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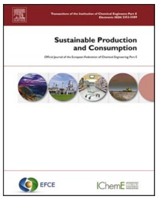

Review Article

Review of current practices of life cycle assessment in electric mobility: A first step towards method harmonization

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ABSTRACT

It is widely acknowledged that unharmonized methodological and data choices in life cycle assessments (LCAs) can limit comparability and complicate decision-making, ultimately hindering their effectiveness in guiding the rapid transition to electric mobility in Europe. The electric mobility sector aims to harmonize these assumptions and choices to improve comparability and better support decision-making. To support these efforts, this article aims to review the LCA practices across various sources in order to identify where key differences in assumptions, methodological approaches, and data selection occur in relevant LCA topics. In addition to this primary objective, we highlight certain practices that could serve as starting points for ongoing harmonization attempts, pointing out topics where it is challenging to do so. Our results showed that cradle-to-grave system boundary is the most commonly adopted in vehicle and traction battery LCAs, with maintenance and capital goods often excluded. The distance-based functional unit is dominant. Choices in Life Cycle Inventory (LCI) showed the greatest diversity and need for harmonization. Data quality and availability vary significantly by life cycle stage, with no standardized data collection approach in place. A lack of primary data is most prominent in the raw material acquisition and end of life (EoL) life cycle stages. Electricity consumption is a key topic in the EV sector, with major debates surrounding location-based versus market-based and static versus dynamic modeling. Multifunctionality problems are vaguely defined and resolved in the literature. For EoL multifunctionality, cut-off and avoided burden are prevalent, while allocation is common upstream. Impact assessments primarily follow the ReCiPe and CML-IA methods, with climate change, acidification, photochemical ozone formation, and eutrophication being the most reported impact categories. Systematic uncertainty propagation is rare in interpretations, with sensitivity analyses typically focusing on energy consumption, total mileage, and battery recycling rates. Overall, the review showed a big variation in assumptions and choices in EV LCA studies, particularly in the LCI stage. Among the discussed topics, we identified multifunctionality and electricity modeling as particularly contentious.

List of abbreviations

APOS	Allocation at the Point of Substitution
BOM	Bill of Materials
CED	Cumulative Energy Demand
CFF	Circular Footprint Formula

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EoL	End of Life
EV	Electric Vehicles
FTP 75	Federal Test Procedure (an US EPA-implemented city driving cycle)
FU	Functional Unit
GO	Guarantee of Origin
HDV	Heavy-Duty Vehicle
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IMDS	International Material Data System
IPCC	Intergovernmental Panel on Climate Change
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MLC databases	Managed LCA Content (formerly GaBi) databases
NEDC	New European Driving Cycle
NGOs	Non-Governmental Organizations
OEM	Original Equipment Manufacturer
pkm	passenger·kilometer
PM	Particulate Matter
SFTP US06	Supplementary Federal Test Procedure (US EPA implemented)
tkm	tonne·kilometer
TTW	Tank-to-Wheel
vkm	vehicle·kilometer
WLTP	Worldwide Harmonized Light Duty Vehicle Test Procedure
WTT	Well-to-Tank
WTW	Well-to-Wheel

Abbreviations for guidelines and standards

CATARC	LCA research progress of China Automotive Technology and Research Center
Catena-X	Catena-X product carbon footprint rulebook
CFB-EV	Harmonized rules for the calculation of the carbon footprint of electric vehicle batteries (CFB-EV)
eLCAr	Guidelines for the LCA of electric vehicles
GBA	Greenhouse gas rulebook-Generic rules by Global Battery Alliance (GBA)
PACT	Pathfinder framework- guidance for the accounting and exchange of product life cycle emissions
PCR-Buses and coaches	Product category rules public and private buses and coaches
PEFCR-Batteries	Product Environmental Footprint Category Rules for high specific energy rechargeable Batteries for mobile applications
PFA	Life cycle assessment applied to a vehicle or a vehicle equipment – methodological recommendations by La Plateforme automobile (PFA) in France
RISE	LCA guidelines for electric vehicles- How to determine the environmental impact of electric passenger cars and compare them against conventional internal-combustion vehicles by Research Institutes of Sweden (RISE)
VDA-PC	Guidance for Conducting Life Cycle Assessment Studies of Passenger Cars by Verband der Automobilindustrie (VDA) in Germany

1. Introduction and policy context

Road transportation bears significant responsibility for exacerbating various environmental problems, aligning closely with the triple planetary crisis delineated by the United Nations (United Nations, 2022). Within the European Union (EU), transportation contributes to about a quarter of the EU's greenhouse gas (GHG) emissions. Three-quarters of these come from road transport (European Environment Agency, 2024).

From a policy standpoint, the European Green Deal, adopted by the European Commission in December 2019, emerges as a cornerstone initiative aimed at combatting climate change. It encompasses more ambitious actions slated for the forthcoming decade and endeavors to fulfill the objectives outlined in the Paris Agreement. A key component of the European Green Deal, the European Climate Law, solidifies the EU's pledge to achieve climate neutrality by 2050. This legislation also establishes an interim target of reducing net GHG emissions by at least 55 % by 2030, relative to 1990 levels (European Commission, 2019).

In this context, electrification emerges as one of the most prominent strategies for decarbonizing road transportation, reflected in the rapid growth of the Electric Vehicles (EVs) market in recent years (IEA, 2024a), and initiatives such as the EU's Sustainable and Smart Mobility Strategy which advocates for an irreversible transition to zero-emission mobility (European Commission, 2020).

Nonetheless, it is acknowledged that focusing only on direct emissions during vehicle use carries the risk of burden shifting to other environmental concerns or to other life cycle stages. A pronounced example here is the concern around the traction batteries supply chain (Xia and Li, 2022), which is associated with high GHG emissions in the cells production, but also increased impacts on, e.g., toxicity and abiotic resource and water use linked to the supply of raw materials. Life cycle assessment (LCA) can play a fundamental role in assessing this potential burden shifting risk and wisely guiding the intended transition.

Life cycle thinking became increasingly integrated into European policymaking in the last decades (Sala et al., 2021), particularly related to the automotive industry. This is evident in the European Commission's latest regulation on rechargeable batteries (European Parliament, 2020), which mandates that traction batteries entering the European market by 2026 should declare a life-cycle-based carbon footprint and comply with maximum thresholds. Additionally, there is voluntary reporting of life cycle CO_2 emissions by 2026 in the new CO_2 emission performance standards for passenger cars and light commercial vehicles (European Parliament, 2023a).

Over the past ten years, a plethora of LCAs on EVs and batteries have been conducted. However, different implementations of critical modeling and data choices by different practitioners can lead to very diverse results even for the same product (Bouter and Guichet, 2022; Marmiroli et al., 2018; Nordelöf et al., 2014; Xia & Li, 2022), which hampers comparability and transparency and thus decision-support and communication with end-users. Consequently, there is a dire need to harmonize how LCA is applied in the EV field ensuring that all stakeholders can calculate, monitor, communicate, and support decisions departing from a common ground. The European project TranSensus LCA seeks to achieve this by bringing together leading figures in the automotive and LCA fields across Europe. To support this endeavor, this article takes an important step towards harmonization by analyzing the state-of-the-art (SotA) practices in EV LCA to understand where we are starting from.

A handful of scientific reviews were done in this field, but they are either limited to scholarly literature, a specific part of the EV (e.g., battery) (Arshad et al., 2022), a single methodological issue (e.g., multifunctionality) (Nordelöf et al., 2019), or they focus only on the LCA results and not the method (Dillman et al., 2020). Therefore, a comprehensive overview of the SotA practices encompassing the key methodological aspects across the entire EV life cycle is still missing. This article aims to do this by reviewing LCA practices across various sources (sectorial guidelines and standards, and studies from academia, industry, and other institutions) in order to identify where key differences in assumptions, methodological approaches, and data selection occur in relevant LCA topics to the EV sector. In addition to this main goal, we highlight certain practices that could serve as starting points for method harmonization in the future. We also highlight topics where it is challenging to do so. This is discussed together with the review results in Section 3 after explaining the review method in Section 2. Finally, conclusions are provided in Section 4.

2. Materials and methods

In this article, the exact powertrains considered under "EV" are Battery Electric Vehicles (BEVs), Hybrid Electric Vehicles (HEV), and Plug-in Hybrid Electric Vehicles (PHEVs). An overview of the review process is provided in Fig. 1. It starts with defining the review scope, then defining the type of sources (documents) to review, choosing and collecting them, and defining the review criteria. The following paragraphs detail each stage.

