Sustainable Production and Consumption 50 (2024) 556–570

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc

Review Article

Towards consistent life cycle assessment modelling of circular economy strategies for electric vehicle batteries

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A R T I C L E I N F O

Editor: Dr Rodrigo Salvador

Keywords:
Battery
Electromobility
Circular economy
Life cycle assessment
Harmonisation

A B S T R A C T

Circular economy strategies for electric vehicle (EV) batteries are gaining importance to reduce dependence on primary raw materials for the energy and mobility transition. Modelling circular economy strategies in the Life Cycle Assessment (LCA) of EV batteries comes with a number of key challenges to ensure sound support to decision-making, including i) solving multifunctionality, whether regarding End-of-Life, processes of secondary raw materials production or product level, ii) capturing material quality aspects and iii) using adequate resource indicators. This study provides a review of LCA guidelines and scientific literature relative to EV batteries. The objective is two-fold: i) identifying key gaps in the guidelines regarding these modelling challenges, and ii) discussing how to fill them based on the state-of-the-art research. The analysis shows that the handling of multifunctionality is addressed in all analysed guidelines but is treated very differently. Major efforts are expected in terms of standardisation and harmonisation, building on the existing state-of-the-art research. A guiding question for standardisation is whether multifunctionality shall be always treated in the same way or whether special rules are appropriate. Instead, material quality and indicators of mineral resource losses are not at all, or to a very limited extent, addressed by existing guidelines. For material quality and mineral resource dissipation and accessibility-based indicators, research developments shall be pursued. Associated research outcomes are ultimately expected to be fed back into the guideline development in a more mid to long-term. The approach for handling these modelling challenges could and should be consistent between different products and sectors of the energy and mobility transition, to avoid double counting and burden shifting.

1. Introduction

1.1. Growing demand and circular economy strategies for electric vehicle batteries

Meeting the European Union's (EU) ambitious policy targets, including net-zero by 2050, will drive an unprecedented increase in materials demand in the short to more long-term future (Carrara et al., 2023). In particular, the expected growth of the e-mobility sector in the coming decades will induce a large rise in demand for several raw materials. Battery raw materials are limited and Europe is dependent on global supply chains (Kallitsis et al., 2024; Liang et al., 2022). Reflecting the associated supply risks, a lot of these raw materials are classified as critical or strategic (European Commission, 2023a). Circular economy strategies, including material recycling, appear to be one way to keep the value of these mineral resources in the economy and accordingly reduce reliance on extraction from geological stocks (Geyer et al., 2016). Legislations in the EU such as the Battery regulation also put the establishment of a sustainable circular economy into focus (European Parliament and European Council, 2023). In the next years, the Battery regulation will step-wise establish and increase mandatory target values for recycling rates of battery materials and secondary material shares

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https://doi.org/10.1016/j.spc.2024.09.001
Received 13 June 2024; Received in revised form 30 August 2024; Accepted 3 September 2024
Available online 4 September 2024
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(European Parliament and European Council, 2023). While the EU legislation has a focus on recycling, different strategies exist to establish a circular economy – the so-called R-strategies (see Fig. 1).

The Battery regulation also demands the declaration of the CO_2-footprint of electric vehicle (EV) batteries (European Parliament and European Council, 2023). To quantify and label the environmental footprint, Original Equipment Manufacturer (OEMs) need to perform a life cycle assessment (LCA) for their EV batteries.

1.2. Core LCA modelling challenges in the context of circular economy strategies

The implementation of circular economy strategies in the life cycle of EV batteries leads to a range of challenges in LCA modelling.

i) Handling the multifunctionality at End-of-Life (EoL)

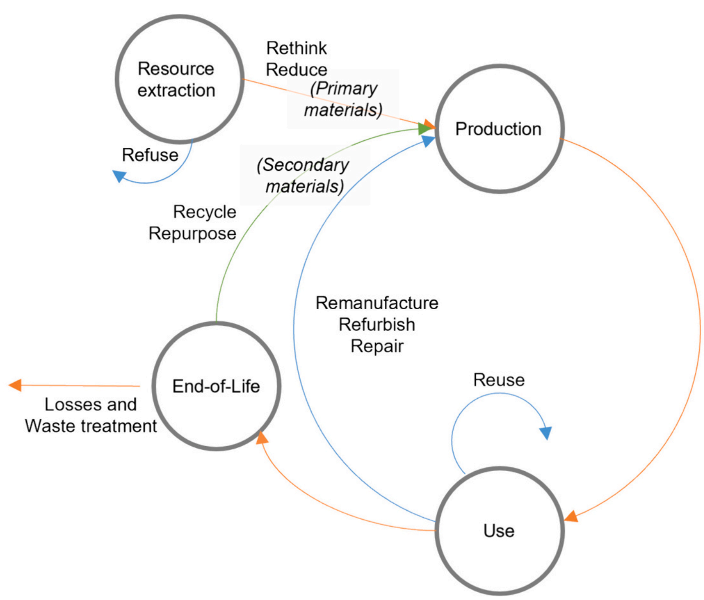
With the regulatory pressure, the recycling of EV batteries is becoming common practice in the industry and needs to be modelled in the LCA of EV batteries to capture the full life cycle impacts. Recycling processes provide two distinct functions: treating a waste battery, and producing secondary materials. With recycling, the materials are used in more than one battery life cycle. This indicates that the impacts and also the benefits of recycled materials need to be split between at least two products. This multifunctionality needs to be handled as part of the LCA.

ii) Handling the multifunctionality in processes of secondary material production

Recycling processes usually target more than one material and are accordingly multi-output processes (Friedrich and Schwich, 2021). Therefore, the challenge is to model this multifunctionality of the recycling processes properly and declare the environmental impacts of all materials on a transparent and consistent basis.

iii) Handling multifunctionality on product level

Different circular economy strategies also affect the use phase. The repurposing of EV batteries to use them in secondary applications such as stationary systems after their use in an EV is gaining interest. During this second use, the battery provides an additional function but also delays recycling and therefore prevents the reuse of the materials to produce new products or batteries. Trade-offs between the circular economy strategies appear which need to be evaluated. Rethinking the use of EV batteries includes vehicle-to-grid (V2G) and battery swapping. V2G is defined as follows: "*The EVs can return electricity to the grid in a controlled manner by means of specifically enabled bidirectional chargers. In this way, EVs can render additional services to the grid, such as frequency regulation*" (European Environment Agency, 2022, p. 164). The battery provides two functions: driving and supplying electricity to the grid. In case of battery swapping, driving is provided by more than one specific



Refuse	Smaller batteries are used in EVs
Rethink	Car and ride sharing, Vehicle to grid, Battery swap
Reduce	Less scrap in the production of batteries, material and energy efficiency
Reuse	Reuse of the EV battery in another EV
Repair	Repair of EV batteries
Refurbish	Restore and improve battery for a use in an EV or another application as a used battery (lower quality than new battery)
Remanufacture	Use battery in an EV again after replacing cells, modules or other components to reach at least 90% of original capacity
Repurpose	Use (parts of) EV batteries for stationary applications
Recycle	Recovery of materials as secondary materials
Recover	Recovery of energy from battery discharging and waste processing

Fig. 1. R-strategies for the circular economy applied to the case of electric vehicle (EV) based on (DIN e.V., n.d.; European Parliament and European Council, 2023; Harper et al., 2023).

battery. The concept is not yet developed on a large scale. It means that one battery can be used in multiple different vehicles. The battery is usually charged in a dedicated facility at a later time (Zhao and Baker, 2022). Consequently, this makes the task of doing an LCA of the battery very difficult since there is no direct link between the service provided by the battery and the distance driven by the vehicle. It depends on the number of vehicles in which the battery will be used and the number of other batteries used for the same vehicles.

iv) Reflecting material quality as part of the LCA

For the use of secondary materials in EV batteries, their quality plays a key role (Latini et al., 2022). With primary and secondary materials used to produce EV batteries, a consideration of the different material qualities in the LCA becomes necessary. However, material quality is mostly neglected in LCAs (Tonini et al., 2022).

v) Resource indicators to capture circular economy effects

The aim of a circular economy is to maintain the value of products, materials and resources in the economy for as long as possible and to minimise the generation of waste (European Commission, 2015). Therefore, Circular Economy Action Plans are initialised to maintain the values of products, materials and resources (European Commission, 2020, 2015). Also, the Battery regulation reports resource issues as key for EV batteries and claims the importance for more resource-efficient production pathways (European Commission, 2023a). While the importance of resource use for the electromobility sector is recognised in the political context and in research, including in the LCA field (e.g., Mikosch et al., 2022), resource use-related impacts are not frequently addressed in LCA studies (Dolganova et al., 2020). This limit particularly affects how far LCA enables an assessment of impacts and benefits of the transition from thermal to EV, including potential impact transfers from some environmental and resource categories to others (e.g., reduced contribution to climate change but larger impacts on mineral resources (Xia and Li, 2022)). The need for sound mineral resource indicators is even more pronounced in the context of circular strategies, particularly aimed at reducing resource use.

