the present time. Appropriate discount rates vary between studies and are typically based on the perspective and time line of the study as defined in the goal and scope (Swarr et al., 2011). For example, discount rats are typically much higher for end-user perspectives versus societal perspectives (e. g. 9.5%-11% for vans/cars for end-users, and 4% for societal perspective in (Ricardo et al., 2018). Discount rates were not always included in the reviewed tools, reports or scientific literature. When included, the used rates can vary significantly ranging from 1 to 10%.

V.4 Phase III. Impact Assessment

In contrast to LCA, impact assessment does not form part of LCC as the results are a calculated cost expressed in a single unit of measure (currency), making characterization and weighting of different cost categories unnecessary. Different currencies or time periods might be used but this should be addressed in the inventory phase (e. g. using appropriate discount rates).

V.5 Phase IV. Interpretation

Interpretation: Summary of key findings from the review

- Unlike LCA, LCC results are expressed in a single currency unit, eliminating the need for an impact assessment phase.
- Several LCC studies and available tools compare their results with LCA to explore environmental-economic trade-offs. Potential double counting however can occur when comparing financial results with LCA or other environmental impacts.
- The interpretation phase should be conducted iteratively, just like LCA, providing recommendations to the audience and ensuring high-quality results through analysis of completeness, consistency, and uncertainty.
- It is important to address result sensitivity, especially for cost components with a high potential to impact overall life cycle costs and those prone to market uncertainty. However, comprehensive sensitivity analyses are infrequently conducted, though some LCC tools allow parameter variations (in particular fuel price) to demonstrate their effects on final results.

The interpretation phase of **C-LCC** results is more characterised by financial evaluation techniques such as payback time or net present value (e. g. calculation of the optimum vehicle replacement point in the e3 LCC calculator) (De Menna et al., 2016).

The definition of the interpretation phase for **E-LCC** can be adapted from ISO 14040/44: as "systematic procedure to identify, qualify, check and evaluate information from the results of the LCI and/or LCIA [cost accounting] of a product system, and to present them in order to meet the requirements of the application as described in the goal and scope of the study" (Swarr et al., 2011, p. 53). Considering that E-LCC was established to be conducted in parallel with LCA, the results should typically also discuss environmental-economic trade-offs (Swarr et al., 2011). Thies et al., (2021) for example, compare the results of the E-LCC with LCA (as well as S-LCA) of an EV Li-ion battery system based on a fully aligned LCA and LCC system.

Some **TCO** and **C-LCC** studies also compare their results with LCA or other environmental impacts to identify trade-offs and co-benefits. (Messagie et al., 2013) for example, compare the results of the TCO (expressed in total cost per km) with the LCA (expressed in total ReCiPe points) for different EV models to identify the most cost efficient and clean vehicles currently on the market.

For **S-LCC** studies, care must be taken for double counting when comparing the financial results with LCA or other environmental impacts.

Furthermore, just like LCA, the interpretation phase needs to be conducted in an iterative manner, ultimately providing recommendations to the audience. To ensure a high quality of results, it is recommended to analyse the LCC study regarding completeness, consistency and uncertainty.

The importance of addressing sensitivity of results is highlighted by (Swarr et al., 2011), but only a few reviewed studies conducted a comprehensive sensitivity analysis. Cost components with large potential to affect the overall life cycle costs and which are also exposed to great uncertainty (e. g. market-driven costs such as electricity or fuel prices) should be emphasized as significant issues. Although comprehensive sensitivity analyses are rarely conducted, parameters such as fuel prices can be varied in all examined LCC-tools to demonstrate the effect on the final results (e. g. the LCC-KALKYL FÖR PERSONBILAR does explicitly include a separate scenario for increased fuel costs).

VI. Discussion and conclusions

In this final chapter, we summarize the main conclusions from the review for the three methodologies (i. e. LCA, S-LCA and LCC), and try to point out the areas with least consensus in the reviewed work and those with certain level of consensus. However, it must be highlighted that the judgement here entails inevitable subjectivity. Furthermore, if a point has a certain level of harmonization in the reviewed documents, this does not mean that it is fully harmonized. In other words, it is just an attempt from the experts who compiled this report to increase its usefulness to the subsequent TranSensus LCA project tasks where needs and gaps will be defined (Task 1.2) and the harmonization tasks in WP2.

VI.1 Environmental LCA

LCA is a well-established method to evaluate potential environmental impacts of products and services. Understanding life cycle environmental impacts is a prerequisite for improving products and technologies and, ultimately, achieving climate targets. LCA should, therefore, be employed to guide the transition to fossil-free transportation in Europe. However, encompassing models like those employed in LCAs rely on certain assumptions and choices. As long as these choices are not harmonized across the LCA community, different results can be obtained for the same product when different choices are taken. This leads to a certain incomparability across LCA studies, which limits the full potential of the methodology.

In this report we have reviewed the different methodological choices based on an exhaustive literature review which covered documents from academia, industry, policy-making organizations.

The first phase of LCA, **goal and scope definition**, is where important decisions are made which will guide the whole LCA study in the subsequent stage. Harmonizing goal and scope choices should start from defining the time-relevance and product-scale, also the intended final application so that proper choices could be made. These choices include the **modelling approach** whether attributional or consequential.

Three scopes were defined in the project: 1) retrospective product-level LCA, 2) prospective product-level LCA, and 3) fleet-level prospective LCA. The first two approaches correspond well with an attributional approach to LCA. The third approach corresponds better with a consequential approach. There is no clear-cut rule for this and in principle, all scopes could be addressed with either an attributional or a consequential approach. We, therefore, suggest to clearly indicate both the scope of an LCA as well as the modelling approach while highlighting any exceptions.

From practical perspective, the review showed that in some studies even when **the modelling approach** is reported, the implications of it are sometimes omitted for the sake of experience and suitability on case-by-case basis. For instance, using system expansion or substitution in a study described as attributional can occur if this reflects more the reality of the market dynamics according to the LCA practitioner. In fact, the review revealed that some studies use mixed principles from attributional and consequential LCA. The review also showed that the modelling approach is not mentioned at all in a considerable amount of the reviewed work. However, the choice how multi-functionality is dealt with can have a significant influence on results and is a key issue for further harmonization.

Obviously, the harmonized methodology of TranSensus LCA is intended to be systematic as much as possible, however it is also required to be adaptable to different **technologies** of powertrains and core components like batteries. This is because the very details of each powertrain can also require deviate from the default methodological choices to be more suitable. Although the influence of the studied technology on basic methodological choices is expected to be minimal, it should not be overlooked.

A very controversial topic in scope definition is **functional unit**. For battery focused LCAs (across all sources considered in the review), the most common FU was "1kWh of the total energy provided over the service life by the battery system". Other FUs used for were "1 kWh (or 1 MJ) or battery storage capacity" or "1 kg of battery used", which are narrower in scope and therefore not useful for a comparison of ZEVs or batteries over their lifetimes. Mass-based is a very questionable choice as mass property is not a functional unit by itself as it does not consider the actual function of a battery which is storing and supplying energy. For vehicle-focused LCAs, distance-related FUs (passenger*km for passenger vehicles, tonne*km for freight vehicles and vehicle*km) were identified as most common. OEM reports on the other hand adopted "transport of passenger or goods over the vehicle service lifetime" as the base to determine the functional unit. Harmonization of functional unit should start from agreeing on the underlying rules to estimate the essential parameters such as the expected mileage of vehicles or the lifetime of a single battery pack within a clear usage pattern.

The review also showed a strong interdependency between the goal, the **system boundary** and the functional unit. When different vehicles are compared, the distance travelled is a common functional unit. When the focus is on the battery, it is typically the energy provided by the battery, while for EoL studies and cradle-to-gate (production of different battery chemistries), the functional unit is often mass-based. Guidelines & standards apply cradle-to-gate or cradle-to-grave system boundaries. These are also the predominant system boundaries in existing studies. Most OEM reports define the system boundary as cradle-to-grave. a noticeable non-harmonized area is the cut-off rules for flows and processes. The description of the system boundary often does not include sufficient information especially regarding the use phase. Here it would be crucial to also define the system boundary of the energy carriers (well to wheel vs. tank to wheel, and whether capital goods are included – i. e. fuel production facilities or electricity generation equipment). It is recommended to look at the permitted cut-off in the context of the scope (e. g. product vs fleet) while avoiding over complicating data collection and processing whenever possible.

Data is the backbone of any LCA study. The ZEV's life cycle stages differ widely regarding data sources, modelling approaches, and level of harmonisation achieved. A standardised way to collect **inventory data** from different stakeholders across the supply chain is still missing, despite its potential benefits in terms of enhancing data exchange, transparency, and reproducibility. **Primary data** availability is also a significant issue that was reported repeatedly by industry within the consortium and brought up in academic work whether due to complete absence or level of transparency in reporting. We observed that the absence of primary data is particularly noticeable for the raw material acquisition and EoL stages. Approaches to foster primary data disclosure may include the implementation of a standard approach to data collection and/or a dedicated traceability system (e. g., digital battery passport) to facilitate data sharing between stakeholders without compromising confidentiality. However, since no LCA study can rely entirely on primary data, secondary data sources such as scientific literature, engineering models, technical datasheets, and LCI databases will continue to play a relevant role.

Thus, LCA practitioners and databases developers are encouraged to continuously expand and improve the availability and quality of LCI datasets as well as models for inventory data generation, while practitioners must be aware that secondary data sources can differ in terms of key methodological aspects, which can have large influence on the final results. This points out the importance of the heavy involvement of database developers in the harmonization effort because their models should reflect and be adaptable to the outcomes of TranSensus LCA

Finally, **data quality requirements** also vary widely across the reviewed sources, suggesting the need for further harmonisation of the recommended indicators.

