

MADITRACE

Life Cycle Assessments of selected materials and products

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Summary

This document presents the cradle-to-gate-plus-grave life cycle assessment (LCA) of a product system composed of a lithium-ion battery pack and permanent magnets for electric vehicles, focusing on the supply chain of four commodities: lithium, cobalt, natural graphite and neodymium. The LCA was conducted based on the methodological guidance developed in MaDiTraCe D4.6 "LCA methodology for primary and secondary flows", within the context of the CERA 4in1 certification system.¹ Some deviations from the guidelines were implemented due to practical reasons. These deviations were documented in Table 1. Starting from the selection of publicly available life cycle inventory (LCI) datasets, the assessment involved the adaptation of the datasets in reference to the guidelines. Here, we identified the environmental hotspots of the supply chain of the product system, illustrated the application of the D4.6 guidelines, and illustrated the effect of alternative modelling decisions on the environmental profile of the system. Supplementing the report, the adapted datasets, life cycle inventories, direct emission checklist and characterised results are publicly available in Zenodo (<https://zenodo.org/uploads/18403764>).

The core of this document is presented as a research article entitled "How Data and Modelling Choices in Critical Raw Material Supply Chains Shape the Environmental Footprint of Electric Vehicles", which is intended to be submitted for peer review to a scientific journal.

Keywords

Life Cycle Assessment; Mining; Recycling; Batteries; Permanent magnets; Lithium (Li); Cobalt (Co); Graphite; Neodymium (Nd); Environmental performance; Traceability; Critical raw materials; Environmental regulations.

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





Abbreviations and acronyms

Acronym	Description
AMP	Active material production
CERA 4in1	CERTification of RAw Materials for sustainable development in mining
CRediT	Contributor Roles Taxonomy
EF	Environmental footprint
EoL	End of Life
EV	Electric vehicle
GHG	Greenhouse Gas
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
OTH	Others
PCR	Product Category Rules
PEF	Product Environmental Footprint
REEs	Rare earth elements
WP	Work Package





Research article

Declaration: This article is part of the doctoral research of B. Miranda Xicotencatl. See the author and contribution statement in Appendix B.

How Data and Modelling Choices in Critical Raw Material Supply Chains Shape the Environmental Footprint of Electric Vehicles

Abstract

The transition to global net-zero greenhouse gas emissions relies on electric vehicles (EVs), whose environmental performance is strongly influenced by the supply chain of critical raw materials such as lithium, cobalt, graphite, and neodymium. Lithium-ion batteries and Nd-Fe-B permanent magnets rely on these critical raw materials. Life Cycle Assessment (LCA) is central to evaluating the potential environmental impacts of these components; however, further methodological harmonisation is required to achieve comparability and compliance with emerging European regulations (e.g., the Battery Regulation, the Critical Raw Materials Act, and the Corporate Sustainability Reporting Directive). This study applies regulation-aware LCA guidelines developed within the MaDiTraCe project to assess a product system comprising an NMC811 battery pack and Nd-Fe-B magnets.

The analysis adopts a cradle-to-gate-plus-grave perspective, with a basket functional unit, encompassing the functions provided by the battery and rotor magnets. Datasets for Li, Co, Nd, graphite, magnets and battery were sourced from peer-reviewed literature and adapted for guideline compliance, compatibility with ecoinvent v3.10.1 and reproducibility in open-source software. The impact assessment followed the Environmental Footprint LCIA method v3.1. We explored alternative modelling decisions, including recycling allocation and sourcing scenarios, and their effects on the environmental profile of the EV components.

The battery supply chain accounts for most of the environmental burden of the product system, while the magnets contribute less than 7% in every impact category. Anode and cathode manufacture and cell assembly dominate impacts in 13 of 16 categories (28%-87%), while cathode raw material acquisition drives Ionising radiation (56%), Particulate matter (34%) and Water use (68%).

Modelling decisions significantly affect results. Allocation by substitution in recycling scenarios offsets burdens, from -8% to -121% compared to the reference cut-off, approach, leading to apparent benefits in acidification. Commodity sourcing alters climate change impacts by up to 16% (i.e. Co data sourcing).





1 Introduction

Strategies for achieving global net-zero greenhouse gas (GHG) emissions around the second half of the 21st century often envision a massive deployment of electric vehicles (EVs), wind turbines, solar photovoltaic panels, fuel cells, and other clean energy technologies (IEA, 2021; IPCC, 2022; Rostami et al., 2024). In fact, with over 7 million EVs already on the road in 2020, the growth of EVs already exceeded last decade scenario projections and, more recently, 250 million EVs were projected to exist by 2030 (Alonso et al., 2012; IEA, 2025; Sprecher and Kleijn, 2021). However, the environmental impacts of EV deployment must be evaluated from a life cycle perspective to ensure that they deliver the expected climate benefits without shifting burdens to other life cycle stages or impact categories.

The environmental performance of EVs is closely tied to the materials used in their components, with batteries and permanent magnets depending on the use of critical raw materials such as lithium, cobalt, graphite and neodymium (European Commission, 2023a). The production of battery-grade lithium hydroxide, cobalt sulphate, and graphite involves high GHG emissions, as well as other environmental issues linked to water use, land use, and loss of biodiversity (Giljum et al., 2025; Istrate et al., 2024). Within the supply chain of Nd-Fe-B magnets required for EV rotors, the production of neodymium oxide entails high GHG emissions due to energy-intensive processes, and the voluminous use of chemicals for its extraction drives acidification, photochemical ozone formation and terrestrial eutrophication (Marx et al., 2018; Miranda Xicotencatl et al., 2023).

Assessing the environmental profile of these products is essential to advancing a sustainable mobility transition, with life cycle assessment (LCA) playing a central role; for example, in the EU policy context, with the Critical Raw Material Act and in the Battery Regulation (European Commission, 2024, 2023b). The LCA literature on batteries and their raw materials is extensive (Arshad et al., 2022; Lai et al., 2026). However, despite this growing body of work, a lack of harmonisation in LCA methodological and data choices is still recurrently acknowledged; not only for EV applications (Beylot et al., 2025; Crenna et al., 2021; Eltohamy et al., 2024), both also in other sectors (e.g., Rinke Dias De Souza et al., 2021; Segura-Salazar et al., 2019; Zamagni and Cutaia, 2015; Zumsteg et al., 2012). Harmonisation needs have been identified in the context of TransensusLCA (Beylot et al., 2025; Eltohamy et al., 2024), at the EV level, and in the context of the EU-funded MaDiTraCe project, at the EV raw material and component level (Miranda Xicotencatl et al., 2025a).

Despite broad recognition of the need for harmonisation, existing literature largely focuses on qualitative rather than quantitative assessments. For example, Eltohamy et al. (2024) and Beylot et al. (2025) reviewed scientific LCA studies and existing EV guidelines, and conducted surveys to identify recurring unharmonized topics, such as divergent approaches to handling multifunctionality, differences in electricity supply modelling, or reliance on heterogeneous data sources. Only a limited number of studies have quantified how such methodological and data choices influence the environmental profile of EVs. For instance, Kallitsis et al.(2024) and Peiseler et al.(2024) assessed how different raw material supply sources affect the carbon footprint of lithium-ion batteries, while Eltohamy et al. (2025) assessed how modelling choices, such as multifunctionality and electricity modelling, affect a broader set of environmental impacts for EVs. However, these and similar studies typically



focus either on variability in battery raw material supply chains (primarily from a carbon footprint perspective) or on modelling choices related to EV manufacturing and use. A comprehensive, integrated assessment on how both methodological and data choices within all critical raw materials (i.e., including neodymium) propagate through to influence the environmental profile of EV components is still largely missing. Understanding this and formulating actionable recommendations is crucial in the context of the operationalisation of environmental footprinting under the EU Battery Regulation, Critical Raw Material Act and the Corporate Sustainability Reporting Directive (European Commission, 2024, 2023b, 2022).

The EU-funded MaDiTraCe output D4.6 “LCA methodology for primary and secondary flows” provides methodological guidance for conducting life cycle assessments within the context of the CERA 4in1 certification system (Nowaz et al., 2025), aiming at 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 (Miranda Xicotencatl et al., 2025a).

This study addresses the question: *How do methodological and data choices regarding the supply chain of critical raw materials for EVs influence their environmental profile?* It builds on the methodological guidance developed in MaDiTraCe D4.6, to assess the environmental impacts of an EV product system composed of a lithium-ion battery pack and permanent rotor magnets. The assessment includes hotspot identification and sensitivity analysis of modelling decisions.

2 Method

2.1 Goal and scope definition

The primary goal of this study is to evaluate how methodological and data choices in raw materials supply influence the environmental profile of EV components, specifically batteries and permanent magnets. This analysis aims to:

- Identify environmental hotspots across the supply chain of critical raw materials used in EVs (lithium, cobalt, graphite, and neodymium).
- Assess the sensitivity of LCA results to alternative methodological and data sourcing decisions.
- Demonstrate the application of the methodological choices outlined in MaDiTraCe D4.6 (Miranda Xicotencatl et al., 2025a) and formulate implications for stakeholders.

The product system assessed in this study consists of an NMC811 (nickel-manganese-cobalt) lithium-ion battery and Nd-Fe-B (neodymium-iron-boron) permanent magnets used in EV traction motors. The analysis adopts a cradle-to-gate-plus-grave perspective, encompassing raw material extraction and refining of battery-grade material, component manufacturing, and end-of-life management and recycling. The use phase is generally considered beyond the direct influence of manufacturers, and thus, has been excluded from the system boundaries (European Commission, 2023b).





Companies already have to comply with voluntary and mandatory environmental impact reporting schemes (Akpınar et al., 2025; Nowaz et al., 2025). With cascading implementation dates, depending on the elaboration and implementation of delegated acts, the Battery Regulation demands information in the form of digital product passports (expected to be mandatory for EV batteries from 18 February 2027), and sets carbon footprint requirements (European Commission, 2023b; Rajaeifar et al., 2025). Furthermore, Article 31 of the Critical Raw Materials Act introduced forthcoming obligations for environmental footprint declarations of priority critical raw materials. To comply with these requirements, companies need clear guidance and data; not only on their processes, but also further upstream in their supply chain.

Furthermore, the EVs supply chain is distributed globally, with various actors being owners of the information of specific blocks. Companies may already have access to many actual measurements on their own processes. To cover data gaps, they shall resort to secondary data such as third-party databases (e.g., ecoinvent; Wernet et al., 2016), and other sources. Although D4.6 provides some recommendations for the collection of primary data, this study does not deal with the collection of primary data. However, here we provide publicly available data that can be used for reference when assessing the commodities, intermediate products and components in the supply chain of EV vehicles. The compilation of datasets for the commodities and the components in the supplementary information can be used as a reference to see if the coverage of processes is complete and what kind of environmental flows may be associated with various unit processes. Furthermore, this information allows for identifying data gaps based on the contribution analysis and data quality assessment.

2.2 LCA methodological choices

Article 7 of the Battery Regulation sets the ground for the harmonised calculation and reporting of the carbon footprint of various battery types. The delegated acts, in delayed development, would set the requirements for carbon footprint declarations and establish carbon footprint performance classes and maximum life cycle thresholds (European Commission, 2023b; Rajaeifar et al., 2025).

The MaDiTraCe methodological guidelines, here applied according to Table 1, align with the overarching guidelines ISO 14040:2006 and ISO14044:2006 (ISO, 2006a, 2006b). Furthermore, the MaDiTraCe guidelines, in the scope of carbon footprint, are consistent with the Battery regulation (European Commission, 2023c) and with the draft act supplementing the regulation, whose final version and commission adoption are upcoming (European Commission Services, 2024). While the evaluation of other impact categories besides *Climate change* lies beyond the scope of these reference documents, the MaDiTraCe guidelines recommend the evaluation of at least *Climate change*, *Particulate matter*, *Freshwater ecotoxicity*, *Minerals and metals resource use*, and *Water*, in order to avoid burden shifting.

