Integration of Life Cycle and Criticality Assessments: Case-Based Investigation of Lithium-Ion Battery Technologies

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Abstract Critical Raw Materials (CRM) are gaining increasing attention in both European policy and corporate strategies due to their essential role in emerging technologies and associated supply risks. Life Cycle Assessment (LCA) has been employed in various criticality studies to evaluate the environmental impacts of CRMs, while also offering tools to assess the sustainability of resource use, including material dissipation and short-term geopolitical supply vulnerabilities. Based on a comprehensive review of methodologies for CRM assessment and resource evaluation in LCA and a case study on lithium-ion battery production, recommendations are done in this SCORE LCA project to integrate LCA and criticality frameworks to support sustainable resource management and inform policy development.

1 Introduction

Due to their vital role in today's technological advancements, economic growth, and the green and digital transitions, critical raw materials (CRMs) are gaining increasing attention. RMs are necessary for essential applications, ranging from rare earths in electronics to lithium and cobalt in batteries. To emphasise the significance of CRMs, policy frameworks like the European Union's Critical Raw Materials Act (CRMA)

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highlight the necessity of securing supply chains and reducing reliance on vulnerable sources.

It remains challenging and resource-intensive to assess the 'criticality' of materials, which is determined by supply risk and economic or technical importance (Schrijvers et al. 2020), particularly for small- and medium-sized enterprises. On the other hand, life cycle assessment (LCA) has become a widely adopted and standardised approach for assessing the environmental impacts of materials and products. Impacts assessed in LCA include those related to the use of natural resources, such as their depletion, scarcity, and dissipation, which are mostly related to impacts on their availability. With LCA, businesses may gain insights into the environmental impacts of using raw materials, but often lack information on their accessibility. Several studies have addressed this issue, proposing various methods, and some have also evaluated the compatibility of these methods with LCA (Berger et al. 2020; Luthin et al. 2023; Hackenhaar et al. 2024). However, the debate still lies in whether and how LCA and criticality assessment (CA) can be integrated, especially since none of the proposed methods have been implemented in an LCA software yet. Hence, a significant gap exists in decision-making due to the lack of an integrated tool or a holistic approach that is widely accessible. Exploring means to improve accessibility and effectively integrating CA with LCA is essential to close this gap.

This study presents the results of the SCORE LCA project 'LCA and critical raw materials' (SCORE LCA 2024), which investigated the concept of criticality, explored its relationship with LCA, and illustrated the potential for synergy between the two using a practical case study. Consequently, recommendations are made to support resource management strategies that are more resilient and cognizant, and to aid both economic and environmental objectives.

2 State of the Art

Criticality assessments are 'outside-in' in nature, assessing the potential effects of external factors such as political unrest on the system under study. This is in contrast to LCA's 'inside-out' approach, which models how a system's actions impact resource or environmental domains. This distinction is vital: while criticality assessments evaluate and support resilience alternatives such as material substitution, supply diversification, or an increase in recycling potential, LCA quantifies potential environmental impacts.

2.1 Environmental Impacts in Criticality Assessments

Environmental impacts are increasingly recognised as essential factors in assessing the criticality of raw materials. Schrijvers et al. (2021, 2020) outline four distinct perspectives on how environmental impacts relate to material criticality, which are

(1) Environmental Regulation as Risk Factor: Environmental impacts increase the likelihood of regulatory actions (e.g. restrictions or bans), which can disrupt the supply of a material.
(2) Corporate Reputation and Social License to Operate: Use of materials with high environmental or social impacts can damage a company's reputation or social license to operate.
(3) Direct Environmental Burden of Use: The actual environmental impact is associated with using the material itself (e.g. emissions, resource depletion).
(4) Environmental Consequences of Supply Disruption: A disruption in the supply of a material leads to environmental harm, either through substitution with more damaging alternatives or halting environmentally beneficial applications.

In addition, there are underlying causal mechanisms behind the four perspectives mentioned on environmental impacts in assessing the criticality of raw materials, which influence whether they are classified as 'outside-in' or 'inside-out' and determine the appropriate LCA approach, as depicted in Fig. 1.

