MADITRACE

LCA methodology for primary and secondary flows

Deliverable 4.6

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Summary

This document provides methodological guidance for conducting life cycle assessments (LCAs) within the context of the CERA 4in1 certification system, facilitating compliance with the EU Battery Regulation and Critical Raw Materials Act and enhancing interoperability with other existing standards and guidelines. The guidance is tailored to the domain surrounding critical raw materials for energy applications, namely batteries and rare earth magnets. The guidance is classified into general aspects concerning the complete supply chain of batteries and magnets, and specific aspects concerning the supply chain of four key commodities: lithium, cobalt, natural graphite, and neodymium. The addressed aspects include considerations relevant to primary and secondary materials.

To develop this document, we first performed a focused literature review of a selection of European regulations, guidelines and standards. The main objective of the review was to ensure that the LCA methodology proposed in MaDiTraCe aligns with established LCA standards and guidelines to an optimal degree and to identify methodological areas of opportunity. The screened literature consisted of focused exploratory queries that were expanded with the input of an interdisciplinary group of experts. Many sustainability framework documents refer to the LCA thinking framework. However, we excluded most of these frameworks from the literature review because methodological guidance specific to LCA was out of their scope. We identified three significant areas of opportunity in the documents offering methodological guidance:

- Guidance on the assessment of raw materials in impact categories beyond climate change.
- Guidance on data collection.
- Guidance on addressing co-production and recycling

In response to these identified gaps, we proposed strategically expanding the selection of impact categories and elaborated on traceable and strategic data collection for life cycle inventories. Furthermore, we analysed the implications of several alternatives to address multifunctionality in co-production and recycling.

A comprehensive assessment would include several of the following impact categories: Climate change, Ozone depletion, Human toxicity (cancer and non-cancer effects), Particulate matter, Ionising radiation, Photochemical ozone formation, Acidification, Eutrophication (terrestrial, freshwater and marine), Land use and Water use.

The intended impact of this methodological guidance is to enhance the capability of organisations to comply with reporting regulations and conduct environmental impact assessments by streamlining the data collection efforts for confidential and public reporting commitments. Adopting this guidance may reduce the barriers for organisations to conduct LCAs and enhance standardisation efforts. These guidelines will be evaluated in D4.7 through case studies that involve the curation of baseline life cycle inventories.

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Keywords

Life Cycle Assessment; Mining; Recycling; Batteries; Permanent magnets; Lithium (Li); Cobalt (Co); Natural graphite; Neodymium (Nd); Sustainability standards; Traceability; Environmental performance; Critical raw materials; Stakeholder engagement; Environmental regulations.

Abbreviations and acronyms

Acronym	Description
AI	Artificial Intelligence
BESS	Battery Energy Storage System
CERA 4in1	CErtification of RAw Materials for sustainable development in mining
CF	Carbon Footprint
CFB	Carbon Footprint of Batteries
CFB-EV	Carbon Footprint of Batteries for Electric Vehicles
CFB-IND	Carbon Footprint of Batteries for Industrial Applications [JRC calculation rules proposal]
CFF	Circular Footprint Formula
CRediT	Contributor Roles Taxonomy
CRM	Critical Raw Materials
DLE	Direct Lithium Extraction
DPP	Digital Product Passport
DQR	Data Quality Rating
EF	Environmental Footprint
EoL	End of Life
EPD	Environmental Product Declaration
ESG	Environmental, Social, and Governance
EU	European Union
EV	Electric Vehicle
GBA	Global Battery Alliance
GHG	Greenhouse Gas
IEA	International Energy Agency
ILCD	International Reference Life Cycle Data System
ILiA	International Lithium Association
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
JRC	Joint Research Centre [European Commission]
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory

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LD	Linearly Degressive [allocation approach]
LIB	Lithium-Ion Battery
MRA	Multi-Recycling [allocation] Approach
NLP	Natural Language Processing
pLCA	Prospective Life Cycle Assessment
PCF	Product Carbon Footprint
PCR	Product Category Rules
PDF	Portable Document Format
PECFR	Product Environmental Footprint Category Rules
PEF	Product Environmental Footprint
PEFCR	Product Environmental Footprint Category Rules
REE	Rare Earth Elements
REO	Rare Earth Oxides
US EPA	Environmental Protection Agency, United States
WP	Work Package
WPA	Waste Price-based Allocation [approach]
WP	Work Package
LCA	Lyfe Cycle Assessment

1 Introduction

This document is the MaDiTraCe report D4.6 and provides methodological guidance for conducting life cycle assessments (LCA) within the context of the CERA 4in1 certification system[1]. The guidance is tailored to the domain surrounding critical raw materials for energy applications; namely **batteries** and **rare earth magnets**. In particular, it provides guidance general to the complete supply chain of these two applications (Section I) and guidance specific to the supply chain following four key commodities: **lithium, cobalt, natural graphite, and neodymium** (Section II).

MaDiTraCe's selected key commodities (herein after referred to as *selected commodities*) and products (batteries and magnets, herein after referred to as *selected products*) are critical and strategic to the European Union (European Commission, 2023a, n.d.).

The guidance addresses aspects related to the sourcing of the selected commodities that are relevant to their sourcing from mineral deposits (as **primary flows**) and to the implications of their recycling potential (as **secondary flows**).

We implemented the following highlights to facilitate the reading of this document:

Light blue boxes present recommendations.

Yellow boxes present terms, concepts, and any additional supplementary information. Note that the sources used for definitions do not necessarily represent an endorsement to the source.

1.1 Project context

The MaDiTraCe project aims to develop a set of tools for material traceability in the framework of due diligence regulations and the entry into application of the battery Digital Product Passport (DPP).

The certification system CERA 4in1, formerly conceived within the framework of a project funded by EIT RawMaterials, is under further development within the scope of MaDiTraCe (Erdmann and Franken, 2022; European Commission, 2023b). CERA 4in1 aims to ensure the tracking and responsible sourcing of mineral raw materials from primary and secondary sources. As such, its components cover the mineral value chain from exploration to the final product (Förster and Mischo, 2022).

Raw materials production induced environmental impact is one of the topics that due diligence regulations, DPPs and that CERA 4in1address.

Life cycle assessment (LCA) is a methodology to assess the potential environmental impacts of product systems and services throughout their entire life cycle, from the extraction of raw materials to end-of-life disposal (ISO 14040:2006).

LCA in the framework of the CERA4in1 is a recommended tool rather than a mandatory requirement. It is envisioned that the LCA methodology will support organizations in fulfilling some of the requirements of the CERA 4in1 standard, such as the definition, implementation and evaluation of objectives and strategies to manage the environmental

[1] **CE**rtification of Mineral **RA**w Materials for a sustainable development in mining (CERA 4in1).

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aspects related to their operations. By identifying hotspots across operations and the value chain, LCA provides useful data that supports better decision making, helping companies set goals, evaluate solutions, and track progress in various aspects; for example, **GHG emissions, water management, and air quality**. In order to comprehensively address sustainability aspects, LCA should be complemented with other frameworks and methodologies, e.g., risk assessments and Environmental, Social and Governance (ESG) frameworks.

1.2 Life cycle assessment and the European regulatory landscape

LCA has been widely applied to evaluate the environmental impacts of critical raw materials (CRMs) such as lithium (Schenker et al., 2022), graphite (Engels et al., 2022), cobalt (Rinne et al., 2021), and neodymium (Deng and Kendall, 2019), as well as their secondary production (Ali et al., 2024).

Previous research has highlighted a wide variety of methodological choices, assumptions, and data sources when conducting LCAs of CRMs and associated products, which substantially influence the LCA results. Achieving a harmonized and consistent LCA methodology and data collection approach is further complicated by the intricate supply chains, involving numerous production steps and actors dispersed globally. In practice, downstream actors in the supply chain often require LCA results from their suppliers to assess the impacts of new products. Consequently, there is a risk that LCA data exchanged among various actors may be based on varying assumptions for the same aspects, leading to inconsistencies.

The European Critical Raw Materials Act opens the door for future environmental footprint assessment requirements for CRMs placed on the Union market (European Commission, 2024). Furthermore, manufacturers, importers and distributors of batteries must provide information according to the EU Batteries Regulation (European Commission, 2023c), which concerns cobalt, lithium and natural graphite. Article 7(1) of the EU Batteries Regulation introduces mandatory carbon footprint declaration for each battery model per manufacturing plant, applying to EV batteries, rechargeable industrial batteries with capacity greater than 2 kWh and light means of transport batteries. The reporting obligations in these regulations aim to ensure compliance with sustainability and safety standards, promote transparency in the battery supply chain, and facilitate the transition to a circular economy.

The digital product passport (DPP) is an innovative solution for streamlining data exchange across supply chain actors. LCA data can be incorporated into the DPP, enabling downstream manufacturers to use more reliable data in assessing the environmental impacts of their products. The EU Battery Regulation establishes that a digital battery passport will be mandatory for certain batteries by 2027. Mandatory LCA-related data to be included in the digital battery passport include the battery carbon footprint and the breakdown of the battery carbon footprint per life cycle stage. Ongoing DPP initiatives focused on batteries, like the Battery Pass, stick to the carbon footprint requirements as per the EU Battery Regulation. Other impacts beyond climate change, such as acidification, eutrophication, human toxicity, or abiotic resource use, have also been suggested as potential attributes in the DPP (Berger et al., 2023). While the DPP can facilitate the exchange of LCA data, it does not directly address the challenge of methodological inconsistencies. In this context, sustainability standard systems could serve as a valuable tool.

Sustainability standard systems are designed to drive environmental, social, and governance (ESG) performance, showcasing that companies are operating responsibly. There are at least 11 standard systems addressing mining and related supply chains (Erdmann and Franken, 2022). These standards typically consider greenhouse gas (GHG) emissions, often stipulating generic requirements such as the identification and measurement of GHG emissions by the operating company, or adherence to widely accepted reporting standards like the Greenhouse Gas Protocol, implying a certain level of life cycle perspective (IRMA, 2023, 2018). While these requirements may encourage companies to monitor and report their GHG emissions, they may prove insufficient for consistently exchanging LCA data throughout the supply chain.

Combining the DPP with a standard system holds the potential to streamline the exchange of LCA data while ensuring it follows a harmonized and consistent methodology. In this scenario, the standard system could certify that the LCA data integrated into the DPP adheres to pre-defined LCA methodology rules that are specific to each product and production step. Moreover, the standard system should provide the LCA methodology that all actors in the supply chain must adhere to.

1.3 Existing LCA standards and guidelines

This section provides an overview of existing LCA standards and guidelines, both generic and specific for the selected commodities and products. The selection of the screened standards and guidelines consisted of a focused exploratory query that was expanded with the input of an interdisciplinary group of experts. Many sustainability framework documents referred to the LCA thinking framework. However, these frameworks were excluded from the literature review because of their lack of methodological guidance specific to LCA.

Rather than delving into the methodological specifics of each guideline—which will be covered in subsequent sections—this overview aims to map all applicable guideline documents (Figure 1).

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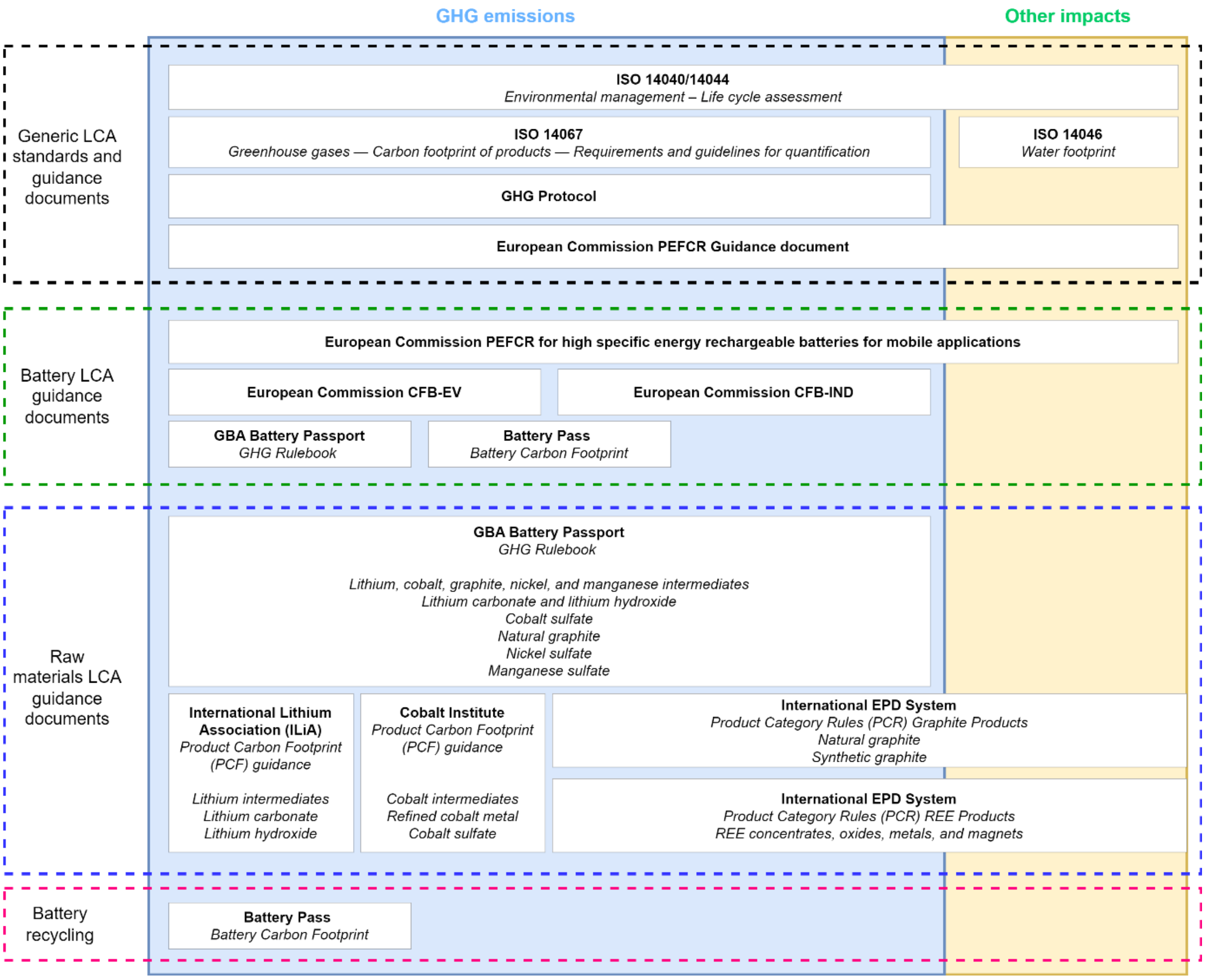

Figure 1: Overview of existing LCA standards and guidelines relevant to MaDiTraCe's selected commodities and products. See also Table 9 and Table 10 in **Appendix A.**

The basis of LCA is provided by the ISO 14040/14044 standards. The ISO also represents the basis of any other LCA guideline document. The International Reference Life Cycle Data System (ILCD) is an initiative by the European Commission-Joint Research Center (JRC) to enhance the consistency and quality of LCA (European Commission, 2010). In this regard, the Product Environmental Footprint Category Rules (PECFR) guidance relies on the ILCD but it is centred on providing guidance for specific product groups.

Several guideline documents have been developed to support the application of LCA to batteries. Notably, at the European Union level, the PEFCR for high specific energy rechargeable batteries provides the rules for conducting Product Environmental Footprint (PEF) studies. In the context of the EU Battery Regulation, the carbon footprint of batteries shall follow the PEF, PEFCR, and the battery-specific carbon footprint methodology specified in the delegated act.

LCA guidance for all the selected commodities (lithium, cobalt, neodymium, and natural graphite) has been provided to certain extent by one or several documents, yet with certain limitations.

Guidance for conducting carbon footprint assessment of lithium and cobalt products is provided in guideline documents published by the corresponding industry associations, namely the International Lithium Association (ILiA-PCF) (International Lithium Association,

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2024) and the Cobalt Institute (Cobalt Institute, 2023). These documents reflect a multistakeholder consensus involving manufacturers, LCA practitioners, academia, and more. Yet, the primary focus is on carbon footprint (i.e., climate change impacts), while omitting other environmental impacts.

Although these documents provide comprehensive guidance for applying LCA to lithium and cobalt product systems, their primary focus is on carbon footprint. Consequently, they may not comprehensively cover methodological aspects specific to other environmental impacts. Furthermore, in many instances in which other impact categories are evaluated, the scientific community has adopted diverse approaches rather than a common approach (e.g., the impact associated with water consumption in lithium production).

We identified three significant areas of opportunity in the documents offering methodological guidance:

- Guidance on the assessment of raw materials in impact categories beyond climate change.
- Guidance on data collection.
- Guidance on addressing co-production and recycling.

1.4 Scope of this document

This document provides methodological guidance on conducting LCA for the primary and secondary supply of MaDiTraCe's selected commodities (lithium, cobalt, neodymium, and natural graphite). The methodology spans from the mining and processing of mineral resources to the refining, production of selected products, and their recycling into secondary materials. The objective of the present document is to provide a harmonized and consistent approach for conducting LCAs in alignment with established standards and guidelines. Therefore, it builds on international standards and reference documents on LCA in general (ISO 14040, ISO 14044, ISO 14067, GHG Protocol, etc.) as well as on existing LCA guidelines and scientific literature specific to critical raw materials, batteries, and magnets (EC-PFCR for batteries, GBA Battery Passport, etc.).

This document seeks to identify and address gaps found in these established standards and documents, with particular emphasis on the life cycle inventory (LCI) data collection process. It explores potential synergies with sustainability standards to help fulfil LCI data requirements effectively. This document aims to facilitate compliance with the environmental footprint obligations established by the European Critical Raw Materials Act (European Commission, 2024) and the Batteries Regulation (European Commission, 2023c).

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Section I: General aspects concerning the complete supply chain

2 General LCA definitions and guidelines

2.1 Function, functional unit, and reference flow

The definition of the function, functional unit, and reference flow in LCAs of primary and secondary raw materials depends on the life cycle stages covered by the product system. For example, if the analysed product system includes only mining and concentration, the main function is concentrate production; if refining is included, it focuses on producing refined material; and if battery recycling, including recovery of secondary materials, is covered, the function may be the end-of-life battery management.

