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LCA and critical materials

Synthesis

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SCORE LCA is an association that has been created to financially support collaborative research on LCA and related topics. It aims to promote and organize cooperation between companies, institutional and scientists in order to support the evolution of LCA methods and its practical implementation at European and international level.

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- The information and conclusions presented in this document were established on the basis of scientific and technical data and regulatory and normative framework in force at the date of the publication of documents.

WeLOOP has been working in collaboration with ISM-CyVi, BRGM and ScoreLCA on the links between Life Cycle Assessment (LCA) and Criticality. Critical raw materials are increasingly important in regulations and decision-making strategies, both at the European political level and within companies. The environmental impacts associated with their production, assessed through LCA, can be an important lever for assessing their criticality. In LCA, there are numerous methods for assessing the impacts associated with using resources, including those focusing on dissipation and short-term supply risks. This project aims to further integrate the notion of criticality into LCA studies while using LCA results to enrich environmental analysis in criticality assessments, to improve strategic decision-making.

The objectives of the project are as follows:

- Understand how LCA practices could evolve to integrate the concepts of availability and geopolitical risks, thus criticality.
- Complement LCA methods and practices by integrating criticality assessment, evaluating existing indicators that are not fully incorporated but are increasingly considered for inclusion in LCA.
- Analyse how the environmental impacts of production can complement the assessment and decision-making regarding the management of critical raw materials

Through a state-of-the-art review, two case studies, and a sensitivity analysis, this project establishes the current state of the art on criticality methods, resource assessment, and environmental analysis, highlighting the complexity of integrating these approaches. The project also provides recommendations for linking LCA and criticality to support short-term and medium-to-long-term decision-making, as well as recommendations on criticality mitigation measures.

1. State-of-the-Art

'Critical' resources are those that are essential to a value chain or an economy and pose a supply risk in a specific context. Several metals classified as critical in Europe or France are vital for the energy transition (e.g., lithium, cobalt, and rare earths) and other strategic technologies (e.g., gallium, used in semiconductor manufacturing). An increasing number of countries, regions, and industries are concerned about these issues, mainly due to the dependence of these technologies on numerous metals, whose global demand is growing exponentially.

Raw materials are considered critical if they score relatively highly on two key dimensions, often presented as the two axes of a matrix: the probability that the supply of a raw material will be disrupted (commonly referred to as 'supply risk') and the vulnerability of a specific system to such a disruption (also called 'importance'). Graedel et al. (2012) introduced a third dimension, "environmental implications" but most criticality methodologies adhere to the two-axis approach (supply risk and vulnerability), aligning with classical risk theory.

The European Commission carried out an initial criticality study in 2011 and the most recent one is from 2023, the results of which are shown in Figure 1. In their study, environmental impacts are not considered as a risk factor. However, it should be noted that due to the diversity in the perimeters of the different criticality studies and the diversity of supply risk indicators, different studies produce divergent lists of critical raw materials; there is no universal list of critical raw materials.

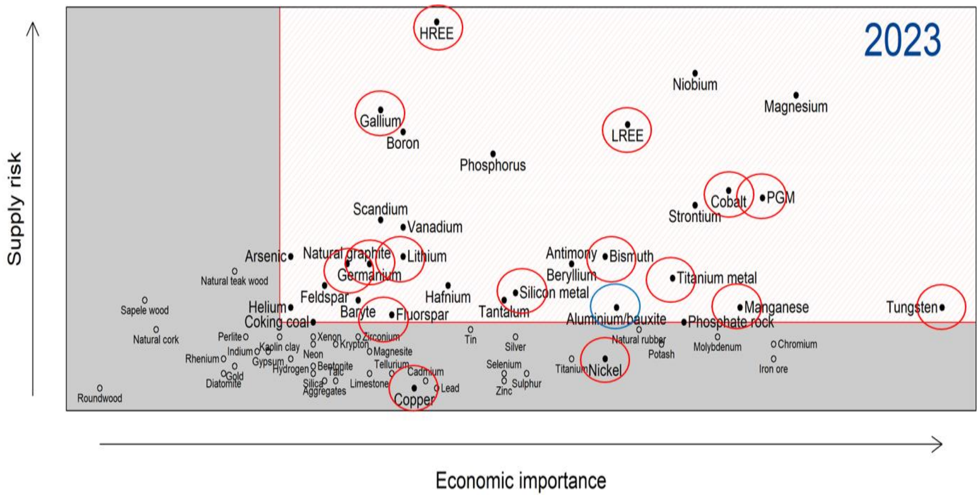


Figure 1 Results of the 2023 criticality assessment by the European Commission

The supply risk for critical resources typically comes from a strong dependency on imports of a resource from a specific country for which various factors contribute to uncertainty about supply capacity. In addition, environmental impacts are sometimes considered risk factors, as raw materials associated with high environmental impacts can be affected by regulations, taxes or can lead to reputational damage.