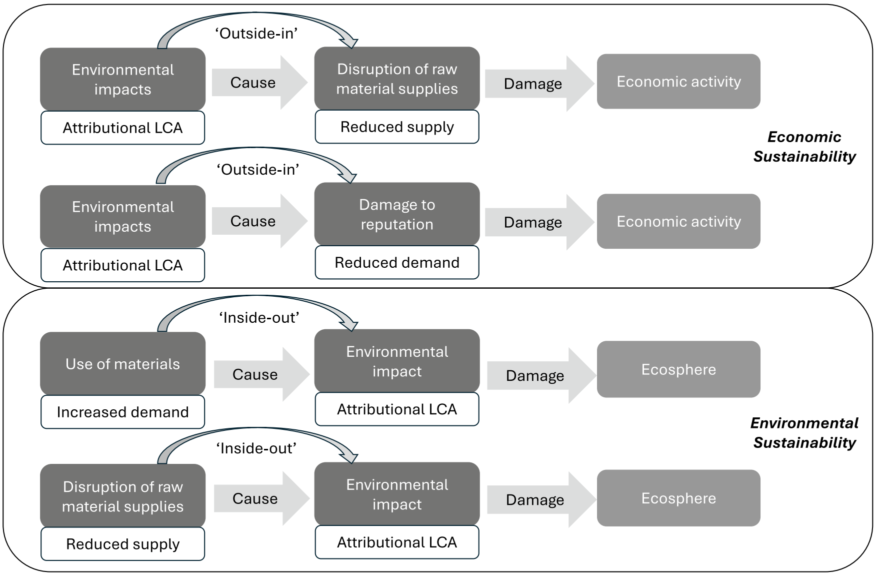

Fig. 1 Illustration of the underlying causal mechanism of four perspectives regarding environmental impacts in the assessment of the criticality of raw materials, their classification into 'outside-in' or 'inside-out', and the corresponding LCA approach (adapted from (Schrijvers et al. 2021))

2.2 Resources in LCA

A variety of resource indicators have been developed to assess the environmental and economic impacts of resource use in LCA. Examining the traditional and dissipation-based methods reveals their individual focus areas and relevance in evaluating the fate of CRMs from extraction to their entry into the economy. The Abiotic Depletion Potential (ADP) (van Oers et al. 2020a) represents a traditional method that focuses on extraction rates and geological scarcity. In contrast, dissipation-based indicators, such as Average Dissipation Rate (ADR) (Charpentier Poncelet et al. 2021) and Environmental Dissipation Potential (EDP) (van Oers et al. 2020b), assess the permanent loss and irreversibility of resource emissions. Others, including the Lost Potential Service Time (LPST) (Charpentier Poncelet et al. 2021), integrate economic dimensions to evaluate the future availability and value of resources permanently lost. Overall, the dissipation-based indicators offer a more nuanced and future-oriented perspective on resource availability, addressing both environmental and economic consequences.

However, there is a general consensus that ‘abiotic resources’ are not directly linked to environmental concerns (Sonderegger et al. 2017). Methods developed to quantify damage in the ‘resource use’ area of protection primarily focus on reducing the value creation potential in alternative product systems. However, the AoP ‘resources’ is not merged with the economic AoP ‘prosperity’ in the new framework for life cycle sustainability assessment (LCSA), which was developed in the ORIENTING project (Hackenhaar et al. 2024). Moreover, one could argue that the value obtained from resources leads to the satisfaction of human needs, leading to increased human well-being, which is another distinct AoP in the framework of (Hackenhaar et al. 2024). Consequently, there is still no consensual framework for assessing resources alongside environmental LCA, and a parallel assessment of environmental impacts and resource use impacts is therefore the current best practice.

2.3 Integrating Criticality Assessment and Life Cycle Assessment

There are two main approaches to integrating CA into LCA: one at the results level and the other at the methodological level. The advantages, limitations, and interrelations of these approaches have been widely discussed in the LCA community, particularly in the context of combining and integrating life cycle and environmental risk assessment (Guineé et al. 2017). Result-level integration maintains methodological clarity and is easier to apply, but outputs may not be directly comparable due to differing scopes, metrics, and assumptions. Methodological-level integration allows for more comprehensive assessments, enables joint interpretation under a single functional unit or spatial boundary, but requires more detailed data and there is a lack of standardised tools. Both approaches are complementary, and their combination can improve decision support in early design or regulatory contexts.