Terms and concepts: Function, functional unit, and reference flow

A **product system** is "*a set of unit processes interlinked by material, energy, product, waste or service flows*" (Guinée, 2002). In the context of LCA, every product system performs one or more defined **functions** by delivering one or more goods or services.

The **functional unit** describes "*the primary function(s) fulfilled by a product system and indicates how much of this function is to be considered in the intended LCA study*" (Guinée, 2002).

The **reference flow** is "*a measure of the outputs from processes in a given product system which are required to fulfil the function expressed by the functional unit*" (Guinée, 2002).

The different functions and products result in different functional units for each product system. LCAs focusing solely on the mining stage are uncommon, as mining and concentration stages are often vertically integrated. However, whether the output product is ore or concentrate, it is essential for the functional unit to encompass the characteristics of the product (Segura-Salazar et al., 2019). A common recommendation found in the literature is to define the functional unit of mining/concentration as "*one kg of metal contained in the respective material, further indicating the concentration of the metal*", such as "1 kg nickel in nickel concentrate, 7.5% nickel" (Global Battery Alliance, 2023; Segura-Salazar et al., 2019). Therefore, the functional unit for mining/concentration could be defined based on a unit mass of metal, the output product, and the metal concentration in the product. However, this approach may not be practical if downstream users have knowledge about the amount of concentrate used rather than the actual amount of metal required. Moreover, some concentrates may contain multiple valuable metals, such as nickel concentrate with significant amounts of both nickel and copper. Therefore, a more practical definition of the functional unit could instead focus on a unit mass of the concentrate combined with the concentration of its constituent metals (e.g., one kg nickel concentrate at 7.5% nickel and 3.71% copper).

For refined materials (e.g., lithium carbonate, lithium hydroxide, or cobalt sulphate), the iLiA-PCF mentions "1 kg of lithium carbonate 99.0% Li_2CO_3 (18.6% Li)" as an example of functional unit (International Lithium Association, 2024), while the Cobalt Institute shows as example "1 kg of cobalt sulphate heptahydrate; 21% Co" (Cobalt Institute, 2023). Both examples include some common terms, namely a unit mass of refined material, the refined product, the purity, and the metal content. In some cases, it is key to consider the hydrated form (i.e., lithium hydroxide monohydrate instead of lithium hydroxide) in the functional unit due to the water content.

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Box 1: **Definition of the function, functional unit, and reference flow**

The following steps should be followed to define the function, functional unit, and reference flow. First, the function(s) of the product system to be assessed must be identified. Secondly, the functional unit should be defined to reflect the function(s) of the assessed product system and should encompass the characteristics of the output product. The functional unit should include the following elements:

Ore/concentrate: ***amount of product + concentration of the valuable metals in the product***

Refined material: ***amount of product + refined material + purity + desired metal content***

Example of function, functional unit, and reference flow definition across different stages of the raw materials supply chain:

Stage	Main product	Primary function	Functional unit	Reference flow
Mining	Ore	To extract ore from underground or surface mines	1 kg of ore, specifying the concentration of the desired metal in the ore	Amount of ore required to deliver 1 kg of metal
Concentration	Concentrate	To produce a concentrate with a higher concentration of the target metal than the initial ore	1 kg of concentrate, specifying the concentration of metal in the concentrate	Amount of concentrate required to deliver 1 kg of metal
Refining	Refined metal	To produce a refined material ready to be incorporated into the production of new products	1 kg of refined product, specifying the purity and the metal content	

2.2 System boundaries

Terms and concepts: System boundaries and cutoff

The **system boundaries** define which life cycle stages and which unit processes are included in the analysed product system (European Commission, 2010). In theory, all unit processes and/or inputs/outputs should be included within the system boundaries. In practice; however, non-relevant life cycle stages, unit processes, and/or inputs/outputs are often omitted (i.e., they are cut-off).

The definition of the system boundaries is crucial in the context of data exchange across the supply chain. For an accurate assessment of the environmental impact of the system of interest, each actor in the value chain will require and use LCA data from their suppliers. To prevent potential double counting, intermediate products in the supply chain should be analysed from **cradle-to-gate**. Depending on the actor, the **gate** may represent the factory gate of the producer of the **intermediate product** that will be further processed by the next downstream actor, or the **final product** that will be further distributed to the final user. **Figure 2** illustrates the approach through the example of two companies involved in the natural graphite supply chain.

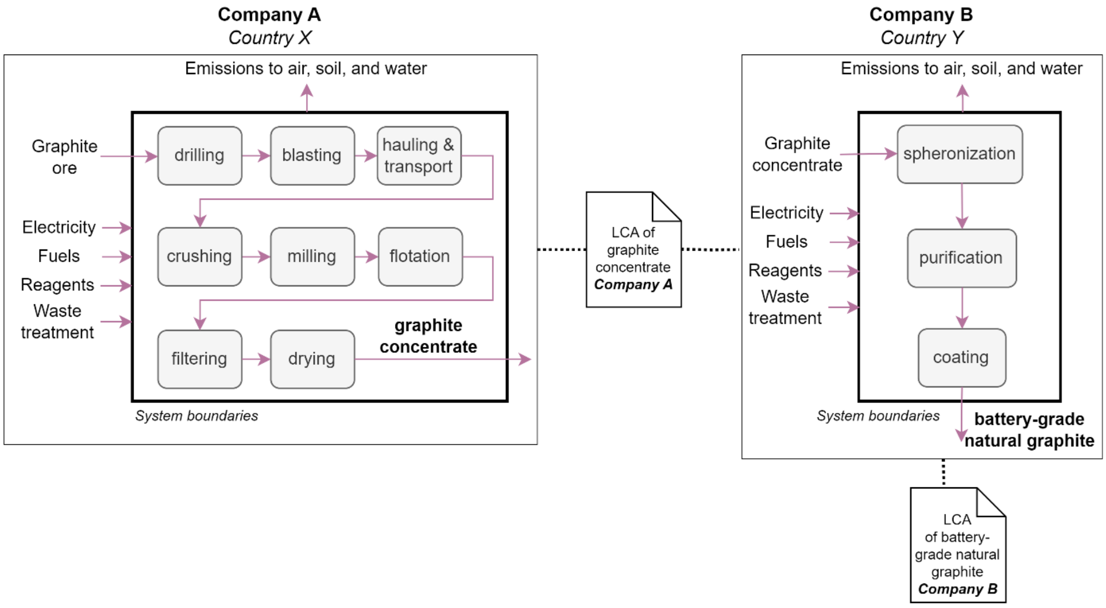

Figure 2: Example of system boundary definition for two companies involved in the natural graphite supply chain.

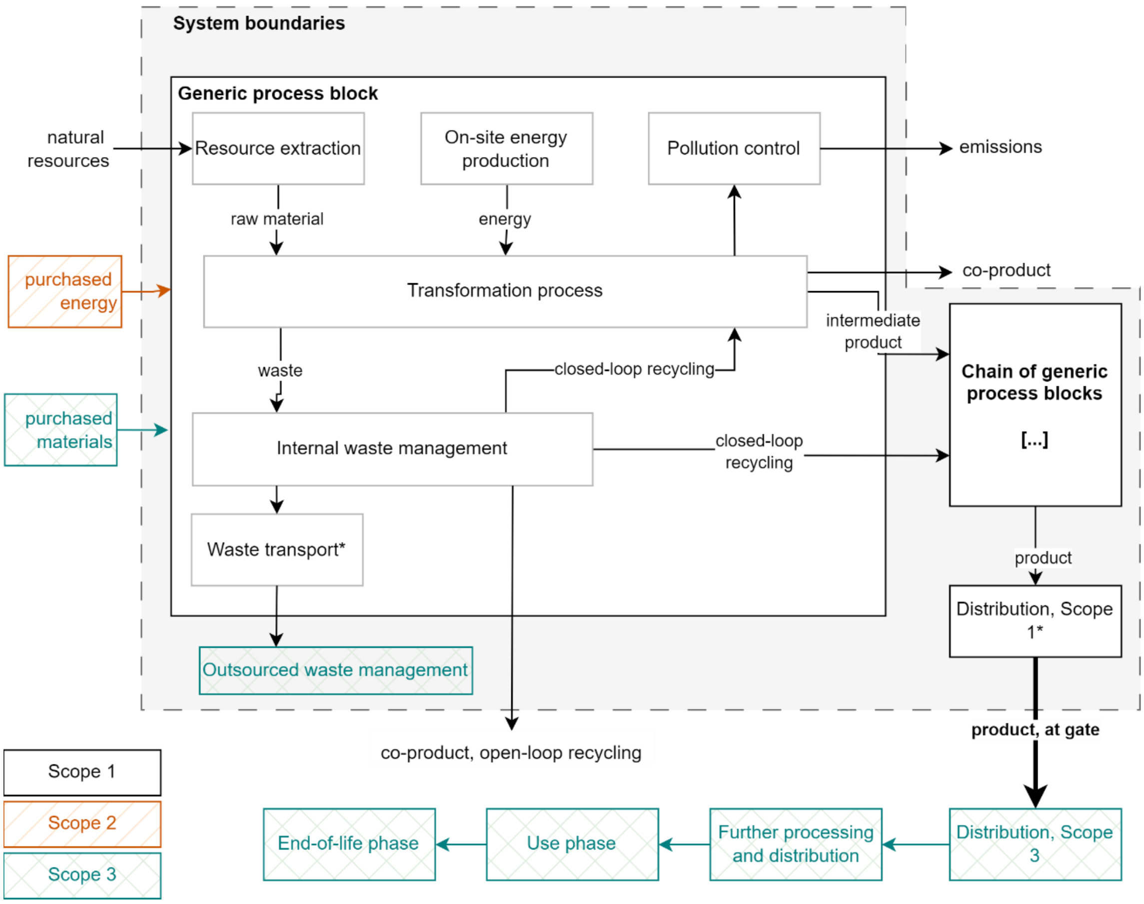

Figure 3: Generic flowchart of the cradle-to-gate system boundary defined per actor. *For some actors, all forms of Waste transport and Distribution belong to Scope 3.

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Box 2: **System boundaries definition**

The system boundaries for intermediate and refined materials should be defined as cradle-to-gate.

The cut off criterion could be determined based on the relative contribution to the overall environmental impacts (European Commission, 2010). However, determining the cut-off based on the contribution to the total impact requires estimating 100% of the impact, which is not straightforward. Alternatively, cut-off criteria based on the contribution to the total mass have been used.

The CF rules for the Battery Regulation state that "*a general cut-off of 1% in mass may be applied to material inputs per system component, by neglecting input and output flows that make up less than 1% to the total mass of the system component*". This cut-off can be applied to battery manufacturing processes as well as to upstream processes such as mining and concentration. This cut-off criterion differs from the one specified in the PEFCR for batteries, which states that "*a maximum of 3% of greenhouse gas emissions may be excluded across the processes (cumulatively over all processes)*". This cut-off criterion is also adopted in specific guidelines such as the GBA Battery Passport, ILiA-PCF, and Cobalt Institute PCF. Table 11 in **Appendix A** compares the cut-off rules in existing guidelines.

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2.3 Product systems of batteries and magnets

2.3.1 Batteries for electric vehicles

Figure 4 illustrates the system boundaries that shall be considered for LCAs of electric vehicle batteries. In alignment with the initiative supplementing Regulation (EU) 2023/1542 (European Commission Services, 2024), the stages and items with yellow background shall be included in the life cycle assessment of batteries for EV vehicles. The stage and items surrounded by dotted lines may be excluded from the assessment. If the stage and items that may be excluded in the assessment are included in the life cycle inventory model, the characterised results and inventory tables caused by these stage and items shall be reported separately.

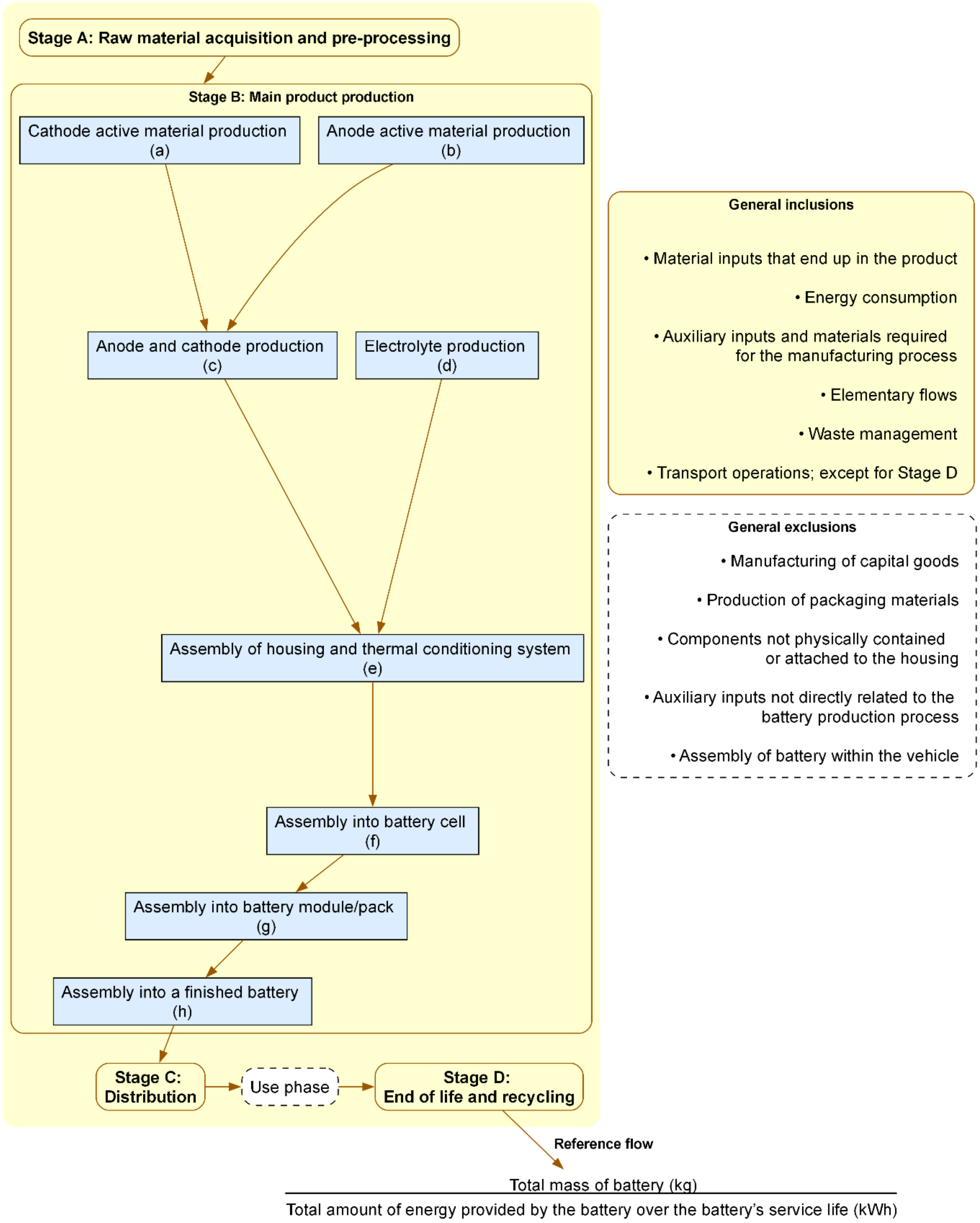

Figure 4: Flow diagram of the product system of an electric vehicle battery.

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2.3.2 Sintered magnets

Figure 5 illustrates the system boundaries that shall be considered for LCAs of sintered magnets. Drawing from the initiative supplementing Regulation (EU) 2023/1542 (European Commission Services, 2024) and combining with the PCR for rare earth products (EPD INTERNATIONAL, 2024a), the stages and items with yellow background shall be included in the life cycle assessment of NdFeB sintered magnets. The stage and items surrounded by dotted lines may be excluded from the assessment. If the stage and items that may be excluded in the assessment are included in the life cycle inventory model, the characterised results and inventory tables caused by these stage and items shall be reported separately.

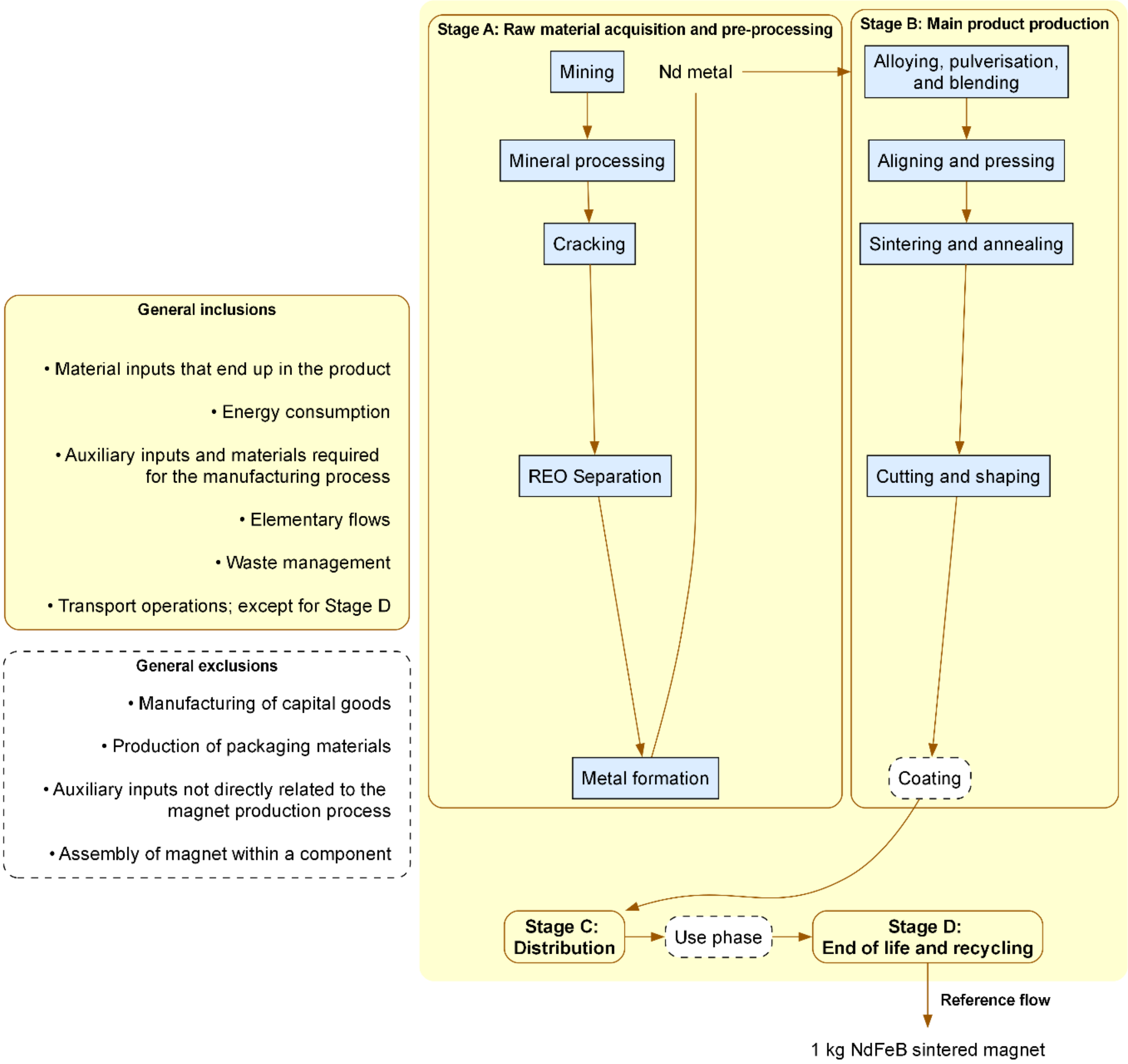

Figure 5: Flow diagram of the production of NdFeB sintered magnets.