While there are other topics which are relevant in the contexts of LCA or circular economy of EV batteries, only the five above-listed overarching challenges, with specific applications and developments in the LCA of EV batteries, were included in this review. Toxicity and ecotoxicity, for example, are highly relevant in the context of EV batteries (Nordelöf et al., 2014) and need more robust indicators as well (Mikosch et al., 2022). The main limitation to address here is the characterisation factors (CF) (Mikosch et al., 2022), implying limited LCA developments specific to EV batteries. Instead, regarding resource indicators, more work is needed at the life cycle inventory (LCI) stage. To better capture losses of mineral resources, new LCIs shall be modelled (Beylot et al., 2024). This implies the overarching need to compile new LCI data specific to EV batteries at stake. Similarly, raw materials criticality, which enables to capture the supply risks and vulnerability to supply disruptions (Dewulf et al., 2016; Knobloch et al., 2018; Sonderegger et al., 2020), is neither further addressed in this study.

1.3. Research gap and objectives of the publication

These challenges are usually overlooked in LCA studies which may lead to altered quality of the results and interpretation and consequently, the decision-making derived from these studies. While several scientific reviews have been performed on LCA applied to assess the environmental footprint of battery EVs and batteries over the last two decades (e.g., (Arshad et al., 2022)), to the best of the authors' knowledge, no broad overview exists on how to deal with the described modelling challenges in a consistent and transparent way. In the last two decades, also many LCA studies on batteries have been published. There are various studies focusing on the whole life cycle of an EV battery or several life cycle stages, as shown in the extensive review done by (Popien et al., 2023). There are also studies focusing on specific life cycle stages linked to the R-strategies (e.g., (Ali et al., 2024; Bobba et al., 2018; Koroma et al., 2022) and others). However, the modelling challenges are not explicitly and methodologically addressed in these studies.

The goal of this paper is twofold: i) to analyse current LCA guidelines regarding modelling challenges on circularity, including the identification and discussion of key gaps, and ii) to pave the way towards their filling through state-of-the-art research and further research developments. In Section 2, the method of this paper is described including reviewed guidelines and literature. In Section 3, the modelling challenges are described in detail followed by an analysis of how they are addressed in the guidelines and in the state-of-the-art research. In Section 4, the gaps and the way forward to fill these are further discussed followed by a conclusion in Section 5.

2. Methods: review framework

Based on the two-fold goals to analyse the common practice in current LCA guidelines and to pave the way towards filling these gaps based on the state-of-the-art, the conducted review consists of three main steps:

1) Review of existing guidelines for the LCA of EV batteries and derivation of key issues with regard to the modelling challenges identified
2) Review of state-of-the-art research on the identified modelling challenges
3) Further analysis and reflection to identify next steps for filling existing gaps

2.1. Review of existing guidelines and derivation of key issues

For step 1), existing guidelines specific to the LCA of EV batteries in Europe were identified:

- The Greenhouse Gas Rulebook v1.5 published in 2023 (Global Battery Alliance, 2023). Hereafter referred to as GBA.
- The harmonised rules for the calculation of the carbon footprint of electric vehicle batteries (CFB-EV) draft published in 06/2023 (Andreasi Bassi et al., 2023).
- The PEFCR – Product environmental footprint category rules for high specific energy rechargeable batteries for mobile applications published in 2018 (Siret et al., 2018).

Additionally, the DIN ISO 14040 (International Organization for Standardization 14044, 2007) as the generic LCA standard which provides guidance for all applications was included in the review. This allows us to analyse where the EV battery-specific guidelines build up on the generic standard and where they deviate from it.

The GBA is developed by the Global Battery Alliance which is a multi-stakeholder organization dedicated to establishing a sustainable battery value chain. The rulebook was developed to track and calculate the greenhouse gas footprint of batteries in EVs (Global Battery Alliance, n.d.). The CFB-EV is published by the European Commission Joint Research Centre (JRC). The goal is to provide technical support to the development of secondary legislation on the carbon footprint of batteries in line with the Battery regulation. Several stakeholders were part of the development process in the form of workshops and consultations (European Commission, 2023b). The PEFCR is developed by RECHARGE based on the Product Environmental Footprint (PEF) method by the European Commission and provides detailed guidance on how to perform a PEF study for batteries. As part of RECHARGE material

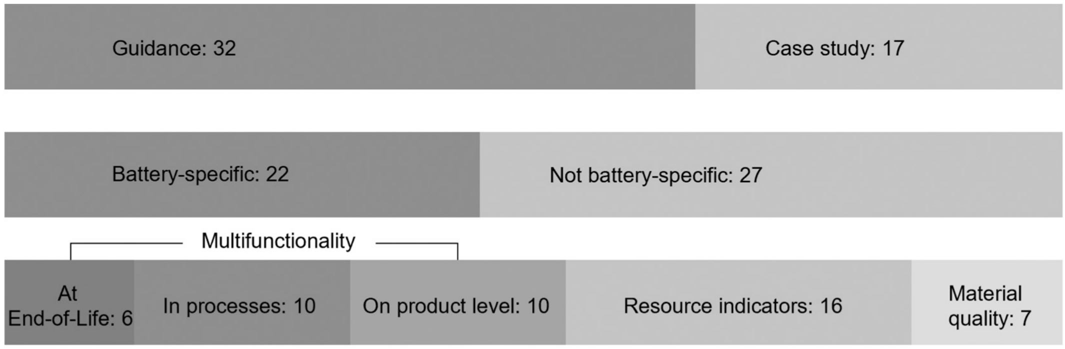


Fig. 2. Publications collected per scope of the publication, per application chosen and per modelling challenge identified.

suppliers, battery OEMs, recyclers and others were involved in the development process (Siret et al., 2018).

2.2. Review of state-of-the-art research and further analysis

We started the review based on the expertise of the authors and the knowledge gained from the previous review in TranSensus LCA. As part of the project TranSensus LCA,[1] an extensive review of LCA practices in the electromobility sector was performed (Bein et al., 2023). This includes guidelines as well as practices in the literature. The review of the scientific literature in TranSensus LCA was performed as follows: It was built upon an existing review to cover all relevant literature until 2018 (Ricardo et al., 2020). For literature from 2018 to 2023, a systematic search on the Web of Science was performed followed by initial screening based on relevance and snowball readings from the collected articles when deeper analysis (e.g., regarding methodological aspects) was necessary (Bein et al., 2023).

While the focus in the review as part of TranSensus LCA was on the electromobility sector, with this publication, we are performing a more detailed analysis of the LCA modelling associated with the circular economy of EV batteries with the focus on the five core challenges described in the introduction. For the review in this publication, again, a screening of the available scientific literature was performed to evaluate their relevance. The collected literature was extended with snowball readings and more specific research for literature where gaps remained. A total of 49 publications were collected and analysed (see Fig. 2).

The collection of literature was organised in two steps: first, with a focus on publications directly related to batteries and their materials. If no specific publications on batteries were available, the scope was broadened to generic concepts or approaches from other sectors. In this case, the transferability of the concepts to the case of batteries is discussed. In both steps, the focus lies on finding publications which provide and discuss guidance on the different modelling topics on the circular economy or provide an extensive overview of current practices. If neither is available, case studies are included and analysed to identify the current practice. The current practice is then further discussed concerning the level of standardisation as well as strengths and shortcomings and gaps to be filled in the future. Fig. 3 shows the main approach for the review and the guiding questions for each step of the analysis.

[1] The project TranSensus LCA aims to develop a baseline for a European-wide harmonised, commonly accepted and applied single life cycle assessment (LCA) approach for a zero-emission road transport system. The project is funded by the European Union. https://lca4transport.eu/

3. Review results

3.1. Multifunctionality at end-of-life

The ISO 14044 provides a hierarchy on how to handle multifunctionality in general. First, if possible, allocation is avoided by a subdivision of the process. The next step would be system expansion (International Organization for Standardization 14044, 2007). ISO 14044 allows for two interpretations of system expansion: i) the system expansion in the traditional sense where additional functions are included in the system and ii) system expansion as substitution where additional functions are subtracted from the system (Finkbeiner, 2021). If system expansion is also not possible, the multifunctionality is solved with allocation, either based on physical properties (e.g., mass) or on other properties such as economic value (International Organization for Standardization 14044, 2007). System expansion in the traditional sense would completely change the functional unit, which is usually not compatible with the LCA goal.