Besides data collection and sources, the inventory phase entails **modelling choices and assumptions** that have significant influence on the results and which remain largely unharmonized. Multifunctionality, either at the **EoL stage or upstream in the supply chain** (e. g., co-mining and refining), is a major aspect to deal with. We identified five main options to deal with **EoL multifunctionality** across the reviewed sources. While the PEF recommends the use of the CFF, it is not considered by other guidelines and standards, and it is also rarely applied in the scientific literature. Room for improvement was also suggested to promote the applicability of CFF in real LCA studies which usually contain complex inventories. We also identified up to four options to deal with **batteries second life**. Conversely, upstream multifunctionality issues are generally not so emphasized in the reviewed sources as the EoL. Allocation seems like a more favoured option here in most cases, as recommended by some guidelines particularly in the battery production context even if most guidelines recommend the ISO hierarchy as the default way to deal with multifunctionality. Typically, physical or economic allocation is applied. Yet, a harmonised approach to how to apply economic allocation is still lacking.

To harmonize the way to deal with multifunctionality in the LCA of ZEVs, the following needs or recommendations could be signalized in a step-by-step process: a) identify the common multifunctional processes across the supply chain of ZEVs; b) identify which of these processes can be broken down into individual single-function processes; c) if not possible, propose a consistent allocation approach.

Electricity modelling is also major aspect to consider. We found a wide variability concerning recommendations on the electricity mix that should be considered in the vehicle and/or battery use stage, ranging from EU grid mix to country-specific or national residual electricity mixes. Overall, a static average electricity mix for a reference year is the predominant approach across all the reviewed sources. Hence, the evolution of the electricity mix over the vehicle and/or battery lifetime remains largely overlooked. This is problematic, as this variation is projected to be highly significant in many markets due to actions taken to tackle climate change. However, there is currently lack of agreement / availability on official projections for this change. Similar issues also exist for the future hydrogen production mix. In addition, for the production phase there is some debate over the use of certificates/guarantees of origin for renewable electricity, due to additionality concerns, and lack of consistency with the EU's rules for RFNBOs (including hydrogen).

We also reviewed the trends in **impact assessment phase**. Climate Change is by far the most studied and sometimes the solely studied, but we oppose this trend since it increases the risk of burden shifting and green washing. The choice of which impact categories to prioritize/ compulsory to report should be a core discussion for a harmonized LCA approach for ZEVs and batteries. The Environmental Footprint **LCIA method** (EF3.0 and 3.1) should be ideally followed in European context; however, it will also be important to consider additional indicators from the LCI phase, particularly cumulative energy demand (CED) – highly relevant to European policy objectives. In addition, other indicators should also potentially be explored, e. g. those relating to circularity and critical materials (which may require further development prior to application in the future). But, how to present these indicators is still an open issue for further harmonization in order to avoid overlapping with other conventional impact categories. Similarly, replacing resources depletion indicators with resources dissipation is argued to be important to look at in the future.

Lastly, a unified way of reporting and interpreting the results from LCI and LCIA is of utmost importance. **Interpretation** is the fourth and last phase of LCA in which certain checks should be made to reflect on the robustness of the LCA study and its results and conclusions. Harmonization should focus on defining a feasible way to run uncertainty analysis and/or sensitivity analysis. Perhaps the most impactful parameters underlined in this report can be prescribed in the harmonized approach as benchmarks. Furthermore, a clear verification process is needed in which a third-party verifier should assess the overall quality in addition to completeness and consistency.

There is also a need for future scenario analysis for the development and penetration of battery and EV technologies, upgrades and efficiency improvements to grid transmissions and evaluation of capacity for the grid to handle surges in energy demand. Evolution in renewable energy generation systems is in some cases modelled in the LCA scenario analyses, and in others recognised as a gap in the study by its authors.

To conclude, the following Table VI-1 summarizes some of the points for which some pattern of harmonization could be noticed in the review (exceptions are always present). Furthermore, it shows that most of topics are not harmonised and they will require further efforts (e. g. within the TranSensus LCA project).

Table VI-1. The status of key LCA topics from harmonization perspective

LCA phase	**Some harmonization could be identified**	**Less well harmonized**
Goal and scope definition	• FU for batteries	• FU for ZEV vehicles, • Underlying assumptions, e. g. vehicle lifetime, mileage, or battery cycle lifetime, • Inclusion of use and EoL within batteries system boundaries, • Inclusion of infrastructure & maintenance within system boundaries, • Cut-off criteria
Inventory analysis	• Vehicle energy consumption (use of measurements or documented tests), • Accounting for battery charging losses	• Standardised approach to inventory data collection through the ZEVs supply chain, • Accounting for non-exhaust emissions during use (e. g., from tires and brakes), • Accounting for maintenance (e. g., whether to consider tires replacement only or also regular maintenance), • Battery or fuel cell replacement, • EoL multifunctionality, • EoL processes and data sources, • Batteries second life allocation, • Upstream multifunctionality issues,

LCA phase	Some harmonization could be identified	Less well harmonized
		• Electricity modelling for vehicle and/or battery use stage, • Data quality requirements
Life cycle impact assessment	• Impact categories and impact assessment methods (EF)	• Additional indicators like dissipation of abiotic resources, circularity of resources, criticality of abiotic resources and cumulative energy demand
Interpretation	• Comparison of results reported between ZEVs and conventional powertrains (ICEVs), • Reporting styles and interpretation approaches – adopting of contribution analysis as a default, inclusion of sensitivity analysis in general.	• Reporting styles – preferably by life cycle stages, over materials, • Consistency in choice of parameters chosen for sensitivity studies, particularly geographically relevant (dynamic) grid mix modelling, vehicle lifetime activity (v.km), battery service lifetime vehicle occupancy and EoL Allocation methods. • A dedicated single harmonised methodology to aggregate uncertainties in automotive LCA, • Potential future scenarios, second life impacts, such as use of EoL batteries in non-transport applications.

VI.2 Social LCA

There is no harmonization attempt for S-LCA at Zero Emission Vehicle level. The review of S-LCA highlights that there are no publicly available Original Equipment Manufacturer (OEM) reports on the topics covered, limiting the review's scope to scientific literature. The two main databases available for S-LCA are SHDB and PSILCA, providing access to social data on a country-specific sector level, aiding in assessing social risks associated with sectors and product systems. Different methodologies underlie these databases, influencing risk level assignments. The content then delves into the Goal and Scope Definition stage, where the goal and target audience of the study are reviewed. Manufacturers and the public are identified as key audiences. However, access to scientific articles may limit reaching the public. The content also covers the Scope Definition step, where some elements are well-defined, while others, such as data quality and allocation, are often overlooked.

In the Inventory Analysis phase, various methods are used to collect data, and the importance of literature review in understanding relevant social issues is emphasized. The role of stakeholders, such as the local community, is highlighted in assessing relevant social sub-categories.

The use of S-LCA dedicated databases is common, but it's essential to recognize their limitations.

The Impact Assessment phase is thoroughly examined, with the reference scale/performance reference point method being commonly used. Workers are consistently identified as the category most negatively impacted, while the local community experiences the highest positive impact.

The Interpretation phase receives significant attention, as it helps derive insights from impact assessment results and provide actionable recommendations for decision-makers. Completeness and consistency checks, uncertainty and sensitivity analysis, data quality assessment, and materiality assessment are key steps in this phase. However, it's noted that some case studies lack emphasis on the interpretation phase, indicating the need for further research in this area.

VI.3 Life Cycle Costing

The Life Cycle Costing (LCC) is a useful methodology ZEVs to provide comprehensive understanding of the total costs over the entire life cycle. Typical use case examples of LCC for ZEVs include providing decision support for vehicle procurement choices by governments, enabling consumers to compare the total cost of ownership of different drive trains, and offering decision support for technology choices by OEMs.

While LCC has been established for several decades, only a few technology or sector specific guidelines and standards exist. For instance, there are LCC guidelines available for the building sector and water treatment technologies; however, specific guidelines for ZEVs are currently lacking. While several aspects of LCC are relatively well harmonized across the literature (e. g. vehicle acquisition cost, fuel costs, maintenance and repair), there are still many others that require further harmonization efforts. The main aspects include:

1) **Clear guidance on LCC type:** Three main LCC types where defined, including societal LCC, environmental LCC, conventional LCC and total cost of ownership (TOC). These concepts separate each other through three key focus areas including 1) user-perspective 2) sustainability dimension and 3) life cycle included. However, there is currently a lack of guidance on when to use each LCC type in specific contexts. Establishing clear guidelines would help practitioners in making informed methodological choices.
2) **Quantification of environmental and social impacts:** LCC studies face the challenge of quantifying environment and/or social impacts in monetary terms. While some LCC studies monetize externalities indirectly as they are already internalised (e. g. CO_2 taxation in fuel prices, emission-based road tolls), others directly include non-internalized externalities by applying conversion factors to specific pollutants (e. g., assigning a monetary value to emitting 1 kg of NOx). While the former is relatively straight forward

because monetized externalities already form part of the cash flow, the latter remains highly contested in the literature. A key issue here is the different choices regarding monetary conversion factors of externalities and lack of consistency between studies.

3) **Addressing potential double counting when integrating LCC with (S)LCA**: Another point of debate here is the potential for double counting when conducting the LCC in parallel with (S)LCA. In this case, the monetization of pollutants that are not internalised already (or soon to be internalised) are accounted in both the economic and environmental/social domain. Clear guidance on such double counting however does not exist.
4) **Harmonizing the choice of Discount Rate:** The choice of **discount rate** is another critical element that significantly differs between studies. While some studies do not include discount rates at all, others use a wide variety of rates. Harmonizing the choice of discount rates will enhance the comparability and credibility of LCC assessments for ZEVs.
5) **Assumptions on future energy costs:** In addition, there are a wide variety of assumptions made on the current and future projections of **energy costs** between studies, which significantly hamper comparability. In some instances there are official projections available (e. g. for policy analysis in the UK), however this is generally another area where there is generally a significant lack of information and standardisation (i. e. similarly to the projected future energy mix for environmental LCA).