In the case of integrating criticality into LCA, this implies that either the results of criticality assessments for raw materials can complement the outcomes of a product system's LCSA, thereby providing a broader perspective on the sustainability implications of resource use, or elements of supply risk can be incorporated directly into the LCSA framework at the life cycle impact assessment by applying characterisation factors derived from a comparative risk assessment model, similar in approach to USEtox (Rosenbaum et al. 2011).

3 Case-Based Investigation of Lithium-Ion Battery Technologies

This section summarises the case study conducted within the SCORE LCA project (SCORE LCA 2024).

3.1 Goal and Scope Definition

Lithium-ion batteries (LIBs) play a central role in the transition towards a low-carbon society, powering electric vehicles (EVs) and facilitating the integration of renewable energy. They dominate the rechargeable battery market due to their high energy and power density and low self-discharge rate, and LIBs contain materials considered critical and/or strategic by the European Commission. By 2030, the most relevant chemistries are projected to be NMC (nickel–manganese–cobalt) and LFP (lithium iron phosphate) cathodes, both with graphite anodes (IEA 2025). This makes NMC811 and LFP batteries highly relevant for comparative LCA and criticality assessments. Furthermore, complete inventories are available in ecoinvent 3.10. To enable a fair comparison between the two battery types, their energy storage capacity must be equivalent. The average battery capacity for electric vehicles is approximately 65 kWh, which is used as the functional unit for the assessments.

3.2 Life Cycle Impact Assessment Methods

The analysis was performed using the Environmental Footprint method version 3.1 (EF 3.1), developed by the European Commission. A cradle-to-gate approach is applied with SimaPro v10.0.1.2. Inventory data were sourced from ecoinvent v3.10. Within EF 3.1, the mineral and metal resource use category is based on ADP, which relies on extraction rates and reference reserves (typically the ultimate reserve) (van

Oers et al. 2020a). To address additional aspects of resource use, complementary indicators are added: ADR reflects physical scarcity by considering depletion relative to known reserves, making it more responsive to short- and medium-term supply constraints and Potential Value Loss from Resource use (PVLR) introduces a socio-economic dimension by estimating the potential long-term economic loss due to resource extraction, taking into account both scarcity and market value.

3.3 Criticality Assessment Methods

The IRTC Tool (IRTC 2023) is a decision support tool that was developed as part of the IRTC Business project funded by EIT RawMaterials to address the lack of explicitly applied cause–effect mechanisms in earlier criticality assessments. It incorporates cause–effect chains that reflect business-relevant supply risks, identified through stakeholder workshops involving methodology developers, companies, and governmental institutions. The tool addresses three primary concerns faced by companies in relation to CRMs: physical accessibility issues, high price volatility, and reputational risks, which are addressed by 24 indicators. GeoPolRisk method (Gemechu et al. 2015) evaluates the geopolitical risk related to the supply of abiotic resources (energy and non-energy) for LCA. It assesses the supply risk of raw materials for an economic actor over a given year, providing both a dimensionless score and a CF for LCA resource elementary flows, expressed in kg Cu-eq/kg (Koyamparambath et al. 2024). The calculation comprises three components: the concentration of mining production, the share of imports weighted by political instability (using the Worldwide Governance Indicator, which measures political stability and the absence of violence), complemented by domestic production, and the traded price of the raw material.

ESSENZ plus (Yavor et al. 2021) is a comprehensive method that measures the multiple dimensions of resource efficiency of products, including supply risk, and integrates it into LCA. It covers 11 categories (including concentration of reserves and production, political instability, and trade barriers) related to socio-economic availability, each represented by specific indicators (Herfindahl–Hirschman index, Worldwide Governance Indicator, and Enabling Trade Index), set against target values. The default target values are based on expert opinion and stakeholder surveys, normalised using global production data.

3.4 Case Study Results

The cell and electronic components are the primary sources of environmental impacts for both LFP and NMC811 batteries, with copper being the most consistent contributor. In LFP batteries, the cathode has a limited impact, whereas in NMC811 batteries, the use of nickel and cobalt sulphates increases the environmental burden by introducing sulphur, in addition to copper. Gold and silver have minor contributions in both technologies, primarily through electronic components.