2.1. Review scope definition

Given the diversity of potential LCA contexts in the EV field, we delineate three archetypes aiming to encompass prevalent LCA applications. Fig. 2 illustrates these archetypes, linking them to scale and time dimensions. First, LCA of existing products. This is the typical LCA that studies a product (in this case vehicle or battery) that is already deployed or ready to be deployed on market scale (i.e., technologically mature). Sometimes this is called "retrospective LCA" or "ex-post" (Sandén and Karlström, 2007), however we refrain from using these terms to avoid potential confusion for some readers, since some life cycle stages (e.g. end of life (EoL)) still exist in the future. This regards the "temporal positionality" as described by Arvidsson et al. (2023). Another type is future-oriented LCAs or prospective LCAs, among other terms used (Arvidsson et al., 2023; Cucurachi et al., 2018; Guinée et al., 2018). This type usually evaluates emerging technologies or product systems in the future. This is typically employed by car manufacturers to compare for example different components under research before mass production and full adoption. Lastly, fleet-level LCA targets a much larger scale than a single product (vehicle or component). It analyses the impact of the entire fleet of vehicles in a specific region for example or specific timeframe, usually for reporting and analytical purposes, or to support policies adjustments (e.g. (Field et al., 2000; Garcia and Freire, 2017)). LCA of existing products is the sole focus of this article since it covers the majority of current LCAs in the field. The latter two archetypes are addressed in Eltohamy et al. (2023b).

2.2. Source categories definitions

This review aims to offer a broader perspective on current practices beyond the scientific literature. Therefore, after defining the scope, the following source categories were chosen to be targeted in the review:

- Guidelines and standards
- Scientific literature
- Vehicle manufacturers' or Original Equipment Manufacturers' (OEMs') reports on commercial products
- Life Cycle Inventory (LCI) databases

Available guidelines and standards are of utmost importance because LCA practitioners rely on them to guide their choices. Moreover, some of these guidelines are in the process of becoming legally binding. On the other hand, the OEMs' reports offer insight into how the industry conducts its LCA studies and the types of information they choose to share with the public. Their approach can differ significantly from what is typically seen in the academic community. Finally, the main differences in methodological choices between major LCI databases were examined. These choices can represent a significant source of inconsistency and may greatly influence the results, given that all LCAs rely heavily on these databases.

2.3. Sources collection

To gather all relevant LCA studies from the scientific literature, we started from the comprehensive review by Ricardo et al. (2020), which covers all related literature until 2018. This review included 228 studies categorized as LCAs, covering all relevant power trains and identifying key methodological choices including impact categories, system boundary and life cycle stages, electricity production chain, and EoL modeling among other topics. We supplemented this with a new search targeting scientific review articles from 2018 to 2023, conducted in three steps: systematic search primarily on Web of Science (See Table S1 in SI for keywords used), screening based on relevance (resulted in the selection of 11 review articles), plus 5 other reviews from Google Scholar, and finally "snowball" readings (i.e., further sources listed as references in the initially reviewed literature) when relevant. The sample of reviews without the snowball readings (16 studies) covered more than 200 studies published until 2023. It is worth mentioning that there are overlaps between these reviews in terms of original LCAs analyzed (also between these reviews and Ricardo's study before the year 2018), therefore the net number of studies captured could be less than 200. For example, despite the common reviewed studies between Dolganova et al. (2020) and Marmiroli et al. (2018), the prior focus on resources use in EVs and the latter focus on electricity modeling.

For the other source categories, the most relevant sources were identified, accessed, and collected thanks to the diverse areas of expertise of the TranSensus LCA consortium, which resulted in 11 guidelines and standards, 15 OEMs' reports and 3 LCI databases. A flowchart depicting the selection process and the final number of reviewed sources in all categories is provided in Fig. S1 in SI, with full source lists in Tables S2 and S3.

2.4. Definition of review criteria

Review criteria were developed iteratively among the co-authors, targeting various methodological topics within each phase of LCA. The full review criteria are provided in Tables S4 and S5 in SI. For publication convenience, we focus on selected high-concern topics in this article. These topics are system boundary, cut-off rules, functional unit, data choices in the different life cycle stages, choices in electric energy modeling, multifunctionality, impact assessment methods, and addressing uncertainty. These topics were considered of high-concern due to large divergences in the approaches implemented and/or their impact on results and interpretation.

2.5. Reviewing and reporting

Following the definition of the review criteria, the chosen sources discussed in Section 2.3 were reviewed (i.e., information was extracted and mapped according to Tables S4 and S5 in SI which represent the full review criteria). Finally, the results were interpreted and synthesized to create concise meaningful results, which were then reported in the article.

3. Results and discussion

In this section we show and analyze the results of the review. This is done per topic where each heading represents a topic of those mentioned in Section 2.4. To improve the readability, and depending on how the topic is handled in the reviewed literature, subheadings are added to some topics, namely data choices, electricity modeling, and

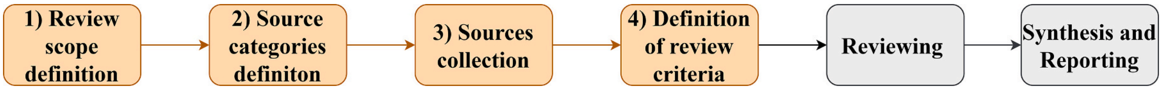

Fig. 1. Overview of the review process.

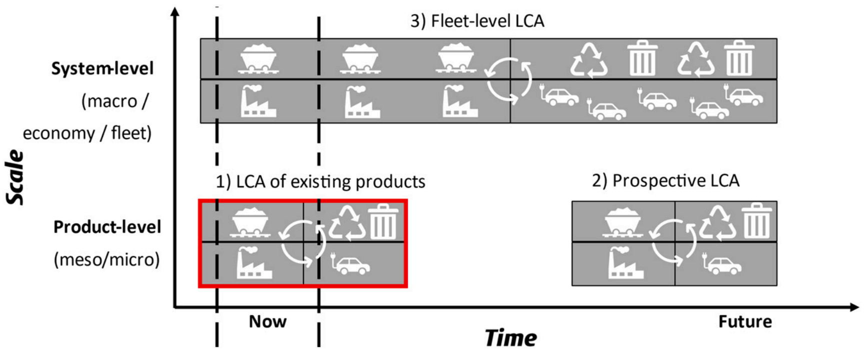

Fig. 2. The three archetypes of LCA application in the EV field. This review focuses on the first archetype, namely the LCA of existing products.

multifunctionality.

3.1. System boundary

Generally in LCA, terms like cradle-to-gate, gate-to-gate, or cradle-to-grave are used to describe the system boundary. However, in the mobility sector, additional terms such as Well-to-Tank (WTT), Tank-to-Wheel (TTW), and Well-to-Wheel (WTW) are used, particularly when the LCA has a strong focus on assessing the energy carrier supply chain (e.g., fuel or electricity) (Hauschild et al., 2018). Fig. 3 depicts how these terms translate into a vehicle life cycle.

Generally, cradle-to-grave and cradle-to-gate are the most dominant system boundaries applied and they are the most reported in guidelines. China Automotive Technology and Research Center (CATARC) (2022), Global Battery Alliance (GBA) (2022), and Catena-X Automotive Network (2023) adopt a cradle-to-gate system boundary. CATARC additionally includes the use stage. All other guidelines and standards recommend adopting a full cradle-to-grave system boundary which includes the end of life (EoL) stage.

The reviewed OEM reports uniformly adopt cradle-to-grave system boundaries. EoL treatment steps often include dismantling and shredding, while recycling impacts are typically excluded. Many reports lack clarity on whether capital goods (infrastructure) are considered.

The coverage of the life cycle in scientific literature differs slightly, as a high portion of EV research is now focused on energy generation and carriers (i.e., fuel and electricity). This can be noted from the following list of the most studied life cycle stages, ranked in descending order (Ricardo et al., 2020):

1. WTT for fuel production
2. TTW for vehicle use
3. Vehicle/component production
4. EoL
5. Maintenance
6. Infrastructure

Nonetheless, it should be noted that Ricardo et al. (2020) had a very wide scope, which included also conventional ICEV and vehicles running on alternative fuels (e.g. synthetic fuels). Hence, TTW comes in second place, typically used to compare the performance of different powertrains. Specifically for batteries, Arshad et al. (2022) showed that most of the 80 studies that they reviewed adopted cradle-to-gate (often to compare battery chemistries until production). Although such a practice may seem reasonable given the common knowledge of battery manufacturing being the most impactful stage in a battery life cycle, omitting other life cycle stages can lead to incomplete picture of hotspots when looking at the entire vehicle life cycle. Following the same example, a certain battery chemistry might be environmentally