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Appendices

A1 Review Method

A1.1 Initial survey results

The number of respondents to the survey and their professional background is shown in Figure A1.1

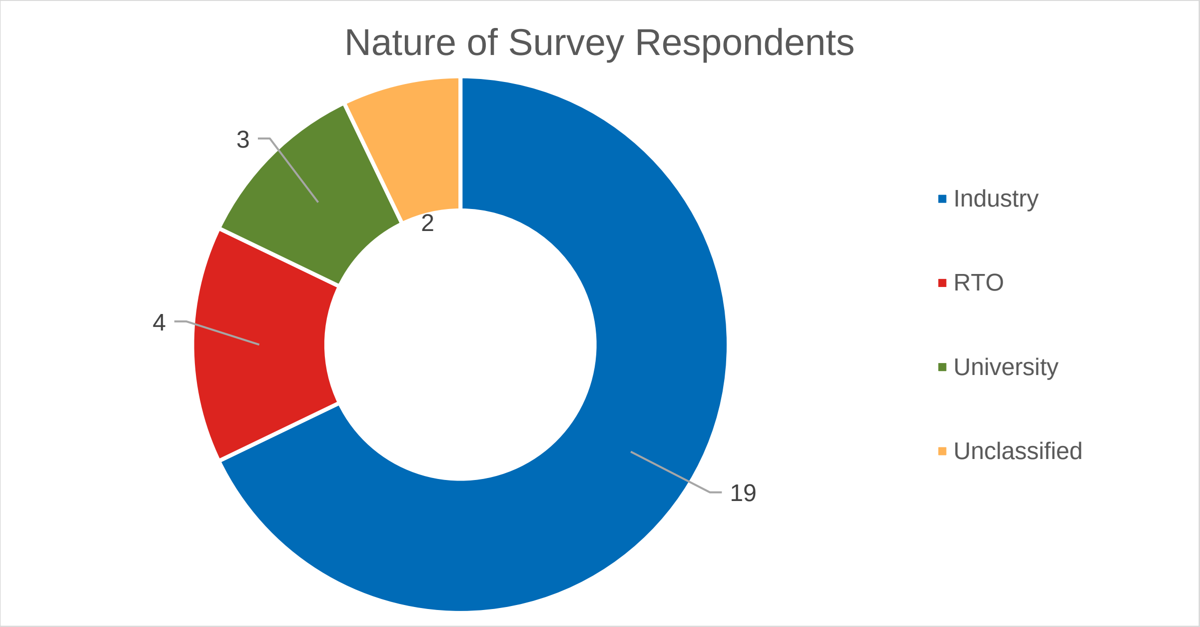


Figure A1.1: Number and Background of Respondents

The questions and answers are summarized below:

- Q1: How important do you view the following goals/applications being considered for the harmonised LCA methodology as part of the development by TranSensus LCA?

A list of four choices were given and respondents were asked to give a score to each choice ranging from 1 to 5 where 5 means extremely relevant. The answers and their average score are reported in Table A1.1.

Table A1.1: Answers to Question 1 of the survey

Answer	Average score
Product LCA/reporting (i. e. LCA of final completed products for internal and external/public stakeholders - e. g. for environmental product declarations, certification, marketing, customer information)	4.5

Answer	Average score
Supporting/ providing a basis for compliance with potential national or European legislative requirements	4.3
Utilization in policy analysis to inform decision-making (i. e. identification of key hotspots where legislative instruments might be needed to aid mitigation)	4.0
b) Support in the development/design of sustainable products/eco-design (i. e. internal focus, informing new/future products/technologies)	3.9

- Q2: Which questions are you trying to answer with your LCAs?

The respondents were given the chance to provide their own answers in a free text style. Then the answers were furtherly elaborated then summarized as shown in Table A1.2. The number of votes in second column shows how many times a specific topic was brought up by respondents.

Table A1.2: Answers to Question 2 of the survey

Topic	Number of votes	Additional comments by respondents
Comparative LCA	9	What is the life cycle environmental impact of one vehicle/powertrain compared to another. Different fuels and use cases etc.
Life cycle impact of a product	9	Env impacts of a vehicle and its value chain.
Hotspots	6	What are the hotspots in the value chain?
Improvements	4	Tracking/follow up on improvements
Guide decisions and action plans	3	How to make the right decisions and where to put first efforts
Evaluating components/technology changes in vehicle	3	What kind of design or technology changes has less impact during the life cycle

- Q3. What are key issues (obstacles) for you when performing LCAs on batteries/EVs/ZEVs (e. g. electricity modelling or recycling, etc)? Which key issues would you hope TranSensus LCA can provide solutions for?

The answers were asked in a similar manner to Q2. The answers are summarized in Table A1.3.

Table A1.3: Answers to Question 3 of the survey

Topic	Number of votes	Additional comments by respondents
Lack of primary data	11	Raw material, battery data, data from suppliers, manufacturing data, material losses in supply chain
Lack of database data	7	Lack of data on batteries, electronics,” novel” materials, recycled materials etc.
Functional unit	4	Lack of common understanding of FU in commercial vehicles and how to define FU to allow for fair comparisons
Future electricity grid mixes	4	How to account for changes and scenarios in electricity mix, reference scenario
Lack of harmonized way to collect value chain LCA data	3	Hard to ask suppliers for data
Common methodology	3	-
Lack of clear rules and guidance to ensure comparability	3	-

One more open question was asked that can help guide the review and project in general. The question and its raw answers are provided below.

- Q4. Do you have any other suggestions or inputs to the work in WP 1&2 or the project in general?
    - ➢ Recommend that the difficult discussions in the recent projects around the Batteries Passport and Carbon footprint declaration of batteries is taken into account to further progress (see Batteries Technical Secretariat by RECHARGE, German project BatteryPass, GBA project for Carbon Footprint, etc ...).
    - ➢ One set of rules to be ALL on the same page BUT practical rules, easy to use. Accuracy is one thing, but it might lead us/you in never ending discussions or legal fields that will block the move => some limit or assumptions in the set of rules to ease the process, to allow a quick start to learn might be a good way.
    - ➢ Try to find alignment with existing initiatives. Be as specific as possible.
    - ➢ Agreement / decision on the limits of relevant or not relevant content.
    - ➢ Harmonize & standardize data/inventory, LCA methodology clarification/standardization.
    - ➢ Just in general: it was obvious that WP1 and WP2 need to work strongly together especially in the beginning. Both WPs started that way, please keep this up, exchanging your findings and progress.
    - ➢ Establish the link between the outcome of TranSensus LCA and European Commission LCA methodology & UN ECE IWG A- LCA.

- I suggest guaranteeing a full alignment and harmonization with the Carbon Footprint Battery - EV expected in the New Battery Regulation. It's a countersense to manage a different approach/method for the battery.
- Identify properly the links among the 3 dimensions of sustainability and not only focus on the environmental part.
- It would be useful to also develop a matrix that would help visually illustrate which elements might be standardized or be different depending on the different goals/applications of the LCA.
- Regarding the electric battery value chain “Company 1” has done extensive analysis about different actors, availability of the information and different ways the information could be shared. We have encountered various specific questions from many stakeholders and would like to contribute to the development of the use case. We are more than happy to provide industry view on the SoTA and participate in the workshops to provide additional information. Progress in LCA with real data has given us a unique position to support in the gap analysis of the project.
- We would recommend getting feedback at an early stage from standards developers where the vehicle lifecycle emissions may be used. Some industry-based standards developers are the GHG protocol (WBCSD, WRI) and SBTi. Some relevant legislative initiatives are CountEmission.eu and Corporate Sustainability Reporting Directive.
- We would also recommend getting inputs from end users (such as shippers, LSPs and carriers). We want to enable the energy transition to be ‘driven’ by the demand side, not just by the supply-side or legislation. Hence, it would be vital to also get consensus from along the value chain, even at the tail end. More concretely, the users will be effectively guided or constrained in how they report the vehicle lifecycle portion of their emissions. As such, we need to incorporate their input unto the functionality and outputs the LCA methodology provides to enable them to do what they need (related to the standards point above).
- Related to both points above, we would welcome WP1 & 2 to make use of a session on vehicle LCA at the Smart Freight Week hosted by Smart Freight Centre on 19th April.

A1.2 Extended Consultation Activities Description

The objective of the targeted survey was to gather insights and views on the use of LCA methods for road vehicles from the current experience and knowledge of the EU automotive industry. The responses are used to inform and guide the harmonisation effort, especially focusing on the areas that have been identified as more critical.

The survey ran for three weeks, from 9 May 2023 to 30 May 2023, in an online platform. It was sent to all industrial partners of the TranSensus LCA project consortium and other industry contacts.

The survey was divided into six different sections including:

1. LCA practice: This section included questions about the organisation's current and future LCA practice as well as data collection.
2. LCA methodology: This section included key questions concerning methodological choices for LCA of ZEVs and batteries.
3. Application and scenarios: This section was dedicated to topics beyond LCA that have an influence on the requirements of the LCA approach. This includes current and future mobility scenarios as well as current and future end of life (EoL) / circular economy (CE) scenarios.
4. Social responsibility: This section included questions about the organisation's management of social issues, like human rights, health and safety and discrimination.
5. Social LCA: This section was dedicated to more detailed questions about social LCA which were only to be answered by organisations that conduct an S-LCA.
6. Life cycle costing assessment (LCC): This was a short section containing questions on whether and how organisations also use LCC.

Considering the breadth of the topics covered, it was recognised that respondents would not necessarily have expertise and knowledge across all areas. Therefore, they were allowed to select the survey sections that they could provide answers to and skip the sections not selected entirely.

All TranSensus LCA project partners were required to engage with the first three sections as a minimum but external respondents could select any sections.