Terms and concepts: Metal formation

It refers to the reduction of the rare earth oxide into its metallic form (EPD INTERNATIONAL, 2024a). For neodymium, this is mostly achieved through molten salt electrolysis (see Section 6.1).

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Neodymium oxide co-occurs with other rare earths in their mineral deposits. The mix of rare earth oxides (REOs) are separated through solvent extraction and precipitation. LCAs in scientific publications often assume that the distribution of separated REOs resembles to the composition of their original mineral deposits (Schulze et al., 2017; Vahidi and Zhao, 2017). The co-production of other rare earths is addressed in Section 6.2.1.

2.4 Life cycle inventory data collection

Data to be collected for each unit process includes economic and environmental inputs and outputs, such as energy and materials consumption or emissions of CO_2.

Definition of primary and secondary data

Primary data: Company-specific data. We can distinguish two primary data sources. First, data on processes run by the company conducting the LCA, and second, data on processes run by third parties in the supply chain and shared with the company conducting the LCA.

Secondary data: Data used to model a process that is not company-specific. This data may come from databases, literature, default emission factors from national inventories, calculated or estimated data, expert opinion, etc.

Primary data shall be prioritized over secondary data whenever reasonably available. As a general rule, there is a trade-off between the compilation of highly accurate data and the available resources for the data collection, as illustrated in **Figure 6**. When company-specific data is not available, secondary data can be compiled by using methods such as process simulation, process calculations, the modelling of the underlying thermochemical phenomena (e.g., based on stoichiometry or molecular structure models), or the use of proxies (Parvatker and Eckelman, 2019). Further guidance on the compilation of both types of data and the assessment of data gaps is presented in **Sections** 2.4.1 and 2.4.2.

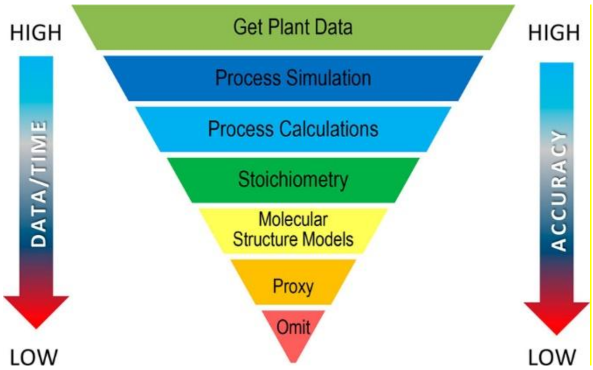

Figure 6: Methods for the compilation of LCI data. Reproduced from (Parvatker and Eckelman, 2019).

For estimation purposes, the transformation and source of both data types should be transparently reported. Furthermore, the suitability of the data for the purpose defined in the Goal and Scope phase should be addressed in the interpretation phase, based on the data quality.

2.4.1 Primary data

Primary data can be obtained directly from measurements or calculated based on measurements (Catena-X Automotive Network, 2023). Collecting primary data typically

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requires sourcing data from monitoring and control systems, which may involve continuous measurements of specific flows or tracking material transfers and energy consumption. Monitoring and control systems are often requirements of sustainability standards, while information on material transfers is usually addressed by chain of custody models. Therefore, a clear synergy exists between the data required for performing an LCA and complying with standard requirements, as sketched in **Figure 7.**

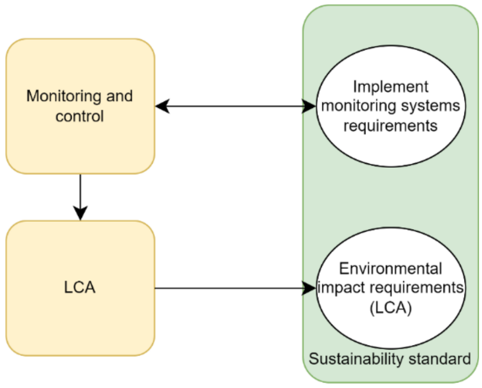

Figure 7: Data overlaps between LCA data collection and compliance with sustainability standards.

In practice, the company-specific data is not readily available in a format that can be directly used to draw the life cycle inventory. Therefore **Section 9.2** in **Appendix A** presents a protocol to guide the compilation of **primary data sources for Scope 1** and identify data gaps that may be strategically addressed. The protocol follows the classification and considerations presented in Table 1 regarding the difficulty of collecting Scope 1 data, given the monitoring and tracking systems already implemented by the relevant actor.

Table 1: Considerations for the classification and transparent reporting of Scope 1 data. The difficulty of collection is ranked as 1 (baseline), 2 (more difficult), and 3 (most difficult). Decision points, guiding questions, and recommended follow up actions are formatted in italics.

Classification	Sub-classification	Difficulty of collection
Primary data; Scope 1	Information that is already automatically tracked or measured.	1
Primary data; Scope 1	Information that will be measured with the sole purpose of performing the LCA.	2
Decision point	*Information that is not feasible to measure for the scope of the life cycle assessment. (Or information that is already automatically tracked but that will not be used because of company policies).*	
Primary data; Scope 1	• Acknowledgement and description of data that will not be measured	1
Decision point	• ***Will the impact be estimated?***	
Guiding question	• *If **the impact will not be estimated**, is there any evidence or information hinting that the goal of the LCA can still be met despite the exclusion of information?*	

Classification	Sub-classification	Difficulty of collection
Decision point	• *If there are* ***grounds for data exclusion****:*	
Primary data; Scope 1	• Report if the exclusion is based on company-specific data or policies	1
Secondary data; Scope 1	• Report if the exclusion is based on secondary guidelines or sources, such as scientific literature or in the context of widely accepted guidelines (refer to **Section 0**).	2
Follow up action	• *If there is* ***no evidence justifying the omission****, adjust goal and scope or report on the implications of the exclusion when assessing data quality or interpreting the results.*	
Secondary data	• If **the impact will be estimated**, report on the estimation processes and the data quality of the secondary data (see **Section 2.4.2**).	3

There are two intended results from following the protocol in **Section 9.2** in **Appendix A**. The first one is an inventory of the processes to be assessed, their connections, and the reach of Scope 1, all of which can be represented in a flowchart such as **Figure 3**. The second one is an extensive overview of the data sources available to account for the mass and energy flows that matches the resolution of the flowchart. Table 2 illustrates data categories and a non-extensive list of possible collection procedures

Table 2: Data collection procedures for Scope 1 processes.

LCI data category	Data collection procedures
Material inputs and outputs(wastes, emissions etc.)	• Company information system: purchase records, bills, stock inventories, emission records, waste and recycling reports,etc. • Bill of materials
Energy consumption directly and indirectly (electricity, heat, steam, etc.)	• Company information system: energy bills • Electricity consumption obtained from a monitoring system installed in the facility
Transport distances and means of transport	• Company information system: records of transportation
Process emissions from chemical reactions	• Monitored via measurements • Calculation: stoichiometric
Emissions from fuels combustion on-site	• Calculation: stoichiometric, based on fuels consumption (for CO_2)

Is data disclosed by an upstream or downstream actor also primary data?

Data disclosed by upstream or downstream actors belongs to Scope 2 or Scope 3. **Information concerning Scope 2 and 3 usually falls under the category of secondary**

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data. However, it could be the case that the data disclosed by an upstream or downstream actor fully or partially matches the criteria of primary data if it can be traced to a collection process of company-specific data where the disclosing actor collected primary data on their own processes. For example, if the upstream actor would follow the classification and considerations in **Table 1** and the data they would disclose fell under "Primary data; Scope 1" for their own system boundaries, then the actor receiving the data could consider that data as "Primary data; Scope 2" for their own purposes.

2.4.2 Secondary data

A major challenge is harmonising the secondary data sources used by the different actors throughout the supply chain. Strategies to harmonize secondary data include the provision of prescriptive secondary datasets or the definition of hierarchies of preferred secondary data sources. For example, the CF rules for the EU Battery Regulation provides specific requirements for the secondary data to be used in developing company-specific datasets. **Figure 8** illustrates the hierarchy of preference of secondary data sources in LCA guidelines.

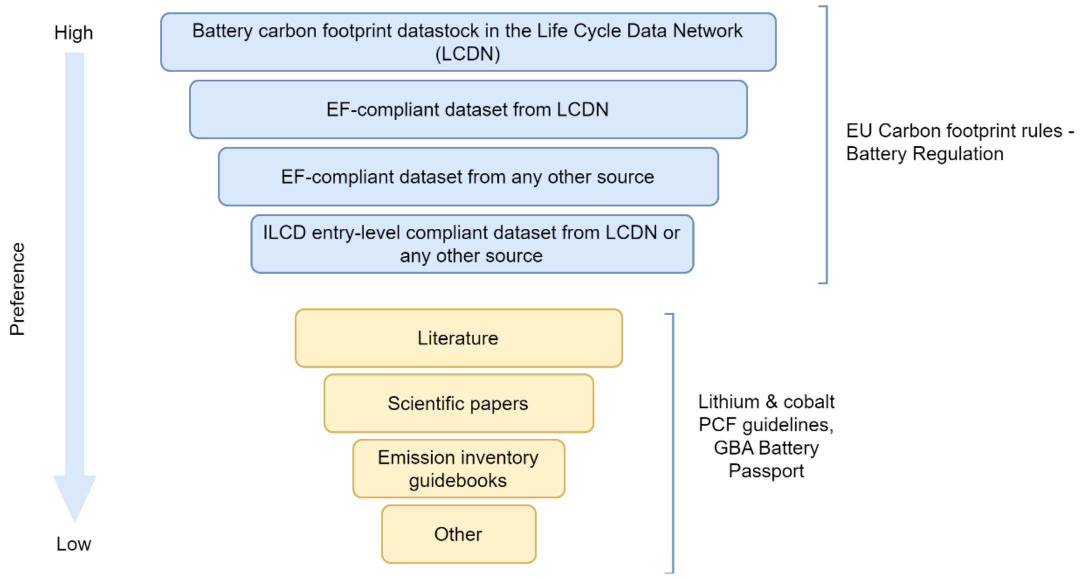

Figure 8: Secondary data sources hierarchy combining EU Battery Regulation and other LCA guidelines.

The hierarchy of preference in **Figure 8** is not explicit about the role of multiple actors in elaborating a life cycle assessment. When the secondary data originates from external actors such as suppliers, it is preferable that the suppliers provide the complete LCI dataset. When only characterised results are available, this should be explicitly reported.

A note on LCI databases

As of 13 May 2024, the GHG Protocol website listed a non-exhaustive list of 53 public (e.g., EPD library) or commercial databases (e.g., ecoinvent) that are available without the purchase of consulting services or licenses for specific software tools. The list includes search engines indexing LCI datasets from multiple providers, such as GLAD and Nexus. Furthermore, the European Platform on LCA lists nine nodes of public and paywalled LCI datasets that are compliant with the Product Environmental Footprint LCA method.

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By limiting the number of databases and versions from which secondary data is sourced, it is easier to ensure consistency among the various LCI datasets and their underlying assumptions. However, comparing the data from different sources is a means of validation. The trade-offs should be reasonably balanced, and the data-sourcing decisions should be transparently reported.

2.4.3 Electricity modelling

Electricity consumption is often a major contributor to environmental impacts in CRM supply chains (Nuss and Eckelman, 2014), such as in the production of batteries (Peters et al., 2017), or magnets (Wulf et al., 2017). Thus, accurately accounting for the impacts of electricity supply is essential in any LCA. Quantifying these impacts requires two key pieces of information: the amount of electricity consumed by a specific process (e.g., annual kWh of electricity) and the impact intensity of the electricity supply (e.g., impacts per kWh of electricity).

The impact intensity of electricity supply depends on how the electricity is generated and supplied. There are three main types of supply:

(i) on-site generation;
(ii) grid supply;
(iii) a combination of the two.

Moreover, companies may enter contractual agreements with renewable electricity producers via instruments such as Guarantees of Origin or Renewable Energy Certificates, which allow claiming ownership of renewable electricity, even when it is not generated on-site. The modelling of this approach is considered separately.

On-site electricity generation

On-site electricity generation refers to producing electricity directly at the location of the consuming facility. This can be achieved through fossil fuel generators and renewable energy technologies (e.g., wind turbines or solar panels), among other options (see the box below). On-site electricity generation is particularly common at mining sites located in isolated areas without direct access to the power grid (Igogo et al., 2021). Moreover, the growing transition to renewable power generation technologies across mining, refining, and manufacturing facilities is likely to further drive reliance on on-site electricity generation.

On-site electricity generation options

There are three main options for on-site electricity generation: (a) using fossil fuel-based generators, such as diesel generators; (b) renewable power generation technologies combined with a battery energy storage system (BESS) to ensure dispatchability; and (c) renewable power generation technologies combined with a fossil fuel generator as a backup. The environmental impacts associated with these options arise both from the electricity generation activity itself (e.g., emissions from burning diesel) and from background activities, such as the manufacturing of renewable energy technologies or diesel generators.

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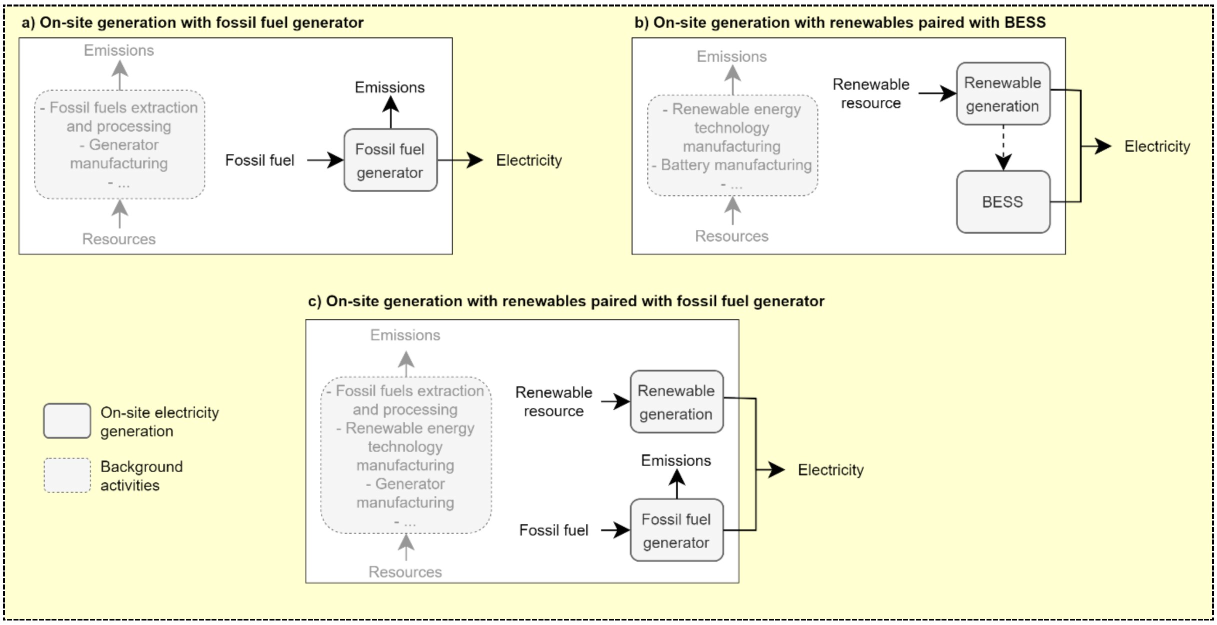

The approach for calculating the environmental impacts of on-site electricity generation varies depending on the generation option:

- **Electricity is generated on-site with fossil fuel generators.** Impacts should be calculated using the annual fuel consumption (e.g., MJ of diesel consumed by the generators) in combination with:
  - **Emission factors**: GHG emissions from fossil fuel combustion can be estimated using either the carbon content of the fuel or default emission factors (e.g., from the IPCC guidelines). The impacts associated with the supply chain of the fuel should be accounted for by using the corresponding LCI dataset (e.g., a LCI dataset representing the diesel supply chain obtained from a background LCI database). This modelling approach is recommended in various product carbon footprint guidance documents, including those for lithium (International Lithium Association, 2024), cobalt (Cobalt Institute, 2023), as well as the GBA GHG Rulebook (Global Battery Alliance, 2023).
  - **Background LCI datasets**: Environmental impacts can also be estimated by considering a background LCI dataset representing the electricity production activity (e.g., using a LCI dataset for electricity production via a diesel generator from a background LCI database). This approach can be more suited for assessing other impacts beyond climate change (for which emission factors might not be available).
- **Electricity is generated on-site with renewables combined with a BESS.** Renewable electricity supply (e.g., from solar or wind) is used in combination with a battery energy storage system (BESS) to ensure dispatchability by storing electricity generated during periods of excess resource availability and discharging as needed. Impacts should be calculated considering the annual amount of electricity directly supplied by the power generation technology and the amount of electricity supplied through the BESS in combination with:
  - **Background LCI datasets**: Representative LCI dataset for the supply chain of the renewable power generation technology and the BESS.
- **Electricity is generated on-site with renewables combined with a fossil fuel generator.** Renewable electricity supply (e.g., from solar or wind) is used in combination

with a fossil fuel generator which acts as a backup. Impacts should be calculated considering the annual amount of electricity directly supplied by the power generation technology and the annual amount of fuel consumed by the fossil fuel generator (based on the most recent internal data). These amounts should be combined with proper emission factors and/or background LCI datasets as described in the previous points.