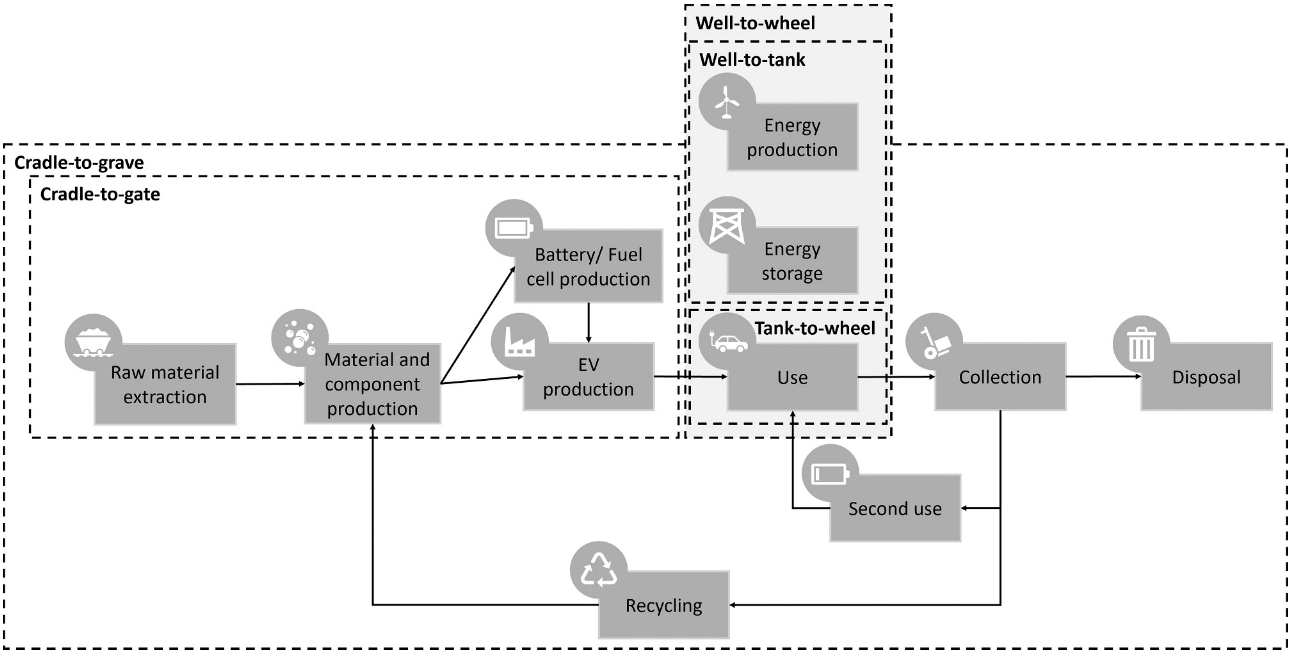

Fig. 3. Commonly applied system boundaries in an EV LCA.

promising in its production stage but environmentally problematic in its use or EoL stage, which is a clear burden shifting situation (Majeau-Bettez et al., 2011; Shu et al., 2021).

In conclusion, we believe that full cradle-to-grave or cradle-to-cradle (i.e., circular systems) LCAs should always be encouraged, and any deviation from this should be approached with caution. This is simply because cradle-to-grave or cradle-to-cradle is the true translation of a "life cycle", a principle which LCA practice was based on since its very beginning: *"Life-Cycle Assessment is one of the tools used to examine the environmental cradle-to-grave consequences of making and using products or providing services"* (The Society of Environmental Toxicology and Chemistry, 1993).

3.2. Cut-off rules

The rules for cut-off (i.e., exclusion) of flows were found to be based either on a percentage of total mass, total energy, or environmental significance. The cut-off criteria are defined quite differently by the guidelines and standards: eLCAr (Del Duce et al., 2013) and Research Institute of Sweden (RISE) (Van Loon et al., 2019) guidelines do not specify a cut-off rule at all. GBA and Product Environmental Footprint Category Rules for high specific energy rechargeable batteries for mobile applications (PEFCR-Batteries) (Recharge, 2023) focus on the cut-off of flows, adhering to the 3 % rule from the Product Environmental Footprint guidelines (PEF) (EC-JRC, 2021). According to PEF, processes and elementary flows can be cut off if they account for a maximum of 3 % (cumulatively) in the total sum of material and energy, and environmental significance (single overall score) of the system. In practice, the same concept was followed by some OEMs reports, stating, for example, that 99 % of the vehicle's mass is included in the calculation (Renault Group, 2015, 2017).

At the process or activity level, there is a widespread tendency observed across all source categories to exclude maintenance activities and capital goods. Further details on how guidelines address this cut-off issue can be found in section S5 in SI. The exclusion of activities such as maintenance and capital goods has been debated and challenged in the literature (Frischknecht et al., 2007), yet this practice may be deemed acceptable in certain contexts where they are environmentally insignificant. Thus, there is a need for increased transparency regarding what parts come under capital goods or maintenance. For example, replacing a battery is not a minor maintenance task to overlook, given its significant cradle-to-gate impact. Dillman et al. (2020) highlighted in their review that only one study outlined a clear method for incorporating battery replacement, while the others either excluded, neglected, or ambiguously addressed it. In this context, a consistent approach to addressing this issue is proposed by Ricardo et al. (2020). Following this approach, the number of batteries required over the vehicle's lifetime is adjusted following changes to battery size and lifetime mileage.

In a nutshell, cut-off rules are commonly employed in LCA models to reduce resources dedicated to data collection and processing. However, adopting a mass-based cut-off approach poses risks due to the inadequacy of mass as a measure of environmental significance (e.g., dioxins emissions in waste incineration systems (Istrate et al., 2020)). A more meaningful option would be to use environmental significance as the criterion for exclusion, but two dilemmas arise here: (i) how to define "environmental significance" univocally (when in reality there are many independent and scientifically incommensurable environmental impact categories. This inevitably entails subjective value choices in setting weighting factors when combining results for different environmental impact categories), and (ii) how to determine the significance of a flow without initially including it. Consequently, when some reviewed studies designate environmental significance as the reference for cut-off, ambiguity arises. We propose that, ideally, the rule for cut-off should be no "intentional" cut-off as long as data, computational capacity, and time permit; however, if these resources are lacking, conducting screening studies before implementing a cut-off can serve as a solution, as recommended by the Catena X and PEF guidelines. Many methods are proposed and explored in scientific LCA literature (e.g. (Cucurachi et al., 2022; Kim et al., 2022)). Ultimately, reporting the actual cut-offs and the criteria they were based on is paramount, as this provides transparency on what the LCA includes or excludes which also facilitates comparability with other studies.

3.3. Functional unit

The choice of functional unit (FU) can vary depending on whether the study focuses on the vehicle life cycle or the battery life cycle. However, across the studies reviewed, distance-based FUs emerged as the most common choice for both situations, reflecting the eventual function required from either systems (Arshad et al., 2022; Dolganova et al., 2020; Renault Group, 2017; Scania, 2021; Tolomeo et al., 2020). This is expressed as "passenger·km" (for passenger vehicles), "tonne·km" (for freight vehicles) and "vehicle·km" (without referring to capacity or specific main designated function). 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. Either "driven distance over the service lifetime of the vehicle (expressed in km)" or "passenger·km" (MAN Truck and Bus SE, 2022; Solaris, 2022), and "tonne·km"(Scania, 2021) were utilized for buses and trucks, respectively. These choices also align with the typical reference flows for transportation in LCI databases such as ecoinvent and Sphera Managed LCA Content (MLC; formerly GaBi). A notable difference in these databases is found in passenger car datasets which adopt a functional unit based solely on distance (vehicle*km), without considering capacity. This simplification may stem from the assumption that the number of passengers has a minimal effect on the inventory related to the functional unit. We contend that the "passenger·km" and "tonne·km" would be preferable for passenger and buses, and freight vehicles, respectively, because they explicitly reflect the intended "function" of the vehicles in question, i.e., "transporting passengers" or "transporting goods". Furthermore, they explicitly include considerations of capacity (passenger or tonne), which enables more accurate and meaningful comparisons across different vehicle types.

While there appears to be a wide agreement on this FU choice, a primary challenge lies in estimating the service life of the vehicle (lifetime mileage). This is crucial for this type of FU as it dictates how impacts are amortized over each km driven. Moreover, it dictates the significance of the WTW cycle, thereby influencing the impact distribution between production and use stages. The assumptions on service lifetime however vary substantially in the reviewed studies even within the same segment, as depicted in Fig. 4.

When batteries are the sole subject of the studies and not the entire vehicle, three other distinct types of FUs could be identified. Firstly, throughput-based FU expressed, for example, as "1 kWh of the total energy provided over the service life by the battery system". This FU is recommended by all reviewed battery-focused LCA guidelines and standards. Secondly, capacity-based FU expressed as "1 kWh (or 1MJ) of battery storage capacity". This is the second most common practice in scientific LCAs on batteries after the aforementioned distance-based functional unit (Arshad et al., 2022; Dolganova et al., 2020; Tolomeo et al., 2020).