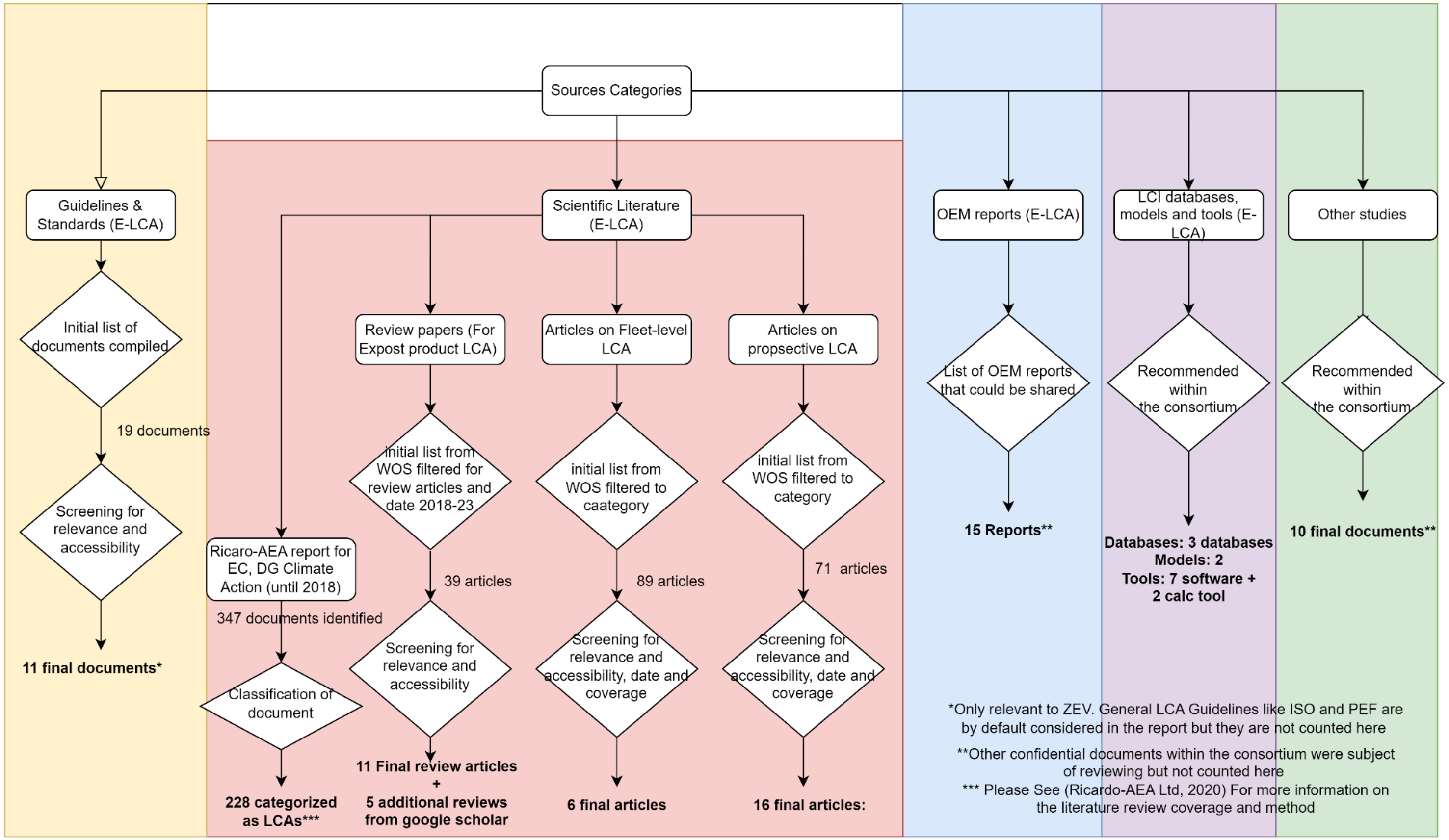
Overall, 17 stakeholders responded to the survey. An overview of their responses has been incorporated in the relevant sections in the main report.

A1.2.1 Targeted interviews (Ongoing activity)

Following the review of the survey responses, targeted interviews were organised to clarify and explore some of the responses of selected industry stakeholders in more detail. Based on each stakeholder's response, a tailored interview guide was developed with 5-10 questions to guide the one-hour online discussions.

The interviews are currently taking place. To date we have conducted two interviews and expect to organise two more.

A1.3 Literature selection process



*Only relevant to ZEV. General LCA Guidelines like ISO and PEF are by default considered in the report but they are not counted here

**Other confidential documents within the consortium were subject of reviewing but not counted here

*** Please See (Ricardo-AEA Ltd, 2020) For more information on the literature review coverage and method

Figure A1.2: LCA sources selection process

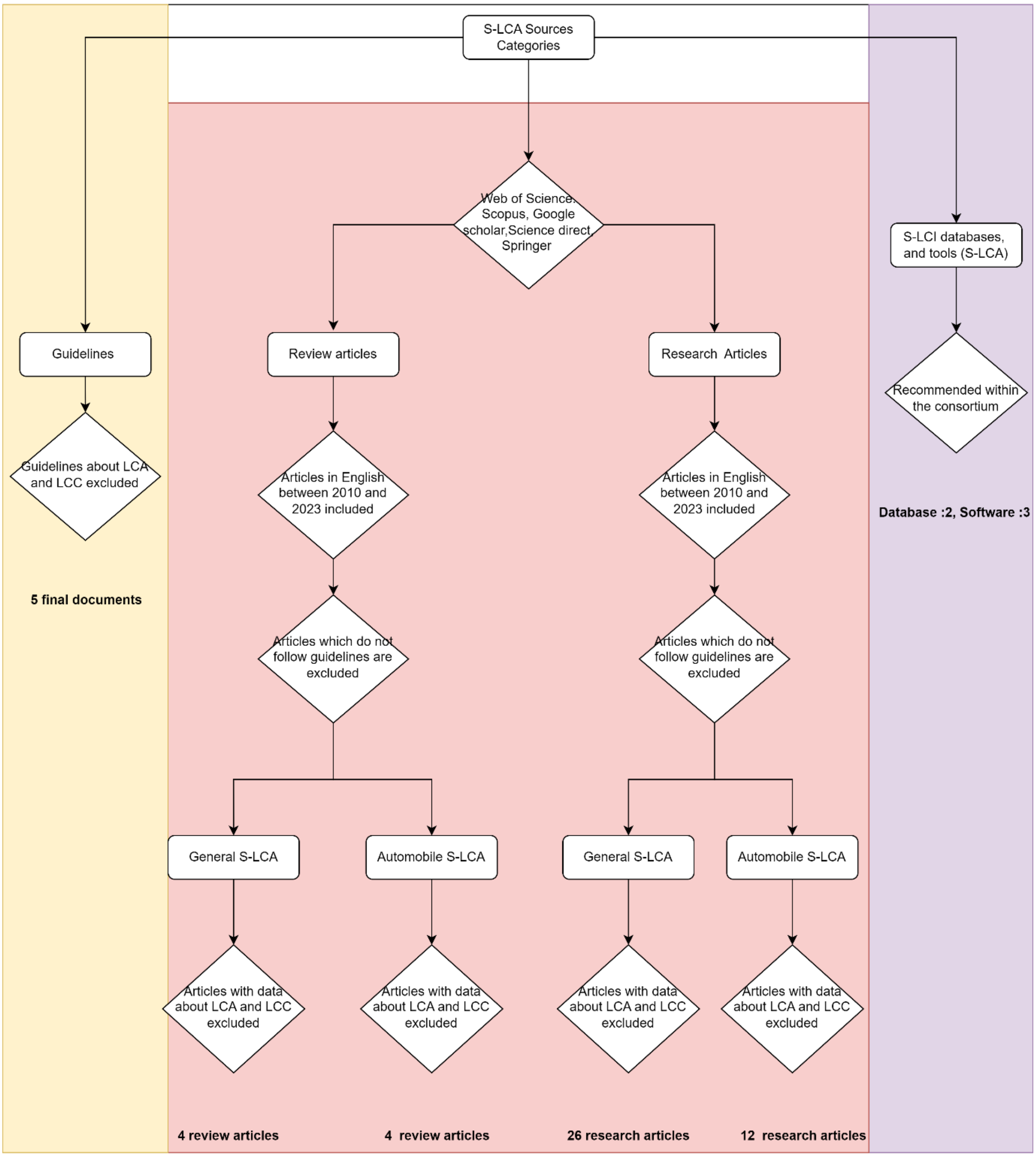
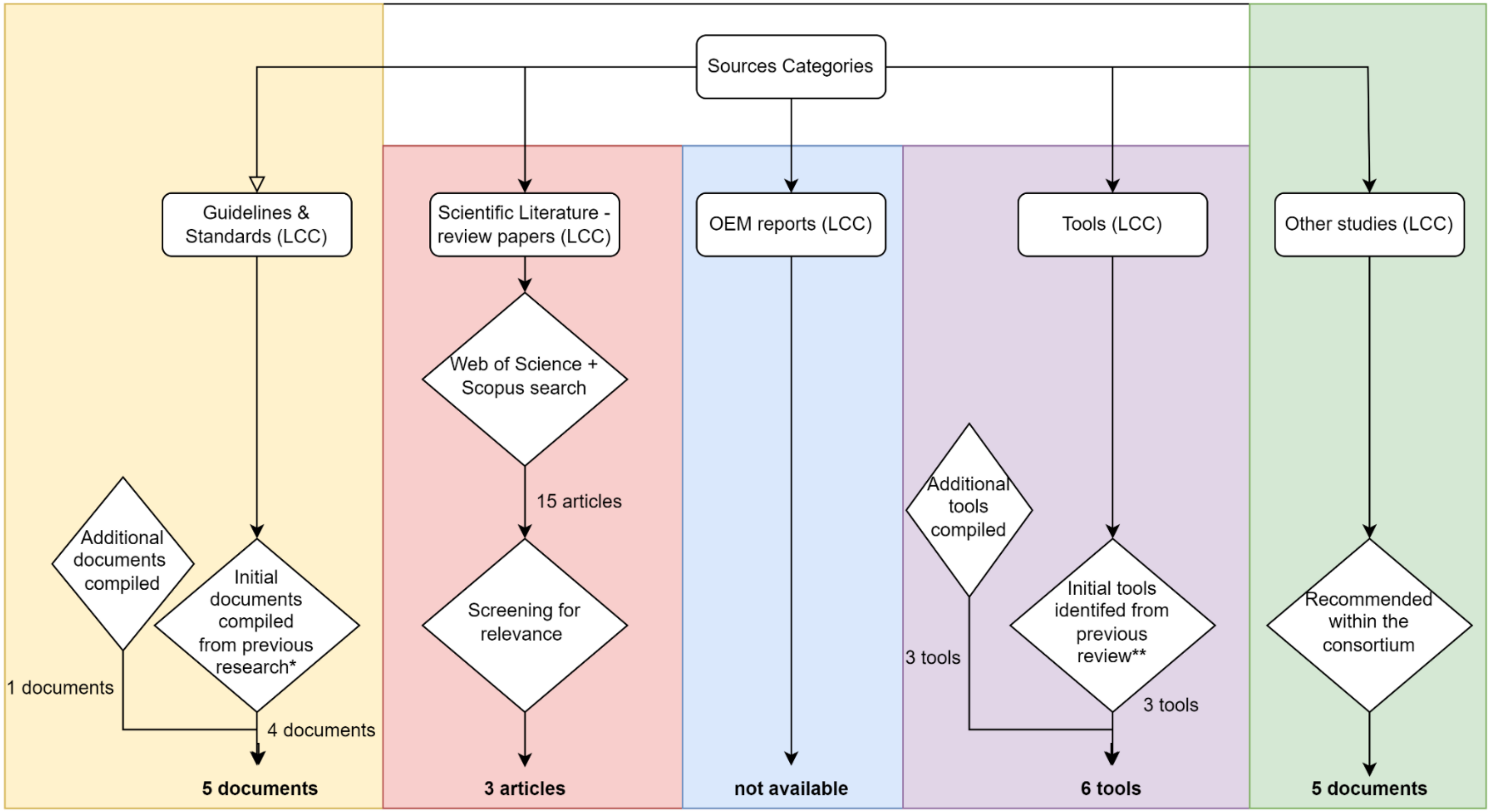