Table 1 provides an overview of the LCA aspects included in the methodological guidelines provided in MaDiTraCe D4.6 (Miranda Xicotencatl et al., 2025a) and how these were addressed in this study. While some recommendations indicate a single approach, others imply making a choice. Some recommendations fall beyond the scope of this study or cannot be applied due to study constraints. The choices and deviations are also described in this table. The deviations from the MaDiTraCe D4.6 guidelines do not lead to deviations from ISO 14040:2006 and ISO 14044:2006. For ease of reference, the boxes and figures referring to MaDiTraCe D4.6 have been included in Appendix A.



Table 1: Aspects of the MaDiTraCe guidelines and their implementation in this study

LCA aspect	Relevant section in MaDiTraCe D4.6	Relevant section in this study	Deviations and choices
Definition of the function, functional unit and reference flow	Box 1	2.3	Although this assessment declares the environmental impact of the intermediate commodities as in Box 1, the focus is on the product system merging the EV battery and magnets for the EV rotor. Deviation: The merge is not specified in the D4.6 guidelines.
System boundaries definition			
• Assessment of commodities	Box 2	2.4.1, 3.2.1	No choice or deviation required
• Assessment of EV components	Figure E 1, EV battery, and Figure E 2, rotor magnet.		Deviation: Given the goal and scope of this study, no scenarios were created to report on Stage C: Distribution.
Life cycle inventory phase			
• Data quality requirements and assessment	Box 3	2.4.2, 3.2.2	Choice of ecoinvent 3.0 pedigree matrix (Ciroth et al., 2016; Wernet et al., 2016) for data quality assessment.
• Primary data collection	Section 2.4.1	NA	Deviation: Out of scope in this study.
• Secondary data collection	Section 2.4.2	2.4.2, 2.6, 3.2.2	<ul style="list-style-type: none"> • Choice of scientific papers as secondary data sources. Complete LCI datasets were used. • Choice of ecoinvent v3.10.1 (cut-off) as background LCI database.
• Electricity modelling	Section 2.4.3	NA	Deviation: secondary data sources not analysed for sources of supply (on-site generation, grid supply or combination).





• Multifunctionality			
○ Co-production	Table 13	NA	Deviation: approach to multifunctionality inherited from secondary data sources.
○ Modelling waste treatment	Box 4	NA	Choice not to use the Circular Footprint Formula and to follow the "polluter-pays" principle.
○ Recycling in EoL phase	Box 5; Table 4 and Table 14	2.6, 3.2.2	Deviation: Follows the "polluter-pays" principle instead of using the CFF. Choice: sensitivity analysis comparing the chosen approach with the system expansion method (with offset).
Impact assessment	Box 6	2.4.3	Choice to follow best practice and to report on the full list of EF impact categories.

NA= Does not apply

Regarding data sourcing, several guidelines envision strategies to harmonise secondary data that include the provision of prescriptive secondary datasets or the definition of hierarchies of preferred secondary data sources. The "data stock" referred to in the draft act supplementing the regulation (European Commission Services, 2024), to comply with the calculation of the carbon footprint of batteries, is not yet available (Chen, 2024). In the spirit of the use of harmonised datasets, an alternative to the use of the proprietary database ecoinvent would have been the use of the PEF-compliant datasets available in the nodes provided by the European Platform on LCA. However, mapping the ecoinvent environmental flows used in the selected datasets to the PEF-compliant datasets was out of the scope of this study.

2.3 Functional unit and reference flows

The definition of the function, functional unit, and reference flow in LCAs depends on the life cycle stages covered by the product system. In this study, we analysed the product systems at two levels of the supply chain; upstream, at the commodity level, and downstream, at the EV component level. This study defines a basket functional unit (Sanabria Garcia et al., 2025) for the EV components and declares characterised results at the commodity level (see Table 2).

The functional unit for the product system is equivalent to that defined for the battery pack in the Battery Regulation:

"The functional unit is defined as one kWh (kilowatt-hour) of the total energy provided by the battery system over the battery's service life, measured in kWh. The total energy is obtained from the number of cycles multiplied by the amount of delivered energy over each cycle." (European Commission, 2023b)

As a means of reference, the amount of magnets mediating the transformation of electricity into mechanical energy over the battery's service life would be 48 magnets in a rotor;



ca.1.26 kg Nd-Fe-B (Nordelöf et al., 2019, 2018). The magnets are assumed to deliver their intended function over the whole battery service life, without replacement or relevant performance degradation.

Table 2: Primary functions of EV commodities and components at various stages of the supply chain

Commodity or component	Stage	Stage product	Primary function	Declared* or functional unit
Li	Concentration & Purification	lithium carbonate	Produce a battery-grade commodity.	1 kg*
Li		lithium hydroxide		
Co		cobalt sulfate		
Graphite	Refining	natural graphite		
Graphite		synthetic graphite		
EV battery	Battery manufacture	NMC 811 battery pack	Store and distribute electricity to power the EV.	Use capacity for 1 kWh of the total energy provided by the battery system over the battery's service life.
Magnets for rotor	Magnet manufacture	Nd-Fe-B magnets	Mediate the transformation of electricity into mechanical energy.	
Nd	Refining	Nd metal	Produce a refined material ready to be incorporated into the production of new products.	1 kg*

Section 2.4 provides more details regarding the modelling of the focus commodities (Li, Co, Graphite and Nd) and components (EV battery and magnets for rotor). Further information regarding the bill of materials, the link between the commodities and the components, and the representation of other economic and environmental flows is available in the associated repository (Miranda Xicotencatl et al., 2026).

2.4 Inventory Analysis

2.4.1 System boundaries

Figure 1 presents the system boundaries of the compound product system, with a focus on the modular structure of the LCA model. While this representation may serve as a map to navigate the contribution analysis and the model documentation, the sequence in which the processes occur is better captured in Figure E 1, for the EV battery, and Figure E 2, for the magnets.

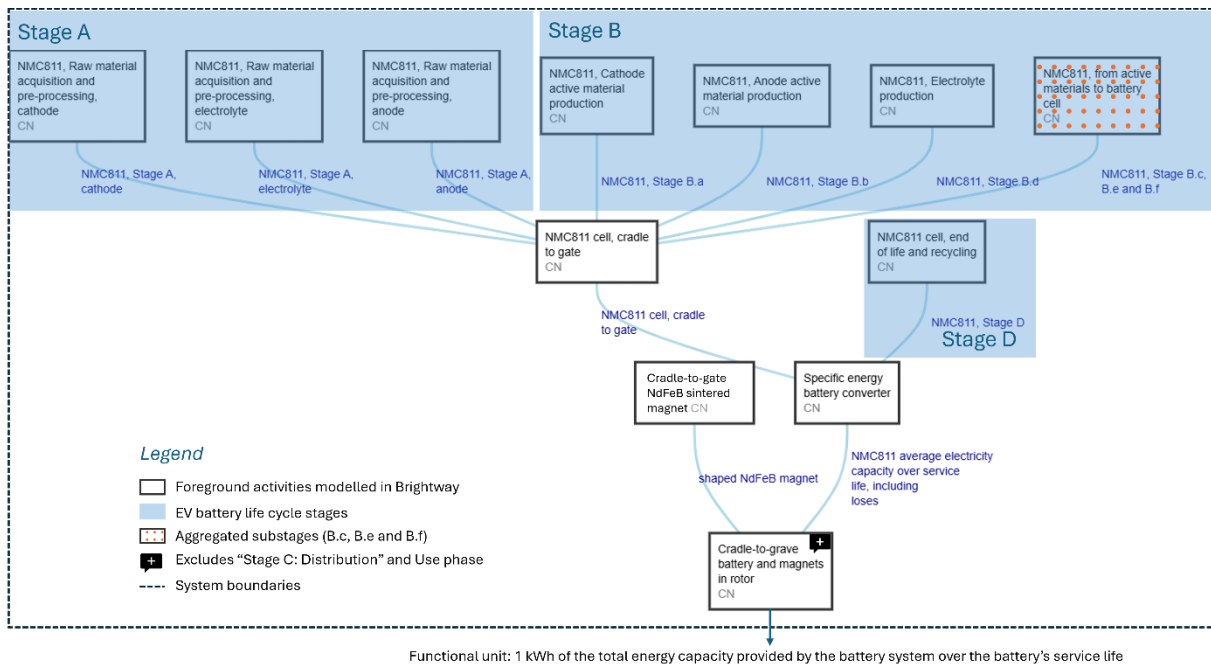


Figure 1: Flowchart for the production system of battery and magnets in an EV, referring to 1 kWh energy capacity over the battery's service life.

2.4.2 Selection of LCI datasets on EV components and commodities

Figure 2 presents which stages (mining, concentration, purification, refining) happen in which location, according to identified open LCI datasets for Co, Li, Graphite and Nd, aimed to depict the global market in 2023 (Lai et al., 2026). In some cases, the data available in the datasets can be associated with a specific stage (e.g., Li mining and concentration in Chile). In others, a location spans across different stages, without further resolution. If a location refers to a country rather than to a site or deposit, it means that the dataset aims to represent the production at the country level, but that the data sources are not traceable to data on specific sites. We performed a geographical coverage analysis to determine to what extent the identified datasets represent the geographical distribution of the supply chain. The analysis compares the locations associated with the LCI datasets with global production data on commodity production, with a resolution traceable to countries and types of deposit (see section 3.1.2).

To model the environmental impact of our product system, we selected the LCI datasets compiled by Istrate et al. (2024) and by Miranda Xicotencatl et al. (2025b) to represent the Li, Co, Nd (for Bayan Obo mine in China, Southern Provinces in China, and Mount Weld in Australia) and graphite commodities. Additionally, the datasets representing Nd from the rare earth deposits in Mountain Pass (US) and Sichuan (China) were sourced from Lai et al. (2026). These datasets, based on peer-reviewed literature (see, e.g., Table 3), are used with ecoinvent v3.10.1 and are available in a standard Brightway format. The data quality of the datasets was evaluated employing the ecoinvent pedigree matrix (Table 1 in Ciroth et al., 2016). Section 3.2.2 summarises the data quality assessment.