In all cases, it is important to base the annual consumption of fuel or power generation on the most up-to-date internal data available. Similarly, the selection of background LCI datasets should reflect the latest version of the chosen LCI database. To ensure accuracy, this may require annual updates, incorporating newly available internal data and updated background databases (e.g., ecoinvent typically releases a new version each year).

Certain special situations related to on-site electricity generation warrant attention:

- **On-site generation with contractual instruments**: When electricity is generated on-site, but a portion is sold to a third party (e.g., through renewable energy certificates), the impacts of electricity consumption should be modelled using the corresponding grid mix (see below for details). This recommendation is found in multiple guidelines, including the PECFR (European Commission, 2018), cobalt PCF document (Cobalt Institute, 2023)
- **On-site generation exceeds demand**: A multifunctionality situation may arise if the amount of electricity generated on-site exceeds the demand, and the exceeding electricity is sold to the grid (European Commission, 2018). This is because the product system provides multiple functions, namely, producing the product, producing electricity and supplying it to the grid. There are various recommendations on how to deal with this:
    - Approach A: Account only for the impact of the equivalent amount of electricity used on-site. Therefore, no credits shall apply for the electricity exported to the grid. This approach is adopted, e.g., in the carbon footprint of EV batteries rules within the EU Battery Regulation.
    - Approach B: Apply subdivision if possible, or substitution if not considering that the extra electricity would avoid an equivalent amount of electricity supplied by the country-specific residual electricity mix. This approach is indicated in the PEFCR.

Grid supply

Electricity can be sourced from the national electricity grid if the production site is connected to it. When modelling electricity supply from the grid, there is often a choice between using the consumption electricity mix or the residual electricity mix (see the box below for definitions) (Holzapfel et al., 2023). Existing LCA guidelines recommend prioritizing country-specific residual electricity mixes where available. If these are not available for the country under study, country-specific consumption electricity mixes should be used instead (European Commission, 2018). In cases where neither option is available, a supra-national consumption electricity mix, such as the EU grid mix, may be considered.

Consumption vs residual electricity mix

Consumption electricity mix: The consumption electricity mix corresponds to the average mix considering all the electricity consumed within a country over a period of time.

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Residual electricity mix: The residual electricity mix is equal to the consumption mix but excludes the electricity that has been claimed via certificates.

The environmental impacts associated with electricity sourced from the grid (either consumption or residual mix) can be estimated by considering the annual amount of electricity consumed based on internal data combined with:

- **Emission factors**: Emission factors for national electricity grids (e.g., in kg CO_2-eq per kWh of electricity) are typically provided by various sources, including the International Energy Agency (IEA).
- **Background LCI datasets**: LCI dataset representing the country-specific residual/consumption electricity mix can be obtained from background LCI databases. This approach can be more suited for assessing other impacts beyond climate change (for which emission factors might not be available).

The annual electricity consumption from the grid must be based on the most up-to-date internal data available, while the emission factors or background LCI datasets for the grid mix should reflect the latest version.

On-site electricity generation combined with grid supply

If electricity is sourced from both on-site generation and the grid, impacts from both sources should be accounted for based on their specific contribution to electricity consumption. On-site electricity generation should be equal to the total electricity demand less the amount of electricity sourced from the grid.

Electricity via contractual instruments

Existing LCA guidelines specify that electricity supply via contractual agreements can only be considered if certain minimum criteria are met to ensure the reliability of the contractual instruments. The relevant criteria outlined in the European Commission's PEFCRs for such agreements are: 1) conveying attributes, 2) ensuring a unique claim, and 3) aligning closely with the time period of application (European Commission, 2018). The criteria are based on the GHG Protocol Corporate Standard and are widely adopted in other LCA guidelines, such as the PCF guidance document for cobalt (Cobalt Institute, 2023) or lithium (International Lithium Association, 2024). If the contractual instruments do not meet the mining criteria, then the electricity supply from the grid mix, as described in the previous section, should be considered (European Commission, 2018). As such, we recommend adhering to the aforementioned PEFCR criteria when carrying out an LCA that includes electricity supply via contractual agreements.

2.4.4Data quality assessment

Data quality refers to aspects that determine the quality of inventory data and, in turn, the accuracy of the LCA results. It encompasses how effectively the data represent the product system being assessed. ISO 14044 outlines key aspects of data quality, including representativeness and precision, as well as methodological consistency, data sources, and reproducibility. The ILCD Handbook defines six **data quality criteria**: technological representativeness, geographical representativeness, time-related representativeness, completeness, precision, and methodological appropriateness and consistency (European Commission, 2010). Four of these criteria are adopted in the PEF, namely technological representativeness, geographical representativeness, time representativeness, and precision/uncertainty (European Commission, 2018). Catena-X PCF recommends evaluating five data quality indicators: technological representativeness, geographical representativeness, temporal representativeness, completeness, and reliability. Other LCA guidelines relevant to the selected commodities and products have varying data quality requirements and assessment criteria, often derived from these established frameworks (see Table 12 in Appendix A). These approaches may differ in their scope regarding data quality evaluation; some focus on datasets, while others may pertain to individual input/output flows and/or final LCA results. Users of the GBA Battery Passports must meet certain data quality requirements, yet no quantitative assessment of data quality is required (Global Battery Alliance, 2023). Moreover, industry-specific product carbon footprint guidelines (e.g., for lithium and cobalt) do not specify data quality requirements, but they refer to general standards.

Definition of data representativeness criteria

The following definitions of data quality criteria are based on the ILCD Handbook (European Commission, 2010):

Technological representativeness: The characteristics of a technology have a large influence on its environmental performance. Therefore, inventory data must reflect the specific attributes and operational conditions of the technology. However, technology-specific data is not always readily available, resulting in the use of proxies. In this context, the technological representativeness criterion evaluates how accurately the data used (both within the foreground and background systems) represents the actual technology being assessed.

Geographical representativeness: The geographical location determines the conditions under which a process or technology operates (e.g., the type of technologies used or the electricity mix), thus affecting its environmental performance. The geographical representativeness criterion evaluates how accurately the data used matches the geographical scope according to the goal of the study.

Temporal representativeness: Technologies and their performance evolve over time, making relying on outdated inventory data risky. The absence of up-to-date data often requires the use of older data when building an LCI. The temporal representativeness criterion evaluates how well the data used reflects the technology's performance at the declared time relevant to the goal of the study.

The assessment of data quality criteria/indicators often employs a **pedigree matrix approach**, assigning scores from 1 to 5 (sometimes from 1 to 3) to each indicator, where 1 represents the highest quality, and 5 indicates the lowest quality. The exact definitions of these scores can vary slightly across guidelines. For example, in the PEF's approach, a score of 1 is assigned to technological representativeness if the data is "measured/calculated and verified", while a score of 5 applies if "rough estimates with known deficit" (see Table 38 in the PEFCR guidelines by the European Commission, 2018). Catena-X PCF assigns a score of 1 to technological representativeness if data is "measured from the production technology under study" and a score of 3 if "data is approximated from similar production of the company under study" (see Table 7 in Catena-X Automotive Network, 2023).

The assessed data quality criteria can be used to calculate a **data quality rating (DQR)** for each dataset as well as for the final LCA results. For example, under the EU Battery

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Regulation, a DQR shall be calculated for the declared battery carbon footprint based on three data quality indicators: technological representativeness, geographical representativeness, and time representatives (refer to Table 2 in Regulation (EU) 2023/1542 for the evaluation criteria). The DQR for the declared carbon footprint can be determined by calculating the arithmetical mean of the scores for these three criteria.

The data quality requirements and assessment criteria can vary widely depending on the followed LCA guidelines. The recommendation here is to apply a data quality assessment considering various data quality indicators and focusing on the dataset level.

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Box 3:**Data quality requirements and assessment**

A data quality assessment shall be reported following a semiquantitative approach (e.g., the pedigree approach) and evaluating various data quality indicators (e.g., technological representativeness, temporal representativeness, etc.). The specific recommendations according to different situations are:

Situation A: Existing LCA guidelines are followed, and the guidelines require data quality assessment

If existing LCA guidelines are followed (e.g., Catena-X PCF), including a data quality assessment system based on various data quality indicators, the results of this assessment should be reported accordingly, and its application should be documented transparently.

Situation B: The LCA guidelines followed do not require data quality assessment, or no guidelines are followed

If the LCA guidelines followed do not include a data quality assessment system, or if no other guidelines are applicable, a data quality assessment should be conducted based on an alternative established data quality system. The following list shows existing LCA guidelines containing comprehensive data quality assessment system that could be implemented: ILCD Handbook, PEF, EU Battery Regulation, Catena-X PCF

In both situations, the process of data quality assessment involves the following steps:

1- **Select a data quality assessment system**: Choose the followed system based on an existing LCA guideline document (depending on the situation).
2- **Assess data quality criteria**: Assign score to each criterion (e.g., technological representativeness, geographical representatives, etc.) for all the datasets directly used in the LCA model. Scores are assigned using a pedigree matrix provided in the chosen LCA guidelines.
3- **Calculate datasets contribution to total impacts**: Determine each dataset contribution to the total impact in a specific impact category c, as follows:

$$s_{i,c} = \frac{intensity_{i,c} \cdot activity_i}{impact_c}$$

where $s_{i,c}$ is the percentage contribution of dataset i to the total impact in category c, $intensity_{i,c}$ is the impact intensity of dataset i in category c (i.e., impact per unit of output), and $impact_c$ is the impact per functional unit in category c.

4- **Calculate the DQR for each criterion**: Compute the DQR for each one of the criterions as the weighted average of the quality scores and the percentage contributions of the datasets, as follows:

$$DQR_{q,c} = \sum_i score_{q,i} \cdot s_{i,c}$$

where $DQR_{q,c}$ is the data quality rating for criterion q (e.g., technological representatives) in the impact category c and $score_{q,i}$ is the quality score assigned to criterion q for dataset i.

5- **Calculate the overall DQR**: The overall DQR for the product system's impact in an impact category c is the average of the DQR values across all criteria. For

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example, if three criteria are considered (technological representativeness, geographical representativeness, and time representatives), the DQR is calculated as:

$$DQRtot_c = \frac{TeR + GeR + TiR}{3}$$

where TeR, GeR, and TiR represent the quality rating of the criteria of technological, geographical, and time representativeness

Note that the calculation of the overall DQR is specific to each impact category because the contribution of datasets varies across categories. In this regard, the recommendation is to perform this analysis at least for the climate change impact category.

2.5 Multifunctionality

A process is multifunctional when it provides more than one function, i.e., the process delivers several goods and/or services (or simply co-products) (European Commission, 2010). In an LCA the interest is typically in only one of the co-functions. Therefore, the process inputs and outputs of the specific function need to be isolated. This (i.e., solving the multifunctionality) can be achieved using different approaches. Existing guidelines generally differ in their recommendations for solving multifunctionality.

2.5.1 Co-production

A key difference in the recommended approach for addressing multifunctionality due to co-products lies in whether system expansion via substitution is advised. LCA guidelines like the GBA Battery Passport, Cobalt Institute-PCF, and ILiA-PCF prefer system expansion via substitution over allocation, except in the case of metal co-production. In contrast, the EU Battery Regulation CF methodology does not allow the application of substitution and the consideration of credits. These approaches are compared in Table 13, in the **Appendix A**.

2.5.2 Process waste treatment

Several guidelines address the potential co-production derived from waste treatment address (see open-loop recycling in Figure 3). Two main approaches emerge from the guidelines compared in Table 3. One is to consider the potential co-product as burden free (also known as the polluter pays) and the other one is to allocate credits from the (potential) recovered energy or co-product.

Table 3: Approaches for solving multifunctionality due to waste treatment adopted in existing LCA guidelines.

Guideline	Approach
CX-PCF Rules	The system boundaries shall include the full environmental impacts from the treatment of waste. Any energy or product from waste should be treated as burden-free.
PEFCR Batteries	Circular footprint formula
CFB-EV	Circular footprint formula
ILiA-PCF	System boundaries shall include waste incineration and landfilling and wastewater treatment. Possible credits from energy recovery substituting regional grid mix or heat from natural gas or sludge used as a fertilizer substituting synthetic fertilizer (if a third-party can verify the economic value of the by-product).

Guideline	Approach
EPD guidelines (valid for the PCR graphite products and the PCR for REE products)	System boundaries shall include the full environmental impacts from waste treatment until the point where the end-of-waste criteria are fulfilled. The end-of-waste criteria include the use of the recovered material or a positive economic value. There is a distinction between co-product and waste allocation and (see section A.4 in EPD INTERNATIONAL, 2024a). While the potentially benign environmental impacts of energy and material recovery or open-loop recycling can be modelled and declared, these should be reported separately and should be excluded from any form of aggregated results (see section A.7 in EPD INTERNATIONAL, 2024a).
PCF guidance for cobalt	System boundaries shall include waste incineration and landfilling and wastewater treatment. Possible credits from energy recovery substituting regional grid mix or heat from natural gas or sludge used as a fertilizer substituting synthetic fertilizer (if a third-party can verify the economic value of the by-product).

Box 4:**Modelling waste treatment**

The European Commission favours the use of the Circular Footprint Formula when modelling waste treatment, as described on the PEF method (European Commission, 2021; European Commission Services, 2024). If the CFF is not applied, the recommendation is to follow the "polluter-pays" principle, thus allocating the full environmental impacts from process waste treatment to the generator of the waste. No credits are allocated from recovered energy or products.

2.5.3 Recycling

The European Battery Delegated Act mandates that most batteries, including electric vehicle batteries, containing cobalt, lithium, or nickel in their active materials must provide documentation specifying the percentage of these materials sourced from recycled origins, either through recovery from battery manufacturing waste or post-consumer waste (European Commission, 2023c). The regulation also establishes phased minimum recycled content targets for these materials in battery active materials:

- By 2031, batteries must contain at least 16% recycled cobalt, 6% recycled lithium, and 6% recycled nickel.
- By 2036, these targets increase to 26% recycled cobalt, 12% recycled lithium, and 15% recycled nickel.

In addition, the European Critical Raw Materials Act sets the way for establishing potential minimum recycled content requirements for neodymium in permanent magnets (European Commission, 2024). These requirements emphasize the necessity of considering recycling processes of those materials and their contributions into the LCA of batteries and permanent magnets.

Numerous LCA studies have explored the environmental impacts associated with recycling processes (Gaines, 2018; Hao et al., 2017; Kallitsis et al., 2022) . However, the findings of these studies often vary significantly due to differences in modelling approaches, system

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boundaries, geographical contexts, and data inputs (Domingues and De Souza, 2024). A particularly contentious issue in these assessments is the choice of allocation methods, as recycling—similar to co-product production—interacts with multiple product systems and introduces complexities related to the multifunctionality of processes (Du et al., 2022).

The definition of the goal and scope in an LCA plays a pivotal role in determining the selection of modelling approaches for end-of-life recycling processes (Domingues and De Souza, 2024). Moreover, while modelling end-of-life processes in the foreground is inherently challenging, it is generally more straightforward than addressing their consideration in background processes, which present a higher level of complexity (Andreasi Bassi et al., 2021).

Additional challenges emerge when evaluating the recycling of materials or products that have not yet been recycled or when recycling technologies are still in the early stages of development or implementation (Moni et al., 2020). These scenarios often require the application of prospective LCA (pLCA) methodologies, which rely on assumptions about future technological advancements and market developments (Heiho et al., 2023; Raugei and Winfield, 2019). While pLCA offers a forward-looking perspective, it also introduces additional uncertainties and modelling challenges (Cerdas et al., 2024).

Despite the significance of addressing these complexities associated with end-of-life recycling processes, most existing standards and guidelines fail to provide sufficient guidance in this area (Ekvall et al., 2020). This limitation is compounded by significant divergence in the recommendations provided by these guidelines, particularly regarding the allocation of burdens and benefits of recycling processes (TranSensus LCA, 2023). These inconsistencies highlight the absence of a universally accepted approach for modelling end-of-life processes, and the production of secondary materials derived from recycling. In this context, several approaches have been identified (Du et al., 2022; Husmann et al., 2024), including:

Circular footprint formula (CFF): Part of the updated Product Environmental Footprint (PEF) guidelines (European Commission, 2021), the CFF method is applicable to all type of product recycling. It considers market supply and the demand balance of different recyclable materials with the aim to reflect market realities and tendencies.

Cut-off approach: Excludes the second use of recycled materials from the analysis. Environmental burdens are allocated exclusively to the initial lifecycle, with no credits given to waste streams containing recyclable materials. Secondary raw materials are only assigned the environmental burdens associated with their collection and recycling. This approach is commonly applied in scientific literature and recommended by the GHG protocol.

End-of-life (EoL) recycling approach: System expansion method considered in ISO 14044. Material recovery is explicitly modelled, expanding the system to include the co-functions of the process or product. When incorporating the consideration of the recycling process, the associated environmental burdens can be offset by reducing the demand for primary material production. Closed-loop recycling assumes the material is reused multiple times, with the final life cycle bearing the burden of unrecyclable material.

Waste price-based allocation (WPA): Allocates environmental impacts based on the economic value of recyclable materials and primary products. Higher-value recyclable materials are assigned a larger share of the burdens. Needs of stable market prices for its consistent application.

50:50 approach: Equally divides the environmental burdens and benefits of recycling between the product's current life cycle and the next. This method can be presented as a compromise, sharing responsibility between the producers of recyclable materials and the users of recycled content. While rarely recommended in formal guidelines or standards, it is occasionally applied in practice (Saner et al., 2012).