Figure A1.3: S-LCA sources selection process



* EU H2020 project: Refresh D. 5.2 "Methodology for evaluating LCC"

** "Ch. 3 Mapping life-cycle costing tools and practise" in OECD 2022, Life-Cycle Costing in Public Procurement in Hungary

Figure A1.4: LCC sources selection process

Table A1.4: Summary of finally selected scientific articles in all three methodologies:

Document title	Author (s)	Methodology	Source category	Sub-category
Electricity generation in LCA of electric vehicles: A review	Marmiroli B, Messagie M, Dotelli G, Van Mierlo J	E-LCA	Scientific literature	Retrospective LCA
Life cycle assessment of electric vehicle batteries: An overview of recent literature	Temporelli A, Carvalho ML, Girardi P	E-LCA	Scientific literature	Retrospective LCA
Environmental Life Cycle Impacts of Automotive Batteries Based on a Literature Review	Aichberger C	E-LCA	Scientific literature	Retrospective LCA
Review and meta-analysis of EVs: Embodied emissions and environmental breakeven	Dillman KJ, Árnadóttir Á, Heinonen J, Czepkiewicz M, Davíðsdóttir B	E-LCA	Scientific literature	Retrospective LCA
Update on the Life-Cycle GHG Emissions of Passenger Vehicles: Literature Review and Harmonization	Raugei M	E-LCA	Scientific literature	Retrospective LCA
Comparative Life Cycle Assessment of Merging Recycling	Zhou Z,Lai Y, Peng Q, Li J	E-LCA	Scientific literature	Retrospective LCA
End of Electric Vehicle Batteries: Reuse vs. Recycle	Kotak Y, Marchante Fernández C, Canals Casals L, Kotak BS, Koch D, Geisbauer C,Trilla L, Gómez-Núñez A, Schweiger HG	E-LCA	Scientific literature	Retrospective LCA
Methodological Approaches to End-Of-Life Modelling in Life Cycle Assessments of Lithium-Ion Batteries	Nordelöf A, Poulikidou S, Chordia M,Bitencourt de Oliveira F, Tivander J, Arvidsson R	E-LCA	Scientific literature	Retrospective LCA

Document title	Author (s)	Methodology	Source category	Sub-category
The greenhouse gas emissions of automotive lithium-ion batteries: a statistical review of life cycle assessment studies	Bouter A, Guichet X	E-LCA	Scientific literature	Retrospective LCA
A review of life cycle assessment studies of electric vehicles with a focus on resource use	Dolganova I, Rödl A, Bach V, Kaltschmitt M, Finkbeiner M	E-LCA	Scientific literature	Retrospective LCA
Application of life cycle assessment to lithium ion batteries in the automotive sector	Tolomeo R, De Feo G, Adami R, Osséo LS	E-LCA	Scientific literature	Retrospective LCA
Life cycle assessment of battery electric vehicles and internal combustion vehicles using sugarcane ethanol in Brazil: A critical review	Lavrador RB, Teles BA	E-LCA	Scientific literature	Retrospective LCA
Life cycle assessment of electric vehicles in comparison to combustion engine vehicles: A review	Verma S, Dwivedi G, Verma P	E-LCA	Scientific literature	Retrospective LCA
Literature Review-Electric Vehicles Life Cycle Assessment	Tintelecan A, Dobra AC, Marțiș C	E-LCA	Scientific literature	Retrospective LCA
Life Cycle Cost Assessment of Electric Vehicles: A Review and Bibliometric Analysis	Ayodele BV, Mustapa SI	E-LCA	Scientific literature	Retrospective LCA
A review of the life cycle assessment of electric vehicles: Considering the influence of batteries	Xia X,Li P	E-LCA	Scientific literature	Retrospective LCA
Critical review of life cycle assessment of lithium-ion batteries for electric vehicles: A lifespan perspective	Lai X, Chen Q, Tang X, Zhou Y, Gao F, Guo Y, Bhagat R, Zheng Y	E-LCA	Scientific literature	Retrospective LCA

Document title	Author (s)	Methodology	Source category	Sub-category
Prospective Life Cycle Assessment of a Structural Battery	Zackrisson M, Jönsson C, Johannisson W, Fransson K, Posner S, Zenkert D, Lindbergh G	E-LCA	Scientific literature	Prospective LCA
Life Cycle Assessment of Fuel Cell Systems for Light Duty Vehicles, Current State-of-the-Art and Future Impacts	Usai L, Hung CR, Vásquez F, Windsheimer M, Burheim OS, Strømman AH	E-LCA	Scientific literature	Prospective LCA
Life Cycle Assessment of Sodium-Ion Batteries	Peters J, Buchholz D, Passerini S, Weil M	E-LCA	Scientific literature	Prospective LCA
Life-Cycle Impacts from Different Decarbonization Pathways for the European Car Fleet	Dirnaichner A, Rottoli M, Sacchi R, Rauner S, Cox B,Mutel C, Bauer C, Luderer G	E-LCA	Scientific literature	Prospective LCA
Net Emission Reductions from Electric Cars and Heat Pumps in 59 World Regions over Time	Knobloch F, Hanssen SV, Lam A,Pollitt H, Salas P, Chewpreecha U, Huijbregts MA, Mercure JF	E-LCA	Scientific literature	Prospective LCA
Trade-off between Critical Metal Requirement and Transportation Decarbonization in Automotive Electrification	Zhang C, Zhao X, Sacchi R, You F	E-LCA	Scientific literature	Prospective LCA
The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework	Bauer C, Hofer J, Althaus HJ, Del Duce A, Simons A	E-LCA	Scientific literature	Prospective LCA
Prospective Life Cycle Assessment of a Flexible All-Organic Battery	Zhang S, Ericsson N, Sjödin M, Karlsson Potter H, Hansson PA, Nordberg Å	E-LCA	Scientific literature	Prospective LCA

Document title	Author (s)	Methodology	Source category	Sub-category
Life Cycle Assessment of Battery Electric Vehicles: Implications of Future Electricity Mix and Different Battery End-of-Life Management	Koroma MS, Costa D, Philippot M, Cardellini G, Hosen MS, Coosemans T, Messagie M	E-LCA	Scientific literature	Prospective LCA
Does Size Matter? The Influence of Size, Load Factor, Range Autonomy, and Application Type on the Life Cycle Assessment of Current and Future Medium- and Heavy-Duty Vehicles	Sacchi R, Bauer C, Cox BL	E-LCA	Scientific literature	Prospective LCA
When, Where and How Can the Electrification of Passenger Cars Reduce Greenhouse Gas Emissions?	Sacchi R, Bauer C, Cox B, Mutel C	E-LCA	Scientific literature	Prospective LCA
Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles	Cox B, Mutel CL, Bauer C, Mendoza Beltran A, van Vuuren DP	E-LCA	Scientific literature	Prospective LCA
Electrification of Light-Duty Vehicle Fleet Alone Will Not Meet Mitigation Targets	Milovanoff A, Posen ID, MacLean HL	E-LCA	Scientific literature	Prospective LCA
Prospective Time-Resolved LCA of Fully Electric Supercap Vehicles in Germany	Zimmermann BM, Dura H, Baumann MJ, Weil MR	E-LCA	Scientific literature	Prospective LCA
Prospective Life-Cycle Assessment of Greenhouse Gas Emissions of Electricity-Based Mobility Options	Rüdisüli M, Bach C, Bauer C, Beloin-Saint-Pierre D, Elber U, Georges G, Limpach R, Pareschi G, Kannan R, Teske SL	E-LCA	Scientific literature	Prospective LCA