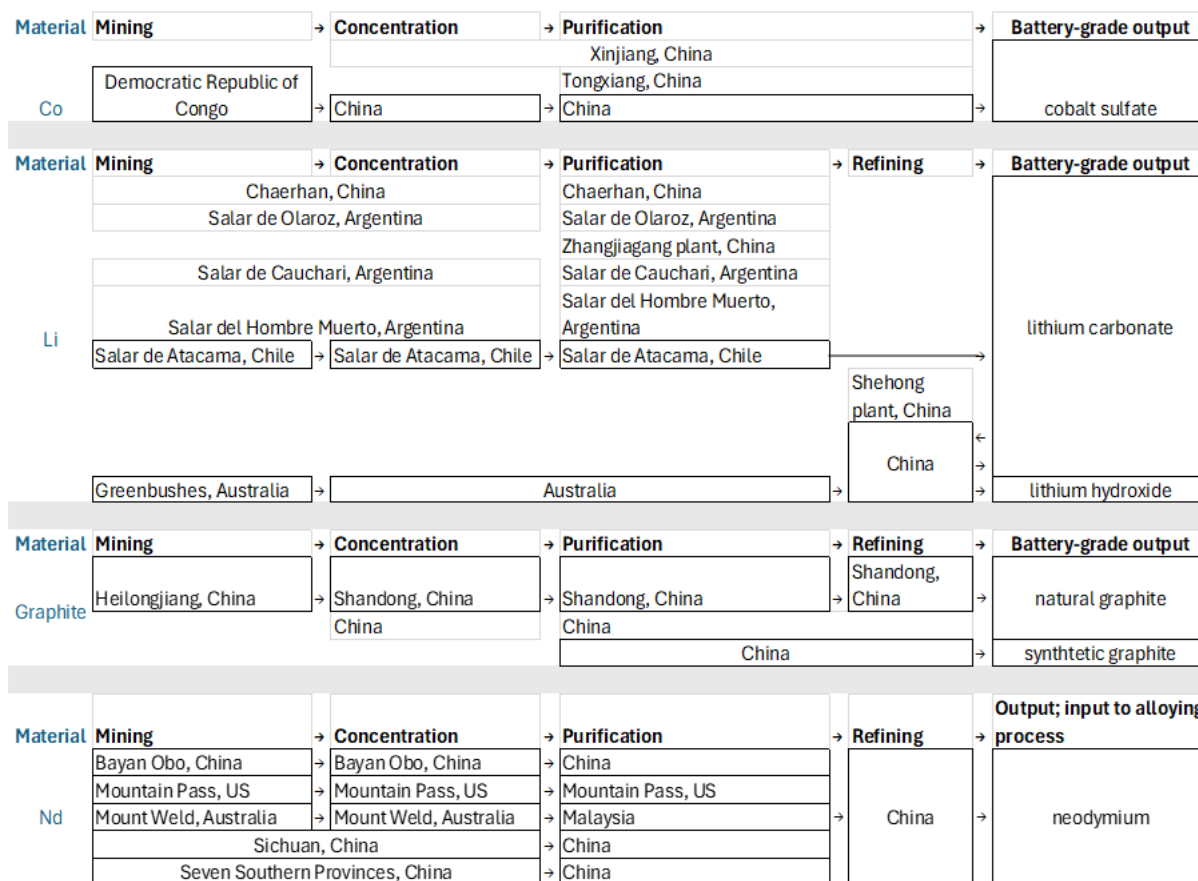


Figure 2: Geographical coverage of commodity's supply chain in a selection of open LCI datasets. The scopes of the LCI datasets used in this study have a black border. Other scopes available in the data compilation by Lai et al. (2026) have a grey border.

Regarding the scope from Co, Li and graphite commodities to End of life and recycling of the NMC811 battery (Stage B to D in Figure 1), we selected the LCI dataset compiled by Šimaitis et al. (2023). This dataset was available in a custom Brightway format and intended to be used with ecoinvent v3.7. Therefore, we migrated the dataset for its use with ecoinvent v3.10.1, remapped the exchanges to better align with the stages in Figure 1 and made it available in a standard Brightway format (Miranda Xicotencatl et al., 2026).

2.4.3 LCIA method

We evaluated the sixteen midpoint impact categories from the Environmental Footprint LCIA method version 3.1 (Andreasi Bassi et al., 2023), according to Table A 1.

2.5 Contribution analysis on the component and commodity level

Classifying the intermediate flows into process groups based on their functions allows reducing the amount of contributor data points while still transparently reporting on the function that these intermediate flows perform (van der Meide et al., 2025). Here, we mapped the intermediate flows according to "functionProcessGroups.xlsx". In addition to the categories Electricity consumption, Process heating, Fuels consumption, and Reagent consumption, which were proposed by Istrate et al. (2024), we further classified the intermediate flows into waste treatment services, infrastructure and transport. The group "Other" consists of the intermediate flows excluded from the proposed categories.



2.6 Methodological and data choices

We assessed a range of methodological and data choices in the supply chain of the selected raw materials. These choices are further categorised into: (i) EoL and recycling, and (ii) commodity traceability.

Table 3: Scenarios on modelling decisions

Choice	Scenario characteristic	Reference scenario description
EoL and recycling	Allocation by Substitution - The displaced burden from recycled materials is deducted from the environmental profile of the product system, following the displaced material assumptions in Šimaitis et al. (2023).	The burden of battery recycling is allocated to the EoL battery.
Commodity traceability *	Co: LCI dataset from ecoinvent v3.10.1 as a proxy for an alternative sourcing.	LCI data from Arvidsson et al. (2022) and Dai et al. (2018).
	Graphite: 100% natural; LCI data from Engels et al. (2022).	Combined supply; 50% natural graphite, 50% synthetic graphite.
	Graphite: 100% synthetic; LCI data from Carrère et al. (2024).	
	Li: 100% from Brine; LCI data from Schenker et al.(2022) and Kelly et al. (2021).	
Li: 100% from Spodumene; LCI data from Kelly et al. (2021) and Wernet et al. (2016).	Combined supply; 50% Li from brine, 50% lithium from spodumene.	

* Except for the Co dataset from ecoinvent, all the LCI datasets were implemented as compiled by Istrate et al. (2024).

3 Life Cycle Impact Assessment results

3.1 LCA Characterisation

3.1.1 Characterisation

Table 4 presents how each of the components contributes to the characterised results of the functional unit. The characterised results for the declared units for the commodities are available in the associated Zenodo repository (Miranda Xicotencatl et al., 2026).

Table 4: Characterised results for the basket functional unit.

Impact category	NMC 811 battery pack	Nd-Fe-B magnets	Functional unit*	Unit



Acidification	2.80E-02	2.70E-04	2.83E-02	mol H ⁺ eq
Climate change	2.11E+00	3.14E-02	2.15E+00	kg CO ₂ eq
Freshwater ecotoxicity	2.11E+01	9.62E-01	2.21E+01	CTUe
Resource use, fossil	2.66E+01	3.59E-01	2.70E+01	MJ
Freshwater eutrophication	1.15E-03	8.20E-06	1.15E-03	kg P eq
Marine eutrophication	2.61E-03	1.40E-04	2.75E-03	kg N eq
Terrestrial eutrophication	2.86E-02	5.52E-04	2.92E-02	mol N eq
Cancer effects	9.43E+00	5.98E-01	1.00E+01	CTUh
Non-cancer effects	1.86E-07	4.61E-10	1.86E-07	CTUh
Ionising radiation	1.71E-01	1.41E-03	1.72E-01	kg U ²³⁵ eq
Land use	3.06E-09	2.63E-11	3.09E-09	points
Resource use, minerals and metals	2.53E-04	4.77E-07	2.53E-04	kg Sb eq
Ozone depletion	4.18E-08	6.40E-10	4.24E-08	kg CFC-11 eq
Particulate matter	2.05E-07	4.95E-09	2.10E-07	disease incidences
Photochemical ozone formation	9.39E-03	1.27E-04	9.52E-03	kg NMVOC eq
Water use	2.85E+00	1.33E-02	2.87E+00	m ³ water

* Use capacity for 1 kWh of the total energy provided by the battery system over the battery's service life.

3.1.2 Geographical coverage

This section presents a geographic comparative analysis between the available LCIs identified in Figure 2 and the supply chains of Li, Co, natural graphite, and Nd (from data on rare earth elements, REEs) in 2022. The goal of this analysis is to provide an overview of how representative the available LCIs are of the mining and processing projects for these materials.

The starting point was the work by Martins da Cunha et al. (2025), who investigated the supply chains, including the main mining and processing countries and projects for these materials in 2022. The first analysis focuses on how representative the LCIs are in terms of amounts produced and was done at the country level. We compared production data from the British Geological Survey (2026) with the LCI data coverage identified in Figure 2. While these values do contribute to the coverage per country production, they do not account for the variability between operations in the same country.

Cobalt supply chains typically involve a strong separation between extraction and refining, meaning that countries dominating mine production may differ from those dominating refined output. The charts in Figure 3 help identify whether LCI availability aligns with where most production occurs in each stage, and where coverage gaps could materially affect



results (e.g., when large shares of production fall into “No LCI”). The values show that, while the LCI data only covers China and the Democratic Republic of the Congo, most of the production is covered, as these are the main producers. The datasets presented in Figure 2 mostly refer to national (*country-level*) data and not site-specific (or regional), which should be noted as the technology and associated impacts in the different projects can vary significantly, as would be the case for the Democratic Republic of the Congo, where there are several mining sites varying from formal to artisanal sites. So while there is a large share of flows covered by at least national LCIs, the uncertainty is likely to be very high when using these LCIs instead of primary data. The shares of mine production in the category OTH (Other) correspond to Chinese production.

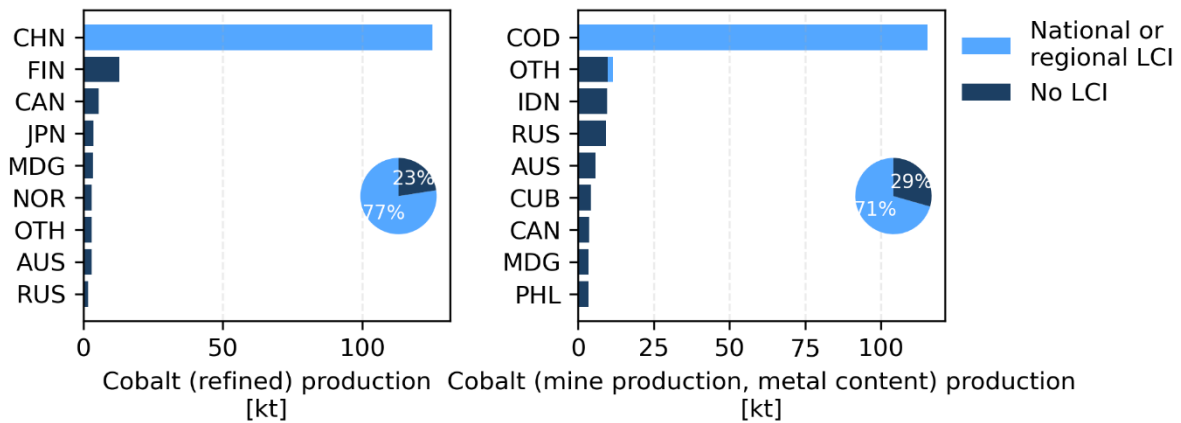


Figure 3: Refined cobalt production and mined cobalt production in 2022 compared with LCI data availability. Countries are identified with their ISO3 code, and “OTH” groups countries with the smallest producing shares.

Lithium minerals production in 2022 is shown by country, split into volumes that are associated with an LCI dataset versus volumes with no identified LCI coverage in Figure 4. The figure aggregates all “Lithium minerals ...” variants (e.g., Li content, carbonate-Li content, chloride-Li content, hydroxide) to provide a consolidated view of upstream supply. Several producing countries display a mixed profile—part of their production is linked to LCI data while another share is not—highlighting that LCI availability depends on the specific product form and dataset coverage rather than on the country alone. As for cobalt, while datasets focus only on a few of the producing countries, most production can be covered by LCIs for the country or sites.