Multi-Recycling Approach (MRA): Focuses on material pools rather than individual products, distributing burdens across multiple life cycles based on material losses and recyclability. For cascading systems, an extended version accounts for primary material inputs alongside recycled content. Although rarely included in formal standards or guidelines, it is occasionally referenced in scientific literature (Mengarelli et al., 2017).

Linearly Degressive (LD) Method: Distributes the impacts of primary production and disposal across life cycles in a linearly decreasing manner. Recycling process burdens are split equally between adjacent life cycles, with the first cycle bearing the most primary production impact and the last cycle absorbing disposal impacts. While not included in formal standards, this method is discussed in scientific literature (Malabi Eberhardt et al., 2020).

Table 14 in **Appendix A** summarizes the formulas for each allocation method discussed. Table 4 provides a comparative overview of the allocation approaches based on qualitative criteria, offering insights into their strengths and weaknesses. This analysis aims to aid in understanding their applicability and limitations, given the current lack of consensus on which approach is most suitable for modelling recycling processes.

Table 4: Comparative analysis of allocation approaches based on qualitative criteria

Criteria	**CFF**	**Cut-off**	**EoL Recycling**	**WPA**	**50:50**	**MRA**	**LD**
Feasibility	Challenging, dependent on market data and supply-demand	Easy to implement, requires minimal data	Moderate, requires robust data for recycling and avoided impacts	Moderate, requires economic data for market value	Easy, relies on simple numerical allocation	Challenging, needs detailed lifecycle and material loss data	Challenging, relies on accurate lifecycle tracking
Harmonization in Application	Moderate, offers flexibility for balancing recycled and recyclable content	High, commonly used but inconsistent boundaries	Moderate, harmonized for some closed-loop applications	Low, application depends on market stability	High, simple and widely understood	Low, not widely adopted yet	Low, limited practical examples available
Intended life cycle coverage	Balances supply chain inputs and outputs	Limited to primary lifecycle	Covers both primary and secondary lifecycles	Considers market effects on recycling incentives	Covers adjacent lifecycles	Focused on material pools rather than individual products	Broad, spans multiple lifecycles with linear allocation
Clarity/Example of	Moderate, requires	Clear, straightfor	Clear for closed-	Less clear, examples	Straightforward,	Complex, few	Complex, evolving

reference case studies	parameter customization	ward examples available	loop scenarios, less so for open-loop	rely on specific market systems	examples often cited	examples difficult to generalize	examples for open-loop scenarios
Risk of Double Counting	Low, allocation parameter balances burdens	Low, system boundaries prevent overlap	Low for closed-loop, moderate for open-loop	Low, economic value helps distribute impacts	Moderate, simplified allocation can cause errors	Low, focuses on material pools, not specific products	Moderate, risk of inconsistency in lifecycle tracking
Prospective LCA (pLCA)	High, explicitly accounts for market trends	Limited, not forward-looking	Moderate, adaptable for future recycling processes	Moderate, depends on future market projections	Limited, static allocation method	High, aligns with material lifecycle trends	Moderate, aligns with evolving recycling scenarios

No single method achieves high performance across all the criteria outlined in Table 4. The results highlight a trade-off between accuracy and ease of application or communication among the methods. For example, the CFF method captures relevant aspects but is complex to implement, whereas the 50:50 approach is simpler to apply but has notable limitations in its considerations. Table 4 offers a structured way to evaluate these trade-offs, though the criteria are not sufficient to identify a definitive method, making it difficult to advocate for one approach over the others.

Box 5:**Solving multifunctionality in recycling**

The European Commission favours the use of the CFF in the modelling of recycled content and EoL phase, as described on the PEF method (European Commission, 2021; European Commission Services, 2024).

2.6 Impact assessment

In the **impact assessment phase**, the elementary flows computed in the inventory analysis phase are translated into potential environmental impacts through a set of characterization factors. A wide range of **impact categories** can be assessed by employing a variety of **impact assessment methods**. It is worth noting that climate change is not the only important impact to be assessed. One of the goal of LCA is to avoid burden shifting from one impact category to another (e.g., situations in which climate change impact reduction increases human toxicity). In order to avoid misleading decision making and to follow the ISO standards, all relevant and assessable impact categories should be included.

Box 6:**Impact assessment**

Best practice is to report on the full list of EF impact categories. A selection of the most relevant impact categories depending on the context might be more feasible. Within the context of the EU Battery Regulation, only the carbon footprint is mandatory. For battery studies, climate change, particulate matter, freshwater ecotoxicity, minerals and metals resource use, and water use should be reported as they are the most relevant categories.

However, it is difficult to determine which impacts are relevant for what life cycle stages before undertaking a comprehensive LCA study. Moreover, the relevance of impacts across the supply chain may vary depending on technological choices. The 'International Environmental Product Declaration (EPD) System' uses a default list of eight impact categories, including climate change, acidification, eutrophication, photochemical ozone creation, ozone depletion, minerals and metals depletion, fossil resources depletion, and water use. Within the European context, the Environmental Footprint (EF) methods recommended by the European Commission includes a list of 16 impact categories (Table 5). Studies relevant to the United States should use the latest version of TRACI, an impact assessment methodology by the US EPA. Overall, the best practice is to assess the full list of EF impact categories. However, pragmatically it might be more feasible that a selection of the most relevant impact categories are included initially (BMWK, 2023).

In the scope of the PEFCR for batteries, the most relevant impact categories were identified of being climate change, freshwater ecotoxicity, resource use fossils, resource use minerals and metals, and particulate matter. In contrast, the metal and mining industry recommended five impact categories based on the availability of LCI data that contributes to them and on the maturity of their characterisation methods (Santero and Hendry, 2016a). The impact categories recommended by the metal and mining industry are climate change, acidification, eutrophication, photochemical oxidation and ozone depletion. Both sets of recommendations are mapped to the impact categories of the EF 3.1 method in Table 5.

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Table 5: Impact categories assessed in the EF 3.1 method (Andreasi Bassi et al., 2023) and their inclusion in selected approaches

Impact category EF3.1	**Unit**	**EU Battery Regulation**	**Most relevant PECFR batteries** (RECHARGE, 2023)	**Metal & mining industry recommendations** (Santero and Hendry, 2016b)	**PCR for metal products** (EPD INTERNATIONAL, 2023, 2024b)
Climate change	kg $CO_{2\ eq}$	Yes	Yes	Yes	Yes
Ozone depletion	kg CFC-11$_{eq}$	-	-	Yes	Yes
Human toxicity, cancer	CTUh	-	-	-	-
Human toxicity, non-cancer	CTUh	-	-	-	-
Particulate matter	Disease incidence	-	Yes	-	-
Ionizing radiation, human health	kBq U^{235}	-	-	-	-
Photochemical ozone formation, human health	kg $NMVOC_{eq}$	-	-	Yes	Yes
Acidification	mol $H+_{eq}$	-	-	Yes	Yes
Eutrophication, terrestrial	mol N_{eq}	-	-	Yes*	Yes
Eutrophication, freshwater	kg P_{eq}	-	-	Yes*	Yes
Eutrophication, marine	kg N_{eq}	-	-	Yes*	Yes
Ecotoxicity, freshwater	CTUe	-	Yes	-	-
Land use	Dimensionless (pt)	-	-	-	-
Water use	m3 world eq. deprived water	-	-	-	Yes
Resource use, minerals and metals	kg Sb_{eq}	-	Yes	-	Yes
Resource use, fossil	MJ	-	Yes	-	Yes

*Note: Santero and Hendry (2016) don't specify a compartment for eutrophication.

2.7 Methodological choices not addressed in this document

This document offers guidance on various methodological choices, focusing on three phases of the LCA framework: Goal and Scope Definition (sections 2.1, 2.2 and 2.3), Inventory Analysis (sections 2.4 and 2.5), and Impact Assessment (section 2.6). The topics addressed in this document overlap to some extent with the key points covered by the relevant LCA standards and guidelines related to the value chain of the selected commodities being processed into the chosen products. The compilation of guidelines identified addressed the Interpretation phase mostly by referring to the selection and assessment of data quality (see section 2.4.4).

The guidelines provided in this document will be evaluated in D4.7 through case studies that involve the compilation of baseline life cycle inventories. D4.7 will refer to a specific recommendation or methodological discussion in D4.6. It is expected that the results of D4.7 will make further needs on guidance more evident.

Section II: Commodity-specific aspects

3 Lithium

3.1 Product system

Battery-grade lithium carbonate and lithium hydroxide are currently produced mainly from continental brines and hard rocks (mainly spodumene ores). Production from geothermal brines and clay ores is still in an early stage of development (IEA, 2024).

Brine-based production can vary significantly depending on the brine's chemical composition, especially the levels of impurities like boron, magnesium, and calcium. However, the product system generally involves four major steps: brine extraction and concentration, brine purification, carbonation (lithium carbonate production), and optionally, the conversion of lithium carbonate into lithium hydroxide.

Figure 9 provides an example of product diagram for lithium chemicals production based on Salar de Atacama, in Chile. Here, the brine is extracted and placed in dedicated ponds where it is exposed to sunlight to facilitate evaporation, increasing the lithium concentration in the brine from about 0.15% to 6% (Kelly et al., 2021). Moreover, salts are extracted from the ponds further increasing lithium concentration and facilitating the subsequent purification step. The concentrated brine is then transported by truck to a facility for further purification and precipitation into lithium carbonate. Lithium carbonate precipitation is achieved by heating the purified lithium brine with soda ash at ca. 80 °C. Lithium carbonate can be converted into technical grade lithium hydroxide monohydrate using a liming process or acidification with sulfuric acid or hydrochloric acid and neutralization with sodium hydroxide or potassium hydroxide.

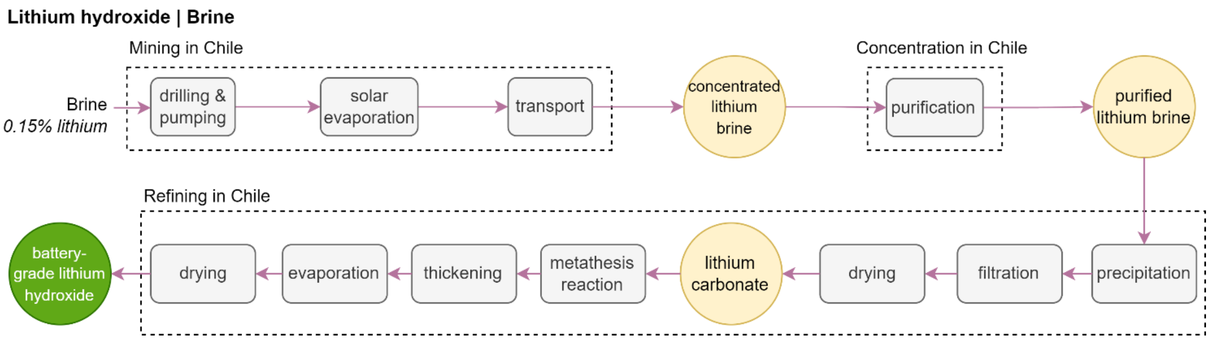

Figure 9: Product system diagram for lithium hydroxide production from brines at Salar de Atacama, Chile. Own elaboration based on Kelly et al. (2021).

New brine-based production sites are increasingly opting for replacing the traditional evaporative ponds by direct lithium extraction (DLE) technologies, including solvent extraction, adsorption, nanofiltration, or membrane electrolysis (Nicolaci et al., 2023).

Ore-based lithium production can be divided into ore mining, ore concentration, and refining. Most of spodumene ore-based projects uses an acid leaching process (Evans, 2014). Australia dominates the mining of spodumene, while the refining is concentrated in China (RFC Ambrian, 2023). In Europe, the mining and refining capacities are expected to grow, with potential projects in Finland and Portugal (European Investment Bank, 2024a, 2024b). Figure 10 further shows an example of a production route of lithium hydroxide monohydrate in China from spodumene concentrate produced in Australia. Spodumene ore is mined and concentrated in Western Australia. The concentration stage consists of a

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series of crushing, grinding, and flotation stages to increase the ore grade from 0.8-0.9% to 6% lithium content. The spodumene concentrate is transported to Australian port via truck and train, shipped to China, and transported by truck to the refining facility. Here, the spodumene concentrate is calcinated and acid roasted to produce lithium sulfate, followed by lithium carbonate or lithium hydroxide production.

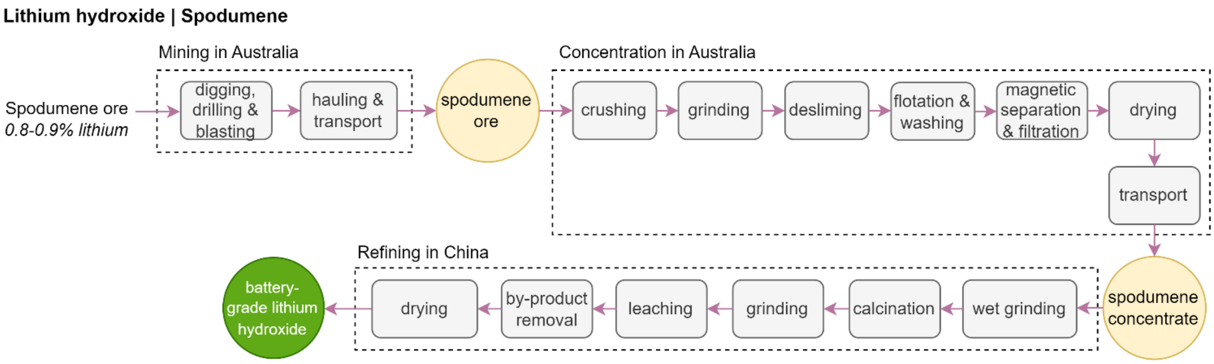

Figure 10: Product system diagram for lithium hydroxide production from spodumene ore, based on Australia and China. Own elaboration based on Kelly et al. (2021).

3.2 LCI Data from Company Reports: Lithium Case Study

This section explores the challenges and opportunities associated with extracting LCI data from company reports, using lithium production as a case study. Various stakeholders may have potential interest in such data, including companies producing LCI data, organizations required to comply with standards and regulations, and entities engaged in supply chain validation or supplier comparison.

As introduced, lithium production involves both mining and refining operations, which can take place either at the same site or across different locations. For this case study, documents from both developing and operating sites were analysed to ensure comprehensive coverage. The analysis identified two primary document types—technical and sustainability reports—as key sources of LCI data, with supplementary information occasionally found in financial statements and press releases. However, these supplementary sources are typically less accessible and/or less relevant for detailed LCI analysis.

- **Technical Reports:** These reports provide detailed site-specific or country-specific data, often focusing on mining activities. While they are valuable for their depth of information, a lack of standardization across reports can complicate comparisons.

- **Sustainability Reports:** Published annually at the company level, these reports include production figures and other operational data. However, their level of granularity and detail varies significantly among companies, which limits their consistency as a data source.

Table 6 summarizes the number of documents identified for each site type (developing or operating) that were accessible for the lithium case study, providing an overview of the available resources for analysis.

Table 6: Overview of Accessible Company Documents for Lithium Production Sites for Potential LCI Data Extraction

	Site type (mining and/or refining)	
	Developing sites	Operating sites
Sites covered	11	17
Technical reports	12 (e.g. Lithium Bank)	>15 (e.g. Mining plus)
Sustainability reports	3 (e.g. Vulcan energy)	>15 (e.g. Ganfeng lithium)
Other sources	1 (e.g. European Metals)	11 (e.g. Livent)

The analysis of the resources summarized in Table 6 revealed several challenges for extracting LCI data effectively:

1. **Lack of Standardization**

- **Technical Reports:** These documents often adhere to country-specific standards rather than global guidelines, resulting in inconsistent presentation of data. Key metrics are frequently embedded within text instead of structured tables, complicating systematic data extraction.
- **Sustainability Reports:** The level of disaggregation and coverage varies significantly between companies, with some reports providing detailed metrics while others are limited to high-level summaries.

2. **Accessibility and Organization of Data**

- Data in both technical and sustainability reports is often presented in a narrative format, requiring manual interpretation to extract relevant LCI information. These reports are predominantly provided in PDF format and are seldom available in more data-extraction-friendly formats, such as Excel.
- Supplementary sources, such as financial statements and press releases, are inconsistently available and rarely contain the level of detail required for comprehensive LCI assessments.

3. **Data Gaps in Refining Operations**

- Technical reports typically emphasize mining activities, leaving significant gaps in data related to refining processes, which are critical for full lifecycle assessments of lithium production.

4. **Knowledge Requirements**

- Effective data extraction requires a deep understanding of lithium production processes and supply chains, posing challenges for analysts who lack industry-specific expertise.

Given these challenges, the following improvement opportunities can be proposed to facilitate the extraction of LCI data from company reports:

1. **Harmonization of LCI data Reporting**

- Adopting a standardized format for data presentation, both within and across technical and sustainability reporting standards, would significantly enhance the reliability and efficiency of LCI data extraction.
- Encouraging companies to adhere to a reporting taxonomy or adopt structured reporting formats, such as including detailed data tables, would significantly enhance data accessibility.

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2. **Technology-Assisted Data Extraction**
- Leveraging advanced tools such as artificial intelligence (AI) and natural language processing (NLP) can streamline the extraction of unstructured data from reports.
- Automating the parsing of narratives and converting them into structured datasets can reduce manual effort and improve efficiency.

3. **Closing Data Gaps**
- Encouraging companies to prioritize reporting on refining operations alongside mining would address critical gaps in LCI data.
- Collaborative industry initiatives could enhance the comprehensiveness and consistency of reporting across the lithium supply chain.

The extraction of LCI data from company reports presents both challenges and opportunities, as can be extracted from the sample of documents analysed in this lithium production case study. While issues such as lack of standardization, limited accessibility, and data gaps pose significant barriers, the adoption of harmonized reporting standards and technology-driven data extraction methods offers promising pathways for improvement. Addressing these challenges could enable company reports to become a more relevant, accessible, and straightforward source of LCI data.