In this regard, total energy provided over the service life of a battery system (i.e., throughput) exhibits an advantage over "battery storage capacity" because it can encompass certain parameters that the latter cannot capture, such as durability and depth of discharge (DOD), which are crucial in comparing different battery technologies (Tolomeo et al., 2020) (see also section S2 in SI). However, this requires standardized and realistic test cycles for batteries, which is an argued drawback compared to the capacity-based FU (Peiseler et al., 2022). On the other hand, a capacity-based FU is not a good candidate for a full cradle-to-grave system boundary as it does not consider the use stage (Peiseler

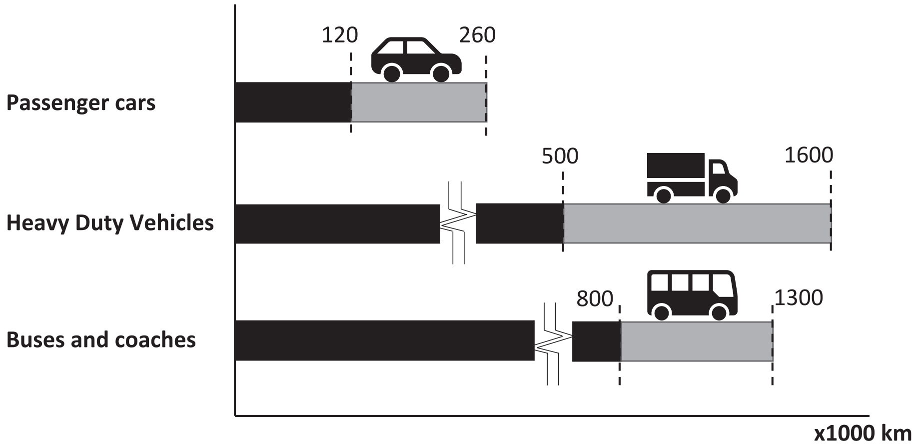

Fig. 4. Typical service life time of different segments of EVs (Grey represents the range of assumptions) (Dillman et al., 2020; Irizar, 2019; MAN Truck and Bus SE, 2022; Renault Group, 2017; Scania, 2021; Solaris, 2022; Volvo Cars, 2021).

et al., 2022).

The third type of FU is battery pack mass (e.g., kg of battery) which is often used when the work mainly targets the battery production stage (e.g., to compare different cathode materials), or EoL recycling context, excluding the use stage (Tolomeo et al., 2020). We argue against this choice and so do others (e.g., Temporelli et al., 2020) since mass does not align with the definition of a FU (i.e., quantification of the function of a system), and clearly the function of a battery is not accurately represented by its mass.

Similar to vehicles, we suggest adhering to a distance-based FU as a final function of a traction battery and then link it to the battery throughput. Considering a cradle-to-grave or cradle-to-cradle system boundary, a distance-based FU best represents the main purpose of a transportation system, which is to transport people or goods over a certain distance. Even in LCAs of traction batteries, these batteries exist to satisfy the same final function (i.e., transportation). As a simplified example, starting from a FU of transporting one passenger over a distance of 1 km, a throughput of a battery of 20 kWh is needed to satisfy this requirement, hence 20 kWh throughput should be considered as the FU for the battery.

Nonetheless, if technical challenges arise in linking the battery performance to the distance, or if the battery is studied in isolation from the vehicle to satisfy a specific goal of the study, a throughput-based FU would be preferred, especially with the foreseen standardization of battery cycles in references like the harmonized rules for the calculation of the carbon footprint of electric vehicle batteries (CFB-EV) (EC-JRC, 2023).

3.4. Data choices

Data are the backbone of any LCA. A standardized data collection approach for LCIs would typically involve defining foreground processes, quantification of flows for each process, determining the type of data to be used, and establishing data quality requirements. Notably, GBA, CFB-EV, PEFCR-Batteries, and Catena-X focus on achieving a harmonized and structured approach for consistent LCI data collection from suppliers. While these guidelines provide data collection templates, many are limited to carbon footprint-related inventory data (e.g., GBA, CFB-EV, and Catena-X). PEFCR-Batteries stand out for collecting data relevant to a broader range of environmental impacts, but its scope is confined to battery production. Despite the potential advantages in terms of enhancing data exchange, transparency, and reproducibility, a standardized comprehensive approach to collecting inventory data is still lacking.

Another problem is the limited availability of primary data, which was pointed out repeatedly in literature. For example, Arshad et al. (2022) reviewed 80 case studies on LCA of batteries finding that only 13 % obtained primary data, and this is only a single part of an entire vehicle. Consultation with the industry showed that the same problem persists also for the industry, where it is hard to acquire primary data from other actors in the vehicle value chain. In light of this primary data gap, secondary data plays a substantial role, with some LCA studies relying almost entirely on secondary data (IVL, 2017; Van Mierlo et al., 2017), while the reutilization of published (sometimes outdated) data is an extended practice (Peters et al., 2017).

LCI databases are the typical source of secondary data. The most commonly used LCI databases by academia and industry to conduct LCA of EVs are ecoinvent, MLC databases, 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). An overview of these three LCI databases is presented in section S6 in SI.

The following subsections delve deeper into raw material extraction, manufacturing, and use stage in order to highlight more characteristic practices in these stages. These are followed by a brief subsection on potential mitigation actions for more representative data.

3.4.1. Raw materials extraction and manufacturing

Depending on the study type, two main options are considered for data collection related to raw materials (natural resources extraction and processing): either full modeling of raw material supply chains (practiced in dedicated material studies or for establishment of generic LCI databases) or use of generic data from LCI databases. The latter is practiced in most scientific and OEM studies focusing on the full vehicle life (Ricardo et al., 2020).

Conversely, for the acquisition of parts and components and the assembly of the vehicle, a majority of OEM reports have employed company-specific, and sometimes, site-specific information. These processes are either directly under the influence of the vehicle OEMs or have established data-sharing ties with their component suppliers. Fig. 5 shows a typical information flow scheme in an OEM until it ends up in the vehicle LCA model. Components acquired from suppliers are fed to the International Material Data System (IMDS, 2000), which is a data sharing platform exclusive to car manufacturers and suppliers. This generates a bill of materials (BoM) which are then categorized into material groups. Material groups are then mapped into generic processes that produce them. These inputs are then linked to datasets from commercial LCI databases and end up in the LCA model. Eventually, related in-house activities are added to the model (e.g., energy consumption for assembly).

Almost all guidelines and standards have specific requirements on data sources and modeling of the manufacturing stage, of either batteries or vehicles. The general recommendation is that company, or even

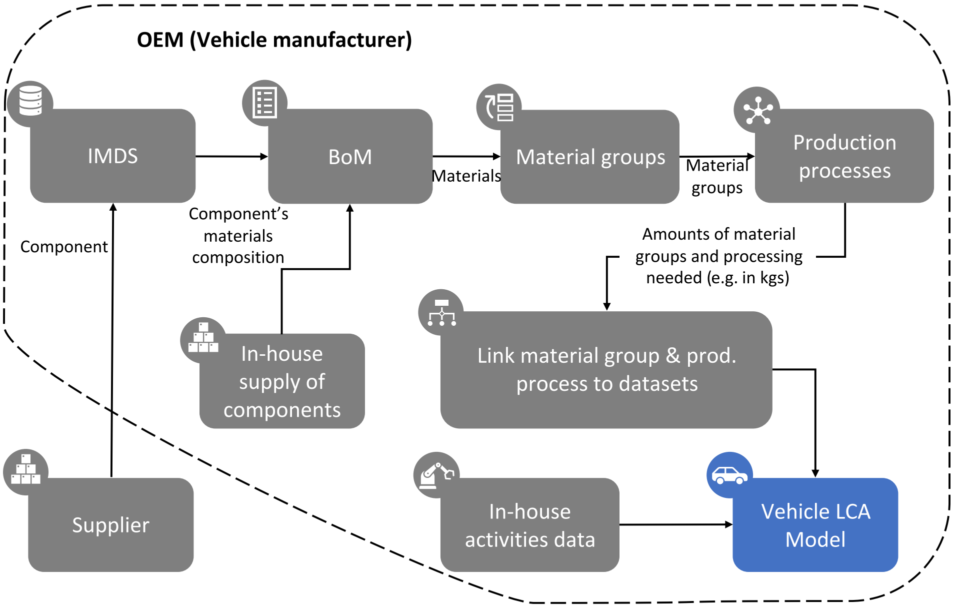

Fig. 5. Typical information flow scheme in OEMs to model the materials in the production stage of a vehicle (IMDS: International Material Data System, BoM: bill of materials).

site-specific (yearly), data shall be used for manufacturing processes as reported by GBA, CFB-EV, PEFCR-Batteries, Catena-X, Product Category Rules for public and private buses and coaches (PCR-Buses and coaches), RISE, and German association of automotive industry (VDA-PC)). The typical activities mentioned are the production of the main parts of the vehicles (i.e., traction battery, electric motor, assemblage of the vehicle, and production of the batteries.)

Scientific literature however is more flexible here. Three patterns were recorded by Ricardo et al. (2020) in manufacturing modeling. First, utilizing aggregated data for vehicles/components. This approach is typically employed in comparative overview studies that primarily focus on the use stage of vehicles. Second, employing differentiated material lists along with corresponding energy consumption and auxiliary substances for generic vehicles or components. Lastly, incorporating highly detailed data provided by manufacturers for specific vehicle models.