Different methods exist on how to handle the multifunctionality at the EoL, which arises because recycling has two functions: treating waste and producing secondary materials. The most common ones are: i) the cut-off method, which is a type of allocation, ii) avoided burdens, which is a type of substitution, iii) the 50/50 method, which combines the previous ones (Allacker et al., 2017; Ekvall et al., 2020). These methods vary in the way process burdens are allocated to the battery life cycle. Fig. 4 shows the allocated impacts to each process or component for the two archetypal methods cut-off method and avoided burdens. The cut-off method allocates all the recycling burdens to the secondary materials produced, and none to waste treatment of the battery (see Fig. 4a). As no impacts are allocated to the waste treatment, the recycling process at the EoL is excluded from the recycled battery lifecycle (see Fig. 4b). Thus, recycling is treated as a production process (Nordelöf et al., 2019).

On the contrary, the avoided burdens method is the application of the principle of substitution to recycling. The burdens allocated to the waste treatment of the battery are the burdens of downstream recycling minus the burdens of primary materials avoided by the recycling (see Fig. 4c). To be consistent between product life cycles, the burdens associated to secondary materials must be considered equal to the burdens of primary materials. The benefits of recycling are allocated to the EV battery that is getting recycled based on the secondary materials produced (see Fig. 4d). Recycling is seen as a waste treatment process at EoL (Allacker et al., 2017; Ekvall et al., 2020; Nordelöf et al., 2019).

The 50/50 and Circular Footprint Formula (CFF) methods are a blend of cut-off and avoided burdens, for which different interpretations exist. The environmental burdens of each recycling process are allocated between the EV battery being recycled and the one using the secondary materials. Some interpretations of the method also split the environmental burdens of raw material production and final disposal between the two product lifecycles (Allacker et al., 2017; Ekvall et al., 2020). The

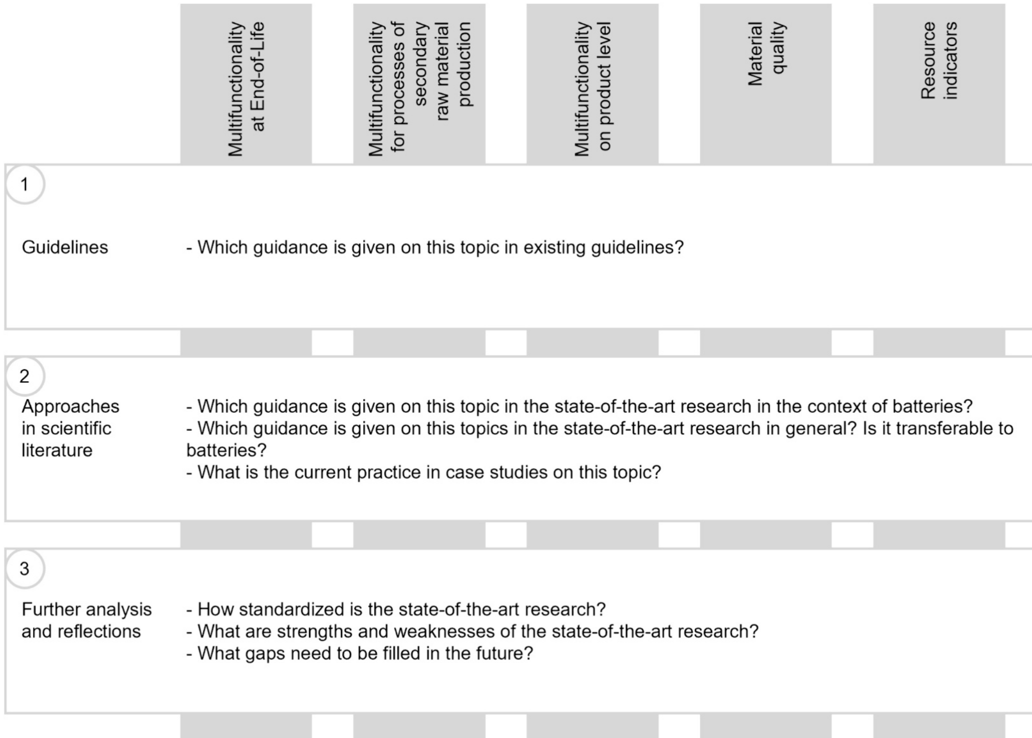


Fig. 3. Review framework of the article with main steps and guiding questions

CFF defined in the PEF (Siret et al., 2018) is built upon the 50/50 method with an adjustable weighting between cut-off and avoided burden.

3.1.1. Guidelines

The ISO 14044 differentiates two scenarios for the multifunctionality in recycling. If the material is recycled closed-loop (no changes to the inherent properties of the material), no allocation is needed because the recycled material replaces the primary material. For open-loop recycling (changes to the inherent properties of the material), allocation shall be applied either based on physical properties, economic value or the number of subsequent uses of the recycled material (International Organization for Standardization 14044, 2007).

The GBA recommends using the cut-off approach to model the multifunctionality at the EoL linked to the recycling of batteries. This is justified with the explanation that it is the most transparent EoL approach. The PEFCR uses the CFF to model the EoL of products. The formula captures the recycled content and is a combination of material, energy and disposal. The major parameters are the allocation factor of burdens and credits between supplier and user of recycled material (A), the allocation factor of energy recovery processes (B), the recycled content (R_1) and the recycling rate (R_2). If the parameter A is set to 1, the CFF would approximate the cut-off approach. If the parameter A is set to 0, it is similar to avoided burdens. However, in the description in the PEFCR, it is stated that A should be between 0.2 and 0.8. This means the PEF method renders the cut-off approach impossible. The CFB-EV also refers to the CFF for the EoL allocation. The formula and the parameters are adapted from the version in the PEFCR. Default values for the major parameters are shown in Table 1. Default values for the emissions are based on the EF-compliant datasets compiled in the PEFCR. The analysis shows that the default values in the PEFCR from 2018 and the CFB-EV are mostly aligned. However, the CFB-EV provides default values for a large number of materials whereas in the PEFCR they are provided on a more aggregated level. Additionally, the default values of the recycled content will soon be outdated as they are lower than the mandatory target values of the EU battery regulation (European Parliament and European Council, 2023). An update of the default values for the recycled content in the PEFCR and the CFB-EV is therefore needed.

3.1.2. Approaches discussed in the scientific literature

Different case studies show that the choice of the allocation method has a significant influence on the estimated environmental impacts (Du et al., 2022; Husmann et al., 2023a). An untransparent and inconsistent application of the allocation approach, such as including recycled materials at the production phase and avoided burdens at EoL, leads to the risk of double counting impacts or benefits from recycling and secondary materials (Nordelöf et al., 2019). Furthermore, it hinders the comparison of results from different studies, as there are large discrepancies between different allocation methods. Therefore, a consistent application of EoL allocation is of high importance. Often, the formulas to apply the allocation are quite simplified and need to be extended to reflect secondary material shared and recycling rates for different materials rather than on the product level as done in (Husmann et al., 2023a). The newest version of the CFF in the CFB-EV includes the material-specific perspective (Andreasi Bassi et al., 2023).

The CFF accounts for many aspects such as the material quality, recovery rates and demand factors based on market conditions. Therefore, specific information and data would be required for the different materials in the EV battery to estimate relevant results. These are quite difficult to obtain. In the guidelines, default values are provided. However, these raise several limitations. Not all guidelines provide material-specific values and by the choice of factor A a high weight is given to EoL recycling, bringing CFF closer to avoided burdens. Another weak point is the missing standards on calculating the material quality (CEA and BRGM, 2023). The guidance on material quality is further analysed in Section 3.4.