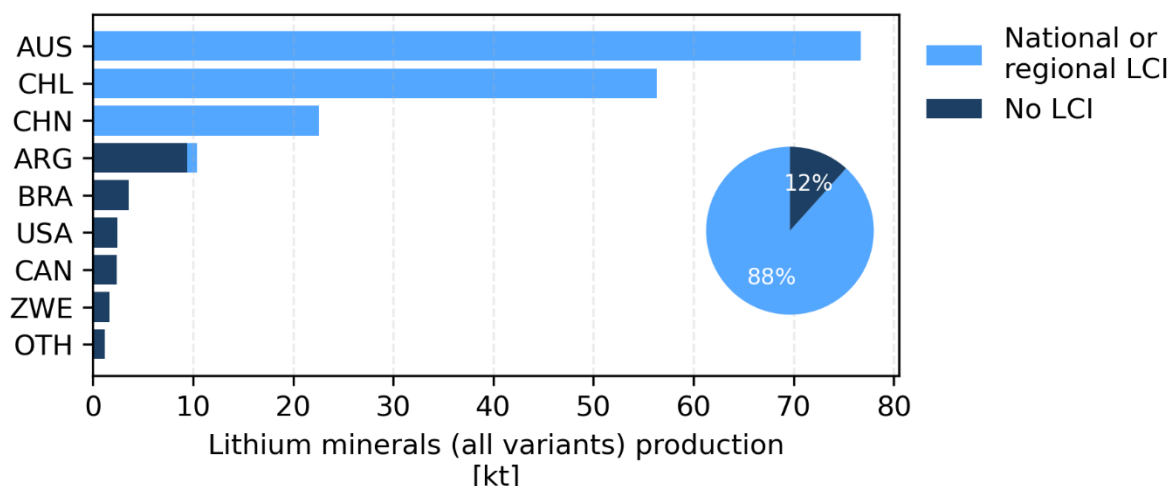


Figure 4: Lithium content of all mined lithium minerals in 2022 compared with LCI data availability. Countries are identified with their ISO3 code, and "OTH" groups countries with the smallest producing shares.

Figure 5 presents the natural graphite production in 2022 by country, split into volumes that are associated with an available LCI dataset versus volumes with no identified LCI coverage. As shown previously in Figure 2, there are only LCIs for natural graphite production for China. In 2022, China accounted for 67% of the produced graphite. Although the LCI datasets at project or country level might be somewhat representative of the majority of the production, it is not possible to establish a formal link. For the remaining 33% of graphite production in other countries, there are no LCI datasets and this will be associated with even greater uncertainty for the environmental impact of the global market.

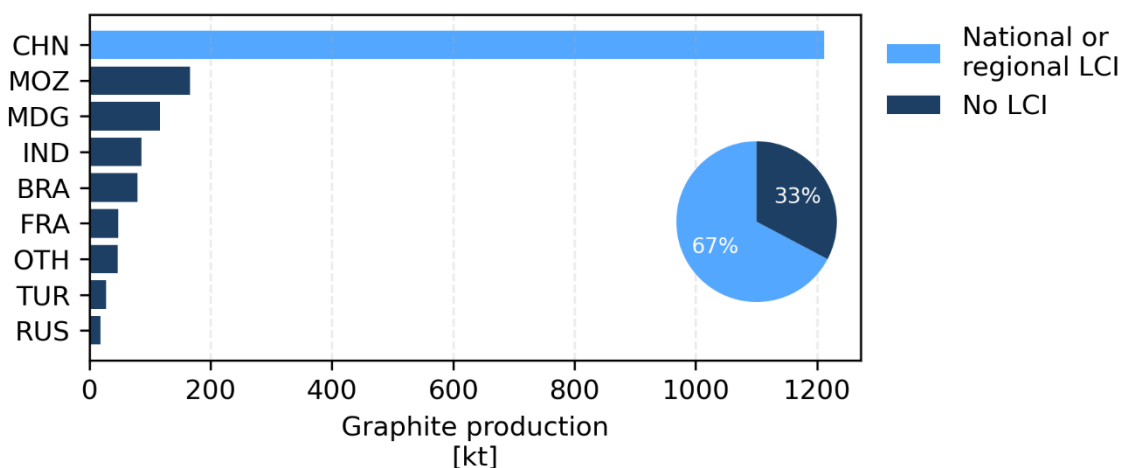


Figure 5: Natural graphite production of 2022 compared with LCI data availability. Countries are identified with their ISO3 code, and "OTH" groups countries with the smallest producing shares.

To address Nd, Figure 6 presents the geographic distribution of REEs production in 2022 and contrasts it with the availability of country-specific LCIs for Nd. The results indicate that LCI availability is concentrated in a small subset of producing countries, and that the "No LCI" share captures remaining production for which inventories would need to rely on proxies or generic datasets, increasing uncertainty and the risk of regional bias. This is



especially relevant for Nd and other REEs because they are typically produced as part of mixed concentrates and co-product streams, meaning that missing regional LCIs may also imply missing representativeness for allocation choices and waste management practices that can drive impacts.

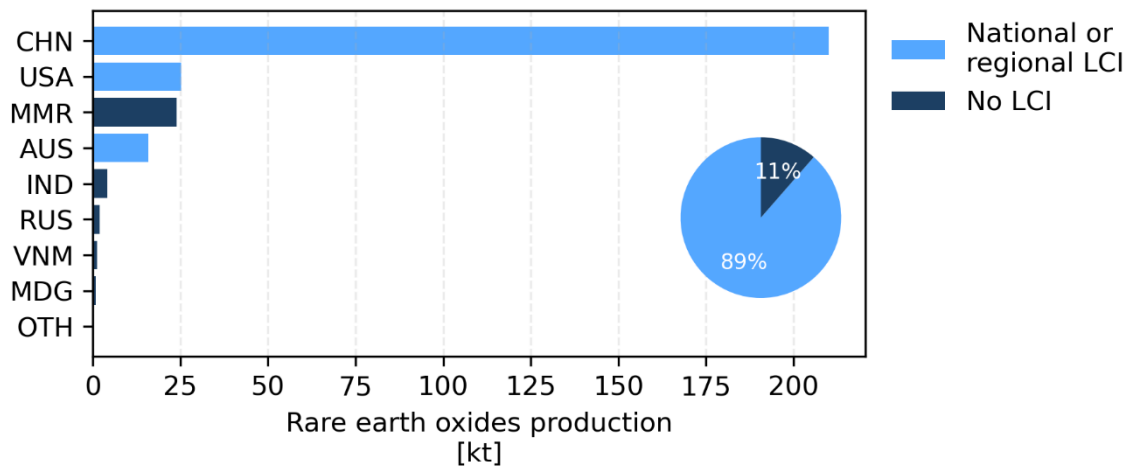


Figure 6: Rare earth oxide production (including Nd) in 2022 compared with LCI data availability. Countries are identified with their ISO3 code, and “OTH” groups countries with the smallest producing shares.

As shown for the case of cobalt, there may be a “national” or regional LCI coverage, but if there are various and diverse projects in that region, the associated uncertainty could also be significant. To further explore this, the sites were also considered. In order to illustrate how representative the LCIs of the different projects and processing plants are, the locations identified in D3.8 (Martins da Cunha et al., 2025) were compared with the LCIs identified in Figure 2. However, production amounts are not covered. There are some data limitations on the supply chain data, as discussed in the report regarding the supply chain D3.8 (Martins da Cunha et al., 2025) For example, natural graphite processing plants only include plants outside of China found on open sources, despite China having natural graphite production. The results of the comparison are presented in the following figures. Four different categories were considered: sites with site-specific LCIs available (Project level LCI), sites with regional LCIs available (Regional LCI), sites with national level LCIs available (National LCI), and all other sites for which one would have to use LCIs based on operations in other countries (No LCI).

Figure 7 maps the identified upstream supply chain locations for cobalt, distinguishing **mines** and **processing plants** and indicating whether an **LCI dataset** is available for the corresponding activity. Points are plotted at the reported latitude/longitude coordinates from the supply chain mapping dataset. The LCI data comparison in Figure 7a) shows that there is generic mining data for the Democratic Republic of the Congo, and for mines in one Chinese region, as previously identified in Figure 2. While this translates into a high production coverage, as shown in Figure 3, it is clear that not only is the uncertainty associated with the covered production very high, as only national data is available, but that there is also a considerable number of projects outside the Democratic Republic of the Congo and China for which no LCI inventory is available. The data for the processing plants in Figure 7 b) shows that while there is one site for which there is data and one region as well, as for the mines, the large majority of projects are not covered by the identified LCIs.



It is clear that considering the origin of the minerals is important, as the impacts can vary according to where the cobalt was mined and processed. Additionally, when comparing LCA results, it should also be noted how much of the data was collected, considering the actual available data coverage.

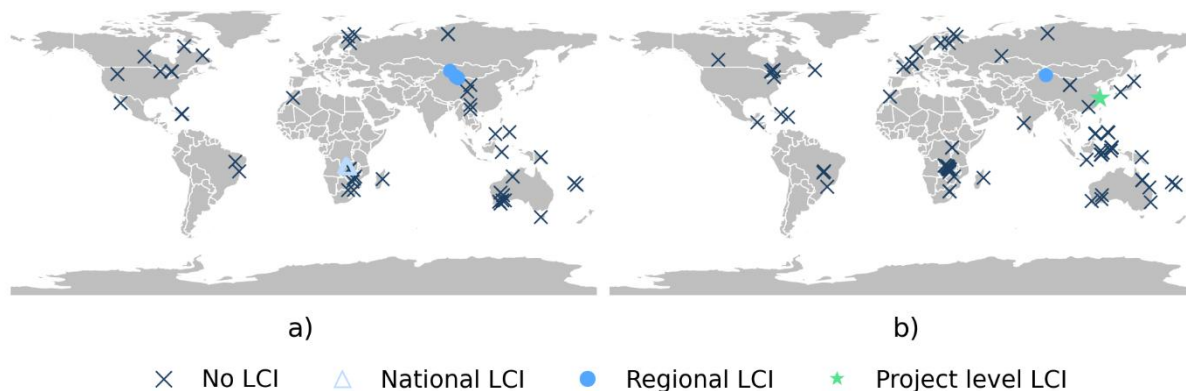


Figure 7: Global distribution of mapped a) mines and b) processing plant locations for cobalt, showing LCI data availability by site. Figure 8 (a) shows that, unlike for cobalt, the production is somewhat distributed between a few regions and within three of the regions, there is at least one site with site-specific data, as is the case for the processing plants in Figure 8 (b). There are, however, clusters and sites for which there is no data available, which suggests that proxy data may be required for parts of the supply chain. This is particularly relevant for lithium because production occurs in multiple product forms (e.g., concentrates and brines upstream, and refined carbonate/hydroxide downstream), and impacts are sensitive to processing route and regional energy and water conditions; consequently, gaps in site-level LCI coverage can translate into higher uncertainty and potential regional bias in downstream assessments. This is noticeable, looking at Australia, for example, where there are multiple mining projects and LCIs for only one region, as is the case for China. While in North America, Europe, Brazil and Africa there is no LCI at all.

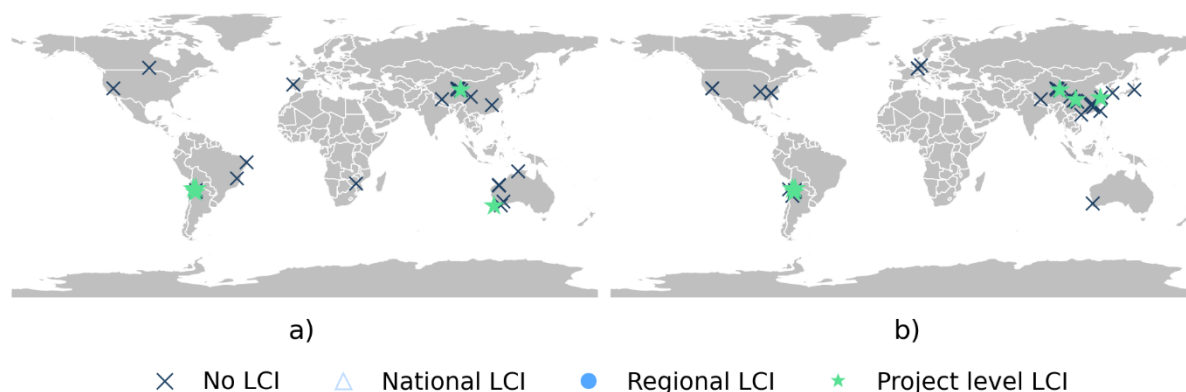


Figure 8: Global distribution of mapped a) mine and b) processing plant locations for Li, showing LCI data availability by site.