Document title	Author (s)	Methodology	Source category	Sub-category
Life Cycle Environmental and Cost Comparison of Current and Future Passenger Cars under Different Energy Scenarios	Cox B ,Bauer C, Mendoza Beltran A, van Vuuren DP, Mutel CL	E-LCA	Scientific literature	Prospective LCA
Prospective Life Cycle Assessment of Alternatively Fueled Heavy-Duty Trucks	van den Oever AE, Costa D, Messagie M	E-LCA	Scientific literature	Prospective LCA
Unraveling the Role of Biofuels in Road Transport under Rapid Electrification	Cavalett O, Cherubini F	E-LCA	Scientific literature	Prospective LCA
Future Greenhouse Gas Emissions of Automotive Lithium-Ion Battery Cell Production	Xu C, Steubing B, Hu M, Harpprecht C, van der Meide M, Tukker A	E-LCA	Scientific literature	Prospective LCA
Prospective Environmental Impacts of Passenger Cars under Different Energy and Steel Production Scenarios	Koroma MS, Brown N, Cardellini G, Messagie M	E-LCA	Scientific literature	Prospective LCA
Prospective LCA of the Production and EoL Recycling of a Novel Type of Li-ion Battery for Electric Vehicles	Raugei M, Winfield P	E-LCA	Scientific literature	Prospective LCA
Evaluation of Alternatives for the Passenger Road Transport Sector in Europe: A Life-Cycle Assessment Approach	Paulino F, Pina A, Baptista P	E-LCA	Scientific literature	Fleet-level LCA
Integration of system dynamics approach toward deepening and broadening the life cycle sustainability assessment framework: a case for electric vehicles	Onat NC, Kucukvar M, Tatari O, Egilmez G	E-LCA	Scientific literature	Fleet-level LCA

Document title	Author (s)	Methodology	Source category	Sub-category
A review of fleet-based life-cycle approaches focusing on energy and environmental impacts of vehicles	Garcia R, Freire F	E-LCA	Scientific literature	Fleet-level LCA
Life-cycle impacts from different decarbonization pathways for the European car fleet	Dirnaichner A, Rottoli M, Sacchi R, Rauner S, Cox B, Mutel C, Bauer C, Luderer G	E-LCA	Scientific literature	Fleet-level LCA
A hybrid life cycle assessment of the large-scale application of electric vehicles	Xiong S, Wang Y, Bai B, Ma X	E-LCA	Scientific literature	Fleet-level LCA
Environmental implications of the ongoing electrification of the UK light duty vehicle fleet	Raugei M, Kamran M, Hutchinson A	E-LCA	Scientific literature	Fleet-level LCA
Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA	RICARDO	E-LCA	Other	N.A.
Energy Efficiency and Conservation Authority Life Cycle Assessment of Electric Vehicles Final Report	ARUP	E-LCA	Other	N.A.
Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emission	ICCT	E-LCA	Other	N.A.
Future Fuels: FVV Fuels Study IV	Frankfurt am Main	E-LCA	Other	N.A.
More Bang For The Buck: A Comparison Of The Life-Cycle Greenhouse Gas Emission Benefits And Incentives Of Plug-In Hybrid And Battery Electric Vehicles In Germany	ICCT	E-LCA	Other	N.A.

Document title	Author (s)	Methodology	Source category	Sub-category
A Global Comparison Of The Life-Cycle Greenhouse Gas Emissions Of Combustion Engine And Electric Passenger Cars	ICCT	E-LCA	Other	N.A.
A Comparison Of The Life-Cycle Greenhouse Gas Emissions Of European Heavy-Duty Vehicles And Fuels	ICCT	E-LCA	Other	N.A.
Lithium-Ion Vehicle Battery Production Status 2019 on Energy Use, CO2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling	IVL	E-LCA	Other	N.A.
How clean are electric cars? T&E's analysis of electric car lifecycle CO_2 emissions	T&E	E-LCA	Other	N.A.
The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries	IVL	E-LCA	Other	N.A.
GREET	Argonne National Laboratory	E-LCA	Databases, Models and tools	N.A.
BatPaC	Argonne National Laboratory	E-LCA	Databases, Models and tools	N.A.
ecoinvent	ETH, ecoinvent	E-LCA	Databases, Models and tools	N.A.

Document title	Author (s)	Methodology	Source category	Sub-category
MLC (former GaBi) database (professional)	Sphera	E-LCA	Databases, Models and tools	N.A.
SimaPro	Pre Consultants	E-LCA	Databases, Models and tools	N.A.
LCA FE (former GaBi) software	Sphera	E-LCA	Databases, Models and tools	N.A.
CMLCA	CML-Leiden University	E-LCA	Databases, Models and tools	N.A.
Activity Browser	Various	E-LCA	Databases, Models and tools	N.A.
Brightway	Various	E-LCA	Databases, Models and tools	N.A.
Umberto	ipoint	E-LCA	Databases, Models and tools	N.A.
OpenLCA	Greendelta	E-LCA	Databases, Models and tools	N.A.
Rigor in social life cycle assessment: improving the scientific grounding of SLCA	Grubert E	S-LCA	Scientific literature	N.A.

Document title	Author (s)	Methodology	Source category	Sub-category
The guidelines for social life cycle assessment of products: just in time!	Beno\^it C, Norris GA, Valdivia S, Ciroth A, Moberg A, Bos U, Prakash S, Ugaya C, Beck T	S-LCA	Scientific literature	N.A.
Social life cycle assessment : state of the art and challenges for product policy support.	Sala S, Vasta A, Mancini L, Dewulf J, Rosenbaum E, Centre. EC	S-LCA	Scientific literature	N.A.
A social life cycle assessment of vanadium redox flow and lithium–ion batteries for energy storage	Koese M, Blanco CF, Vert VB, Vijver MG	S-LCA	Scientific literature	N.A.
Assessment of social sustainability hotspots in the supply chain of lithium-ion batteries	Thies C, Kieckhäfer K, Spengler TS, Sodhi MS	S-LCA	Scientific literature	N.A.
An integrated social life cycle assessment of freight transport systems	Osorio-Tejada JL, Llera-Sastresa E, Scarpellini S, Hashim AH	S-LCA	Scientific literature	N.A.
Social Organizational Life Cycle Assessment of Transport Services: Case Studies in Colombia, Spain, and Malaysia	Osorio-Tejada JL, Llera-Sastresa E, Scarpellini S, Morales-Pinzón T	S-LCA	Scientific literature	N.A.
Social life cycle assessment of lithium iron phosphate battery production in China, Japan and South Korea based on external supply materials	Shi Y, Chen X,Jiang T, Jin Q	S-LCA	Scientific literature	N.A.
Social Life Cycle Assessment in der Automobilindustrie vorgelegt von Diplom-Geoökologin Hannah Karlewski geb. in Tübingen	Karlewski H	S-LCA	Scientific literature	N.A.

Document title	Author (s)	Methodology	Source category	Sub-category
Social impact improving model based on a novel social life cycle assessment for raw rubber production: A case of a Sri Lankan rubber estate	Dunuwila P, Rodrigo VH, Daigo I, Goto N	S-LCA	Scientific literature	N.A.
Material Selection by Taking the Whole System into Consideration-Automobile LCA from Steel Industry's Viewpoint	Takamatsu N, Ohashi H	S-LCA	Scientific literature	N.A.
Towards social life cycle assessment: a quantitative product social impact assessment	Traverso M, Bell L, Saling P, Fontes J	S-LCA	Scientific literature	N.A.
A practical approach for social life cycle assessment in the automotive industry	Karlewski H, Lehmann A, Ruhland K, Finkbeiner M	S-LCA	Scientific literature	N.A.
A practical approach for social life cycle assessment in the automotive industry	Karlewski H, Lehmann A, Ruhland K, Finkbeiner M	S-LCA	Scientific literature	N.A.
Smart and Green Solutions for Transport Systems	Sierpiński G	S-LCA	Scientific literature	N.A.
Social aspects for sustainability assessment of technologies – Challenges for social life cycle assessment (SLCA)	Lehmann A, Zschieschang E, Traverso M, Finkbeiner M, Schebek L	S-LCA	Scientific literature	N.A.
Life cycle costing in sustainability assessment-A case study of remanufactured alternators	Schau EM, Traverso M, Lehmannann A, Finkbeiner M	S-LCA	Scientific literature	N.A.

Document title	Author (s)	Methodology	Source category	Sub-category
Proposal of Major Environmental Impact Categories of Construction Materials Based on Life Cycle Impact Assessments	Jang HJ, Ahn YH, Tae SH	S-LCA	Scientific literature	N.A.
OpenLCA Version: 2.0	Loubert M	S-LCA	Scientific literature	N.A.
Renewable energy recovery potential towards sustainable cattle manure management in Buenos Aires Province: Site selection based on GIS spatial analysis and statistics	Venier F, Yabar H	S-LCA	Scientific literature	N.A.
Step-by-step social life cycle assessment framework: a participatory approach for the identification and prioritization of impact subcategories applied to mobility scenarios	Bouillass G, Blanc I, Perez-Lopez P	S-LCA	Scientific literature	N.A.
Social life cycle assessment revisited	Wu R, Yang D, Chen J	S-LCA	Scientific literature	N.A.
Implementing the guidelines for social life cycle assessment: past, present, and future	Tokede O, Traverso M	S-LCA	Scientific literature	N.A.
A tool to guide the selection of impact categories for LCA studies by using the representativeness index	Esnouf A, Heijungs R, Coste G, Latrille É,Steyer JP, Hélias A	S-LCA	Scientific literature	N.A.
Social aspects of water consumption: risk of access to unimproved drinking water and to unimproved sanitation facilities—an example from the automobile industry	Pastor MM, Schatz T, Traverso M, Wagner V, Hinrichsen O	S-LCA	Scientific literature	N.A.