3.1.3. Further analysis and reflection

All of the common methods in the literature have their strong points and shortcomings (see Table 2). The cut-off method is the most transparent allocation method. It is the easiest to apply and simplest to verify. Since it does not consider recycling at the EoL of the product, it avoids

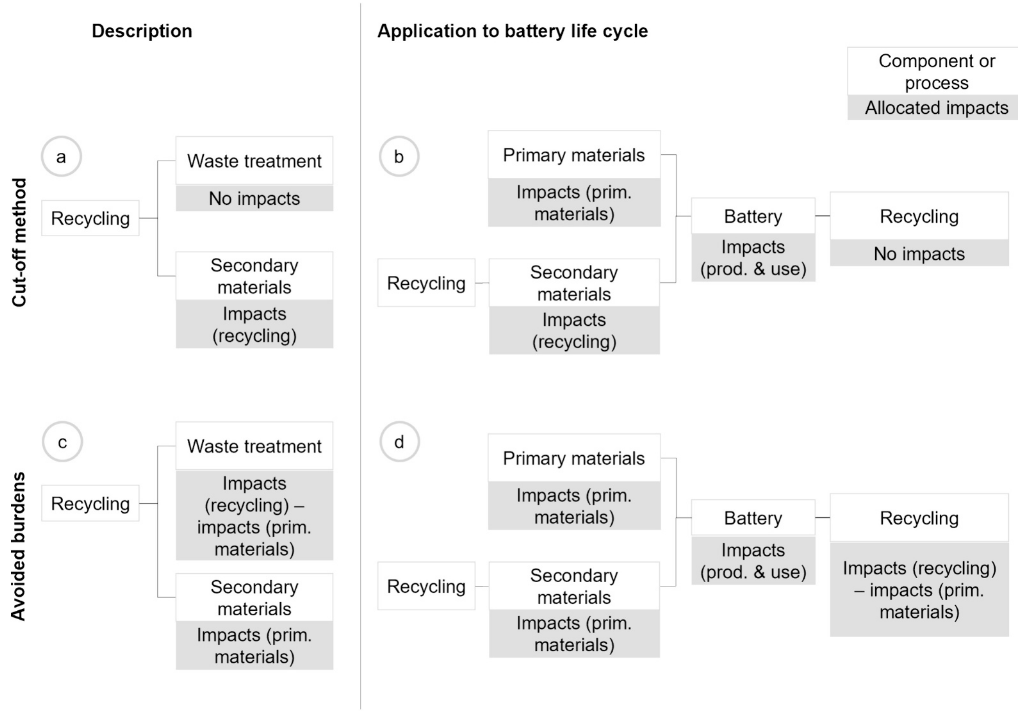


Fig. 4. Dealing with recycling and secondary materials in the End-of-Life (EoL) allocation visualised for the two archetypal approaches cut-off method and avoided burdens. The 50/50 and Circular Footprint Formula (CFF) methods are a blend of both.

Table 1
Comparison of default values for major parameters in the Circular Footprint Formula (CFF) in the Product environmental footprint category rules for high specific energy rechargeable batteries for mobile applications (PEFCR) and the harmonised rules for the calculation of the carbon footprint of electric vehicle batteries (CFB-EV).

Parameters	PEFCR (2018)	CFB-EV
Allocation factor of burdens and credits between supplier and user of recycled material (A)	0.2 for metal 0.5 for plastics	0.2 for metal 0.5 for plastics
Allocation factor of energy recovery processes (B)	0	0
Recycled content (R_1)	0	0 When a company-specific value other than 0 is used, traceability through the supply chain is necessary
Recycling rate (R_2)	Collection for recycling 0.95 for the whole battery Details on the material level are included in the EF (Environmental Footprint) compliant datasets	Values differentiated for different metals and materials, in the range of 0 to 0.9. Differentiation between properly and non-properly collected waste-batteries Company-specific values may be used with verifiable evidence

the prospective dimension of needing to estimate how and with which impacts the EV battery gets recycled, what quality the secondary materials will have, and which primary materials they will replace. Avoided burdens as well as the 50:50 method include downstream recycling and therefore the prospective dimension. Because of the long lifetime of batteries, this increases the risk of inaccurately estimated impacts. The cut-off method puts the emphasis on using secondary materials while avoided burdens incentivizes batteries that will be recyclable at the EoL. The 50:50 method potentially gives incentives for both (CEA and BRGM, 2023; Husmann et al., 2023a; Šimaitis et al., 2023). However, the new EU Battery regulation provides target values for recycling rates and secondary material shares, which gives also incentives to use recycled materials and design recyclable batteries (European Parliament and European Council, 2023). The avoided burdens as well as the 50:50 approach credit savings that have not been realised yet and create a risk of greenwashing, while cut-off focuses on emissions happening for sure at the time of production (CEA and BRGM, 2023).

Finally, the case of EV batteries is specific to the very fast growth of the market (x10 every 10 years). Due to this, at any given time, there are ~30 times more EV batteries being produced than reaching their EoL. The recycled content in a new battery is thus necessarily very low even if a very high fraction of materials from the old battery is recycled. Therefore, the estimation of the impacts by the cut-off method is much larger than the estimation by the avoided burdens method. The estimated impacts of the 50:50 approach or CFF are in between those of cut-off and avoided burdens (Du et al., 2022).

3.2. Multifunctionality of processes of secondary material production

The handling of multifunctionality for secondary material production processes is only to a very limited extent addressed in guidelines and literature. We therefore broaden the scope in this section to general guidance given on multifunctionality handling in guidelines or with regard to primary production processes since these face quite similar challenges. The transferability of the approaches to recycling is then further discussed in this section.

Table 2
Comparison of cut-off, avoided burdens, the 50:50 method and the Circular Footprint Formula (CFF) as End-of-Life (EoL) allocation approach.

	Cut-off	Avoided burdens	50:50 or CFF approach
Data required	Only existing processes at the beginning of life	Prospective processes at EoL for recycling and for avoided primary materials	Prospective processes at EoL for recycling and for avoided primary materials. Weighting factor between cut-off and avoided burdens (0.5 in 50:50, A in CFF).
Incentivizes	Use of recycled material	Design for recycling, if it can be reliably modelled	Use of recycled material as well as design for recycling if it can be reliably modelled
Temporal focus	Focuses on impacts at the time of production	Focuses on future burdens (recycling) and credits (avoided primary materials)	Balances impacts at time of production with future burdens and credits
Risks from the interpretation of the LCA results (Lueddeckens et al., 2020)	Short time horizon potentially leads to shifting emissions from the present to the future (e.g., batteries that are difficult to recycle)	Using future credits as an excuse for not acting today e.g., on battery design (Choice of materials…)	Reliance on the weighting factor
Trend on results in a fast-growing market	Higher calculated impacts (small share of upstream secondary materials)	Lower calculated impacts (large amount of secondary materials at EoL)	Intermediate calculated impacts

3.2.1. Guidelines

Table 3 compares the guidance provided on handling multifunctionality in processes. How ISO 14044 deals with multifunctionality is described in Section 3.1 and is the same in all contexts. The GBA in general follows the recommendations of the ISO. Whenever possible, the allocation shall be avoided by subdivision and if not possible by system expansion. For system expansion, an alternative production route with a well-characterised representative process is needed. Representative processes shall be predominant on the market and not require allocation themselves (or allocation shall be clear and consistent among co-products). For primary production of metals, these representative processes are often not available. Therefore, the GBA introduces material-specific rules for the allocation (see Table 3).

According to the CFB-EV, multifunctionality shall in general be treated by following the EC recommendations 2021/2279 which recommends subdivision, followed by allocation based on underlying physical properties and allocation based on other relationships (e.g., economic value). Additionally, some further material-specific guidance in the primary material production is also provided (see Table 3).

The PEFCR focuses on battery production. They state that there are no identified cases of co-products in the battery production process and therefore no specific guidance is provided on allocation. In case co-products should be associated with the manufacturing process, they refer to the general PEF multifunctionality decision default hierarchy.

3.2.2. Approaches discussed in scientific literature

In scientific literature, different guidance can be found on how to deal with multifunctionality in the primary production of battery materials (focus on metals) (see Table 4). These either extend the ISO guidance or present a different approach. For the recycling of batteries, no guidance exists. This is due to the fact, that recycling is often evaluated from the process perspective by calculating the impacts and the credits of the process and not with focus on the secondary materials produced (Husmann et al., 2023b).

Weidema et al. state in their approach, that all the situations of co-production of the metals sector can be solved with system expansion – some of them with specific forms that can be seen as a representation of allocation by physical relations or economic value. Therefore, the stepwise approach of the ISO would be unnecessary (Weidema and Norris,

Table 3
Comparison of guidance on handling of multifunctionality in the ISO 14040, the Greenhouse Gas Rulebook (GBA), the Product environmental footprint category rules for high specific energy rechargeable batteries for mobile applications (PEFCR) and the harmonised rules for the calculation of the carbon footprint of electric vehicle batteries (CFB-EV).

	ISO 14040	GBA	CFB-EV	PEFCR
General recommendation/ approach	1. Subdivision 2. System expansion 3. Allocation based on physical properties 4. Allocation based on other properties	1. Subdivision 2. System expansion 3. Allocation	1. Subdivision 2. Allocation based on underlying physical properties 3. Allocation based on other relationship	1. Subdivision or system expansion 2. Allocation based on underlying physical properties (substitution may apply here) 3. Allocation based on other relationship
Specifications on different types of metals/ materials (Primary production)	–	- Only metals (without precious or platinum group metals or salt co-products): mass allocation (only at the step where separation occurs) - Base metals and precious or platinum metals as well as battery-grade and lower-grade graphite products: economic allocation	- For processes with base metals or other low-value fractions and precious or platinum group metals: Economic allocation (only for the process step where the precious/ platinum group metal is extracted)	–
Specifications on economic allocation	–	- Average price over the last 10 years - Economic allocation shall only be applied when the ratio of economic values is greater than 4	- 5-year average global market prices for metals (at least 1 year when 5 years are not available) - Economic allocation shall be applied when the price difference between the different products is higher than a factor 4	–

Table 4
Comparison of approaches on solving multifunctionality.