For natural graphite, the mapped sites in Figure 9 show the global distribution of a) extraction and b) processing locations, particularly those outside of China, for which there are no LCIs. While currently the available datasets allow for the calculation of impacts associated with at least national data (89% of the production), the remaining 11% is spread across different regions for which there are no available LCIs.

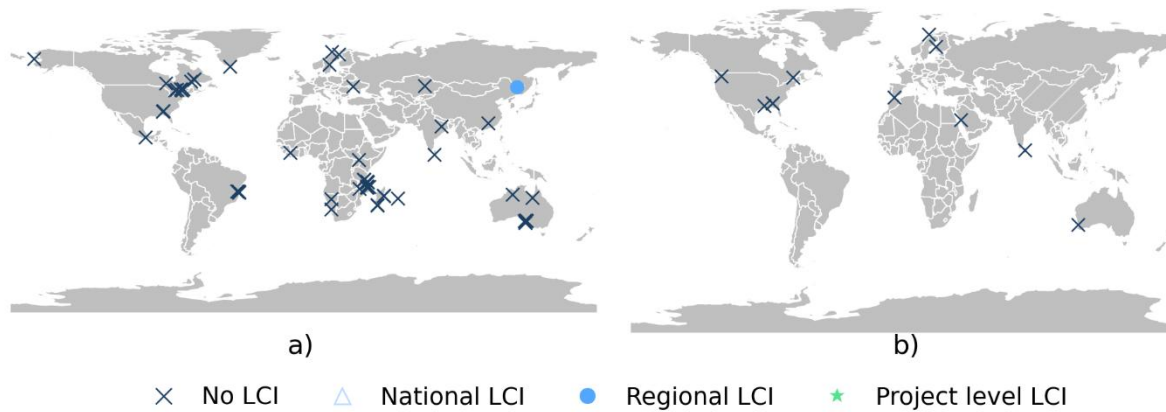


Figure 9: Global distribution of mapped a) mines and b) processing plant locations for natural graphite, showing LCI data availability by site. Plants in China are not covered by the data.

This analysis shows that when looking at production for which there is at least a national LCI, a large share of the production is covered, the site-level analysis shows the geographical coverage is actually quite poor, which means that countries or sites that may want to differentiate themselves by their technologies and impacts, they would not be able to do it based on existing LCIs. This shows the relevance and value of collecting primary data on operations and of having a system, such as Digital Product Passports, to leverage this data further down the supply chain, from product producers to consumers.

3.2 Interpretation

3.2.1 Hotspot analysis on the component and commodity level

On the component level, Figure 10 reveals that the supply chain of the battery drives most of the environmental burden of the product system. In contrast, the magnets, much smaller in mass, contribute less than 7% in every impact category. The aggregated stage from active materials to battery cell ("B.c, B.e and B.f") is the largest contributor to the environmental impact in thirteen categories (28%-87%)². Based on the resolution of the LCI data provided by Šimaitis et al. (2023), this stage aggregates the environmental impact of the following substages: Anode and cathode production (B.c), Assembly of housing and thermal conditioning system (B.e) and Assembly into battery cell (B.f).

In contrast, the cathode raw material acquisition and pre-processing (Stage A, cathode) is the largest contributor to the impacts on Ionising radiation (56%), Particulate matter (34%) and Water use (68%), while contributing notably to Climate change (17%). Anode raw material acquisition and pre-processing (Stage B, anode) stage has notable contributions to Climate change (27%), Fossil resource use (26%), Marine and Terrestrial eutrophication (22%), and Particulate matter and Photochemical ozone formation (20%).

² Acidification, Climate change, Freshwater ecotoxicity, Resource use, fossil, Freshwater eutrophication, Marine eutrophication, Terrestrial eutrophication, Cancer effects, Non-cancer effects, Land use, Resource use, minerals and metals, Ozone depletion, and Photochemical ozone formation.



	Battery							Magnets		
Acidification	21%	10%	0-1%	5%	0-1%	1%	55%	7%	0-1%	0-1%
Climate change	17%	27%	0-1%	15%	0-1%	1%	29%	9%	1%	0-1%
Freshwater ecotoxicity	20%	8%	0-1%	5%	0-1%	0-1%	54%	7%	4%	0-1%
Resource use, fossil	21%	26%	0-1%	13%	0-1%	1%	28%	9%	1%	0-1%
Freshwater eutrophication	14%	9%	0-1%	5%	0-1%	0-1%	64%	6%	0-1%	0-1%
Marine eutrophication	17%	22%	0-1%	12%	0-1%	1%	33%	8%	5%	0-1%
Terrestrial eutrophication	16%	22%	0-1%	12%	0-1%	1%	39%	8%	2%	0-1%
Cancer effects	15%	4%	0-1%	7%	0-1%	0-1%	59%	14%	0-1%	0-1%
Non-cancer effects	6%	2%	0-1%	1%	0-1%	0-1%	87%	3%	0-1%	0-1%
Ionising radiation	56%	12%	0-1%	8%	0-1%	1%	16%	6%	0-1%	0-1%
Land use	16%	13%	0-1%	7%	0-1%	2%	50%	6%	6%	0-1%
Resource use, minerals and metals	20%	0-1%	0-1%	0-1%	0-1%	0-1%	75%	3%	0-1%	0-1%
Ozone depletion	21%	9%	0-1%	12%	0-1%	2%	35%	20%	1%	0-1%
Particulate matter	34%	20%	0-1%	9%	0-1%	1%	25%	7%	2%	0-1%
Photochemical ozone formation	19%	20%	0-1%	11%	0-1%	1%	39%	8%	1%	0-1%
Water use	68%	15%	0-1%	2%	0-1%	0-1%	7%	7%	0-1%	0-1%
	Stage A, cathode	Stage A, anode	Stage A, electrolyte	Stage B.a, cathode AMP	Stage B.b, anode AMP	Stage B.d, electrolyte AMP	Stage B.c, B.e and B.f	Stage D, EOL and recycling	Stage A, magnet	Stage B, magnet

Figure 10: Life cycle stage contribution analysis. For each impact category, the contributions add up to 100%. **Stage A:** Raw material acquisition and pre-processing (disaggregated into anode, cathode and electrolyte materials); **Stage B:** Main product production; **AMP:** Active material production; **Stage B.c, B.e and B.f:** from active materials to battery cell; **Stage D:** End of life and recycling.

The EoL and recycling stage (Stage D) contributes mainly to Ozone depletion (20%) and Human toxicity, cancer effects (14%). On the magnet supply chain, the Raw material acquisition and pre-processing stage is the main hotspot across all impact categories.

On the commodity level, Figure 11 shows the diverse contributions by the functional sources across the eight commodities. *Reagent consumption* emerges as the primary driver for cobalt sulphate and the lithium from brine commodities, with average shares exceeding 50%, while *Electricity consumption* dominates for graphite systems, reaching an average share of 77% for synthetic graphite. *Reagent consumption* also drives the environmental impact of neodymium, with an average share of 38%, with *Electricity consumption* as the second largest contributor. Furthermore, *Process heating* reaches an average share of 48% for lithium carbonate from spodumene. The spread between minimum and maximum contributions by the functional groups with the largest averages (e.g., 7-91% for lithium hydroxide from spodumene) highlights the heterogeneity of environmental burdens across categories, reinforcing the need for addressing the hotspots and data gaps from a systemic perspective.



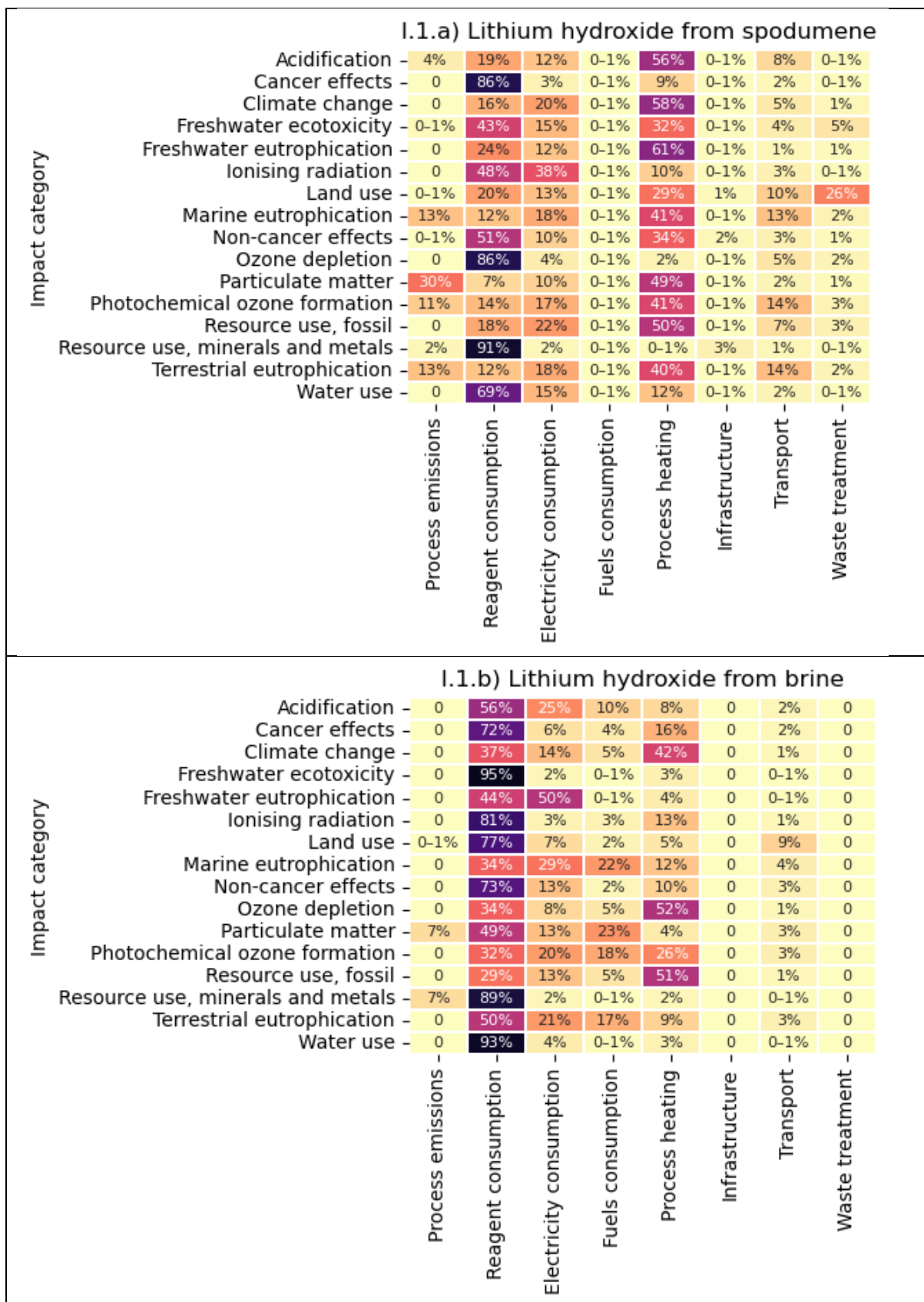


Figure 11: Hotspots on the commodity level for (I.1) lithium hydroxide from (a) spodumene and (b) brine.