However, these conclusions are based on a single case study focused on lithium production, which may not fully represent the broader landscape. Lithium production's close ties to the battery market and sustainability incentives, combined with the availability of two distinct competing production sources—brine, primarily from the lithium triangle, and spodumene, largely from Australia—may result in more documentation for this sector compared to others. Consequently, further studies across diverse industries are needed to validate these findings and generalize the identified challenges and opportunities effectively.

3.3 Multifunctionality issues

The supply chain of lithium can involve many co-products. Table 7 lists the potential co/by-products involved in brine and spodumene lithium production. Sections

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Table 7: Potential co-products and by-products from lithium production routes.

Product	Unit Process	Co/by- product
alpha-spodumene concentrate	Desliming	Tailings (Quarts, feldspar, mica, Iron residues, Al-silicate residues)
alpha-spodumene concentrate	Flotation & Washing	
alpha-spodumene concentrate	Magneticseparation & Filtration	
Lithium carbonate	Leaching & Filtration	
Lithium carbonate	Precipitation & Filtration I	Metals (Mg, Ca, Al, Fe)
Lithium carbonate	Precipitation & Filtration I	Aluminium Hydroxide (AlH_2)
Lithium carbonate	Precipitation & Filtration II	Sodium Sulfate (Na_2SO_4)
Lithium carbonate	Solar Evaporation	Natrium Chloride (NaCl)
Lithium carbonate	Solar Evaporation	Potash (KCl, etc.)
Lithium carbonate	Solar Evaporation	Bischofite ($MgCl_2 * 6H_2O$) & Lithium Carnallite
Lithium carbonate	Solvent extraction	Boron
Lithium carbonate	Precipitation & Filtration I	Magnesium Carbonite ($MgCO_3$)
Lithium carbonate	Precipitation & Filtration I	Tailings (Sulfuric residues)
lithium product, unspecified	Mining, overall	Tantalum
		Niobium
		Tin
		Beryllium
		Caesium
		Rubidium
		Feldspar
		Quartz

3.3.1 Brine concentration

The standard brine concentration method involves solar evaporation, where brine is pumped to the surface and flows through a series of ponds. This process can yield not only concentrated lithium brine but also co-products such as potash and other salts like sodium chloride (NaCl) (Rolinck et al., 2023). For instance, at Salar de Atacama, the brine follows two distinct pathways depending on whether it is directed toward potash or lithium production (Kelly et al., 2021). However, the lithium pathway may partially redirect brine to the potash pathway, requiring the LCI to be allocated between these two products.

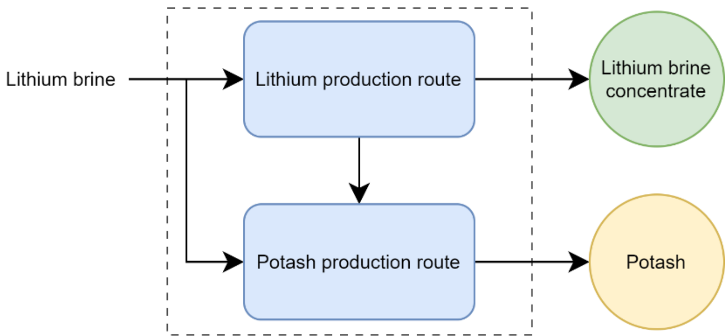

Figure 11: Multifunctionality issue at lithium brine concentration.

3.3.2 Brine purification and precipitation

The concentrated brine undergoes several stages of purification and precipitation, during which several co-products could be recovered. These include boron that could be recovered from solvent extraction or magnesium carbonite that could be recovered during precipitation (Rolinck et al., 2023).

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Although some co-products and many by-products become available as a result of lithium extraction, co-production is scarcely addressed in the existing LCA literature (Khakmardan et al., 2023).

4 Cobalt

4.1 Product system

Figure 12 shows an example of cobalt sulfate product system based on cobalt sulfate heptahydrate production in China from cobalt hydroxide produced in the Democratic Republic of Congo via hydrometallurgical processing of copper-cobalt sulfide ores. The concentration stage consists of hydrometallurgical ore processing. Battery-grade cobalt sulfate heptahydrate production in China.

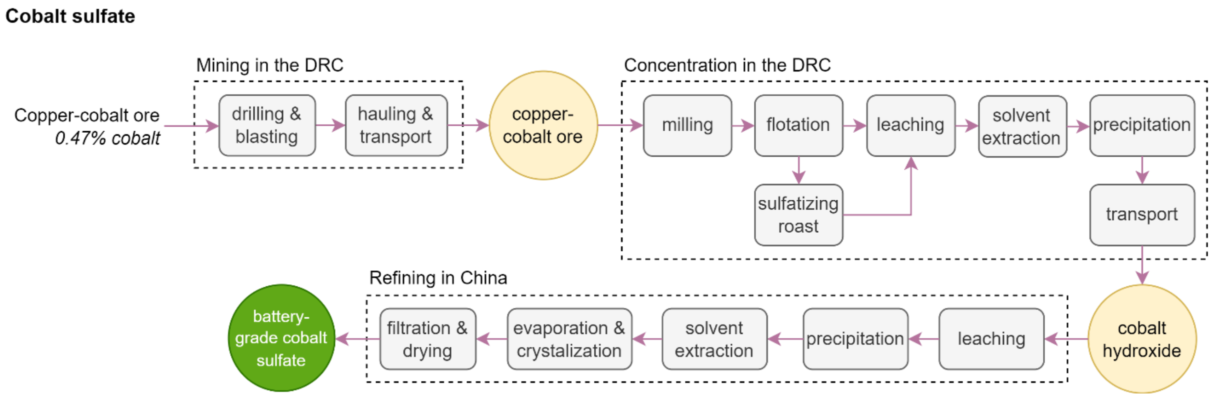

Figure 12: Product system diagram for cobalt sulfate production in China from cobalt-copper ores mined in the Democratic Republic of Congo. Own elaboration based on (Dai et al., 2018).

4.2 Multifunctionality issues

The multifunctionality issue arises as copper cathode and cobalt hydroxide are co-products of the hydrometallurgical processing.

5 Natural graphite

5.1 Product system

Figure 13 shows a typical product system for coated spherical natural graphite, involving mining, concentration, and refining of graphite ores in China. Graphite ore is mined with standard drilling and blasting methods. The concentration stage involves standard flotation process. The concentrated ore undergoes spheronization, purification, and coating to produce battery-grade graphite. Notably, the coating is carbonized in an electrically-heated furnace that operates at 1300 °C.

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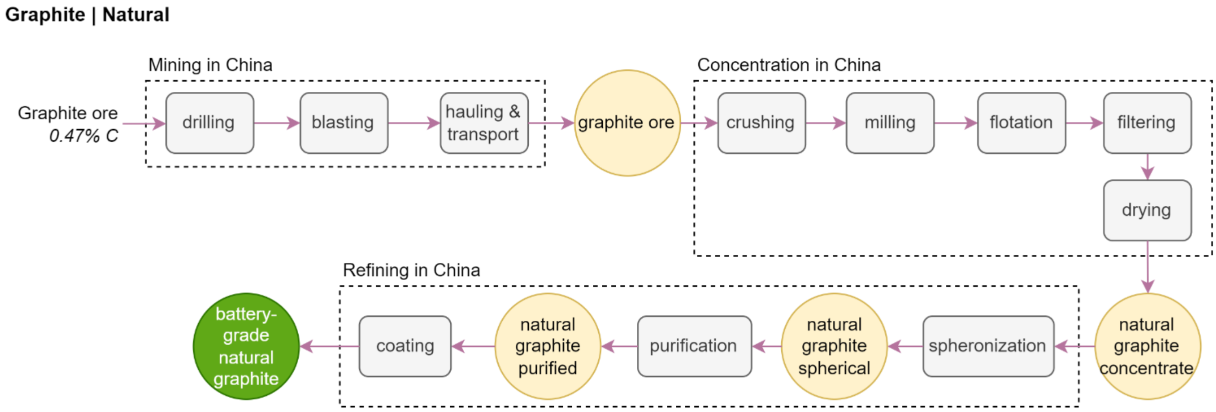

Figure 13: Product system diagram for coated spherical natural graphite production in China. Own elaboration based on Engels et al. (2022).

5.2 Multifunctionality issues

5.2.1 Concentration

The production of natural graphite presents issues of multifunctionality at several stages.

Concentration: concentrates of various graphite flake sizes are produced which are suitable for different applications.

5.2.2Spheronization

Spheronization: Graphite fines are obtained as a low-value by-product.

6 Neodymium

6.1 Product system

The most commonly exploited types of neodymium deposits are bastnaesite-monazite, monazite and ion clays (Bailey et al., 2020; Miranda Xicotencatl et al., 2021). Figure 14 shows the mining, beneficiation, decomposition, separation and refining of neodymium from major deposits.

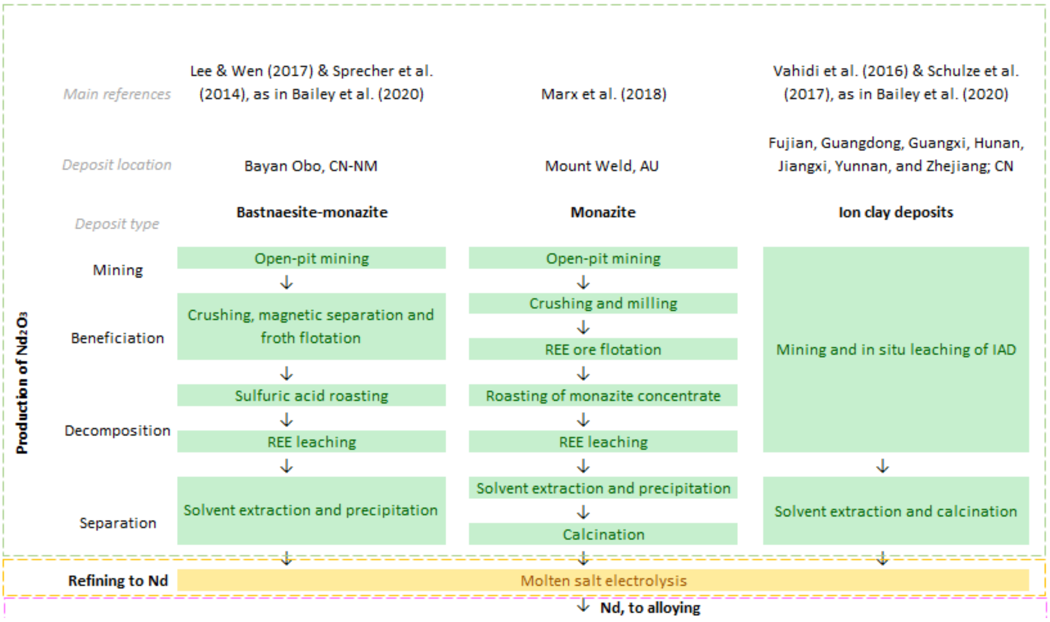

Figure 14: Product system diagram for Nd production.Edited from Miranda Xicotencatl et al.(2021).

6.2 Multifunctionality issues

6.2.1 REO co-production

Neodymium occurs in its natural deposits highly mixed with other rare earths; often in combination with other minerals (Bailey et al., 2020; Marx et al., 2018). Table 8 illustrates the differences in the mineral deposit compositions. The PCR for rare earth products recommends to address co-production with allocation approaches tailored to the specific multifunctional stage (EPD INTERNATIONAL, 2024a).

Table 8: Concentration of REOs across major producing mines. Source: a) Packey and Kingsnorth (2016), b) Lee and Wen (2017), c) Marx et al. (2018).

	Location:	Bayan Obo, China	Sichuan province, China	Mt Pass, US	Southern China	Mount Weld, Australia
REE of interest	**Deposit type** **Rare earth oxide**	Bastnaesite-Monazite (a)	Bastnaesite (b)	Bastnaesite (c)	Ion clay deposits (a)	Monazite (a)
Neodymium (Nd)	**Nd_2O_3**	16.60%	15.00%	11.16%	17.55%	18.12%
Cerium (Ce)	**CeO_2**	50.72%	50.00%	49.59%	3.23%	47.55%
Lanthanum (La)	**La_2O_3**	25.00%	27.00%	33.79%	27.56%	23.88%
Praseodymium (Pr)	**Pr_6O_{11}**	5.10%	5.00%	4.12%	5.62%	5.16%
Samarium (Sm)	**Sm_2O_3**	1.20%	1.10%	0.85%	4.54%	2.44%
Gadolinium (Gd)	**Gd_2O_3**	0.70%	0.40%	0.21%	5.96%	1.09%
Yttrium (Y)	**Y_2O_3**	0.43%	0.30%	0.13%	24.26%	0.76%
Europium (Eu)	**Eu_2O_3**	0.18%	0.20%	0.11%	0.93%	0.53%

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	Location:	Bayan Obo, China	Sichuan province, China	Mt Pass, US	Southern China	Mount Weld, Australia
REE of interest	**Deposit type** **Rare earth oxide**	Bastnaesite-Monazite (a)	Bastnaesite (b)	Bastnaesite (c)	Ion clay deposits (a)	Monazite (a)
Terbium (Tb)	**Tb_4O_7**	0.01%	n.a.	n.a.	0.68%	0.09%
Dysprosium (Dy)	**Dy_2O_3**	0.01%	n.a.	n.a.	3.71%	0.25%
Holmium (Ho)	**Ho_2O_3**	0.01%	n.a.	n.a.	0.74%	0.03%
Erbium (Er)	**Er_2O_3**	0.01%	1.00%	n.a.	2.48%	0.06%
Thulium (Tm)	**Tm_2O_3**	0.01%	n.a.	n.a.	0.27%	0.01%
Ytterbium (Yb)	**Yb_2O_3**	0.01%	n.a.	n.a.	1.13%	0.03%
Lutetium (Lu)	**Lu_2O_3**	0.01%	n.a.	n.a.	0.21%	0.00%

6.2.2Recycling

Recycling of neodymium occurs to a very limited extent. Although many potential recycling routes are being developed, there is no dominant technology yet. Figure 15 illustrates several categories of recycling technologies. Considering the different possibilities for the recovered material to integrate to the value chain, the recycling loops are longer or shorter compared to each other. Short-loop recycling, also known as magnet-to-magnet recycling, involves processing end-of-life magnets or magnetic assemblies directly into new magnetic powders, i.e., from NdFeB to NdFeB (Burkhardt et al., 2023). Long-loop recycling produces individual rare earth oxides that can be reprocessed, e.g., neodymium oxide recovered from NdFeB magnets (Karal et al., 2021). Each route has different technological implications and environmental profiles (Miranda Xicotencatl et al., 2023; van Nielen et al., 2024; Wang et al., 2025).

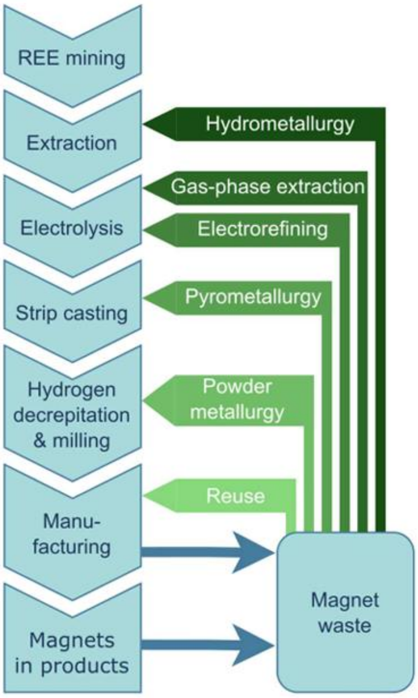

Figure 15:Entry points of recycling flows into the primary production of rare earth magnets. Source: Figure 1 in SUSMAGPRO D7.4

Different recycling technologies may lead to different co-production profiles from recycled magnets, magnetic assemblies or devices. This diversity represents a challenge to the harmonisation of guidelines to model recycling.

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Conclusion and back matter

7 Conclusion

The certification system "CERA 4in1 of responsibly sourced raw materials" aims to ensure the tracking and responsible sourcing of mineral raw materials from primary and secondary sources. As such, it covers the value chain of minerals from exploration to the final product. This document provides methodological guidance for conducting life cycle assessments (LCAs) within the context of the CERA 4in1 standard, facilitating compliance with the EU Battery Regulation and Critical Raw Materials Act and enhancing interoperability with other existing standards and guidelines.

The general aspects of the guidance are applicable to the complete supply chain of batteries and magnets. The specific aspects focus on four key raw materials: lithium, cobalt, natural graphite, and neodymium. Although the recycling of these key commodities occurs only to a limited extent, the aspects addressed in this document include considerations relevant to the foreseen development of recycling capabilities in the supply chain.

The methodological guidance in this document establishes a solid ground to address the environmental pillar of sustainability. It also represents a building block towards addressing other pillars of sustainability from a life cycle thinking perspective. However, further considerations regarding the economic and social pillars of sustainability were out of the scope of this document.

This document reviewed a selection of European regulations, guidelines and standards. The main objective of the review was to ensure that the LCA methodology proposed in MaDiTraCe aligns with established LCA standards and guidelines to an optimal degree and to identify methodological areas of opportunity. We identified and addressed three significant areas of opportunity:

1. *Guidance on the assessment of raw materials in impact categories beyond Climate change*

   Climate change, as an impact category typically used in LCAs, has received more attention than other impact categories by LCA practitioners. The number of specific guidelines to characterise this particular impact category was significantly higher than any other categories recommended for LCAs. A comprehensive LCA would include several of the following impact categories: Climate change, Ozone depletion, Human toxicity (cancer and non-cancer effects), Particulate matter, Ionising radiation, Photochemical ozone formation, Acidification, Eutrophication (terrestrial, freshwater and marine), Land use and Water use.

2. *Guidance on data collection*

   We found several areas of opportunity in the existing guidelines for LCI data collection. For example, we believe that regarding company-specific data as primary data by default (i.e., without verification), in the way the Critical Raw Materials Act proposes, could hinder the efforts for traceability and validation of sustainability claims. In this document, we suggest terms to make the origin of primary LCI data more explicit according to their scope. Besides, we linked the scope, ownership and origin of data sources with appropriate data quality requirements.