	Weidema and Norris (2002)	Santero and Hendry (2016)	Lai et al. (2021)
Description of approach	Only system expansion	System expansion as the preferred approach but often not possible and therefore focus on allocation; Mass allocation for metals with similar values, economic allocation for metals with different values (precious metals, platinum group metals)	1. Subdivision as much as possible 2. Partial subdivision + allocation 3. Only allocation
Applicability to recycling	System expansion faces the same problems as for primary materials.	Challenging to differ between values of co-products because of the large range of metals recovered in one process	Partial subdivision + (mass) allocation complex but applicable

2002). In contrast to this, in several more recent publications, the authors state that system expansion is not a feasible option in the mining sector (Lai et al., 2021; Marmiroli et al., 2022; Santero and Hendry, 2016). To apply system expansion, one single representative mono-production process of industry practice is needed. This is challenging because of the diverse sources of metals and associated process routes. Also, for some metals, no mono-production process exists (Santero and Hendry, 2016).

Lai et al. recommend using subdivision as much as possible and extending it with allocation if needed (Lai et al., 2021). Allocation as a stand-alone option is the last resort. When applying allocation, they suggest using production cost instead of the price as an allocation key for economic value since it is more linked to the process itself (Lai et al., 2021). In practice, prices might be more accessible information for most since production cost is often internal data. With their approach, they extend the ISO with more guidance specific to battery materials.

Santero & Hendry focus their recommendations on allocation and on which allocation key to use based on the metal types (Santero and Hendry, 2016). In general, they state that for upstream processes (e.g., mining) mass allocation shall be used and for downstream processes (e.g., refining) economic allocation, since the upstream processes to produce the ore are independent of the metal types in the ore while for the extraction in the downstream processes, the metal type is relevant. The economic value is equal to the market value (price) in their approach and they recommend using a 10-year average (Santero and Hendry, 2016). This guidance extends the ISO standard for metals by showing best practices and is also adopted by the GBA.

3.2.3. *Further analysis and reflections*

The handling of multifunctionality in LCAs for primary (Santero and Hendry, 2016) and secondary battery material production is not well aligned in practice (Husmann et al., 2023b). This is due to the fact, that while providing general guidance, the ISO standard leaves room for choices by the LCA practitioner. Several case studies show that these modelling choices in the handling of multifunctionality have a high influence on the environmental impacts allocated to primary and secondary materials (Abdelbaky et al., 2023; Fernandez et al., 2024; Paulikas et al., 2020). However, these are seldom transparently described (Husmann et al., 2023b; Marmiroli et al., 2022).

The process technologies for primary and secondary material production have large similarities. Therefore, a lot of the reasoning is transferable from primary to secondary materials (see Table 4). System expansion is often used to evaluate recycling from a process perspective while allocation is the predominant way to solve multifunctionality from a material perspective (Husmann et al., 2023b). Applying only system expansion to solve the multifunctionality in recycling processes leads to the same challenges as in the primary production: representative market processes would be needed which are often not available. The approach of determining the allocation key by Santero & Hendry is also challenging to apply for recycling. Since a scrap battery gets recycled, normally graphite, lithium, manganese, nickel and cobalt are recovered (Blömeke et al., 2022). While the purpose of recycling processes has been driven by economic values in the past, this is likely going to shift due to mandatory recycling rates and secondary material shares for several key materials (European Parliament and European Council, 2023). The choice of an allocation key is therefore challenging. The concept of partial subdivision combined with allocation as suggested by Lai et al. is complex in the application for recycling. However, as shown in Husmann et al., it is possible to combine subdivision with (mass) allocation (there referred to as mass allocation on the unit process level). Since the materials are recovered in different process steps and at different points in the process chain, this approach can also lead to more robust results for recycling (Husmann et al., 2023b).

Allocation keys are not widely discussed in all the approaches. Mass as an allocation key for physical properties is easy to apply. However, it is arguable whether the mass is the (single) driver of material and energy flows associated with a process. Other physical allocation keys could also be used such as energy-based (e.g., enthalpy) allocation. The economic value as an allocation key might be more reflective of the process purpose. However, a common understanding of the economic value as price or cost is needed. In the case of prices, it is also necessary to have a robust value for the market prices because these are experiencing high fluctuations (Santero and Hendry, 2016).

3.3. *Multifunctionality on product level*

3.3.1. *Guidelines*

Multifunctionality on product level is not largely addressed in current guidelines.

3.3.2. *Approaches discussed in the scientific literature*

The multifunctionality on product level is only to a limited extent addressed in the scientific literature. The dominant approach for successive uses of the battery is used for example in (Koroma et al., 2022). It considers that the use in second life substitutes a dedicated fresh stationary battery (see Fig. 5a). The functional unit is related to the BEV only. A scenario where the BEV battery is recycled after its EoL is compared to a scenario where the battery is refurbished and performs a second life before being recycled. For this second scenario, credits are granted for the avoided stationary battery. The avoided battery is supposed to be made of fresh materials, and recycling is modelled through avoided burdens, which partially cancel each other (Koroma et al., 2022).

Another option is to use system expansion (see Fig. 5b) but to scale the impacts to one year of use (Cusenza et al., 2019). The functional unit is 'one year of transport usage + one year of stationary usage', with detailed quantifications of each usage (Cusenza et al., 2019). However, this introduces a new challenge as, the 1st life and 2nd life durations being different, the impacts of production and recycling now have to be allocated between these two functions.

A further approach is to perform only allocation of the production and recycling between first life and second life (Bobba et al., 2018; Cusenza et al., 2019) (see Fig. 5c). A functional unit is associated to each one. In these publications, the authors allocate the impacts in one case based on the energy delivered (Cusenza et al., 2019). In the other case, the impacts are 100 % allocated to the first life (Bobba et al., 2018).

Another approach is, instead of considering that the second life substitutes a dedicated battery, to evaluate credits compared to a situation without any stationary battery (Schulz-Mönninghoff et al., 2021).

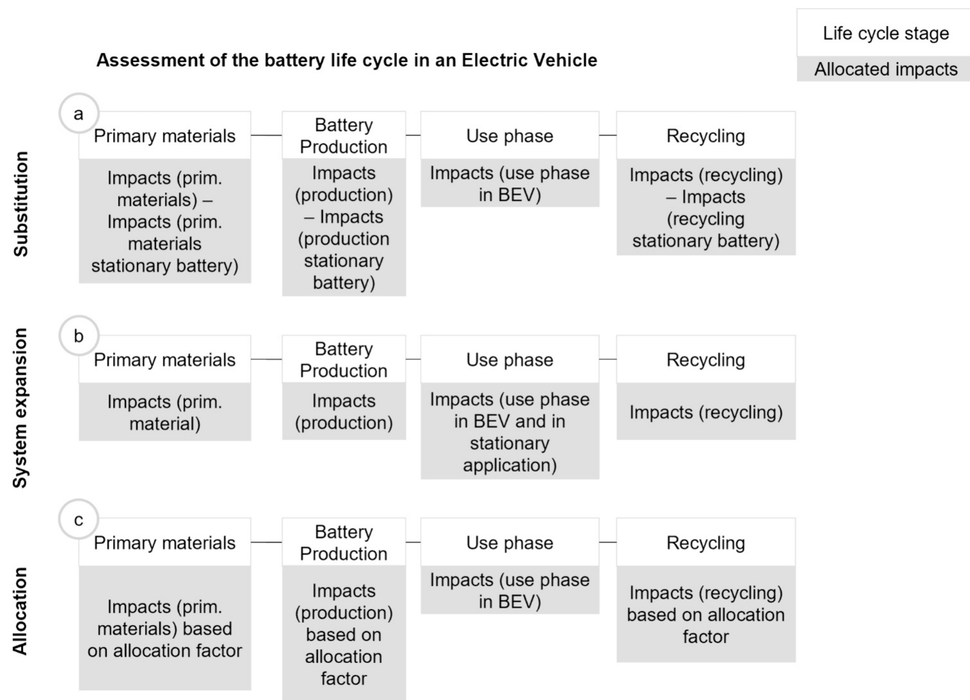


Fig. 5. Handling of multifunctionality on product level for the repurposing of the battery for use in a stationary application.

The use case for the stationary battery is therefore simulated in details, for example to determine how much electricity consumption from the grid is avoided.