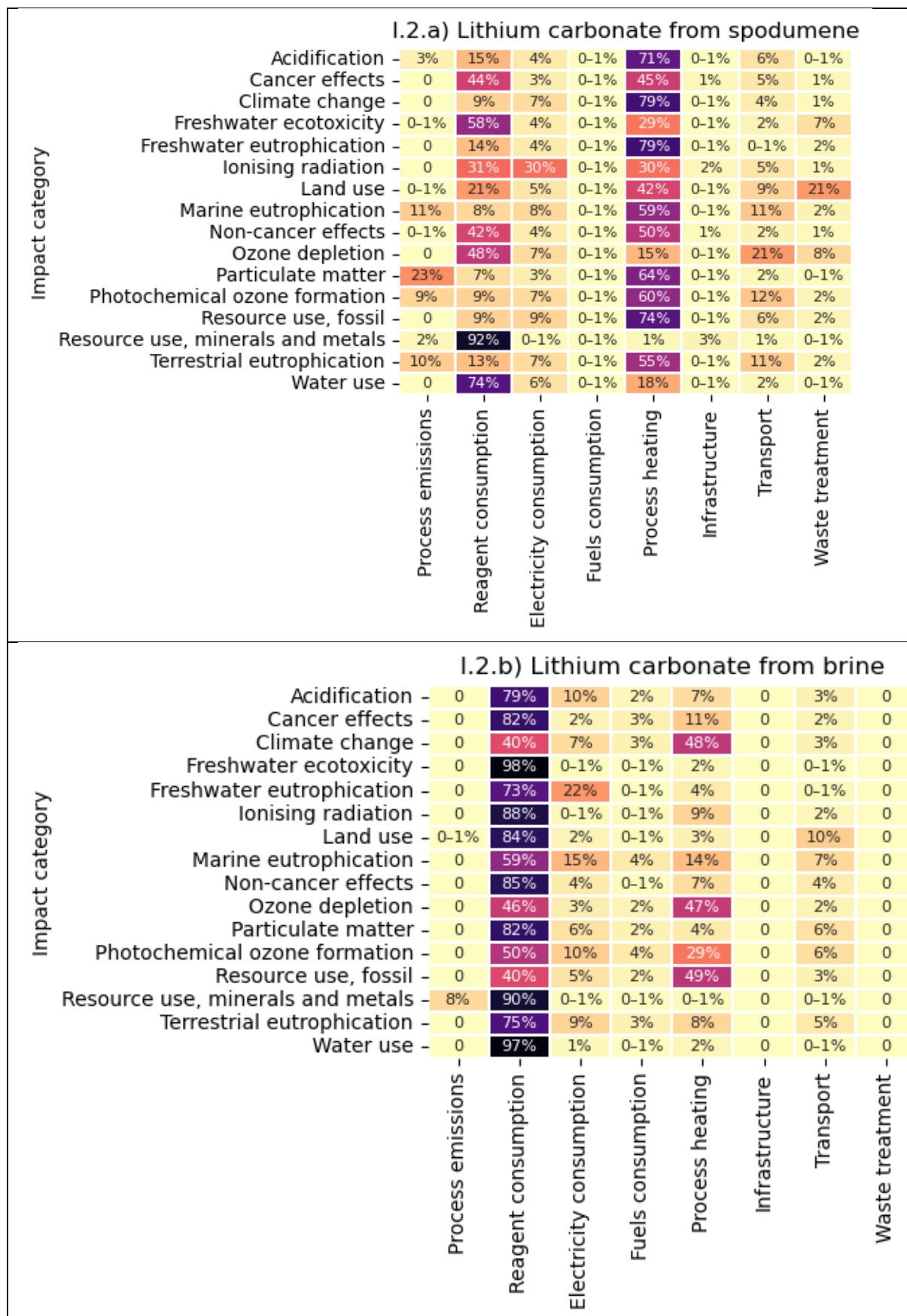


Figure 11 (cont'd) Hotspots on the commodity level for (I.2) lithium carbonate from (a) spodumene and (b) brine.



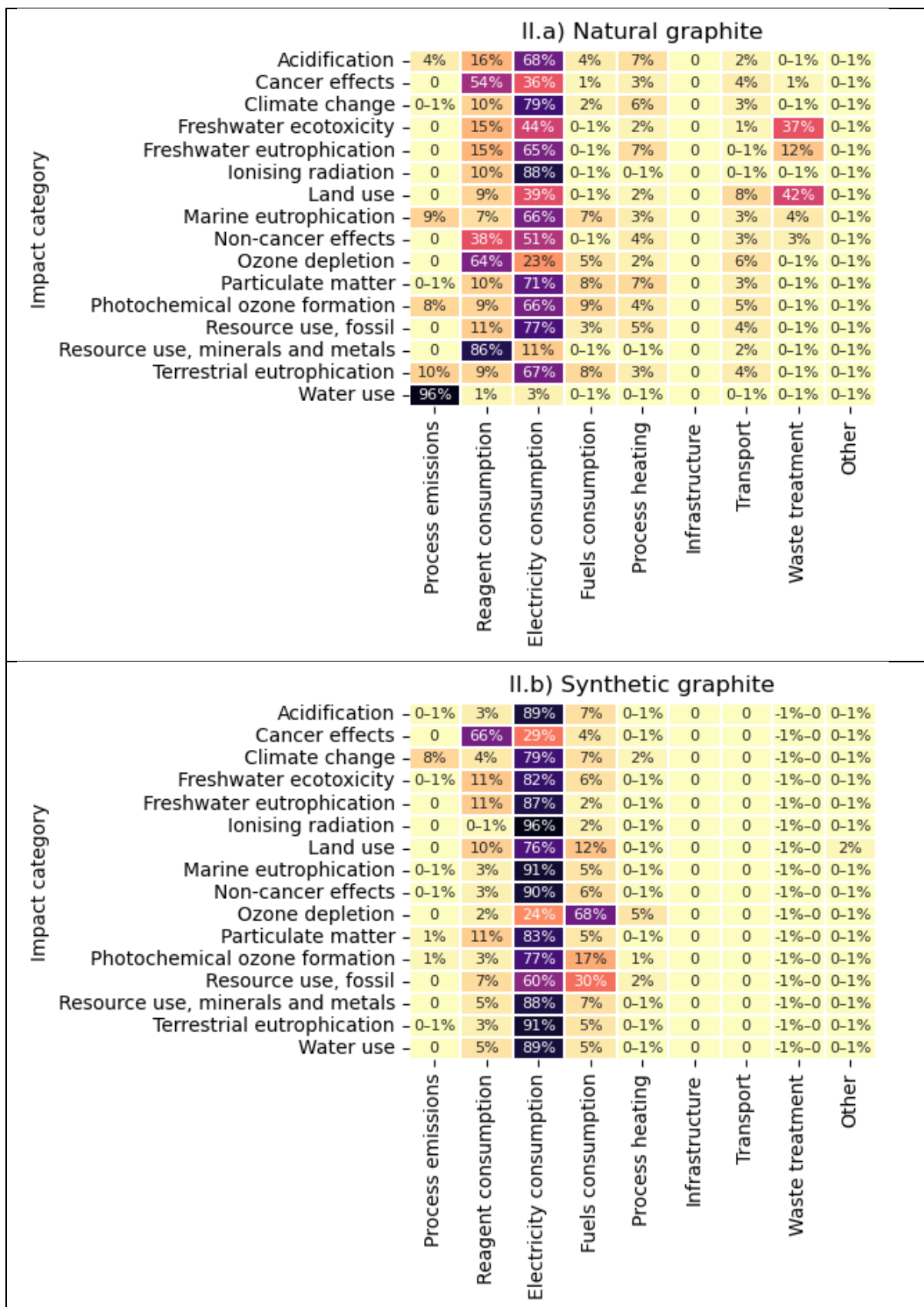


Figure 11 (cont'd) Hotspots on the commodity level for (II.a) natural and (II.b) synthetic graphite.

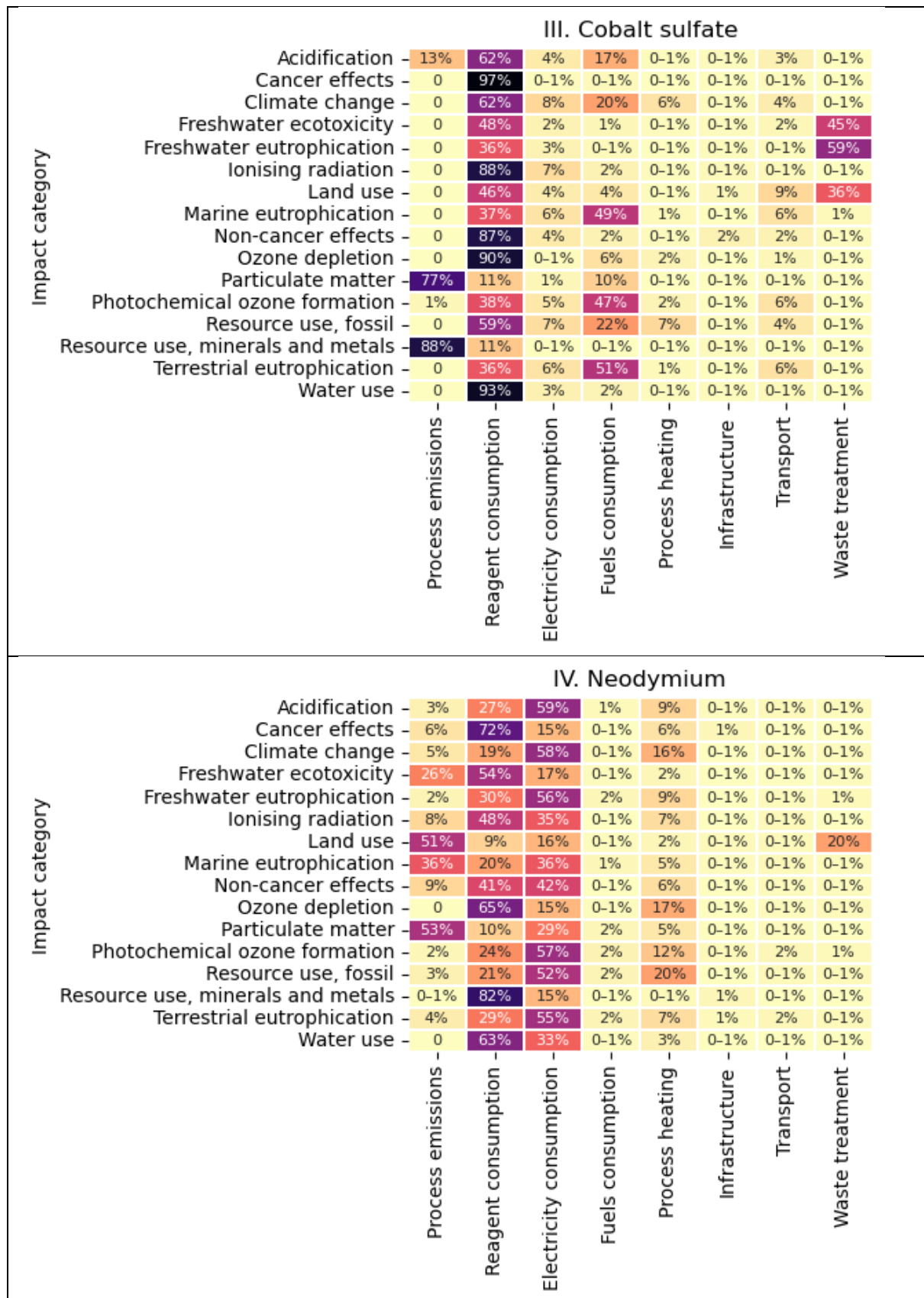


Figure 11 (cont'd) Hotspots on the commodity level for (III) cobalt sulphate and (IV) neodymium.