3.4.2. *Use stage*

Fig. 6 shows typical aspects considered in the use stage of an EV. The most predominant aspect is electricity consumption. Guidelines such as CATARC, PCR-Buses and coaches (The International EPD System, 2022), Filière automobile and mobilités (PFA) (2022), and VDA-PC (German association of automotive industry, 2022) prescribe measurements or documented tests, such as Worldwide Harmonized Light Vehicle Test Procedure (WLTP) (UNECE, 2017), for determining vehicle energy consumption. WLTP is supposed to gradually substitute the outdated New European Driving Cycle (NEDC) (Marotta et al., 2015). Alternatively, RISE provides a calculation method for EVs consisting of four steps starting with an equation to calculate the needed mechanical energy for propulsion and ending with adding auxiliaries (e.g., heating, radio, etc.) standard consumption values from ecoinvent v3. This method of calculating what the authors call 'real world' consumption was inspired by Del Duce et al. (2016). eLCAr guidelines provides a more sophisticated method which incorporates equations to calculate the consumption for the different sub-consumptions (i.e., basic powertrain consumption, heating and air conditioning, auxiliaries, standstill losses, additional consumption of battery charging processes). In some of the examined guidelines, like GBA, CFB-EV, and Catena-X, the use stage of vehicles and batteries is entirely excluded as these documents concentrate on cradle-to-gate impacts.

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 consumption over regionally-relevant drive cycles (such as WLTP and NEDC in the EU, Federal Test Procedure, an US EPA implemented city driving cycle (FTP 75) and US EPA implemented

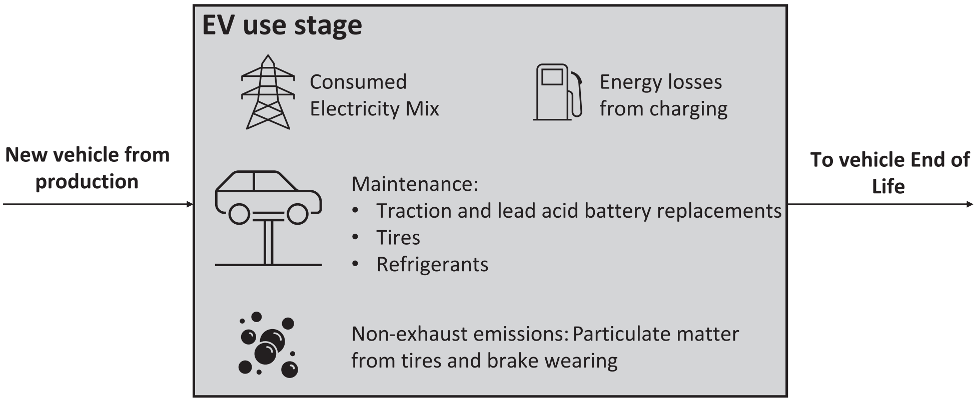

Fig. 6. Typical aspects considered in the use stage of an EV in the reviewed work.

Supplementary Federal Test Procedure (SFTP) in the US; China light duty vehicle test (CLTC) in China and JC8 in Japan), their modeled vehicle's lifetime, and the regional/national electricity mix. LCA studies encompassing Heavy Duty Vehicles (HDVs) used representative urban and regional delivery cycles often using the Vehicle Energy Consumption Calculation Tool (VECTO) (European Commission, 2023). In the same regard, scientific literature shows varied modeling approaches for energy consumption during vehicle use, ranging from simple assumptions (e.g. 20 kwh/km driven) to full vehicle simulations (Ricardo et al., 2020).

Most OEM reports and scientific literature excluded maintenance completely. When considered, maintenance focused on tire and some fluids replacements (i.e., lubricants, coolants, etc.) while all studies assume no traction battery replacement. Notably, maintenance modeling is well-covered in several guidelines (RISE, VDA-PC, CATARC) based on service intervals, in addition to PFA which provides simple lists of vehicle parts to be considered in periodic maintenance. We believe that maintenance, even in its simplest form, should be included in the model. The aforementioned guidelines can represent a good starting point for harmonizing this aspect.

Similarly, non-exhaust emissions, such as emissions from brake pads and tire wear from contact with road surface, are mostly overlooked in OEM reports and scientific literature, which is generally justified by the low impacts relative to the vehicle life cycle (Ricardo et al., 2020). The estimation of particulate matter (PM) emissions in the real world is quite challenging due to the absence of adequate tools, as indicated by industrial partners. Nonetheless, guidelines like the road tire and brake wear guidebook by the European Environment Agency (2019) and guidance from eLCAr and RISE provide a starting point.

In summary, the use stage of EVs warrants attention alongside the manufacturing stage, given that it accounts for more than 90 % of the life cycle energy consumption, according to an ecoinvent average passenger BEV dataset. Same is confirmed by Hawkins et al. (2012). Maintenance and non-exhaust emissions should also be considered in the model, even in simplified forms, until more comprehensive guidance becomes available.

3.4.3. *Mitigation actions for more representative data*

The paucity of primary data, notably evident in raw material acquisition and EoL stages, underscores a significant challenge. To enhance primary data availability, strategies may entail implementing standardized data collection methods or adopting dedicated traceability systems, such as digital battery passports (Battery Pass Consortium, 2023), which should facilitate primary data sharing among stakeholders in the product life cycle. However, given the inherent limitations of relying solely on primary data, concurrent efforts are imperative to enhance secondary data reservoirs, such as engineering models and LCI databases. These auxiliary sources will remain pivotal in supporting LCAs for vehicles, particularly to model the activities situated at the extremities of the value chain, such as raw material acquisition and EoL.

Moreover, to promote standardization and coherence, it is imperative to delineate a clearer demarcation, discerning which activities and material flows within a vehicle's life cycle necessitate modeling with primary (company-specific) data to attain a specific level of LCA quality. This prioritization of primary data for certain activities should stem from the environmental significance of the activity. Pushing for better data should start from the most impactful activities. These hotspots are becoming recognized due to the accumulated experience and knowledge gained from numerous LCAs conducted in the field. This concept has been adopted by important guidelines already like CFB-EV guidelines, which focuses on establishing analogous standards for data choices in the case of batteries (EC-JRC, 2023).

3.5. *Electricity modeling*

In section 3.4.2, we discussed approaches for estimating a vehicle's energy consumption. Here, we examine how the source of this energy is modeled. Electricity production is arguably the primary source of environmental impact for externally charged vehicles (Nordelöf et al., 2014). Consequently, the choice of the electricity supply source is a main driver behind the variability of results of EV LCAs, as concluded by Marmiroli et al. (2018). This topic is explored through the two main arguments in the field: location vs. market-based modeling, and static vs. dynamic modeling.

3.5.1. *Location vs. market-based modeling*

Modeling on-site electricity generation is straightforward as long as it is not connected to a public grid. However, complications arise once the electric grid is utilized, as it becomes impossible to trace grid electricity consumption back to a single supplier (Weber et al., 2010). Thus, location-based and market-based methods emerge as two approaches to estimating the environmental impact of electric energy consumption from the grid. A graphical illustration of the two approaches is provided in Section S3 in SI.

The location-based method establishes the grid electricity based on the physical average consumption mix (sources of energy) of electricity-consuming facilities in a specific geography. In contrast, the market-based method relies on contractual agreements between consumers and specific energy suppliers, verifying the exclusive claim on electricity from specific sources. This is typically done via Energy Attribute Certificates (EAC) or Power Purchase Agreements (PPAs) (WRI and WBCSD, 2015), with Guarantees of Origin (GOs) being the most common type in Europe (Gkarakis and Dagoumas, 2015). When certain parts of the electricity mix are exclusively attributed to specific consumers, this also means that other consumers will not consume the same mix anymore, but a residual mix. Residual mixes result from subtracting these exclusively claimed electricity attributes from the consumption mix. Ideally, residual mixes are used where specific supplier data (represented by EACs) do not exist (Holzapfel et al., 2023; WRI and WBCSD, 2015). This practice is gaining momentum in the EU as decarbonization of production lines becomes a major goal of industries.

Most guidelines provide recommendations on which method to use per life cycle stage, depending on the system boundary set by the guidelines. We detail the choices of these guidelines in Table 1. We also include other generic guidelines since this issue extends beyond the automotive sector.

In contrast, for the use stage, OEMs commonly apply the location based approach by relying mainly on commercial LCI databases that use the location-based approach to provide, e.g., country average mixes (e.g. (AUDI, 2016; Volvo Cars, 2020, 2021)) with some exceptions such as Solaris (2022), which reports using residual mixes. For the production stage, OEM reports are less clear about their choices with a few exceptions which report a location-based method (Polestar, 2020; Scania, 2021; Volvo Cars, 2021). In scientific literature, the location-based method is the common method, which is understandable given the lower importance of the market-based method outside industry. Hence, the scientific LCA community usually relies on location-based electricity mixes from LCI commercial databases (Lai et al., 2022; Verma et al., 2021).