Document title	Author (s)	Methodology	Source category	Sub-category
Social Value Initiative Product Social Impact Assessment of ASM (artisanal small-scale mined) gold in Peru Product Social Impact Assessment of ASM (artisanal small-scale mined) gold in Peru	Mittal A, Hettinger AL, Basf DI, Saling P, Visser D, Dsm AM, Florea A, Oil F, Alvarado C, Yamada H, Kim S, Kim D, Kwon J, Sustainability P, Goedkoop M, Harmens R, Richemont SP, Hürlimann N	S-LCA	Other	N.A.
Social life cycle assessment for material selection: A case study of building materials	Hosseinijou SA, Mansour S, Shirazi MA	S-LCA	Scientific literature	N.A.
Addressing the effect of social life cycle assessments	Jørgensen A, Dreyer LC, Wangel A	S-LCA	Scientific literature	N.A.
Social life-cycle assessment (S-LCA) of residential rooftop solar panels using challenge-derived framework	Bonilla-Alicea RJ, Fu K	S-LCA	Scientific literature	N.A.
Calculation of Fair wage potentials along products' life cycle – Introduction of a new midpoint impact category for social life cycle assessment	Neugebauer S,Emara Y, Hellerström C, Finkbeiner M	S-LCA	Scientific literature	N.A.
Guidelines for social life cycle assessment of products	Benoît C, Mazijn B, Programme. UN, Ciraig., Processes for the Life Cycle of Products SI, Library CE	S-LCA	Guidelines and Standards	N.A.
Berechnungshilfe Lebenszykluskosten Fahrzeuge	Berliner Energieagentur GmbH	LCC	Databases, Models and tools	N.A.

Document title	Author (s)	Methodology	Source category	Sub-category
Clean Fleets Life Cycle Cost Tool	Clean Fleets Project	LCC	Databases, Models and tools	N.A.
Lifecycle Cost Tool for Fleet Managers	E3fleet	LCC	Databases, Models and tools	N.A.
Effektkalkulator for personbiler	The Norwegian Agency for Public and Financial Management (DFØ)	LCC	Databases, Models and tools	N.A.
Electric vehicles: total cost of ownership tool	IEA	LCC	Databases, Models and tools	N.A.
Alternative Fuel Life-Cycle Environmental and Economic Transportation (AFLEET) Tool	Argonne National Laboratory	LCC	Databases, Models and tools	N.A.
Life Cycle Cost Assessment of Electric Vehicles – A Review and Bibliometric Analysis	Ayodele & Mustapa	LCC	Scientific literature	N.A.
Adoption of electric vehicle: A literature review and prospects for sustainability	Kumar & Alok	LCC	Scientific literature	N.A.
A Review of Comparative Vehicle Cost Analysis	Roosen et al.	LCC	Scientific literature	N.A.
ISO 2000, 2001a, 2001b – Petroleum and natural gas industries — Life-cycle costing	ISO	LCC	Guidelines and standards	N.A.

Document title	Author (s)	Methodology	Source category	Sub-category
Buildings and constructed assets – Service-life planning – Part 5: Life-cycle costing	ISO	LCC	Guidelines and standards	N.A.
Standard Practice for Measuring Life-Cycle Costs of Buildings and Building Systems	ASTM	LCC	Guidelines and standards	N.A.
Life cycle costing and Green Public Procurement	EC	LCC	Guidelines and standards	N.A.
ISO 20465-8 – Guidelines for performance evaluation of treatment.	ISO	LCC	Guidelines and standards	N.A.
Assessing the impacts of selected options for regulating CO2 emissions from new passenger cars and vans after 2020	Ricardo	LCC	Other	N.A.
Analysis of long haul battery electric trucks in EU	T&E	LCC	Other	N.A.
How to decarbonize long-haul trucking in Germany	T&E	LCC	Other	N.A.
Techno-economic uptake potential of zero emission trucks in Europe	TNO	LCC	Other	N.A.
Total cost of ownership for tractor-trailers in Europe	ICCT	LCC	Other	N.A.

A1.4 Sample of review criteria

Table A1.5: Review criteria (Guidelines and standards)

Level 0	Level 1	Level 2 (Specific question)
Phase I: Goal and Scope Definition	**Goal/application**	What is the goal/purpose of the guidelines or standards, etc?
		What is the application that the document supports? (linked to the 3 intended applications defined in TranSensus so far)
		Does the document provide guidance for ex-post or ex-ante LCA or both?
		What is the level of prescriptiveness of the guidelines?
	Part Coverage	Does the document target the whole vehicle or only battery or only vehicle?
	Vehicle size	What is the vehicle type(s) considered in the scope?
	Battery	What is the battery technological coverage?
	Powertrain	What are the powertrains targeted by the document?
	Functional/ reference flow	What is/are the recommended functional unit(s)? What is/are the recommended way(s) to determine functional unit(s)?
		What is the provided guidance regarding reference flow and how it should be calculated?
		Methodology for calculating/ defining component/vehicle service life?
	System boundary	What are the life stages discussed by the guidelines/standards?
		What are the cutoff rules provided regarding excluding some parts/stages of the system if any?
	LCA approach	Does the file provide guidance for conducting attributional or consequential LCA?
	Geographical coverage	In which region of the world does the document provide guidance for?
	Regulations/guidelines followed	What are already existing guidelines that the document builds on if mentioned explicitly?
Phase II: Life Cycle Inventory	**Level of detail in modelling**	What is the level of breaking down of the system into phases and processes within the guidelines? Does the document provide a guide to break down the studied system in a specific manner?
	Mass balance	Does the document provide obligations or recommendations about providing a transparent mass balance of the studied system?
		Are there any flow cut-off criteria recommended?
	Primary data collection medium	Do the recommendation include a standard way of data collection from different stakeholders in the life cycle?
	Battery Data Sources and modelling	What are the recommendations/obligations on data sources for raw material acquisition modelling? (e. g. the

Level 0	Level 1	Level 2 (Specific question)
		geographical context has to be accurately modelled as origin of materials have high impacts on results)
		What are the recommendations/obligations on data sources for manufacturing phase modelling? (e. g. electricity consumption and components of battery from suppliers)
		What are the recommendations/obligations on data sources for use phase modelling? (e. g. electricity consumption during use, market vs location, which scenarios/ years)
		Are there any recommendations/obligations for specific parameters to be enclosed for batteries? (regarding load profile, battery life time assumption, parallel services like V2G)
		What are the recommendations/obligations on data sources for EoL modelling? (e. g. data of the collection, dismantling, recycling…etc of the battery)
	Vehicle data Sources and modelling	What are the recommendations/obligations on data sources for raw material acquisition modelling?
		What are the recommendations/obligations on data sources for manufacturing modelling? (e. g. components from suppliers and electricity usage)
		What are the recommendations/obligations on data sources for use phase modelling? (e. g. maintenance, fuel consumption, electricity)
		Are there any recommendations/obligations for specific use cases of vehicles to be enclosed? (e. g. driving behaviour, standard use pattern)
		Are there any recommendations/obligations to account for particulate matter emissions from tires and brakes during use was calculated?
		What are the recommendations/obligations on data sources for Eol modelling? (e. g. for each component if reported)
	Fuel Cell data Sources and modelling	What are the recommendations/obligations on data sources for raw material acquisition modelling?
		What are the recommendations/obligations on data sources for fuel cell manufacturing modelling?
		What are the recommendations/obligations on data sources for fuel cell EoL modelling?
	Hydrogen data Sources and modelling	What are the recommendations/obligations on data sources for hydrogen production in case of Fuel cell ZEV?
		What are the recommendations/obligations on data sources for hydrogen storage in case of Fuel cell ZEV?
		What are the recommendations/obligations on data sources for recharging stations?

Level 0	Level 1	Level 2 (Specific question)
	Data Quality	Are there any data quality requirement provided by the document?
	End of life phase	What are the EoL routes discussed in the guidelines if any?
		Do the guidelines provide guidance on second life (repurposing) modelling of batteries? (e. g. using the retired battery in stationary storage applications)
		Do the guidelines recommend the usage of cut-off or CFF formula or something else? If CFF what are the recommendations regarding the parameters to be used there (e. g. to account for quality and market for generated secondary material)?
		How EoL credits are to be calculated? e. g. calculating the substituted amounts according to stoichiometry
	Multifunctionality apart from EoL	What are the recommendations on dealing with multifunctionality in other parts of the system upstream (i. e. not EoL)?
		How allocation factors should be calculated in case of allocation?
		What is the recommendation on the application of substitution or system expansion? (e. g. choice of substituted technology, substitution factor,..etc)
Phase III: Life Cycle Impact Assessment	**LCIA method**	Which LCIA method shall be used?
	Impact categories	What are the recommended/required impact categories to include?
	Classification	Are there any recommendations on how to deal with elementary flows that are not classified under the different impact categories of the LCIA method? (For example, if a new rare element in battery composition existing in inventory results but has to reflection in the LCIA step, how to deal with this issue?)
	Characterization	Do the recommendations suggest specific characterization models to use other than the default used one in the chosen LCIA method (especially for water, abiotic depletion and human toxicity)?
		How was biogenic carbon accounted for?
		How was carbon capture accounted for?
	Normalization	Is normalization recommended? What is the recommended source of normalization factors?
	Grouping	Do the guidelines suggest grouping approach to be adopted? And what are the groups?
	Weighting	What are the conditions to do weighting? What are the weighting method and factors recommended?