At the same time, metal production contributes significantly to global environmental and social impacts. A paradox emerges: the exponentially growing demand for raw materials for technologies essential to ecological and energy transitions—intended to create a more sustainable world—generates additional socio-environmental externalities. These externalities, combined with governance-related risks, may, in turn, increase the likelihood of new mining projects being abandoned in various regions, thereby limiting the security of supply for materials critical to the energy transition.

The Critical Raw Materials Act (CRMA) is crucial in addressing growing concerns about the security of supply and sustainable management of critical raw materials essential to strategic sectors such as renewable energy, digital, aerospace and defence and modern technologies. The legislation aims to strengthen the European Union's autonomy, reduce dependence on third countries and promote sustainable sourcing and recycling practices.

The promotion of sustainability and circularity is a key aspect of the CRMA. It empowers the European Commission to regulate the environmental footprint of critical raw materials, which must be based on scientific methods and established life cycle assessment standards, including a verification process.

These phenomena can be interpreted from the perspective of LCA, Life Cycle Sustainability Assessment (LCSA) or criticality assessments:

- In LCA, environmental impacts are considered by numerous indicators, within the “ecosystem” area of protection. Impacts on human health and resources are also considered in the ‘human health’ and ‘resources’ areas of protection. In the case of the latter, impacts are associated with the extraction, consumption or dissipation of resources. The ‘social’ impact is limited to those affecting human health. Furthermore, the impacts assessed in LCA are generally marginal and global; they do not account for the environmental, social or economic risks specific to the system under study.
- In LCSA (an approach combining LCA, Social Life Cycle Assessment and Life Cycle Costing), the social impacts are extended to a set of social indicators including working conditions, wages, corruption, etc. Economic impacts are also taken into consideration.
- In criticality assessment, the contextual risks of the regions or countries from which the raw materials come, whether social or politico-economic (linked in particular to governance), and sometimes environmental (in certain approaches), are taken into account.

For resource assessment, LCA methods distinguish between the depletion and dissipation of resources. Depletion methods concern the reduction in certain stocks (natural and anthropogenic), often used as an indicator to determine the availability of mineral resources with the Abiotic Depletion Potential (ADP) indicator, whereas dissipation represents the reduction in the mass of metals available after their extraction (i.e. in the technosphere). These methods adopt an '**inside-out**' approach, meaning that they assess a system under study (product, process, industry, region) based on elementary flows in order to measure its impact (emissions, resource consumption) on the global environment over its life cycle.

The criticality study, on the other hand, follows an '**outside-in**' approach, assessing how dependence on certain resources (e.g. rare metals, critical raw materials) can pose an economic and industrial risk to a product, a process, an industry or a region. These risks arise from several factors such as geopolitical tensions, a concentration of extraction in certain countries or price fluctuations. Supply risk could have a negative impact on a product's performance, leading to an increase in production costs and thereby impacting human prosperity. Initially, three methods aimed to provide information on the criticality of materials as a complement to environmental LCA by taking account of supply risk concepts: the Geopolitical Supply Risk (GeoPolRisk) method, the Economic Scarcity Potential (ESP), and the Integrated Resource Efficiency Assessment (ESSENZ) method. These studies have justified the link between resource criticality and biophysical flows in LCA, presenting resource criticality as a complement to LCA that deals with 'outside-in' impact pathways.

D. Schrijvers et al. analyse how the environmental perspective in raw materials criticality assessments can be evaluated via LCA from the four perspectives shown in Figure 2.