It can be concluded at this point that parallel application of the two methods is a quite common practice. The main issue of parallel application is double counting (Bjørn et al., 2022), which happens due to the double claiming of electricity from specific energy sources such as Renewable Energy Sources (RES). This energy is claimed by both individual EAC purchasing consumers (market-based) and average electricity mix consumers (location-based) (Schneider et al., 2015). Double counting can happen on multiple levels. Fig. 7 shows these possible levels with simplified examples. Levels 2 and 3 are typical cases of parallel application. Level 2 is when average consumption mixes are used simultaneously with certificates in the different activities in the manufacturing stage. Level 3 is when the same happens in the bigger picture of the vehicle life cycle.

Table 1
Location vs market-based electricity modeling in guidelines.

Guideline & standards	Life cycle stages targeted	Location vs market-based
GHG protocol product standard (WRI and WBCSD, 2011)	Entire life cycle	Market-based
ISO 14040/44	Entire life cycle	No information
ISO 14067 (ISO, 2018)	Entire life cycle	Market-based
PEF	Entire life cycle	Market-based for processes controlled by the reporting entity. Location-based for use stage.
PEFCR-Batteries	Entire life cycle	Market-based for processes controlled by the reporting entity allowing location-based as a last resort. Location-based for use stage.
eLCAr	Entire life cycle	Location-based
Catena X	Cradle-to-gate	Market-based allowing location-based as a last resort (mentioned as "grid-specific consumption mixes")
CFB-EV	Entire life cycle (excl. use phase)	Market-based allowing location-based as a last resort.
GBA	Entire life cycle (excl. use phase)	Market-based
CATARC	Entire life cycle (excl. EoL)	No information
PACT	Cradle-to-gate	Unclear, however it considers "purchased electricity"
PCR-Buses and Coaches	Entire life cycle	Market-based, allowing location based as a last resort.
RISE	Entire life cycle	Location-based in use stage, unclear in the rest.
VDA	Entire life cycle	Location based. Market-based approach as scenario option.
PFA	Entire life cycle	Location-based

Moreover, double counting can also occur within each method due to different reasons, as shown in Level 1 in Fig. 7. In location-based, for example, if specific kilowatt-hours consumed at a certain time (hourly-resolved) and geography (e.g., Eastern Europe) are accounted for by a certain factory, and these kilowatt-hours are also part of the average mix (annually resolved all over Europe), these kilowatt-hours are double counted due to geographical and temporal overlap. In market-based, double counting can occur due to how guidelines provide a hierarchy for its application (e.g., PEFCR-Batteries). If the supplier-specific total electricity mix, which comes after supplier-specific electricity product in the hierarchy, is calculated according to the same method as the country-specific total supplier mix, it would also contain exclusively claimed electricity products, hence double counted (Holzapfel et al., 2023).

In conclusion, this issue and its solution extend beyond the automotive sector, and it is difficult to claim that one method is "better" than the other, as evidenced by the lack of uniformity in standards and guidelines. While it is perhaps simpler to harmonize the location-based method to minimize double-counting risks (Holzapfel et al., 2023), disregarding the market-based method altogether may be perceived as unfair to companies which invest in cleaner electricity or located in regions with a fossil-fuel-heavy electricity grid.

3.5.2. Static vs dynamic electricity modeling

Another critical point in electricity modeling is accounting for the ongoing evolution of the grid mix towards decarbonization and how this affects the impacts associated with a vehicle's life cycle. This is particularly relevant to location-based modeling where national/regional grid mixes are improving constantly and significant changes can happen in the long-lasting use stage of a vehicle. Although analyzed by some sources (e.g. Mitsubishi motors, 2019; Scania, 2021; Volvo Cars, 2021), this factor is still under-represented in the literature. Moreover, no clear reference is given on this in the reviewed guidelines and standards.

We argue that dynamic modeling in the use stage should be a part of any harmonization attempt, at least in the most conservative way. The grid evolution witnessed in the last decades is undeniable (IEA, 2024b). Therefore, considering this evolution gives a more realistic picture of the WTT emissions compared to solely relying on present mixes which could lead to unrealistic results. This also aligns with key existing and evolving policies such as the EU Renewable Energy Directive and car and van CO_2 regulations (European Parliament, 2023b; The European Parliament, 2023a). Future grid scenarios can be retrieved from available literature (e.g. Sacchi et al., 2022), or internationally-recognized sources such as the International Energy Agency (IEA, 2023).

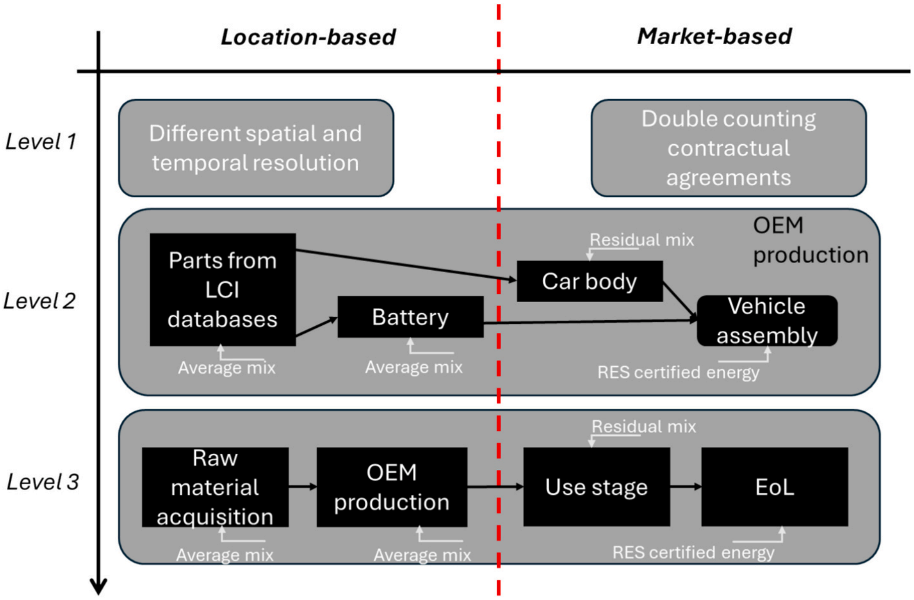

Fig. 7. Possible levels of double counting in electricity modeling. Level 1 is within each approach. Level 2 at the level of the processes in the manufacturing stage. Level 3 at the level of life cycle stages. Note that although commercial LCI databases started to include residual mixes datasets, they still use location-based average mixes in the background of their datasets (Sphera, 2022; Treyer and Bauer, 2016).

3.6. *Multifunctionality*

Multifunctionality problems are unavoidable in LCA, and the employed solution can alter the results quite substantially (Eltohamy et al., 2023a; Schrijvers et al., 2020). In a process-based LCA, a process is multifunctional when it provides more than one functional flow (Guinée et al., 2021). A generic observation from the reviewed works is that multifunctionality is often discussed in two separate contexts: at EoL (with a particular focus on recycling), and upstream to EoL.

3.6.1. *Upstream to EoL*

Multifunctionality can arise at many stages of a vehicle life cycle: as co-production in the raw material processing stage, which is the most discussed (EC-JRC, 2023), in the vehicle manufacturing stage, such as shared manufacturing facilities (EC-JRC, 2023), and as vehicle-to-grid services in the use stage (Helmers and Weiss, 2017). To be more specific, in scientific literature and OEM reports, multifunctionality is not explicitly discussed outside the EoL context except for some abstract recommendations (Tolomeo et al., 2020). This ambiguity has an adverse impact on the transparency of method and results communication.

Some of the reviewed guidelines tackle this topic in more detail, such as CFB-EV, GBA, and Catena-X. Table 2 summarizes the differences between guidelines. It is interesting to see that vehicle guidelines do not emphasize certain processes, unlike batteries-oriented guidelines (e.g., CFB-EV). It is also interesting to see that four of these guidelines do not recommend system expansion or substitution as a way to solve multifunctionality at all, while all other guidelines recommend the ISO hierarchy as a general guide. Notably, substitution and system expansion are treated as synonyms in guidelines that refer to ISO 14044 (ISO, 2020) (e.g., GBA, eLCAr, and Catena X). Often, they mention system expansion but then explain substitution (avoided burden) instead (Heijungs, 2014). Although system expansion and substitution are conceptually equivalent (Tillman et al., 1994), they yield different results that can be considered compatible with one another. This is simply due to the fact that system expansion mathematically "adds" a function, while substitution "subtracts" a function (Heijungs and Guinée, 2007).