3.2.2 Data quality assessment

On the 1-5 scale used in the ecoinvent pedigree matrix, a lower score represents better quality. The ecoinvent pedigree matrix specifies quality assessment criteria on Reliability, Completeness, Temporal correlation, Geographical correlation and Further technological correlation (Ciroth et al., 2016). The data quality assessment matrices are available in Zenodo (Miranda Xicotencatl et al., 2026). Most of the dataset scores range from 1-5 along the criteria, with many datasets scoring 1 at Reliability, Geographical correlation and Further technological correlation. Regarding Geographical correlation, most of the datasets aim at representing specific sites rather than global production averages. Here, the main exception is graphite, whose data scores 5 in Geographical correlation, with no site-specific data and assumptions placing the modelled production processes in China. Similarly, the mining of rare earths holds a high Geographical correlation to specific sites that decreases further downstream, as further processing into commodities is modelled to occur in China.

Across the LCIs of the commodities, many scores rely partly on assumptions, public unverified data, or single-site information. Therefore, the data quality on these commodities would benefit from collecting data from multiple facilities rather than one site, performing multi-year sampling to cover operational variability and promoting direct measurement at the production sites.

3.2.3 Effect of modelling and data choices

Modelling decisions significantly affect results. As Figure 12 shows, the scenario "Allocation by Substitution" deals with the modelling decision with the highest impact among the evaluated scenarios (see Table 3).

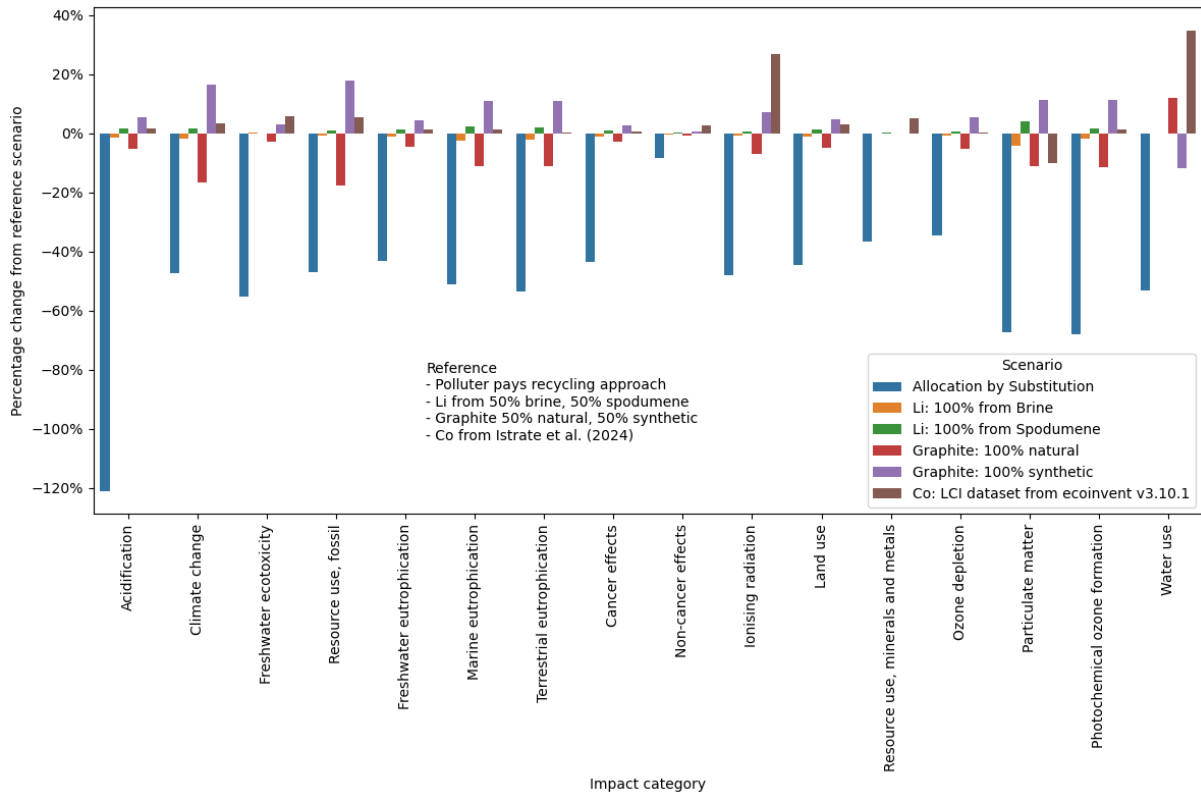


Figure 12: Percentage change indicator results from reference scenario. Scenarios according to Table 3.



The burden displaced by the recycling of the materials assumed by Šimaitis et al. (2023) seems to compensate for the impacts from the product system. The offset leads to apparent environmental benefits on acidification (-121% less than the reference; see also Figure A 1). Commodity sourcing alters climate change impacts by up to 16% (Co data sourcing).

4 Conclusion

This study contributes to improving comparability and transparency in LCAs of EV components, supporting industry compliance and informed decision-making. Here, we illustrated how the environmental profiles of Li, Co and graphite, in an EV battery pack, and of Nd, in an EV rotor, look side to side. With this, we shed some light regarding considerations for prioritisation. EV manufacturers could achieve better environmental performance by managing the environmental profile of their batteries than by managing the environmental performance of their EV rotors. However, rotor manufacturers should ideally remain mindful of the environmental impact of Nd in their magnets.

The Battery Regulation deems to establish carbon footprint performance classes and maximum carbon footprint thresholds. However, given the large impact of underlying assumptions and methodological choices on characterised results, standalone characterised results should not be used as a benchmark for product comparison. With transparently reported assumptions and methodological choices, LCA results can be better interpreted and compared. If multiple LCAs on related product systems followed harmonised procedures, the time for decoding and comparing them would be reduced. Therefore, a clear and comprehensive guide to produce Battery passports or EU-compliant LCA data on critical raw materials would enhance the consistent comparison between products.

With relevance to policymakers, companies, certification bodies and auditors, this study illustrates how the emerging EU Battery Regulation and the Critical Raw Materials Act can be operationalised through harmonising LCA methodologies such as MaDiTraCe D4.6. Certification schemes can therefore reference this study as a concrete example of how to fulfil the data quality, transparency, and traceability requirements embedded in the CERA 4in1 and Battery Regulation frameworks, yet under development.

The deviations from the MaDiTraCe D4.6 guidelines in this study (listed in Table 1), illustrate how certain methodological choices—such as collecting primary data, in-depth electricity modelling analysis, or implementing the CFF for recycling—can demand time-consuming data collection and modelling effort. Implementing these choices may therefore introduce practical challenges (e.g., locating site-specific primary data, reconciling differing allocation rules, or documenting the rationale for deviating from the prescribed approach). Stakeholders should monitor these implementation hurdles closely, document any extra resources required-, and be willing to adapt the LCA workflow if the added complexity outweighs the expected benefits.

Finally, a promising direction for future research is to close the current coverage gap in the LCI data. At present, many mines and processing facilities are either omitted or represented only at a coarse, aggregated level, which limits the ability to reflect the true geographic and technological heterogeneity of the supply chain. Developing higher-resolution datasets that map individual extraction sites and processing plants would therefore improve the representativeness of the assessments. The EU policy push towards the collection of





company-specific data and the development of the Digital Product Passport system may contribute to addressing this gap. In parallel, the existing emission data are heavily weighted toward climate-change indicators; as data-management infrastructures evolve and the processing of information into reporting workflows becomes more streamlined, it will become feasible to capture a broader suite of direct environmental interventions. Incorporating these additional streams would enhance the assessment of impact categories beyond climate change and provide a more holistic picture of the environmental performance of critical raw-material supply chains.



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6 Appendix A

Excerpt of selected elements from MaDiTraCe D4.6 LCA methodology for primary and secondary flows – Extracted for Reference

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	



Box 2: **System boundaries definition**

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



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:

$$s_{i,c} = \frac{\textit{intensity}_{i,c} \cdot \textit{activity}_i}{\textit{impact}_c}$$

where $s_{i,c}$ is the percentage contribution of dataset i to the total impact in category c , $\textit{intensity}_{i,c}$ is the impact intensity of dataset i in category c (i.e., impact per unit of output), and \textit{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 criteria as the weighted average of the quality scores and the percentage contributions of the datasets, as follows:

$$DQR_{q,c} = \sum_i \textit{score}_{q,i} \cdot s_{i,c}$$

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





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

$$DQR_{tot_c} = \frac{TeR + GeR + TiR}{3}$$

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.



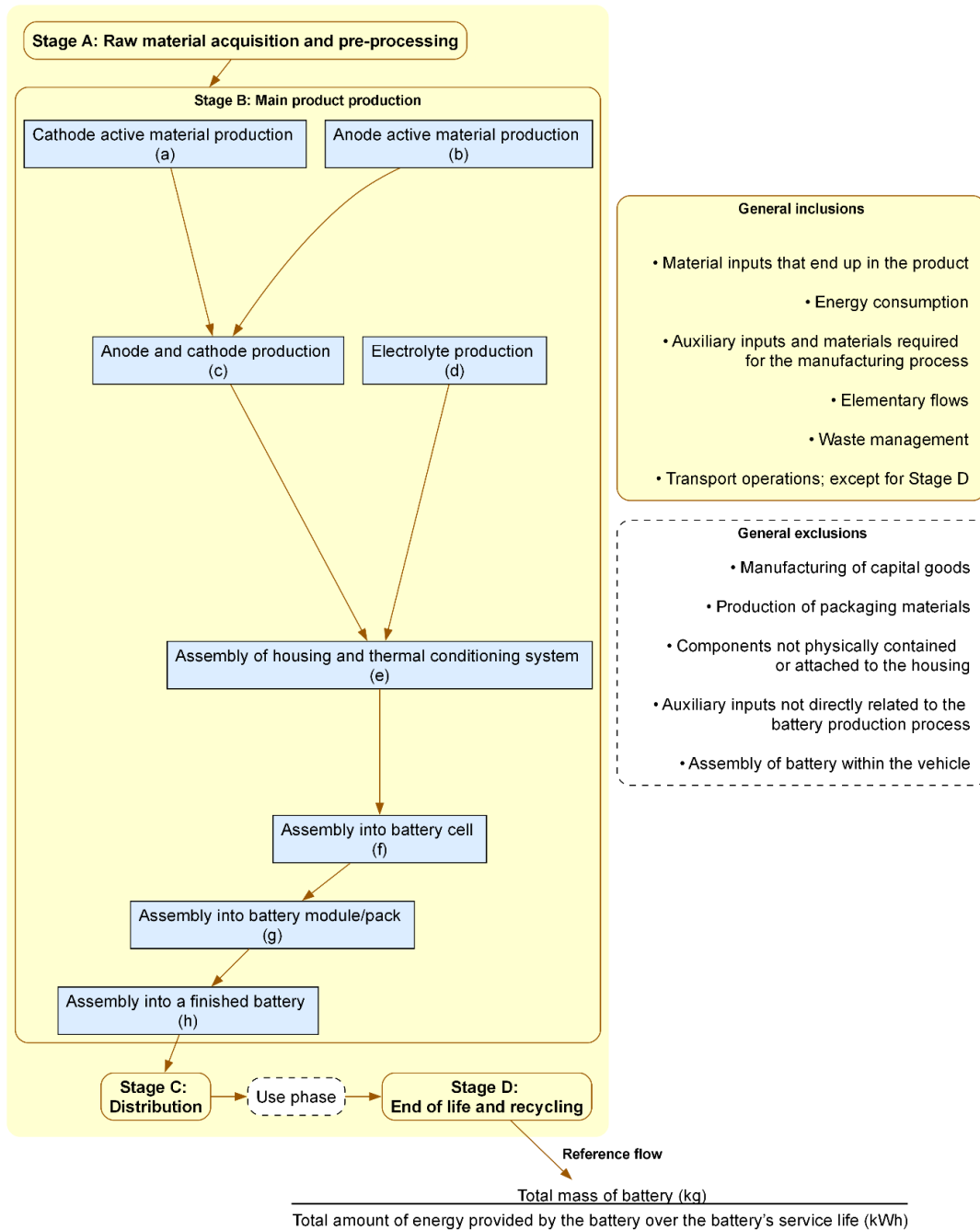


Figure E 1: Flow diagram of the product system of an electric vehicle battery. System boundaries that shall be considered for LCAs of electric vehicle batteries. In alignment with the initiative supplementing Regulation (EU) 2023/1542 (European Commission Services, 2024), the stages and items with yellow 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. *Note: This is Figure 4 in D4.6.*