Level 0	**Level 1**	**Level 2 (Specific question)**
Phase IV: Interpretation	**Reporting**	Does the document give guidance on how the study should be reported? Is there a specific format? (e. g. like a template report)
	Contribution/hot spot analysis	What kind of contribution analysis is recommended if any? (e. g. b stage of LC/ by sources of impact like energy/material consumption, etc)?
	Sensitivity, Uncertainty, scenario analyses	Does the document recognize each as a separate kind of analysis?
		Is there any kind of uncertainty analysis recommended? What are the challenges mentioned if any?
		What kind of scenario/sensitivity analyses should be carried out (e. g. use phase scenarios, EoL scenarios, electricity grid mix scenarios, etc?)
	Verification requirements	What kind of verification process is required?
	Completeness check	Was a completeness check recommended/discussed?
	Consistency check	Was a consistency check explicitly recommended/discussed?
	Needs & Gaps	Where there any specific needs & gaps explicitly identified?
		Where there any specific needs & gaps that seemed implicit (**i. e. Overall reviewer's interpretation**) identifiable in the document?
	Methodological Recommendations in case of review/position paper	What are the recommendations (methodological) of the review/position paper?

A2 Further Discussion on tools and software

Software and tools: Summary of key findings from the review

- Generic tools exist for LCA modelling which help calculating inventories and LCIA results.
- The most used among these generic tools are SimaPro and LCA FE (former GaBi). LCA FE is preferred by industry while academia tends to use SimaPro more.
- There are some tools particularly designed for LCAs on vehicles. Here we discussed GREET (one of the most used overall), NCAP green tool, and carculator.
- Generic tools do not offer pre-set methodological choices and they differ in their computational and modelling capabilities.
- Mobility-specific tools entail pre-set methodological choices that the user has to be aware of to better interpret the outcome from these tools.

There is a wide variety of tools and software to conduct generic-purpose LCA, S-LCA and LCC. SimaPro, developed by PRé-Consultants, LCA FE, developed by Sphera, and OpenLCA, developed by GreenDelta, are probably the most popular and common choice among LCA practitioners. In addition to this common generic software, there are tools specifically designed for transportation LCAs. GREET is an example of these tools. While GREET is primarily known to be more of a database to retrieve information on energy/fuel supply systems, it has also its graphical user interface (GUI), therefore LCA practitioners in mobility services often report it as an LCA software.

A review of LCAs of LIBs found that SimaPro is the most used software (38% of the reviewed studies), followed by GREET (31%), LCA FE (25%), and OpenLCA (6%), whereas up to 49% of the studies do not specify the tool or software used (Tolomeo et al., 2020). A more recent scientific literature review found that up to 69% of the reviewed LCA studies on LIBs used one of the aforementioned four software. (Arshad et al., 2022)

In industry, however, the ranking of mostly used software is a bit different. Answers from the survey showed that LCA FE is by far the most used LCA software (see Figure A2.1). The “Others” reported in Figure A2.1 include GREET, Microsoft Excel, and company-private tools. Excel can be seen as an option, but only for simple LCA models. Given how complex LCA models and scenarios are nowadays, we believe that very generic software like Excel will struggle to keep up with that.

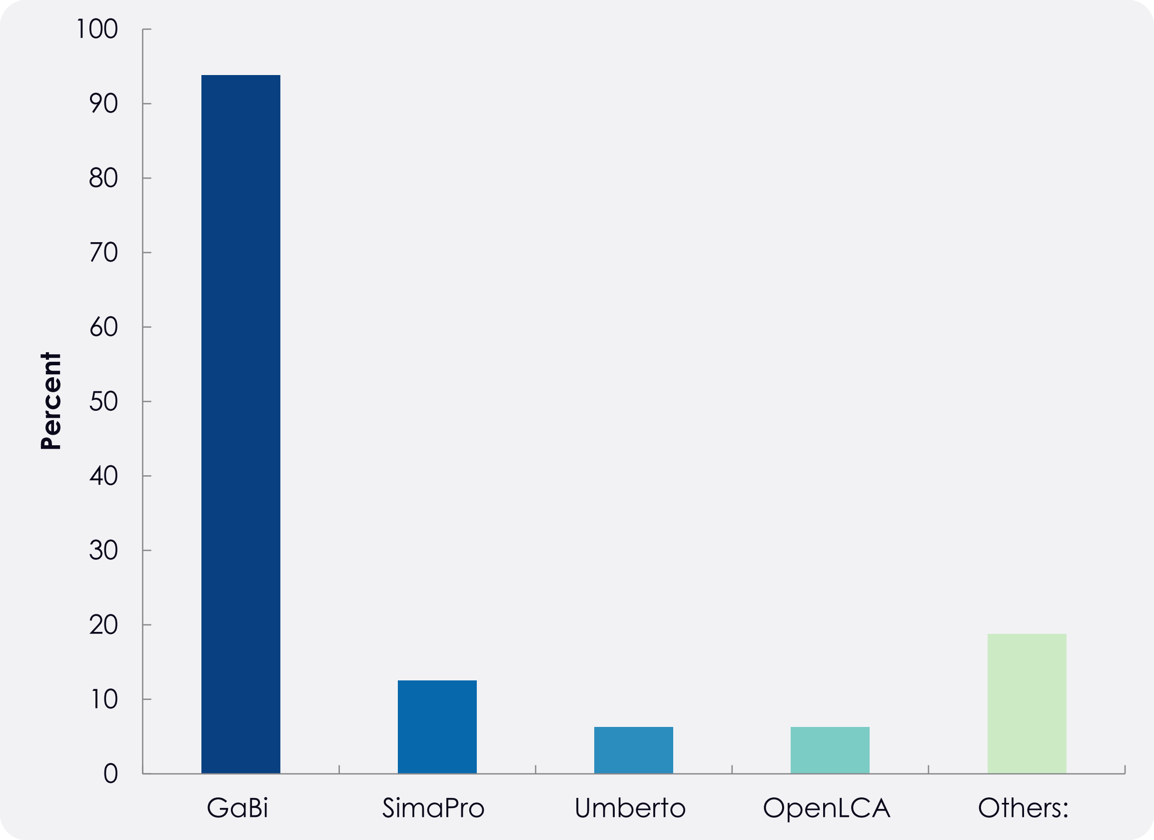


Figure A2.1. Most used LCA software in industry according to the survey

It is hard to tell why the scientific community prefers SimaPro and industry tends to use LCA FE. One reason could be that SimaPro was released prior to LCA FE, and since LCA as a methodology was born in academia before becoming popular in industry, academia adopted SimaPro and by tradition this remained as the case. Another reason could be the database since consultation with industry showed their reliance on MLC databases hence the software.

Other generic-purpose LCA software are Umberto, CMLCA, Brightway, and ActivityBrowser which are used in stricter contexts. Brightway and Activity Browser were developed within academia and are very popular options in academia currently but not yet outside this context. Brightway is written in the Python programming language and requires programming skills (Mutel, 2017). Brightway can be used by LCA practitioners with no programming skills through the ActivityBrowser which is a Python-based software that builds on top of Brightway and provides a graphical user interface (GUI) (Steubing et al., 2020). CMLCA on the other hand is a relatively old software and is rarely used nowadays except for teaching purposes.

Although generic software can do the same basic tasks of LCA, they differ in terms of characteristics, capabilities, and supported databases (Lai et al., 2022). For example, some software has some additional capabilities in running certain types of sensitivity and uncertainty analyses. For instance, the variance-based methods which are implemented in CMLCA, or Brightway2 which allows defining more types of probability distributions for LCI and LCIA data (as in CMLCA and OpenLCA), and the automatic calculation of uncertainty based on pedigree scores (available in CMLCA and OpenLCA). (Igos et al., 2019).

Some of these softwares are free access (e. g. OpenLCA, CMLCA, Brightway, GREET and ActivityBrowser) while others are paid (e. g. SimaPro, LCA FE (former GaBi), Umberto). Furthermore, given the similarity in the underlying framework and matrices-based calculations, some of these softwares are convenient to also handle models intended for S-LCA and LCC. For example, PSILCA database used in S-LCA can be used in OpenLCA since it was developed within the same organization (GreenDelta). Economic inventories for LCC can be handled in most of these softwares as well. SimaPro and Umberto are examples of that.

Besides GREET, Green NCAP (Green Ncap, 2022) is another specialized tool for transportation. NCAP project aim is to provide the LCA data and results for an online life cycle based environmental information system of vehicles for European consumers. The LCA is done for generic global supply chains of vehicle production and energy supply in Europe between 2022 and 2037. The main focus is to estimate significant differences between the vehicles and the main influencing parameters among: Propulsion system; Type of fuel; Energy demand; Vehicle mass; Battery capacity; CH4 and N2O emissions from vehicles equipped with an ICE.

However, it has to be noted that NCAP is limited to global warming and primary energy demand in the evaluation with no other environmental concerns addressed like toxicity. This should not be the case in a full LCA study intended to inform decision making, since as mentioned before in this report, all relevant impact categories should be assessed to avoid burden shifting to other environmental areas of concern.

Another online tool is Carculator, developed by the Paul Scherrer Institut (PSI) as an open-source LCA tool for passenger cars built on top of the Brightway program (Sacchi et al., 2020). It allows for an economic and environmental evaluation of different types of cars under several driving and energy supply scenarios. Carculator relies on parametrized vehicle models coupled with background inventory data from the ecoinvent database to generate tailored LCIs. An interesting feature of Carculator is its ability to use future energy scenarios in the background database, thus enabling prospective LCAs by considering future expected changes in electricity, cement, and steel production, among other sectors.

In conclusion, it must be highlighted that generic-purpose LCA software do not implicit any predefined methodological choices in LCA. They are just tools to help calculate inventories and LCIA. The decision in the modelling is still in the hand of the modeller. The other type of tools designed for transportation are special case since they exhibit high capabilities when modelling mobility systems but they either have their own underlying methodological choices (as discussed for GREET in this report) or adopt other set of choices like Carculator which mainly relies on ecoinvent.