3.6.2. *EoL modeling*

EoL considerations, particularly concerning batteries, have garnered significant attention in recent literature (Nordelöf et al., 2019). Across the reviewed sources, five primary options for EoL treatment have been identified: "Circular Footprint Formula (CFF)" from PEF guidelines, the "cut-off" approach (also known as the "recycled content" approach), the "avoided burden" approach (also known as the "EoL recycling" approach), the "50:50" method, and "Allocation at the Point of Substitution (APOS)". Practically, all these approaches eventually boil down to the two general principles of allocation (partitioning) and substitution (avoided burden); two approaches adopt pure up-front allocation of burdens ("cut-off" and "APOS") (Wernet et al., 2016), one approach considers pure EoL credits ("avoided burden") (EC-JRC, 2010), and one is a hybrid of both principles ("CFF"). 50:50 method, on the other hand, is interpreted in different ways in literature and practice either as a hybrid (e.g. (Obrecht et al., 2021)) or as a pure allocation method (Ekvall et al., 2020). Section S5 in SI provides a more extensive explanation of each of these methods. The two most common approaches in EV studies nowadays are the cut-off and avoided burden which was also acknowledged by Ricardo et al. (2020).

In scientific research on traction batteries, the "avoided burden" approach is predominantly utilized, with fewer studies opting for the "cut-off" approach instead (Nordelöf et al., 2019). Another specificity of batteries is the second life they might have after being removed from the EoL vehicle (DeRousseau et al., 2017). Literature offers four primary approaches to modeling second-life batteries: no accounting (i.e., "cut-off"), comparing of life cycle impact for second-life batteries to a specific reference case, credits for substituting new energy storage systems (i.e., "avoided burden"), and economic allocation (Ricardo et al., 2020). Notably, economic allocation appears for the first time as an option here and not in vehicle or battery end of life.

The debate on EoL modeling is far from reaching any conclusion, with no overall consensus on a single "best" approach emerging. This was highlighted by Ricardo et al. (2020) but could also be seen within the TranSensus LCA project consortium. The "cut-off" approach is generally lauded for its simplicity and conservative stance. Unlike other methods relying on a substitution logic, it follows the polluter pays principle which promotes conservativeness; however, it does not explicitly incentivize a circular economy future (Frischknecht, 2010; Nordelöf et al., 2019). On the other hand, there is an increasing push towards the "CFF" method, with it gaining traction in key European guidelines like CFB-EV and PEFCR-Batteries. Currently however, there is little application of "CFF", neither in OEM reports nor the scientific

Table 2
Recommended approaches by Guidelines and Standards for addressing multifunctionality in prior to EoL processes. The numbers (1,2,3, and 4) in the table refer to the recommended hierarchy of choices.

Guidelines and standards	Process/material	Subdivision	Substitution/system expansion	Partitioning		
				Economic	Physical	Other
Batteries						
GBA	Graphite and metals	1	3	2[a]	4	4
	Sulfuric acid, ammonium sulfate, sodium sulfate, and chlorine by-products	1	2	4	3	4
	By-product salts from brine processing	1	3	4	2[b]	4
	other materials	1	2	4	3	4
CFB-EV (in the final draft released in June 2023)	Metals	1	–	2[a]	3	4
	Other materials	1	–	3[c]	2	4
PEFCR-Batteries		1	2	–	3 (mass)	–
Vehicles						
Catena-X	–	1	2	3	3	3
eLCAr	–	1	2	3	3	3
PCR-B&C	–	1	–	3	2	–
RISE-LCA	–	1	–	2	2	2
VDA-PC	–	1	–	2	2	2
PFA	–	1	–	2	2	2

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

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

[c] Economic allocation becomes the first preferred option when the price ratio is greater than 4.

literature, according to this review.

From a legislative viewpoint, the question surrounding the treatment of EoL is whether the focus is more on promoting recycling (substitution), or the use of secondary materials (cut-off), between which “CFF” tries to strike a balance. The critique that “CFF” often faces is mainly the complexity in the application (Ekvall et al., 2020; Battery Pass Consortium, 2023). Furthermore, it is not yet consistently integrated into commercial databases nor LCA software, making it a daunting task to manually apply it to hundreds of materials in a complex system like vehicles and batteries. Thus, when “CFF” is utilized, it is usually done in a simplified way (e.g., in Ricardo et al. (2020)). The other approaches like “50:50” and “APOS” have seen limited application in recent LCAs.

3.6.3. *A one-size-fits-all approach*

Ideally, dealing with multifunctionality should follow a consistent method within a single product system, as well as across different product systems, thereby minimizing the risk of double counting of impacts and/or benefits. This idea was discussed by many (e.g. Schrijvers et al., 2016). Nevertheless, this is not usually feasible in practice because some approaches are more suited to particular multifunctional processes, or cannot be changed due to predefined choices in commercial databases, or conflicts between sector-specific guidelines. This was also acknowledged by (Galatola and Pant, 2014; Schrijvers et al., 2016). Moreover, overarching standards such as ISO do not help much as they lack clear definitions, and often provide ambiguous categorizations of issues, unclear hierarchies of solutions, and, most significantly, tend to lack a systematic approach to tackling the problem (Guinée et al., 2021). The ensuing debate on how to solve multifunctionality is therefore unsurprising, as there is no single “right” way to solve multifunctionality, as stated by Guinée et al. (2004) and Wardenaar et al. (2012). Nonetheless, at least the approach to defining the problem can be harmonized, for which the framework by Guinée et al. (2021) represents a good base from which to start. It provides systematic three steps to define a multifunctional process and a fourth step to solve via economic allocation. The first three steps could improve transparency and comparability. Then, regardless of the method(s) followed in the fourth step, they must be clearly communicated for all the processes in the product system.

3.7. *Impact assessment*

Four impact assessment methods emerge as being recurrently recommended in the reviewed guidelines and standards: Environmental Footprint (EF), IPCC (in carbon footprint guidelines), CML-IA, and ReCiPe. Out of these, CML-IA and ReCiPe are the most widely used ones in OEM reports and scientific literature (Arshad et al., 2022; Dolganova et al., 2020; Scania, 2021; Solaris, 2022). Additionally, midpoint impact categories tend to be more commonly studied and reported (Ricardo et al., 2020). Notably, some scientific studies and OEMs do not report the used impact assessment method at all (AUDI, 2016; Tolomeo et al., 2020).

Climate change is by far the most reported impact category across all sources, typically using IPCC’s method (i.e., global warming potentials or GWPs). Acidification, eutrophication, and photochemical ozone formation also feature prominently in both scientific literature and OEM reports. Scientific studies also tend to report energy efficiency indicators such as Cumulative Energy Demand (CED) or Primary Energy Demand (PED) more frequently, while these indicators are often omitted from OEM reports (Ricardo et al., 2020; Temporelli et al., 2020; Tolomeo et al., 2020).

Intriguingly, indicators related to abiotic resource depletion receive comparatively little attention in both OEM reports and scientific literature, despite their relevance to the EV field, particularly concerning batteries (Dolganova et al., 2020). OEM reports showed also a complete omission of PM formation indicators, which are pertinent for comparisons between ICEVs and EVs.

Overall, the EF method comprises a comprehensive set of diverse impact categories and indicators. Furthermore, unlike CML-IA and ReCiPE methods, which do not receive periodic characterization factors updates, the EF method is continuously updated (latest update on EF 3.1 occurred in July 2022). Therefore, its adoption appears to be recommendable for the purpose of harmonizing EV LCAs.

The specificity of the EV field however also encourages the consideration of supplementary LCI indicators like CED. This stems from the fact that improving the energy efficiency of systems is an area of high technical importance to meeting climate change mitigation objectives (Hassan et al., 2022), and a central pillar of the EU’s overall climate and energy framework, especially when considering the competition for an ultimately limited supply of renewable energy across multiple sectors (Moriarty and Honnery, 2012).

3.8. *Uncertainty, scenario, and sensitivity analyses*

Uncertainty and sensitivity analyses are staple tools to evaluate the impact of uncertainties on LCAs results and hence conclusions. The reviewed studies show that the parameters most commonly analyzed for sensitivity in electric vehicle (EV) research, including those focused on batteries, can be grouped into three main categories: energy supply, distance driven, and battery components materials and their recycling rate.

Investigations in energy supply typically encompass the energy mix during the vehicle’s use stage and the battery manufacturing process (Ellingsen et al., 2013; Majeau-Bettez et al., 2011). Some OEM studies (e.g., Mitsubishi motors, 2019; Scania, 2021; Volvo Cars, 2021) explore future electricity grid mix scenarios utilizing scenarios published in the World Energy Outlook by the IEA. Also, 100 % “green” energy scenarios of pure wind and/or hydropower are tested in the vehicle use stage (Polestar, 2023, 2020; Volvo Cars, 2020, 2021).

The second category addresses the lifespan of EVs expressed as total distance driven (Ellingsen et al., 2013; Faria et al., 2014). Different mileage estimates are considered to check the sensitivity of the results on this assumed parameter (e.g. MAN Truck and Bus SE, 2022). This resonates with the issue raised in Section 3.3 regarding the variation in the assumed lifetime mileage between the different studies.

The third type of parameter is about the battery component materials and their recycling rates at EoL (Anna et al., 2019). Sensitivity analysis related to these parameters can help identify materials with highest environmental impacts and assess whether material recovery can reduce impacts.