To the best of the authors' knowledge, there is no LCA study on V2G from the perspective of the battery. Existing studies are taking a fleet perspective, which means that they will evaluate the potential environmental impacts of adding V2G to the grid, mostly with a prospective dimension (Xu et al., 2020; Zhao and Baker, 2022). To overcome the issue of multifunctionality, system expansion is often applied leading to functional units such as "'providing electricity and ensuring road transportation in 2050'" (Xu et al., 2020). The two functions of the battery are integrated and there is no need to allocate the impacts. As V2G is considered to degrade the battery quicker, the authors are calculating the number of batteries necessary to answer this functional unit. The impacts caused by additional battery production are allocated to the V2G. However, in these papers, the functional unit is not always clearly stated and the assumptions regarding how the first battery production is taken into account are not fully explained.

For battery swapping, there are no LCA studies available dedicated to one battery used with battery swapping. Existing studies focus on LCAs of a vehicle in a fleet where battery swapping is performed, studying also different charging strategies for the batteries (Finke et al., 2022; Yang et al., 2018; Zhao and Baker, 2022). The number of batteries needed over the vehicle's lifetime and the impacts of the battery production are allocated to the vehicle. Alternatively, one study was done taking into account the battery-swapping station perspective (Charoen-amornkitt et al., 2023), yet it only took into account emissions related to the energy needed to operate the station and charge the batteries. No impacts regarding battery production were allocated to the station. In all these cases the functional unit is not related to the battery itself.

3.3.3. *Further analysis and reflections*

Various approaches exist to model second life. None of them is fully satisfying. The dominant approach considers the substitution of an avoided stationary battery, some consider credits compared to a situation without any stationary battery, and the last approach allocates production and recycling between the two life phases.

Substitution has two shortcomings: it is not clear how the reduced lifetime of the refurbished battery compared to the avoided battery is taken into account, and the two scenarios compared do not immobilise the same quantity of materials during the stationary phase, as the refurbished battery has lost part of its capacity.

All approaches including allocation are extremely dependent on the allocation factor chosen. One suggestion (Cusenza et al., 2019) is the energy delivered, which is debatable because delivering energy onboard of a vehicle is much more valuable than on the ground. Other papers choose to allocate 100 % to the first life based on market considerations (Bobba et al., 2018), which is also debatable.

The substitution framework and the calculation of credits are heavily dependent on the choice of the counterfactual scenario: does the second life replace a fresh battery – and which one – or a scenario without a battery?

Some approaches fail to account for the shorter lifetime of a refurbished battery compared to a fresh stationary one, and some require the definition of allocation factors. But all of them fail to account for the fact that the very purpose of recycling is to make materials available again to the rest of the technosphere. They compare scenarios where different amounts of materials are immobilised for different durations during the stationary phase, which does not appear in any indicator.

For V2G and battery swapping, the current practice is to apply system expansion, including all uses in the functional unit. While this is scientifically robust, it does not allow the performance of comparative LCAs of batteries with or without V2G, with or without swap. Therefore, the approach is limited in its applicability and dedicated approaches including a battery functional unit still need to be developed.

3.4. *Material quality*

3.4.1. *Guidelines*

The definition of open- and closed-loop recycling in ISO 14044, based on changes to the inherent material properties implicitly, touches on the concept of material quality (International Organization for Standardization 14044, 2007). However, material properties or material quality are not further defined.

Material quality is mentioned in the PEFCR and the CFB-EV as part of the CFF. The CFF includes parameters for the quality of ingoing and outgoing secondary materials. These are both set in proportion to the quality of the primary materials. The quality ratios scale the environmental impacts of the in- and outgoing secondary material allocated to the assessed product. The default assumption in the PEFCR is that for metals and other materials the qualities are equal and therefore the ratio is 1. Only for plastics, the quality ratios are set to 0.9. The CFB-EV also defines default values for the material quality. The quality for the ingoing secondary materials and the primary materials equals 1 for all materials. The same quality is assumed. For the ratio of the outgoing secondary material and the primary material, the ratio is 0.8 for polymers and for metals salts and graphite from the cell. Neither of the guidelines specifies how the default values are developed and how they are supposed to be quantified. The GBA does not consider the topic of material quality at all.

3.4.2. Approaches discussed in the scientific literature

As part of the CFF, material quality of secondary material is integrated into the LCA. Besides that, no concepts on how to consider material quality specific for LCAs of batteries and battery materials exist. Direct substitutability is normally assumed for recycled battery materials. Therefore, the avoided burdens method is also frequently used in the assessment of recycling processes by showing the environmental impacts of the process and the given credits for avoided primary production.

The topic of material quality is discussed on different levels in scientific literature, also focusing on different sectors. Viau et al. performed a review of substitution modelling in the case of municipal waste treatment which shows that substitution is not properly defined for the waste streams (Viau et al., 2020). Metal waste streams are also part of the analysis. In this context, the only prerequisite for substitution is the assumed equal quality (Viau et al., 2020).

Besides this review, there are publications focusing on defining the concept of material quality (Tonini et al., 2022) or possible material quality indicators (Roithner and Rechberger, 2020; Vadenbo et al., 2017). Tonini et al. address the lack of definition of quality in the context of recycling, without limiting it to any specific sector (Tonini et al., 2022). They state that in LCA the concept of quality is often understood as the effective substitutability of primary material by secondary material (Tonini et al., 2022). In general, different concepts of quality exist in literature. Some of them are linked to the quality of the materials and others to the quality of the process. Tonini et al. present an extensive review of these concepts and how they relate (see Fig. 6), which also shows that no common understanding of material quality exists and that it highly depends on the sector and material (Tonini et al., 2022).

Roithner and Rechberger for example use statistical entropy as a measurement for purity and integrate this into recycling rates to reflect quality (Roithner and Rechberger, 2020). They correct the quantitative mass balance to qualitative balances with purities based on entropy (Roithner and Rechberger, 2020). The concept is applied in a case study of plastic packaging recycling.

Rigamonti et al. develop a 5-step method on how to calculate the technical substitutability of primary materials by secondary materials in a standardised way (Rigamonti et al., 2020). The first step is to identify the function of the secondary and the primary material. Next, the technical property most relevant to the key function of the materials is identified and quantified. Lastly, the technical substitutability is calculated as the ratio of the technical property of the secondary material and the primary material (Rigamonti et al., 2020). The concept itself is not specific to any materials. For some materials such as wood, paper or plastic, substitutability coefficients are provided.

Vadenbo et al. also propose a framework to calculate the substitution potential. In their framework, substitutability is used to express the functional equivalence between secondary and primary materials (Vadenbo et al., 2017). Functional equivalence means that two products are considered (at least partly) interchangeable alternatives to fulfil a specific function. This is also reflected in the concept of avoided production in LCA. Market-based approaches aim to represent how displaced production depends on the dynamics of supply and demand instead (Vadenbo et al., 2017). The concept is not developed for a specific material. Demets et al. extend the concept focusing on the technical substitutability for plastics (Demets et al., 2021).

These are all possible indicators that could quantify material quality and could be used as an extension of LCA. However, none of the authors provide a direct link on how to include material quality in the LCA. Roosen et al. suggest an approach to quantify the quality of recycling by building upon and combining already existing approaches. The framework is composed of three dimensions: the virgin displacement potential, the in-use stock's lifetime and environmental impacts. The virgin material displacement potential then contains four parameters: the economic viability, the technical suitability for substitutions, the recycling rate and the market weight (Roosen et al., 2023). The authors hereby show an example of how aspects of material quality (as virgin displacement potential) can be integrated into one approach with LCA.

3.4.3. Further analysis and reflections

While the approach of Roithner and Rechberger focuses more on process comparison, entropy as a measurement of purity could also be applied to batteries. This application is limited by the fact that entropy would only give one number for the purity of a material. But it is also important to identify which impurities are present since not all of them have a negative influence on the material, some even enhance the material properties (Zhang et al., 2020).

The 5-step approach of Rigamonti et al. could also be used to define material quality indicators for batteries with the main challenge of identifying the most relevant technical properties and which technical substitutability ratios would be acceptable for battery materials.