In the LCA, NMC811 batteries show slightly higher environmental impacts than LFP batteries, particularly for 'resource use, minerals and metals' as indicated by the ADP method. This is further confirmed by the ADR and PVLR methods, with NMC811 scoring higher on dissipation, particularly for ADR, which indicates irreversible losses of materials. ADP highlights key contributors such as copper, gold, silver, sulphur, and tellurium (the latter due to inventory artefacts), but only copper stands out across both ADP and dissipation analyses. In contrast, dissipation-based assessments highlight additional high-scoring materials, such as gallium, barium, and iron (the latter due to inventory artefacts), reinforcing the benefit of integrating these metrics.

The CAs further identify distinct hotspots (Table 1). For example, both GeoPolRisk from the French perspective and ESSENZ + identify iron as a key contributor in NMC811 (cradle-to-gate), but not in LFP, while copper is flagged only by GeoPolRisk, which can be explained by the price component included in the method.

GeoPolRisk, based on the full LCI and interpreted at the first aggregation level, allows inclusion of primary and energetic raw materials that are consumed both directly in the product system and in the background activities. It identifies nickel, cobalt, lithium, and copper as critical for NMC batteries. IRTC yields a different list of critical elements due to the inclusion of other indicators (e.g. export restrictions) and a different point of assessment (i.e. global supply versus import to France in the GeoPolRisk method). Furthermore, the IRTC method does not include price as a risk

Table 1 Comparison of three criticality assessment methods

	IRTC	GeoPolRisk	ESSENZ plus
Number of metals	More than 50	56	48
Indicators	24	1	21
Scope (assessed risks)	Risks of accessibility, price fluctuations, and reputation damage	Geopolitical supply risk	Socio-economic risks and social acceptability
Data used	Complete LCI	Complete LCI, but the results are presented at the first level of aggregation	Complete LCI
Most critical elements identified for NMC811	Cobalt, tantalum, antimony, graphite, rhodium, magnesium, manganese, silicon, aluminium	Nickel, cobalt, lithium, iron, copper, fluorspar	Iron, sulphur, nickel, magnesium, gallium, lithium, tantalum
Most critical elements identified for LFP	Tantalum, antimony, graphite, rhodium, aluminium	Lithium, copper, fluorspar	Aluminium, iron, selenium, gallium, lithium, tantalum

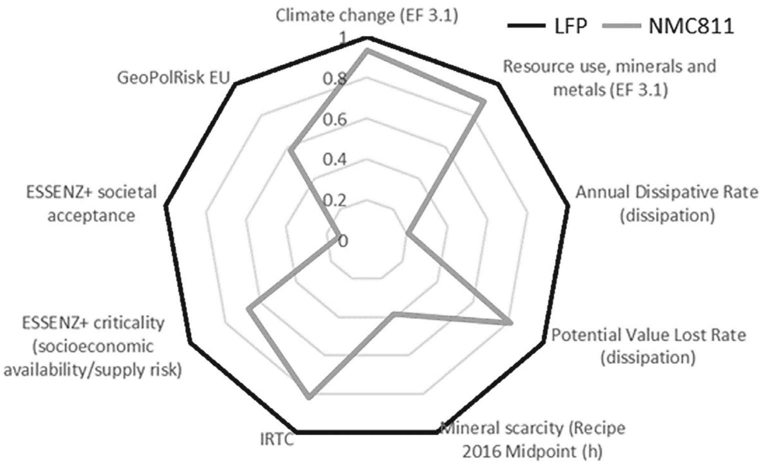

Fig. 2 Comparison of NMC 811 and LFP batteries based on LCA and criticality (SCORE LCA 2024)

factor, while this is predominant in the GeoPolRisk method. ESSENZ + , integrating criticality and social risks, highlights tantalum, cobalt, and lithium, with allocation effects influencing outcomes. This divergence highlights the complementary, yet distinct insights gained by combining LCA and criticality assessments.

To compare the overall criticality and environmental results, overall scores by indicator were calculated for each battery. These overall scores were then normalised and weighted per battery (Fig. 2), with each highest value assigned a score of 100%. Figure 2 shows that although the differences in values between the two batteries vary across all methods, the NMC811 battery consistently exhibits higher impacts across all methods.