These three major themes dominate sensitivity and uncertainty analyses due to their significant influence on results and conclusions (Aichberger, 2020). Less common parameters, such as hydrocarbon emissions from fuel evaporation (i.e. fugitive emissions), are sporadically found in studies (Renault Group, 2015, 2017).

These findings are typically listed under sensitivity or scenario analyses conducted according to the “One At a Time (OAT)” principle, in which one parameter (or set of parameters) is changed in the model to explore its impact on the results, while all the rest are kept constant (Igos et al., 2019). However, on the other hand, “uncertainty analysis” defined as the propagation of uncertainty to the outputs is seldomly done, apart from occasional Monte Carlo simulations in some studies (Arshad et al., 2022).

Relying on simple methods like OAT instead of more rigorous methods is understandable, especially given the overall shortage of uncertainty information (e.g., probability distributions), limited software capabilities, high time requirements, and the fact that the OAT approach does not require a deep knowledge of mathematics. As pointed out by Heijungs (2024), the unfamiliarity of the average LCA practitioner with the principles and techniques for uncertainty and sensitivity analysis is a main reason for the simplicity of techniques used. Yet, it is to be recognized that these analyses are essential components of good LCA practice. Many of the numbers that enter the calculation suffer from uncertainty, and certain assumptions have to be made as well. As a result, the information that is used by the decision maker is subject to uncertainty (Heijungs, 2024; ISO, 2020). It is hereby suggested to handle uncertainty in LCA for EVs perhaps not in the most sophisticated way (due to the aforementioned limitations), but at least in a more structured way than what was found in the reviewed literature. For example, Igos et al. (2019) provide clear practical instructions under the term "Basic approach". Within this approach, the authors recommend a set of simple analyses as a minimum requirement. This structured approach could serve as a foundation for harmonizing how uncertainty is addressed in EV LCA studies, while maintaining practicality due to its relative simplicity.

3.9. A summary and an outlook

Table 3 summarizes the review results alongside the suggested starting points for future method harmonization. For scope definition, a cradle-to-grave system boundary and a distance-based functional unit are encouraged, as these best reflect a full life cycle and the final function of a mobility system, respectively. To boost transparency, cut-offs on the level of flows and processes should be limited, and, where necessary, based on preliminary screening studies with environmental significance as benchmark.

The largest variability in practices was observed in LCI data collection and modeling. To mitigate the impact of this variability, implementing data traceability systems, continuously improving secondary data databases and increasing primary data availability for most impactful processes are essential. Among LCI choices, electricity modeling and multifunctionality present the most significant harmonization challenges. Two key points deserving special attention are the double counting in electricity modeling and the absence of a consistent framework to define a multifunctionality problem.

Among the different impact assessment methods, the EF method is suggested as a starting point for pragmatic reasons due to its continuous updates and its relatively comprehensives coverage of impact categories compared to other methods. We also suggested incorporating supplementary indicators on the LCI level, like CED as a measure of efficiency, which is of utmost importance to policy makers.

Lastly, for data- and assumptions-dependent methods like LCA, uncertainty is unavoidable. Therefore, conducting uncertainty and sensitivity analysis is vital for good LCA practice. These analyses should be addressed in a systematic way that strikes a balance between practicality in terms of resources efficiency (i.e., time and cost), LCA practitioner common knowledge, and method sophistication.

As discussed in the introduction to this article, the apparent benefits of method harmonization include improved comparability, transparency, and consistency—key factors for sustainability-focused policymaking and fair competition in industry. However, harmonization can also have downsides, as it may stifle innovation or lead to suboptimal choices in specific cases where alternative approaches could be more suitable. It is, therefore, essential to clarify that the suggested basic starting points for harmonization might not be the definitive scientifically optimal approach for the EV sector, recognizing that other factors are important when standardizing practices outside the academic context. A successful harmonized method should definitely be scientifically robust. However, it also needs to account for the concerns and limitations of various stakeholders to ensure it can be widely adopted and accepted. This article does not aim to provide a detailed harmonized method. Instead, it seeks to lay the groundwork by reviewing current best practices and proposing broad starting points for ambitious harmonization initiatives like the TranSensus LCA project. Through this project, we engaged with a diverse group of experts, including seven active industry partners. These interactions made it evident that the challenges identified in this review align closely with those faced by industry in current practice.

Table 3
Summary of review results and suggested starting points for future harmonization.

Topic	Review takeaway messages		Suggested starting points for future harmonization
	Vehicle	Battery	
System boundary	Cradle to grave is the most adopted	The most adopted are: • Cradle to grave • Cradle to gate	Cradle-to-grave or cradle-to-cradle (circular systems) are the accurate translation of a life cycle.
Cut-off	Flows cut-off is based on mass, energy, and environmental significance		Cut-off should be avoided as long as resources allow. If not, screening studies should be implemented to justify cut-off decisions based on environmental significance. Also, cut-off flows and processes should be transparently reported.
	Activities highly subject to cutoff are maintenance and infrastructure.	–	
Functional unit	Distance-based functional unit (vkm, pkm, or tkm) is the most used	The most used are: • Distance based (km) • Capacity-based (kWh or MJ) • Throughput-based (kWh or MJ) • Mass-based (kg of battery)	Distance-based functional units are the best representatives of the actual functions of transport systems, but harmonizing mileage assumptions is crucial.
Data	• Lack of a standardized approach to inventory data collection • Data quality and availability varies according to life stage • Lack of primary data in raw material acquisition and EoL is most evident • Apart from the energy consumption, elements considered in the use stage differ significantly. • Industry utilizes special databases (e.g., IMDS) together with commercial LCI databases to model the vehicle production.		Data traceability systems can help primary data sharing. Continuously enhancing secondary data sources is crucial. Pushing for higher share of primary data can start from the most impactful activities.
Electric energy modeling	Two main arguments: 1- Location vs market-based modeling 2- Static vs dynamic modeling		Double counting is a major pitfall to evade.
Multifunctionality	• A distinction is usually found between EoL and upstream processes • Studies are relatively vague on defining and dealing with multifunctionality • A mixture of partitioning and substitution are used upstream to EoL • Five choices in EoL: CFF, Cut-off, Avoided burden, 50:50, and APOS		There is no one "correct" solution. However, at least a framework to clearly defining a multifunctionality problem should be clear.
Impact assessment	• ReCiPe and CML-IA are very common • Mixing impact indicators from different LCIA methods is a common practice		EF method is an adequate choice for harmonization. It can be enhanced with additional

(*continued on next page*)

Table 3 (*continued*)

Topic	Review takeaway messages		Suggested starting points for future harmonization
	Vehicle	Battery	
	• Most reported impact categories are Climate change, Acidification, Photochemical Ozone Formation, Eutrophication		efficiency indicators (e.g., CED).
Uncertainty, sensitivity, and scenario analysis	• Systematic uncertainty propagation is seldom. Instead, usually skipped to (OAT) sensitivity or scenario analyses. • Most tested topics: 1- Energy: use-stage consumption (e.g., regulatory vs ‘real-world’ driving) and electricity grid mixes 2- Total distance driven (mileage)	Battery components and recycling rates is the most tested topic.	It is encouraged to handle uncertainty in LCA for EVs in a more structured way. Scientific research provides abundant guidance in this regard that do not compromise practicality.

4. Conclusions

Harmonizing LCA practices in any field come at the cost of inflexibility, which might lead to adopting suboptimal solutions under specific circumstances; however, having a harmonized reference within a field is crucial for comparability, transparency, and consistency. To support the ongoing harmonization efforts, this article aimed to review the LCA practices across various sources in order to identify where key differences in assumptions, methodological approaches, and data selection occur in relevant LCA topics. The review included available and evolving sectorial guidelines and standards, scientific and industry studies, LCI databases, and other documents. In addition to this main goal, we underlined certain practices that could serve as starting points for future harmonization attempts. We also highlighted topics where it is challenging to do this.

The review showed a big variation in assumptions and choices, particularly in the LCI stage. Some topics seem easier than others to harmonize. Also, our review and internal project discussions showed that some topics (like electricity modeling and multifunctionality) will likely require more effort to come to a consensus on harmonization. This is simply because each standpoint has its valid reasonings, and research is far from conclusive regarding these topics.

Aimed at a diverse audience from academia, industry, and policymakers, we believe this work provides a strong foundation for future efforts to harmonize LCA methods in the EV sector. Additionally, it serves as a comprehensive reference for anyone looking to familiarize themselves with the latest LCA practices in this field.

The main limitation of this review is its limited scope on electric powertrains. Other technologies like fuel cells, hydrogen, biofuels, and e-fuels are not part of this review. The specificities of these technologies can give rise to additional methodological considerations. Also, despite the care given to the use of the most updated versions of guidelines and standards, many of these guidelines versions are in advanced draft stage and evolving rapidly. Yet, we saw the value of following up with all relevant guidelines and initiatives in this review even if final versions in the future may be different.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used [Chat GPT] in order to improve the text for more effective writing. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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