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3. *Guidance on addressing co-production and recycling*

   The recycling requirements established by the Battery Delegated Act and Critical Raw Materials Act emphasize the necessity of considering recycling processes of the selected commodities and their contributions to the environmental impact of batteries and permanent magnets. Despite the significance of addressing the complexities associated with end-of-life recycling processes, most existing guidelines and standards provide little guidance in this area or none at all. Furthermore, the existing guidance on this aspect is often divergent. We compared seven approaches to account for the contribution of recycling to the environmental profile of the supply chains under study. The results highlight a trade-off between accuracy and ease of application or communication among the allocation methods.

Although verified primary data (i.e., backed by measurements) leads to more accurate LCAs, data collection at a high level of detail requires a large amount of time and effort. In this document, we proposed a protocol to facilitate the collection of Scope 1 data[2]. The protocol streamlines the data collection process by building on management systems that a company may have already implemented, such as ISO 9001 and ISO 14001. We foresee that organisations can approach the LCI data collection in multiple iterations. A higher level of resolution could be achieved in each iteration according to the needs of an organisation, with the aim to 1) comply with regulations and 2) strategically maximise their sustainability.

The intended impact of this methodological guidance is to enhance the capability of organisations to comply with reporting regulations and conduct environmental impact assessments, by streamlining the data collection efforts for confidential and public reporting commitments. Adopting this guidance may reduce the barriers for organisations to conduct LCAs and enhance standardisation efforts. These guidelines will be evaluated in D4.7 through case studies that involve the compilation of baseline life cycle inventories.

[2] That is, own company emissions, without accounting for upstream or downstream emissions.

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8 References

Ali, A.-R., Bartie, N., Husmann, J., Cerdas, F., Schröder, D., & Herrmann, C. (2024). Simulation-based life cycle assessment of secondary materials from recycling of lithium-ion batteries. *Resources, Conservation and Recycling*, *202*, 107384. https://doi.org/10.1016/j.resconrec.2023.107384

Andreasi Bassi, S., Biganzoli, F., Ferrara, N., Amadei, A., Valente, A., Sala, S., & Ardente, F. (2023). *Updated characterisation and normalisation factors for the environmental footprint 3.1 method*. Publications Office. https://data.europa.eu/doi/10.2760/798894

Andreasi Bassi, S., Tonini, D., Ekvall, T., & Astrup, T. F. (2021). A life cycle assessment framework for large-scale changes in material circularity. *Waste Management*, *135*, 360–371. https://doi.org/10.1016/j.wasman.2021.09.018

Bailey, G., Joyce, P. J., Schrijvers, D., Schulze, R., Sylvestre, A. M., Sprecher, B., Vahidi, E., Dewulf, W., & Van Acker, K. (2020). Review and new life cycle assessment for rare earth production from bastnäsite, ion adsorption clays and lateritic monazite. *Resources, Conservation and Recycling*, *155*, 104675. https://doi.org/10.1016/j.resconrec.2019.104675

Berger, K., Baumgartner, R. J., Weinzerl, M., Bachler, J., Preston, K., & Schöggl, J.-P. (2023). Data requirements and availabilities for a digital battery passport – A value chain actor perspective. *Cleaner Production Letters*, *4*, 100032. https://doi.org/10.1016/j.clpl.2023.100032

BMWK. (2023). *Battery Passport Content Guidance*. e German Federal Ministry for Economic Affairs and Climate Action.

Burkhardt, C., van Nielen, S., Awais, M., Bartolozzi, F., Blomgren, J., Ortiz, P., Miranda Xicotencatl, B., Degri, M., Nayebossadri, S., & Walton, A. (2023). An overview of Hydrogen assisted (Direct) recycling of Rare earth permanent magnets. *Journal of Magnetism and Magnetic Materials*, *588*, 171475. https://doi.org/10.1016/j.jmmm.2023.171475

Catena-X Automotive Network. (2023). *Catena-X Product Carbon Footprint Rulebook (CX-PCF Rules)*. https://catena-x.net/fileadmin/user_upload/Vereinsdokumente/Geschaeftsstelle_Dateien_Ablage/CX-0029-ProductCarbonFootprintRulebook-v2.0.0.pdf

Cerdas, F., Baars, J., Ali, A.-R., & von Drachenfels, N. (2024). Methodological Challenges of Prospective Assessments. In S. Passerini, L. Barelli, M. Baumann, J. Peters, & M. Weil (Eds.), *Emerging Battery Technologies to Boost the Clean Energy Transition: Cost, Sustainability, and Performance Analysis* (pp. 225–241). Springer International Publishing. https://doi.org/10.1007/978-3-031-48359-2_12

Cobalt Institute. (2023). *Determining the Global Warming Potential of cobalt—The product carbon footprint guidance document for cobalt metal and cobalt sulphate heptahydrate*.

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Dai, Q., Kelly, J. C., & Elgowainy, A. (2018). *Cobalt Life Cycle Analysis Update for the GREET Model*.

Deng, H., & Kendall, A. (2019). Life cycle assessment with primary data on heavy rare earth oxides from ion-adsorption clays. *The International Journal of Life Cycle Assessment*, *24*(9), 1643–1652. https://doi.org/10.1007/s11367-019-01582-1

Domingues, A. M., & De Souza, R. G. (2024). Review of life cycle assessment on lithium-ion batteries (LIBs) recycling. *Next Sustainability*, *3*, 100032. https://doi.org/10.1016/j.nxsust.2024.100032

Draft Delegated Regulation - Ref. Ares(2024)3131389 (2024). https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/13877-Batteries-for-electric-vehicles-carbon-footprint-methodology_en

Du, S., Gao, F., Nie, Z., Liu, Y., Sun, B., & Gong, X. (2022). Comparison of Electric Vehicle Lithium-Ion Battery Recycling Allocation Methods. *Environmental Science & Technology*, *56*(24), 17977–17987. https://doi.org/10.1021/acs.est.2c05755

Ekvall, T., Björklund, A., Sandin, G., Lagergren, J., & Rydberg, M. (2020). *Modeling recycling in life cycle assessment*.

Engels, P., Cerdas, F., Dettmer, T., Frey, C., Hentschel, J., Herrmann, C., Mirfabrikikar, T., & Schueler, M. (2022). Life cycle assessment of natural graphite production for lithium-ion battery anodes based on industrial primary data. *Journal of Cleaner Production*, *336*, 130474. https://doi.org/10.1016/j.jclepro.2022.130474

EPD INTERNATIONAL. (2023). *Fabricated metal products, except construction products* (PCR No. 2023:01; Version 1.02). EPD INTERNATIONAL AB. https://api.environdec.com/api/v1/EPDLibrary/Files/80fd25a3-68f4-4cae-dd44-08dbf085b35e/Data (VALID UNTIL: 2027-01-06)

EPD INTERNATIONAL. (2024a). *General Programme Instructions for the International EPD System*. The International EPD system. https://www.datocms-assets.com/37502/1718799122-gpi5_20240619.pdf

EPD INTERNATIONAL. (2024b). *Rare earth concentrates, oxides, metals, and magnets (for non-construction uses)* (PCR No. 2024:01; Version 1.0.0). EPD INTERNATIONAL AB. https://api.environdec.com/api/v1/EPDLibrary/Files/b3d12a8f-664b-4149-27d0-08dc176fe0d5/Data (VALID UNTIL 2028-01-25)

Erdmann, M., & Franken, G. (2022). *Sustainability standard systems for mineral resources a comparative overview* (Revised version). Bundesanstalt für Geowissenschaften und Rohstoffe.

European Commission. (n.d.). *Critical raw materials* [An official website of the European Union managed by the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs]. Internal Market, Industry, Entrepreneurship and SMEs. Retrieved 3 February 2025, from https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/critical-raw-materials_en

European Commission. (2010). *International Reference Life Cycle Data System (ILCD) Handbook: General guide for life cycle assessment: detailed guidance*. European

Commission - Joint Research Centre - Institute for Environment and Sustainability. https://data.europa.eu/doi/10.2788/38479

European Commission. (2018). *Product Environmental Footprint Category Rules Guidance (Version 6.3)*.

European Commission. (2021). *COMMISSION RECOMMENDATION (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32021H2279

European Commission. (2023a, October 3). *Material and digital traceability for the certification of critical raw materials | MaDiTraCe Project | Fact Sheet | HORIZON*. CORDIS | European Commission. https://cordis.europa.eu/project/id/101091502

European Commission (with Grohol, M., & Veeh, C.). (2023b). *Study on the critical raw materials for the EU 2023: Final report*. Publications Office. https://data.europa.eu/doi/10.2873/725585

European Investment Bank. (2024a, August 23). *AURORA LITHIUM CONVERSION FACILITY*. Projects to Be Financed. https://www.eib.org/en/projects/pipelines/all/20230503

European Investment Bank. (2024b, August 23). *Finland: EU and Sibanye-Stillwater, through its Keliber lithium project, join forces in €150 million deal to improve EU access to and resilience in battery materials*. NewsRoom / All Releases. https://www.eib.org/en/press/all/2024-313-eu-and-sibanye-stillwater-through-its-keliber-lithium-project-in-finland-join-forces-in-eur150-million-deal-to-improve-eu-access-to-and-resilience-in-battery-materials

Evans, K. (Ed.). (2014). *Critical metals handbook*. John Wiley & Sons ; American Geophysical Union.

Förster, L., & Mischo, H. (2022). Excursus into the certification of mineral raw materials – Development and implementation of a sustainability standard. *International Journal of Mining, Reclamation and Environment*, *36*(9), 642–650. https://doi.org/10.1080/17480930.2022.2133428

Gaines, L. (2018). Lithium-ion battery recycling processes: Research towards a sustainable course. *Sustainable Materials and Technologies*, *17*, e00068. https://doi.org/10.1016/j.susmat.2018.e00068

Global Battery Alliance. (2023). *GBA Battery Passport—Greenhouse Gas Rulebook—Generic Rules—Version 1.5*. Global Battery Alliance. https://www.globalbattery.org/media/gba-rulebook-master.pdf

Guinée, J. (2002). *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*.

Hao, H., Qiao, Q., Liu, Z., & Zhao, F. (2017). Impact of recycling on energy consumption and greenhouse gas emissions from electric vehicle production: The China 2025 case. *Resources, Conservation and Recycling*, *122*, 114–125. https://doi.org/10.1016/j.resconrec.2017.02.005

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Heiho, A., Suwa, I., Dou, Y., Lim, S., Namihira, T., Koita, T., Mochidzuki, K., Murakami, S., Daigo, I., Tokoro, C., & Kikuchi, Y. (2023). Prospective life cycle assessment of recycling systems for spent photovoltaic panels by combined application of physical separation technologies. *Resources, Conservation and Recycling*, *192*, 106922. https://doi.org/10.1016/j.resconrec.2023.106922

Holzapfel, P., Bach, V., & Finkbeiner, M. (2023). Electricity accounting in life cycle assessment: The challenge of double counting. *The International Journal of Life Cycle Assessment*, *28*(7), 771–787. https://doi.org/10.1007/s11367-023-02158-w

Husmann, J., Beylot, A., Perdu, F., Pinochet, M., Cerdas, F., & Herrmann, C. (2024). Towards consistent life cycle assessment modelling of circular economy strategies for electric vehicle batteries. *Sustainable Production and Consumption*, *50*, 556–570. https://doi.org/10.1016/j.spc.2024.09.001

IEA. (2024). *Global Critical Minerals Outlook 2024*. International Energy Agency. https://www.iea.org/reports/global-critical-minerals-outlook-2024

Igogo, T., Awuah-Offei, K., Newman, A., Lowder, T., & Engel-Cox, J. (2021). Integrating renewable energy into mining operations: Opportunities, challenges, and enabling approaches. *Applied Energy*, *300*, 117375. https://doi.org/10.1016/j.apenergy.2021.117375

International Lithium Association. (2024). *Determining the Product Carbon Footprint of Lithium Products ILiA*. https://lithium.org/wp-content/uploads/2024/03/Determining-the-Product-Carbon-Footprint-of-Lithium-Products-ILiA-March-2024-v.1.pdf

IRMA. (2018). *IRMA Standard for Responsible Mining IRMA-STD-001*. Initiative for Responsible Mining Assurance. https://cdn.scsglobalservices.com/files/program_documents/irma_standard_v.1.0_final_2018.pdf

IRMA. (2023). *Standard for Responsible Mining and Mineral Processing 2.0*. Initiative for Responsible Mining Assurance. https://responsiblemining.net/wp-content/uploads/2023/10/IRMA-Standard-for-Responsible-Mining-and-Mineral-Processing-2.0-DRAFT-20231026.pdf

ISO. (2006). *ISO 14040:2006 Environmental management—Life cycle assessment—Principles and framework* [Standard]. International Organization for Standardization. https://www.iso.org/standard/37456.html

Kallitsis, E., Korre, A., & Kelsall, G. H. (2022). Life cycle assessment of recycling options for automotive Li-ion battery packs. *Journal of Cleaner Production*, *371*, 133636. https://doi.org/10.1016/j.jclepro.2022.133636

Karal, E., Kucuker, M. A., Demirel, B., Copty, N. K., & Kuchta, K. (2021). Hydrometallurgical recovery of neodymium from spent hard disk magnets: A life cycle perspective. *Journal of Cleaner Production*, *288*, 125087. https://doi.org/10.1016/j.jclepro.2020.125087

Kelly, J. C., Wang, M., Dai, Q., & Winjobi, O. (2021). Energy, greenhouse gas, and water life cycle analysis of lithium carbonate and lithium hydroxide monohydrate from brine and ore resources and their use in lithium ion battery cathodes and lithium ion batteries.

Resources, Conservation and Recycling, *174*, 105762. https://doi.org/10.1016/j.resconrec.2021.105762

Khakmardan, S., Rolinck, M., Cerdas, F., Herrmann, C., Giurco, D., Crawford, R., & Li, W. (2023). Comparative Life Cycle Assessment of Lithium Mining, Extraction, and Refining Technologies: A Global Perspective. *Procedia CIRP*, *116*, 606–611. https://doi.org/10.1016/j.procir.2023.02.102

Lee, J. C. K., & Wen, Z. (2017). Rare Earths from Mines to Metals: Comparing Environmental Impacts from China's Main Production Pathways. *Journal of Industrial Ecology*, *21*(5), 1277–1290. https://doi.org/10.1111/jiec.12491

Malabi Eberhardt, L. C., Van Stijn, A., Nygaard Rasmussen, F., Birkved, M., & Birgisdottir, H. (2020). Development of a Life Cycle Assessment Allocation Approach for Circular Economy in the Built Environment. *Sustainability*, *12*(22), 9579. https://doi.org/10.3390/su12229579

Marx, J., Schreiber, A., Zapp, P., & Walachowicz, F. (2018). Comparative Life Cycle Assessment of NdFeB Permanent Magnet Production from Different Rare Earth Deposits. *ACS Sustainable Chemistry & Engineering*, *6*(5), 5858–5867. https://doi.org/10.1021/acssuschemeng.7b04165

Mengarelli, M., Neugebauer, S., Finkbeiner, M., Germani, M., Buttol, P., & Reale, F. (2017). End-of-life modelling in life cycle assessment—Material or product-centred perspective? *The International Journal of Life Cycle Assessment*, *22*(8), 1288–1301. https://doi.org/10.1007/s11367-016-1237-z

Miranda Xicotencatl, B., Kleijn, R., van Nielen, S., Donati, F., Sprecher, B., & Tukker, A. (2023). Data implementation matters: Effect of software choice and LCI database evolution on a comparative LCA study of permanent magnets. *Journal of Industrial Ecology*, *27*(5), 1252–1265. https://doi.org/10.1111/jiec.13410

Miranda Xicotencatl, B., van Nielen, S., Kleijn, R., & Burkhardt, C. (2021). *Baseline LCA of virgin magnet production* (SUSMAGPRO Deliverable No. 7.1; Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in the Circular Economy, p. 43). European Union's Horizon 2020 research and innovation programme; grant agreement No 821114.

Moni, S. M., Mahmud, R., High, K., & Carbajales-Dale, M. (2020). Life cycle assessment of emerging technologies: A review. *Journal of Industrial Ecology*, *24*(1), 52–63. https://doi.org/10.1111/jiec.12965

Nicolaci, H., Young, P., & Snowdon, N. (2023). *Direct Lithium Extraction A potential game changing technology*. Goldman Sachs.