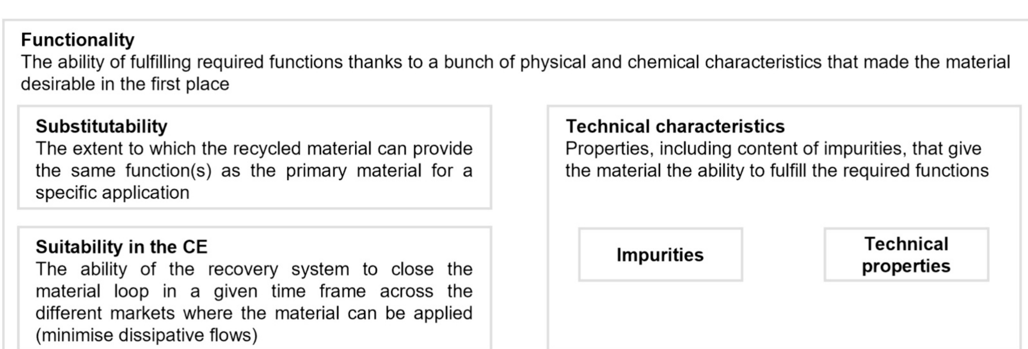


Fig. 6. Contextualisation of criteria for material quality (Tonini et al., 2022).

Roosen et al. are the only ones to show an example of how aspects of material quality (as virgin displacement potential) can be integrated into one approach with LCA. The framework focuses again more on the process but could be adapted to compare primary and secondary material supply chains rather than evaluating recycling alone. However, the approach aggregates the results into one final value. This can be seen critical since a lot of details of the assessment are then not properly reflected.

None of the described concepts has been applied to the case of batteries and battery recycling. To apply any of these approaches to the LCA of battery raw materials, a clear understanding and definition of material quality aspects for these materials is needed, including discussions on how to quantify these values.

3.5. Resource indicators

3.5.1. Guidelines

The GBA and the CFB-EV focus on carbon footprint and greenhouse gas emissions. The PEFCR has a broader scope and includes 18 impact categories. Resource use is expressed with abiotic resource depletion (ADP, ultimate reserves) based on the CML LCIA method.

3.5.2. Approaches discussed in scientific literature

ADP (Guinée et al., 2002; van Oers et al., 2002) has long been widely implemented by LCA practitioners but only finds limited consideration in the context of EV batteries regardless of the highly recognised relevance of resource indicators (Dolganova et al., 2020; Mikosch et al., 2022). This method is in particular recommended by the United Nations Environment Programme (UNEP) Life Cycle Initiative, in the context of the Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM2), for assessing the relative contribution of a product system to the depletion of mineral resources (Berger et al., 2020).

However, ADP is disputed concerning a number of its key aspects (Beylot et al., 2024; Cusenza et al., 2019). Accessibility to, and dissipation of, mineral resources, instead of their potential depletion, has recently been under focus in the development of new methods to address impacts on mineral resources in LCA. Beylot et al. defined dissipative flows (or "*losses*") of mineral resources as "*flows to sinks or stocks that are not accessible to future users due to different constraints*" (Beylot et al., 2020, p. 6). Dissipative flows "*negate circularity*" (Charpentier Poncelet et al., 2022a, p. 1). Dewulf et al. pointed to six human activities which compromise the accessibility of resources, with some of them contributing to dissipation; namely, emitting to the environment, landfilling, disposal of tailings, abandoning, hoarding, and downcycling (Dewulf et al., 2021).

Building on this scope and terminology related to accessibility and dissipation, several methods have been proposed (see Table 5). The rationale of these methods, and their pros and cons as well as the resource flows to which the CFs apply have been extensively discussed in (Beylot et al., 2024).

3.5.3. Further analysis and reflections

Beylot et al. (2024) highlighted that the JRC-LCI method combined with JRC-LCIA, and the ADR and LPST endpoint methods, are relevant to address the damage to "the potential to make use of the value that mineral resources can hold for humans in the technosphere"; i.e. the damage to the safeguard subject for mineral resources as defined by (Berger et al., 2020; Beylot et al., 2024, p. 12). Similarly, the CTI-LCIA (Contribution to Inaccessibility – LCIA (Dewulf et al., 2024)) and EVDP (Economic value dissipation potential (Santillán-Saldivar et al., 2023)) methods also capture the economic value lost, or rendered more or less accessible, along the life cycle of products. Recalling that circularity strategies aim at preserving the value of resources in the economy, these methods may accordingly be fit-for-purpose for what regards the assessment of the benefits and impacts induced by circularity strategies on mineral resources.

So far, compared to extensive implementation of the ADP method in contexts of very diverse sectors, there has been limited application of the more recent accessibility- and dissipation-based methods to case studies; though with notable application to the life cycle of EV batteries, including comparison and discussion of circularity strategies (Dewulf et al., 2024; Lai and Beylot, 2023; Santillán-Saldivar et al., 2023). In their study of the life cycle of a lithium-ion battery for EVs, Lai and Beylot (2023) implement the JRC-LCI method and compare three EoL scenarios, respectively considering current, conservative and optimistic future recycling performance. They identify the EoL and other losses in upstream life cycle stages as mineral resources dissipation hotspots, in mass terms. They note that this differs from the traditional LCA approach building on the ADP method, which focuses on extraction at the mining stage, and on credits gained from recycling. New methods, such as the JRC-LCI method, may accordingly be considered key to support more resource-efficient decision-making for the life cycle of EV batteries, in particular for what regards their EoL. Dewulf et al. (2024) moreover test the CTI-LCIA method considering the same case study. They observe that future scenarios involve substantial changes, from losses in the current situation and future conservative scenario to gains in the future optimistic scenario. These quantified gains reflect the larger accessibility of the resources after this life cycle compared to the initial state, thanks to relatively extensive recycling at EoL in the optimistic scenario. Moreover, Santillán-Saldivar et al. (2023) test the EVDP CFs in a case study on a lithium-ion battery recycling process through hydrometallurgy. They quantify the overall benefit in terms of recovered value attributed to metal recovery (i.e., savings in losses due to dissipation) per kilogram of treated battery. They particularly point to the substances with the largest contribution to the benefit of the studied recycling process. Other dissipation- and accessibility-based methods have so far not been applied to case studies relative to batteries in the electromobility sector.

Table 5
Methods for resource indicators related to accessibility and dissipation.

	Average Dissipation Rate (ADR) and Lost Potential Service Time (LPST) (Charpentier Poncelet et al., 2022b)	Environmental Dissipation Potential (EDP) (van Oers et al., 2020)	Abiotic Resource Project (ARP) (Owsianiak et al., 2022)	Joint Research Centre – Life Cycle Inventory (JRC-LCI) (Beylot et al., 2021)	Joint Research Centre – Life Cycle Impact Assessment (JRC-LCIA) (Ardente et al., 2023)
The main concept of the approach	Service time of resources	Severity of emissions to environment (= dissipative flows)	Classification of flows to the environment as dissipative or not	Reporting of dissipative flows	CFs derived from prices of minerals
Resource flows to which characterisation factors apply	Resources from ground	Emissions to environment	NA	NA	Dissipative resource flows as in JRC-LCI

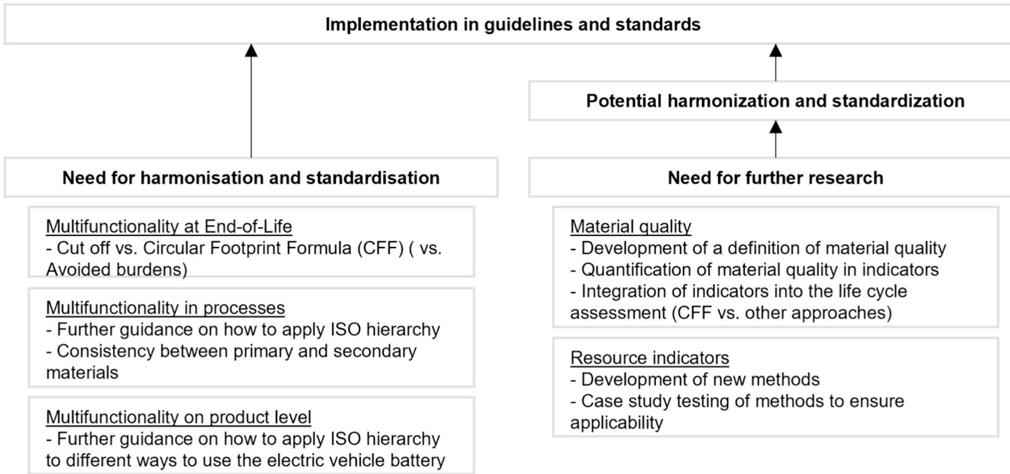


Fig. 7. The way forward to fill existing gaps in battery guidelines

4. Discussion

The analysis in this publication shows that existing guidelines have several gaps regarding the modelling challenges linked to the circularity strategies of EV batteries. The state-of-the-art research is, for several topics, not reflected in the guidelines, as the update of guidelines typically cannot keep up with the speed of research. For some topics, harmonisation and standardisation are needed while for other modelling topics, there is still a need for more research (see Fig. 7).