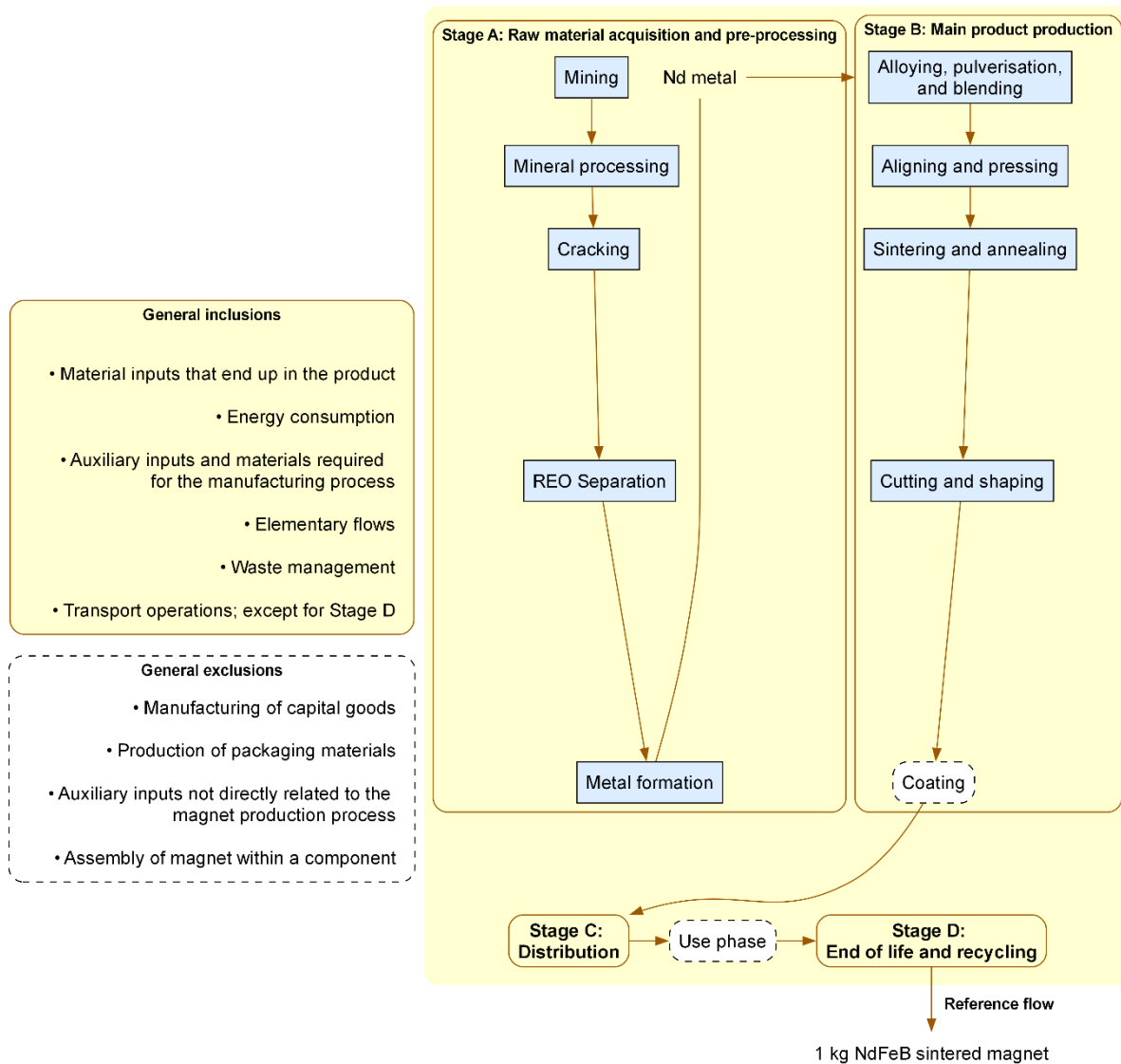


Figure E 2: Flow diagram of the production of NdFeB sintered magnets. illustrates the system boundaries that shall be considered for LCAs of sintered magnets. Drawing from the initiative supplementing Regulation (EU) 2023/1542 (European Commission Services, 2024) and combining with the PCR for rare earth products (EPD INTERNATIONAL, 2024), 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. Note: This is Figure 5 in D4.6.

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.



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).

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.

Supplementary information

Table A 1 Representation of impact categories from the EF LCIA method v3.1. (Andreas Bassi et al., 2023; Mutel, 2017; Steubing et al., 2020)

Impact category	ILCD level ³	LCIA method according to the ecoinvent implementation in Brightway and the Activity Browser
Climate change	I	EF v3.1 climate change global warming potential (GWP100)
Ozone depletion	I	EF v3.1 ozone depletion ozone depletion potential (ODP)
Particulate matter	I	EF v3.1 particulate matter formation impact on human health
Photochemical ozone formation	II	EF v3.1 photochemical ozone formation: human health tropospheric ozone concentration increase
Acidification	II	EF v3.1 acidification accumulated exceedance (ae)
Eutrophication, terrestrial	II	EF v3.1 eutrophication: terrestrial accumulated exceedance (AE)
Eutrophication, aquatic freshwater	II	EF v3.1 eutrophication: freshwater fraction of nutrients reaching freshwater end compartment (P)
Eutrophication, aquatic marine	II	EF v3.1 eutrophication: marine fraction of nutrients reaching marine end compartment (N)
Ionising radiation, human health	II	EF v3.1 ionising radiation: human health human exposure efficiency relative to u235

³ According to ILCD levels: "Level I" (recommended and satisfactory), "Level II" (recommended but in need of some improvements) or "Level III" (recommended, but to be applied with caution)





Human toxicity, cancer effects	III	EF v3.1 human toxicity: carcinogenic comparative toxic unit for human (CTUh)
Human toxicity, non-cancer effects	III	EF v3.1 human toxicity: non-carcinogenic comparative toxic unit for human (CTUh)
Ecotoxicity freshwater	III	EF v3.1 ecotoxicity: freshwater comparative toxic unit for ecosystems (CTUe)
Resource use, energy carriers	III	EF v3.1 energy resources: non-renewable abiotic depletion potential (ADP): fossil fuels
Resource use, minerals and metals	III	EF v3.1 material resources: metals/minerals abiotic depletion potential (ADP): elements (ultimate reserves)
Land use	III	EF v3.1 land use soil quality index
Water use (deprivation)	III	EF v3.1 water use user deprivation potential (deprivation-weighted water consumption)



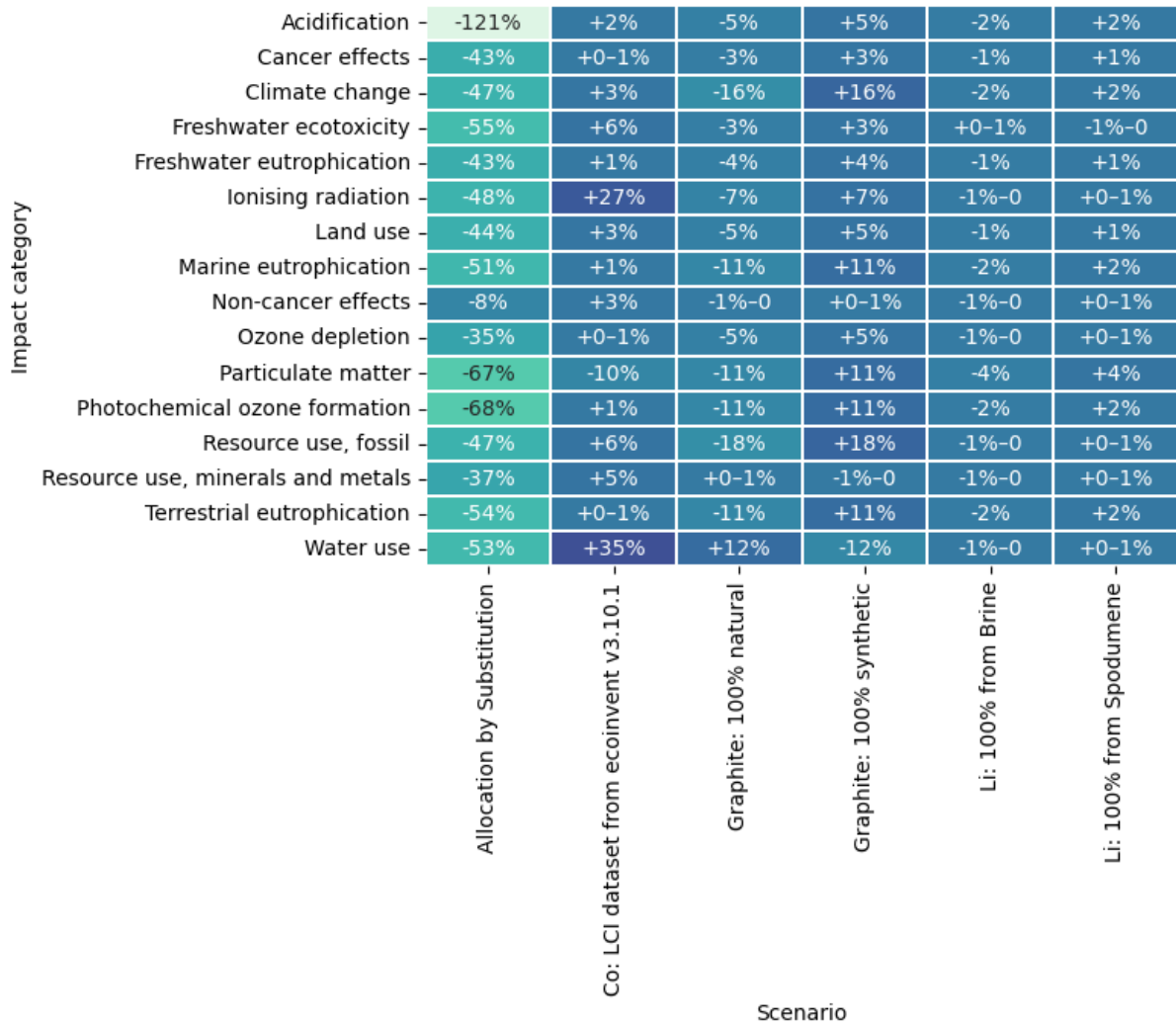


Figure A 1 Heatmap of percentage change indicator results from reference scenario





7 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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