NISO CRediT Working Group. (2022). *ANSI/NISO Z39.104-2022, CRediT, Contributor Roles Taxonomy*. NISO. https://doi.org/10.3789/ansi.niso.z39.104-2022

Nuss, P., & Eckelman, M. J. (2014). Life Cycle Assessment of Metals: A Scientific Synthesis. *PLOS ONE*, *9*(7), e101298. https://doi.org/10.1371/journal.pone.0101298

Packey, D. J., & Kingsnorth, D. (2016). The impact of unregulated ionic clay rare earth mining in China. *Resources Policy*, *48*, 112–116. https://doi.org/10.1016/j.resourpol.2016.03.003

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Parvatker, A. G., & Eckelman, M. J. (2019). Comparative Evaluation of Chemical Life Cycle Inventory Generation Methods and Implications for Life Cycle Assessment Results. *ACS Sustainable Chemistry & Engineering*, *7*(1), 350–367. https://doi.org/10.1021/acssuschemeng.8b03656

Peters, J. F., Baumann, M., Zimmermann, B., Braun, J., & Weil, M. (2017). The environmental impact of Li-Ion batteries and the role of key parameters – A review. *Renewable and Sustainable Energy Reviews*, *67*, 491–506. https://doi.org/10.1016/j.rser.2016.08.039

Raugei, M., & Winfield, P. (2019). Prospective LCA of the production and EoL recycling of a novel type of Li-ion battery for electric vehicles. *Journal of Cleaner Production*, *213*, 926–932. https://doi.org/10.1016/j.jclepro.2018.12.237

RECHARGE. (2023). *PEFCR - Product Environmental Footprint Category Rules for High Specific Energy Rechargeable Batteries for Mobile Applications*. https://ec.europa.eu/environment/eussd/smgp/pdf/PEFCR_Batteries.pdf

Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 Concerning Batteries and Waste Batteries, Amending Directive 2008/98/EC and Regulation (EU) 2019/1020 and Repealing Directive 2006/66/EC (Text with EEA Relevance) (2023). https://eur-lex.europa.eu/eli/reg/2023/1542/oj

REGULATION (EU) 2024/1252 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 April 2024 Establishing a Framework for Ensuring a Secure and Sustainable Supply of Critical Raw Materials and Amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020 (2024). http://data.europa.eu/eli/reg/2024/1252/oj

RFC Ambrian. (2023). *Lithium Projects Review*. https://www.finnewsnetwork.com.au/Presentations/2023_PDFs/Lithium_Projects_Review_Final_Nov_23.pdf

Rinne, M., Elomaa, H., & Lundström, M. (2021). Life cycle assessment and process simulation of prospective battery-grade cobalt sulfate production from Co-Au ores in Finland. *The International Journal of Life Cycle Assessment*, *26*(11), 2127–2142. https://doi.org/10.1007/s11367-021-01965-3

Rolinck, M., Khakmardan, S., Cerdas, F., Mennenga, M., Li, W., & Herrmann, C. (2023). Completeness evaluation of LCI datasets for the environmental assessment of lithium compound production scenarios. *Procedia CIRP*, *116*, 726–731. https://doi.org/10.1016/j.procir.2023.02.122

Saner, D., Walser, T., & Vadenbo, C. O. (2012). End-of-life and waste management in life cycle assessment—Zurich, 6 December 2011. *The International Journal of Life Cycle Assessment*, *17*(4), 504–510. https://doi.org/10.1007/s11367-012-0390-2

Santero, N., & Hendry, J. (2016a). Harmonization of LCA methodologies for the metal and mining industry. *The International Journal of Life Cycle Assessment*, *21*(11), 1543–1553. https://doi.org/10.1007/s11367-015-1022-4

Santero, N., & Hendry, J. (2016b). Harmonization of LCA methodologies for the metal and mining industry. *The International Journal of Life Cycle Assessment*, *21*(11), 1543–1553. https://doi.org/10.1007/s11367-015-1022-4

Schenker, V., Oberschelp, C., & Pfister, S. (2022). Regionalized life cycle assessment of present and future lithium production for Li-ion batteries. *Resources, Conservation and Recycling*, *187*, 106611. https://doi.org/10.1016/j.resconrec.2022.106611

Schulze, R., Lartigue-Peyrou, F., Ding, J., Schebek, L., & Buchert, M. (2017). Developing a Life Cycle Inventory for Rare Earth Oxides from Ion-Adsorption Deposits: Key Impacts and Further Research Needs. *Journal of Sustainable Metallurgy*, *3*(4), 753–771. https://doi.org/10.1007/s40831-017-0139-z

Segura-Salazar, J., Lima, F. M., & Tavares, L. M. (2019). Life Cycle Assessment in the minerals industry: Current practice, harmonization efforts, and potential improvement through the integration with process simulation. *Journal of Cleaner Production*, *232*, 174–192. https://doi.org/10.1016/j.jclepro.2019.05.318

TranSensus LCA. (2023). *Deliverable D 1.1 Review of current practices on life cycle approaches along the electromobility value chain*. https://lca4transport.eu/wp-content/uploads/2023/11/TranSensus-LCA_D-1-1_Final.pdf

Vahidi, E., & Zhao, F. (2017). Environmental life cycle assessment on the separation of rare earth oxides through solvent extraction. *Journal of Environmental Management*, *203*, 255–263. https://doi.org/10.1016/j.jenvman.2017.07.076

van Nielen, S. S., Miranda Xicotencatl, B., Tukker, A., & Kleijn, R. (2024). Ex-ante LCA of magnet recycling: Progressing towards sustainable industrial-scale technology. *Journal of Cleaner Production*, *458*, 142453. https://doi.org/10.1016/j.jclepro.2024.142453

Wang, Q.-Q., Wang, L., Zhao, S., Li, F.-P., Chen, W.-Q., & Wang, P. (2025). A critical life cycle assessment of present and potential rare earth circularity routes from permanent magnets. *Resources, Conservation and Recycling*, *215*, 108106. https://doi.org/10.1016/j.resconrec.2024.108106

Wulf, C., Zapp, P., Schreiber, A., Marx, J., & Schlör, H. (2017). Lessons Learned from a Life Cycle Sustainability Assessment of Rare Earth Permanent Magnets. *Journal of Industrial Ecology*, *21*(6), 1578–1590. https://doi.org/10.1111/jiec.12575

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9 Appendix A

9.1 Summary of existing guidelines

Table 9: List of main LCA guidelines documents applicable to EV's batteries.

Abbreviation	Name	Publisher	Product	System boundaries	Impacts included	Applicability
PEFCR Batteries	PEFCR – Product Environmental Footprint Category Rules for high specific energy rechargeable batteries for mobile applications	Advanced rechargeable & lithium batteries association	LIBs and solid state lithium batteries for e-mobility; LIBs for ICT/CPT equipment; Ni-MH batteries for cordless power tools	**Cradle-to-grave**: Mining & refining → Components manufacturing → Battery manufacturing → Distribution → Use → End-of-life	EF impact categories and methods	Mandatory for PEF studies which results are intended to be communicated; optional for PEF in-house applications
CFB-EV	Rules for the calculation of the Carbon Footprint of Electric Vehicle Batteries (CFB-EV)	European Commission's Joint Research Center (JRC)	EV battery that falls within the scope of Article 7 of the upcoming EU Battery Regulation	**Cradle-to-grave (w/o use):** Mining & refining → Components manufacturing → Battery manufacturing → Distribution → End-of-life	Carbon footprint / GHG emissions	Methodological guidelines for calculating carbon footprint for EVs as required under Article 7 of the upcoming EU Battery Regulation
CFB-IND	Proposal for the rules for the calculation of the Carbon Footprint of rechargeable	European Commission's Joint Research Center (JRC)	Rechargeable industrial batteries that falls within the scope of	**Cradle-to-grave (w/o use):** Mining & refining → Components	Carbon footprint / GHG emissions	Methodological guidelines for calculating carbon footprint for rechargeable industrial

	Industrial Batteries except those with exclusively external storage (CFB-IND)		Article 7 of the upcoming EU Battery Regulation	manufacturing → Battery manufacturing → Distribution → End-of-life		batteries as required under Article 7 of the upcoming EU Battery Regulation
GBA	GBA Battery Passport – Greenhouse Gas Rulebook – Generic Rules	Global Battery Alliance	LIBs for EVs	**Cradle-to-gate:** Mining & refining → Components manufacturing → Battery manufacturing	Carbon footprint / GHG emissions	Users of the GBA Battery Passport
CX-PCF Rules	Catena-X Product Carbon Footprint Rulebook	Catena-X Automotive Network	Vehicles (including EVs)	**Cradle-to-gate:** Mining & refining → Vehicle parts and components manufacturing → Vehicle manufacturing	Carbon footprint / GHG emissions	Reported Product Carbon Footprints (PCFs) in the Catena-X network
PCR Batteries	Product Category Rules (PCR) for batteries	EPD international	Under development			

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Table 10: List of LCA guidelines and standards for raw materials.

Commodity	Abbreviation	Name	Publisher	Product	System boundaries	Impacts coverage	Applicability
Cobalt	Cobalt Institute PCF Guidance	Determining the Global Warming Potential of cobalt - The product carbon footprint guidance document for cobalt metal and cobalt sulphate heptahydrate	Cobalt Institute	Refined cobalt metal and cobalt sulfate heptahydrate	**Cradle-to-gate**: Mining → Beneficiation → Hydrometallurgical processing → Smelting & Refining → Finishing	Carbon footprint / GHG emissions	Only guidance
Graphite	PCR Graphite	Product Category Rules (PCR) Graphite Products	EPD international	Graphite products (including natural and synthetic graphite)	**Cradle-to-gate (optional cradle-to-grave)**	EPD environmental performance indicators[1]	EPD
Rare earth elements (Neodymium)	PCR REEs	Product Category Rules (PCR) rare earth concentrates,	EPD international	Rare earth element oxide, concentrate, metal or magnet	**Cradle-to-gate (optional cradle-to-grave)**	EPD environmental performance indicators[1]	EPD

		oxides, metals, and magnets (for non-construction uses)					
All metals	LCA Mining & Metal industry	Harmonization of LCA methodologies for the metal and mining industry	Mining and metal industry	All metals	**Cradle-to-grave**	Global warming potential, acidification, eutrophication, smog, and ozone depletion	Recommended harmonized LCA methodology by the mining and metal industry
Lithium	ILiA PCF guidance	Determining the Product Carbon Footprint of Lithium Products - Guidance for calculating a product carbon footprint (PCF) of key lithium intermediates and battery-grade lithium carbonate and hydroxide specialty chemicals produced from	International Lithium Association	Battery-grade lithium carbonate and hydroxide monohydrate (also applicable to intermediate products)	**Cradle-to-gate**: Mining → Beneficiation → Hydrometallurgical processing → Smelting & Refining → Finishing	Carbon footprint / GHG emissions	Only guidance

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		brine or rock minerals.					
Notes: [1] EPD environmental performance indicators: (i) global warming potential, (ii) acidification, (iii) eutrophication, (iv) photochemical ozone creation, (v) ozone depletion, (vi) abiotic depletion potential for minerals and metals, (vii) abiotic depletion potential for fossil resources, (viii) water deprivation potential							

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9.2 A protocol for the identification of Scope 1 data sources and data gaps

With the steps defining the goal and scope and the selection of the functional unit, a rough flowchart may already be drafted. The steps below are intended to guide the primary data collection process and increase the level of detail of the flowchart and may help further specify the goal and scope. Use the steps below to identify the data more readily available and potential data gaps, according to the classification and considerations in **Table 1**.

1. Identify the boundaries of the product system to be evaluated; for example:
    a. All the processes referring to a specific products
    b. All the plant operations; which might refer to one or more products
2. Identify the geographic scope of the product system to be evaluated; for example:
    a. All the multiple locations where the company operates to produce a the product of interest
    b. The location of a specific plant
3. Keep in mind the time horizon that the LCA will represent and the resolution in which primary data is available; for example, the average yearly operation of:
    a. The last year
    b. The last five years
4. Identify potential sources of pre-existent information that may facilitate performing the life cycle inventory
    a. Are there any monitoring/tracking systems in place to account for material and energy flows?
        i. Are there any processes/procedures in place to (automatically) use the data from the above mentioned systems in reports?
        ii. Can the systems be queried to repurpose data for a life cycle assessment?
            1. Can the monitoring/tracking systems be mapped to the LCA flowchart? If relevant, modify the flowchart to indicate the level of resolution provided by the monitoring/tracking systems.
    b. Has an LCA related to the product system of interest performed before? If so,
        i. Is the information compiled for that document still representative of the time horizon selected for the current study?
        ii. How do the system boundaries and geographic scope overlap or differ?
    c. Are there any internal or external audit reports concerning Quality Management Systems or Environmental management systems (e.g., ISO9001:2015 or ISO14001:2015)?
5. Identify supporting systems in place. For example, based on 4a and the reports of 4c, the expected results would be:
    a. A list of reporting processes/procedures regarding environmental aspects
    b. A list of support processes/procedures that allow the tracking of material flows and energy

    Based on 4a, 4b and 4c another expected result would be:

    c. A list of primary documentation sources regarding environmental aspects

9.3 Review tables

Table 11: Cut-off rules in existing LCA guidelines

		EU Battery Regulation	PEFCR Batteries	Catena-X	GBA Battery Passport	Mining and metal industry	Cobalt Institute-PCF	ILiA-PCF
Mass cut-off criterion	Inputs/outputs accounting for <1% of the total mass of the system components	X						
Impact cut-off criterion	Inputs/outputs cumulatively accounting for <3% of the product carbon footprint		X		X		X	X
	Inputs/outputs cumulatively accounting for <1% of the product carbon footprint			X				
None	Address data gaps with proxy data instead of cutoff					X		

Table 12: Data quality requirements and assessment in LCA guidelines applicable to the selected commodities and products.

Guideline	Data quality requirement	Data quality assessment
EU Battery Regulation	Requirements for primary and secondary data collection • Use of company-specific data for certain processes • Establishes a hierarchy for the use of secondary datasets • Establishment of a company quality management system to ensure that activity data has been correctly collected and managed	**Data Quality Rating (DQR)** calculated for the declared carbon footprint and all the datasets used in the model based on the evaluation of three data quality indicators: • Technological representativeness • Geographical representativeness • Time-related representativeness
PEFCR Batteries		**Data Quality Rating (DQR)** calculated for each dataset and the total Environmental Footprint study based on the evaluation of four data quality indicators: • Technological representativeness • Geographical representativeness • Time-related representativeness • Precision/uncertainty
Catena-X Product Carbon Footprint Rulebook		**Data Quality Rating (DQR)** of activity data, emission factors, and direct emissions (both primary and secondary data) based on the evolution of five data quality indicators: • Technological representativeness • Geographical representativeness • Temporal representativeness • Completeness • Reliability
GBA Battery Passport – GHG Rulebook	Minimum requirements: • Overall mass and carbon balance of the process • Metal content balance • Minimum data per cluster needs to be collected (based on provided templates) Further requirements:	None

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	• Use of primary data for foreground processes under the responsibility of the company (literature data for filling data gaps need to be verified by a third party) • Use of supply-chain specific data for relevant input materials and components • Completeness of inputs and outputs per unit process • Consistency of data sources • Reproducibility by third party • Representativeness of geographical, temporal, and technology data	
EPD PCR Graphite	Data collection requirements: • Primary data shall be used for the core processes. • Secondary may be used for upstream and downstream processes, if primary data is not available	None
EPD PCR REE	Data collection requirements: • Primary data shall be used for the core processes. • Secondary may be used for upstream and downstream processes, if primary data is not available	None
Cobalt Institute-PCF	None	None
ILiA-PCF	None	None
PCR fabricated metal products	Distinct requirements for specific and generic data.	

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Table 13: Approaches for solving multifunctionality due to co-production adopted in existing LCA guidelines.

<table>
<tr><th>Guideline</th><th>Co-production of metals</th><th>Co-production of other materials</th></tr>
<tr><td>Battery Regulation CF methodology</td><td colspan="2">• Process subdivision
• Physical allocation if ratio of co-products' market prices ≤10
• Economic allocation if ratio of co-products' market prices >10</td></tr>
<tr><td>Catena-X</td><td colspan="2">• Process subdivision
• System expansion via substitution
• Physical allocation if ratio of co-products' market prices ≤5
• Economic allocation if ratio of co-products' market prices >5</td></tr>
<tr><td>GBA Battery Passport</td><td>• Process subdivision
• Physical allocation if ratio of co-products' market prices ≤4
• Economic allocation if ratio of co-products' market prices >4</td><td>• Process subdivision
• System expansion via substitution
• Allocation</td></tr>
<tr><td>Cobalt Institute-PCF</td><td>• Process subdivision
• Physical allocation if ratio of co-products' market prices ≤4
• Economic allocation if ratio of co-products' market prices >4</td><td>• Process subdivision
• System expansion via substitution
• Physical allocation if ratio of co-products' market prices ≤4
• Economic allocation if ratio of co-products' market prices >4</td></tr>
<tr><td>ILiA-PCF</td><td>• Process subdivision
• Physical allocation if ratio of co-products' market prices ≤4
• Economic allocation if ratio of co-products' market prices >4</td><td>• Process subdivision
• System expansion via substitution
• Physical allocation if ratio of co-products' market prices ≤4
• Economic allocation if ratio of co-products' market prices >4</td></tr>
<tr><td>REE-PCR</td><td colspan="2">• Process subdivision
• Physical allocation if ratio of product prices ≤5
• Economic allocation if ratio of product prices >5</td></tr>
</table>

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9.4 Recycling allocation modelling approaches

Table 14: Formulas of the recycling allocation modelling approaches based on Du et al. (2022)

Approach	**Formula** (Step 1 + Step 2 + Step 3)[2]
CFF	$[R_1(1-A)+(1-R_1)]E_v+R_1AE_{recycled}+R_2(1-A)(E_{recycling,EoL}-E_v^*)$
Cut-off	$(1-R_1)E_v+R_1E_{recycled}$
EoL Recycling	$E_v+R_2(E_{recycling,EoL}-E_v^*)$
WPA	$[1-R_1+R_1(P_w/P_v)]E_v+R_1[1-(P_w/P_v)]Er_{ecycled}+R_2(P_w/P_v)(E_{recycling,EoL}-E_v^*)$
50:50	$(1-R_1/2)E_v+R_1E_{recycled}/2+R_2(E_{recycling,EoL}-E_v^*)2$
MRA	$\{E_v+(n-1)[E_{recycling,EoL}+(1-R_1)E_v]\}/n$
LD	$(1-R_1)[(2n-2m+1)/n^2]E_v+(1-R_2)[(2m-1)/n^2]E_v+[(n-1)/n](R_1E_{recycled}+R_2E_{recycling,EoL})$

- **E_v:** environmental impact of virgin material production
- **E_{v^*}:** environmental impact of virgin material productionsubstituted by recycled materials
- **$E_{recycled}$:** environmental impact of recycled materialproduction, including collection, sorting, and trans-portation
- **$E_{recycling,EoL}$:** environmental impact of recycling processes(for upstream products), including collection, sorting,and transportation
- **R_1:** "recycled content of material", which is thepercentage of material in production input that wasrecycled in the previous system
- **R_2:** "Recovery rate of material", which is the percentageof material in the product that is recovered in thesubsequent system, i.e., the ratio between the recyclingoutput and the primary material input
- **P_v:** average market price of virgin products/materials
- **P_w:** average market price of waste products/materials
- **A:** the allocation factor given by the EC Joint ResearchCentre in the CFF method, based on the analysis of themarket situation of different materials, has a factor Avalue between 0.2 and 0.868
- **n:** number of life cycles of material cycle processes
- **m:** order number of current life cycle

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[3] Step 1: Upstream and recycling process environmental burden / Step 2: Current life-cycle primary material production environmental burden Step 3: Environmental burdens and credits of recycling

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10 Appendix B

Contributor Roles Taxonomy (CRediT)

"The Contributor Roles Taxonomy's 14 roles and best practices represent a simple but comprehensive system that enables the range and nature of contributions to scholarly published output to be captured in a transparent, consistent, and structured format." (NISO CRediT Working Group, 2022).

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