4.1. Need for harmonisation and standardisation

The challenges around multifunctionality are in need of harmonisation and standardisation. Guinée et al. described the challenges around dealing with multifunctionality as follows: "*There is no 'correct' way of solving the multifunctionality problem, even not in theory. There are, however, demands one can make to solving this problem, like that solution should be consistent in itself, and that it should be consistent with main methodological principles.*"(Guinée et al., 2004, p. 33).

For the handling of multifunctionality at the EoL and the multifunctionality of processes, harmonisation and standardisation is needed. For EoL situations, different approaches exist. The strengths and weaknesses of these are discussed in several publications and also the effects of choosing one allocation approach or the other are addressed in the literature (CEA and BRGM, 2023; Husmann et al., 2023a; Šimaitis et al., 2023). What is needed is harmonisation and standardisation between the methods – especially between legislations and common practice in research and industry. While the CFF is implemented in the PEF and the CFB-EV, the current literature and also some guidelines start favouring the cut-off approach (Global Battery Alliance, 2023; Husmann et al., 2023a; Šimaitis et al., 2023). In the case of the CFF, further guidance on the parameters used in the formula and how to quantify them will be needed (CEA and BRGM, 2023). The CFF also includes some elements of substitution for primary materials through secondary materials. Therefore, the approach on how to choose these substituted processes also should be harmonised.

The concepts and approaches on how to solve multifunctionality in processes mostly focus on raw material production. Recycling has for a long time only been assessed from a process perspective where the multifunctionality was mostly solved with system expansion (Husmann et al., 2023b). Now, it is more and more seen and modelled also as a production process for secondary materials, e.g., in (Abdelbaky et al., 2023; Ali et al., 2024; Machala et al., 2022), which is necessary when modelling the EoL allocation with cut-off or the CFF. A lot of the challenges and concepts developed for the multifunctionality in primary materials production are transferable to the recycling – e.g., the limited applicability of system expansion as well as capturing the driver of processes with the allocation factors, as shown in Section 3.2 and in (Husmann et al., 2023b). Here, the main focus should also lie on harmonising existing concepts and finding a common approach to handle the multifunctionality in the production processes of primary and secondary materials. This harmonisation could be based on the ISO standard and provide additional guidance for the case of battery materials, by describing under which circumstances which step of the ISO hierarchy is applicable.

For the multifunctionality on the product level, such as, the use in a BEV and in a second application afterwards, or, different ways to use the battery with V2G or battery swap, standardisation in handling them from a battery-centred perspective is needed. This includes guidance on when to use system expansion and when to use allocation. Furthermore, standardised and consistent allocation factors are needed.

An open question for the solving of multifunctionality challenges is, whether there should be one single approach to solve all situations of multifunctionality or if more case-specific rules are needed. In the state-of-the-art research, we see at least two different approaches: one for handling the multifunctionality at EoL and the other for handling the multifunctionality in processes during the life cycle and on product level. For the EoL, special approaches are developed such as the cut-off approach or CFF (Allacker et al., 2017; Ekvall et al., 2020; Nordelöf et al., 2019) while for the multifunctionality in processes and on product level, subdivision, system expansion and allocation are used (Bobba et al., 2018; Lai et al., 2021; Santero and Hendry, 2016). It has to be agreed on whether the harmonisation and standardisation shall overarch all situations of multifunctionality or shall be situation-specific.

4.2. Need for further research

To be able to consider the material quality properly in guidelines and standards, several aspects are missing, including in particular: i) a clear definition of material quality for battery materials, and ii) a mapping of the functionalities of the secondary battery materials and the associated technical characteristics. Based on this, the quality of secondary materials can be quantified and translated into substitutability between primary and secondary materials. When the material quality is properly defined and quantified, this can be further integrated into LCAs – e.g., by providing accurate default values for the CFF or as an additional indicator besides assessed impact categories as shown in Roosen et al. with the virgin displacement potential (Roosen et al., 2023).

The resource indicators as well as considering material quality in the LCA are in need of more research before a standardisation can be reached. For the resource indicators, current guidelines and standards often focus on the GWP or include older indicators such as the ADP. In research, ADP is slowly being replaced by new resource indicators. Different methods have been and are still being developed (Beylot et al., 2024). First case studies in the context of electromobility already exist. Further aspects shall be tested and discussed in case studies:

- the focus on dissipative flows to the environment in EDP, e.g., regarding the contribution of emissions from wear off/corrosion during the use phase, like tyres, breaks etc., compared to other dissipative emissions along the whole life cycle of the system, from extraction to EoL;
- the influence of current EoL recycling rates used in the quantification of the service time of resources to further derive the ADR and LPST CFs, i) compared to potentially larger EoL recycling rates in the future (e.g., conservative and optimistic future recycling performances in Lai and Beylot, 2023), and ii) compared to potentially diverse EoL recycling rates in the LCI modelling.

A harmonisation and standardisation of the newly developed methods will be necessary in the future. The new methods also need to find their way into current LCA software and standard LCI databases (Beylot et al., 2024).

4.3. Limitations

The review focused on the five LCA modelling challenges based on the topics which are currently in focus with regard to the circular economy and circular economy strategies of EV batteries. The implementation of circular concepts and business models is still ongoing and faces challenges such as no common understanding of the “value” of products and materials which is to be maintained (Vulsteke et al., 2024). With the further development of circular economy concepts and business models, new LCA modelling challenges might arise. Nevertheless, the five identified and treated challenges already cover a broad diversity and the insights might be transferable to the further implementation of circular economy strategies as handling multifunctionality might apply to more situations in the circular life cycle of an EV battery and resource indicators are not directly related to a circularity strategy.

Besides further challenges that might become relevant in the future, current challenges which are linked either to the LCA of EV batteries or the circular economy of EV batteries were excluded. This was for example toxicity indicators or material criticality. In future work, the scope of the challenges in the context of EV batteries, LCA modelling and circular economy should be broadened to achieve an even more holistic approach.

5. Conclusions

Comprehensive and standardised guidance is relevant to provide comparability between LCA studies performed by different stakeholders. This is increasingly important in the context of the upcoming mandatory environmental footprint labelling of batteries on the European market. Introducing circular economy for EV batteries comes with five key LCA modelling challenges:

i)- iii) handling the multifunctionality at the EoL, in the processes of secondary material production as well as the multifunctionality on product level,

iv) accounting for different material qualities in circular supply chains.

v) defining resource indicators which represent the loss of materials.

Various gaps in current guidelines and standards were identified regarding these key modelling challenges which should be further addressed considering the state-of-the-art research to enable a transparent and consistent modelling of battery life cycles. While multifunctionality at EoL (i) and in processes (ii) are addressed in all guidelines, the multifunctionality on product level (iii) is not considered. For the multifunctionality at EoL and on the process level, the guidance provided by the guidelines is also not well aligned and leaves some open points in the application. State-of-the-art research could be identified for all challenges linked to the handling of multifunctionality and standardisation is now required. A guiding question for the harmonisation could be whether different multifunctionality challenges should be handled with the same approach or if case-specific approaches (e.g., for EoL, for processes, for products) are better to represent the different decision contexts.

Material quality (iv) is mentioned in some of the guidelines but not with the required level of detail. There are also still several research gaps to fill. This includes defining material quality clearly in the context of batteries, developing accordingly material quality indicators and developing methods to integrate these into the LCA.

Resource indicators (v) are only considered in the PEFCR (with ADP). The state-of-the-art research shows, that new methods for resource indicators are currently being developed, with promising applications to the case of EV batteries life cycle. These need to be further tested and developed for any potential wider implementation. Depending on the method(s) chosen, an update of current LCA software and standard LCI databases would become necessary.

It is important to fill these gaps in guidelines and standards in the near to long term future to account for the true environmental and resource performance of circular economy strategies in the context of batteries and to reach the Climate Targets of the EU. While we focused our work on EV batteries, the implementation of circular economy strategies is relevant in a lot of sectors and various sectors rely on critical and strategic raw materials (Carrara et al., 2023). Especially LCA modelling of other complex products and systems, as part of the energy and mobility transition, will face challenges of handling multifunctionality, accounting for material quality and the use of appropriate resource indicators. The general way of handling these modelling challenges could and should be consistent between the different products and sectors to avoid double counting and burden shifting.

CRediT authorship contribution statement

Jana Husmann: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Antoine Beylot:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Fabien Perdu:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Marie Pinochet:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Felipe Cerdas:** Writing – review & editing, Supervision, Funding acquisition. **Christoph Herrmann:** Writing – review & editing, Supervision, Funding acquisition.

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.

Acknowledgements

The presented work was conducted within the TranSensus LCA project which was granted from the European Union’s Horizon Europe research and innovation program under Grant Agreement Nr. 101056715. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CINEA. Neither the European Union nor the granting authority can be held responsible for them.

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