4 Limitations

A major limitation in combining LCA with criticality assessments lies in the inappropriate merging of environmental impact metrics with supply risk indicators, which can lead to methodological inconsistencies (mismatched system boundaries, functional units, or temporal scopes) and misinterpretations (comparing inherently different types of indicators).

The assessments of criticality and environmental impacts in this study are based on the LCIs, in order to establish a link between LCA and criticality at the level of the application methods. The specific features of the inventories thus have an influence on the results and their interpretation. Allocation plays a key role in LCI and LCA, often based on economic, mass, or energy criteria. However, these practices can introduce elementary flows into the inventory that are neither part of the Bill of

Materials nor the intermediate stages of the process, nor the supporting services such as electricity generation, which was observed, for example, for tellurium. This is one of the limitations of using LCI databases and must be considered when interpreting the results of the impacts of resource use in LCA.

5 Criticality and LCA: Complementary or Contradictory?

While LCA and criticality assessments do not answer the same questions, these methods are complementary, and their cross-referencing is key to making sustainable and strategic decisions, as illustrated in Fig. 3.

The differences in scope, objectives, and underlying data make it difficult to directly merge the two approaches. However, LCA and criticality assessment can effectively complement each other when used in tandem. For instance, juxtaposing results can help identify materials that are both environmentally burdensome and at high risk of supply disruption—crucial information for sustainable decision-making. While LCA primarily calculates potential environmental impacts, criticality adds the layer of supply risks, both guiding mitigation efforts. In practice, the two methods are often used separately in different contexts—such as environmental reporting versus resource security planning—but efforts are also underway to integrate criticality metrics into LCA models. These integration efforts, though promising, face hurdles due to incompatible datasets and differing assumptions, underscoring the need for methodological clarity and cautious interpretation.

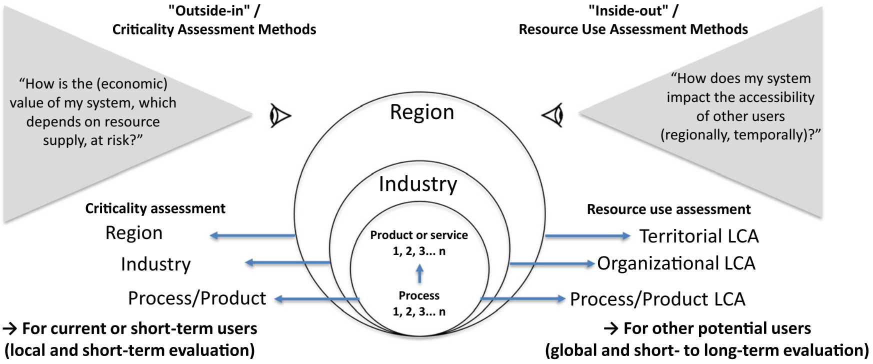

Fig. 3 The 'outside-in' approach to criticality and the 'inside-out' approach to assessing the impact of resource consumption in LCA (SCORE LCA 2024)

6 Conclusion and Outlook

This case study highlights the value of combining LCA and CA to support informed resource management decisions. While LCA highlights raw materials with high environmental impacts, such as nickel and cobalt, CA identifies supply risks and ethical concerns, revealing complementary insights. However, the analysis also exposes limitations in LCI, notably, the reliance on generic, global data that lacks regional or technological specificity. This reduces accuracy, especially for by-products with complex supply chains.

Conceptually, LCA and CA offer contrasting perspectives: LCA takes an ‘inside-out’ view of system impacts, whereas CA applies an ‘outside-in’ lens to external risks. Integration can occur either by juxtaposing results (for example, using IRTC or ESSENZ + alongside LCA) or by embedding characterisation factors (such as done by GeoPolRisk) directly into LCIA, though differences in data granularity and underlying assumptions challenge this latter approach. The merits of integrating CA with LCA are emphasised in this study.

Combining LCA and CA enables more strategic decisions. For instance, relocating lithium production to Europe reduces both geopolitical risk (CA) and emissions (LCA). In a short-term perspective, CA supports the identification of high-risk materials for procurement or policy focus. Therefore, the implementation of CA methods in LCA software is recommended. Integrating circularity strategies and communicating comparative LCA results can further improve environmental performance and resilience.

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