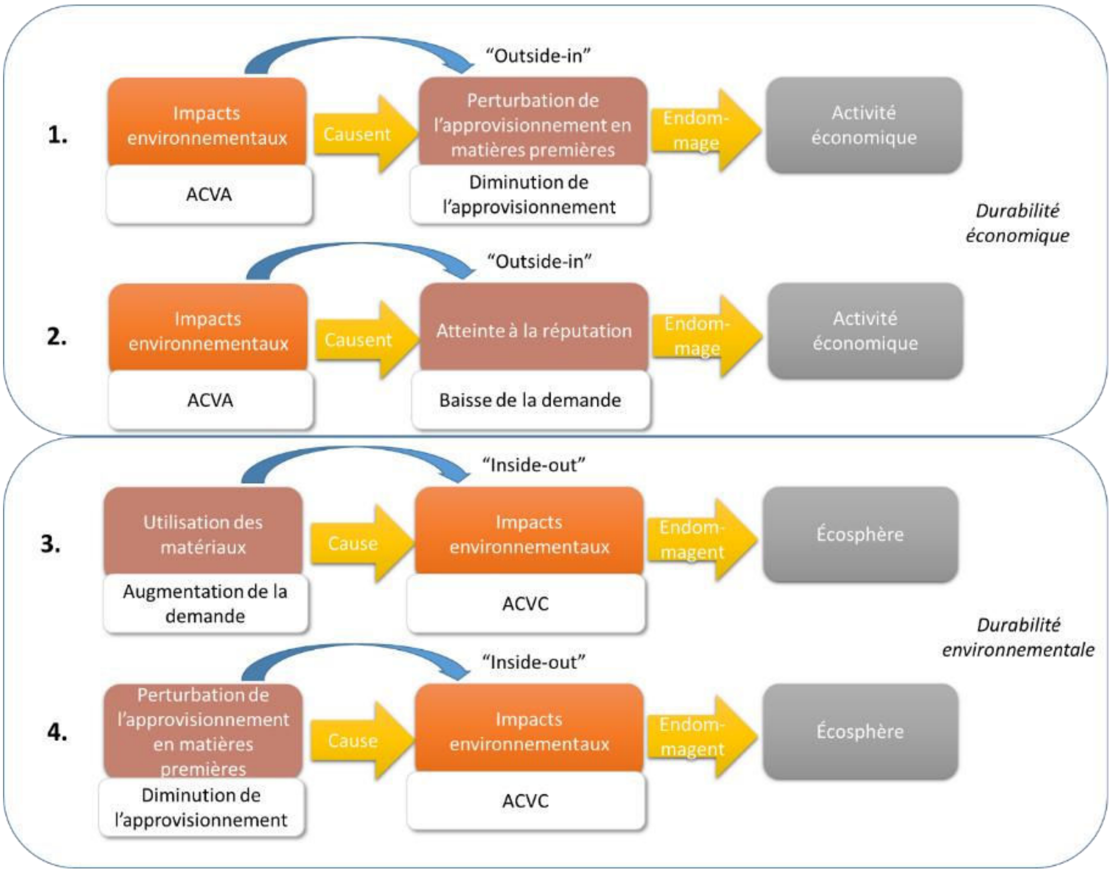


Figure 2 The cause-effect mechanism underlying the 4 perspectives on environmental impacts in assessing the criticality of raw materials, their classification as 'outside-in' or 'inside-out', and the corresponding LCA approach (D. Schrijvers et al., 2021a)

It can be noted that all the perspectives assess a 'change' in the raw materials value chain, manifested either by a change in supply or by a change in demand. Perspectives 1 and 2 consider that *environmental impacts cause a change in the raw materials value chain*. This corresponds to an '*outside-in*' perspective, similar to the perspective applied to supply risk methods in the context of LCA (i.e. GeoPolRisk and others). Perspectives 3 and 4 consider that *a change in the raw materials value chain has an impact on the environment*, which is consistent with an 'inside-out' perspective, which is the general approach to impact assessment in LCA.

The IRTC method was created to address the lack of an explicit cause-and-effect mechanism in previous criticality studies to raise awareness of supply risks from perspectives 1 and 2. The method also includes mitigation measures linked to the cause-effect chain, depending on whether they can mitigate the source of a risk, a company's potential exposure to the risk or the damage suffered by the company.

2. Case studies

Lithium-ion batteries (LiBs) are one of the key sectors targeted by the European Commission for increased regional autonomy in the coming decades, making them a strategic sector. Their composition includes materials considered strategic or critical in Europe (lithium, cobalt), for which the regulation on batteries and waste batteries (EU)2023/1542 sets targets to improve the recycling efficiency of LiBs at the end of their life. The case studies are therefore centred around: in the first, an assessment of the production of lithium hydroxide; in the second, a comprehensive joint LCA and criticality assessment of the production of NMC811 (Nickel-Manganese-Cobalt) and LFP (Lithium- Iron-Phosphate) batteries for electric vehicles; and in the sensitivity analysis, an assessment of the production of recycled cobalt and lithium from electric vehicle batteries in order to comply with the regulations.

2.1. Limits in Life Cycle Inventories

The assessments of criticality and environmental analysis are based on the ecoinvent 3.10 Life Cycle Inventories (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 (BoM) nor the intermediate stages of the process.

The use of a mined mineral/metal compound includes an economic or mass allocation of the various elements making up the mineral, including co-products and by-products. Thus, elements present in small quantities in a mineral/metal used to manufacture a product are allocated in the product inventory, their quantity being allocated to the quantity of mineral/metal used. This is the case, for example, with tellurium in copper, iron/magnesium in nickel and cobalt sulphates or rare earths such as rhodium. When associated with large masses due to the actual use of an associated compound and/or a large characterisation factor, these elements stand out in the results even though they are not actually present in the battery. This is one of the limitations of using LCI databases such as ecoinvent or Sphera and must be considered when interpreting the results.

2.2. Results of the two case studies

2.2.1. Case study 1: lithium hydroxide production in Europe

Lithium has been identified as a critical material in the EU's 2023 criticality assessment. Given the dependency on imported raw materials, which is one of the main factors contributing to criticality, increasing the production of lithium hydroxide in Europe enables the reduction of the European criticality of lithium through the proximity of production and its diversification. In order to study the effect on environmental impacts of lithium production in Europe and compare it with the positive effects it has on criticality, three lithium hydroxide production routes were compared in a cradle-to-gate LCA study: the production of Greenbushes in Australia (AU) which is refined in China (CN), the production of Atacama in Chile (CL) and the production of the Keliber project in Finland (FI).

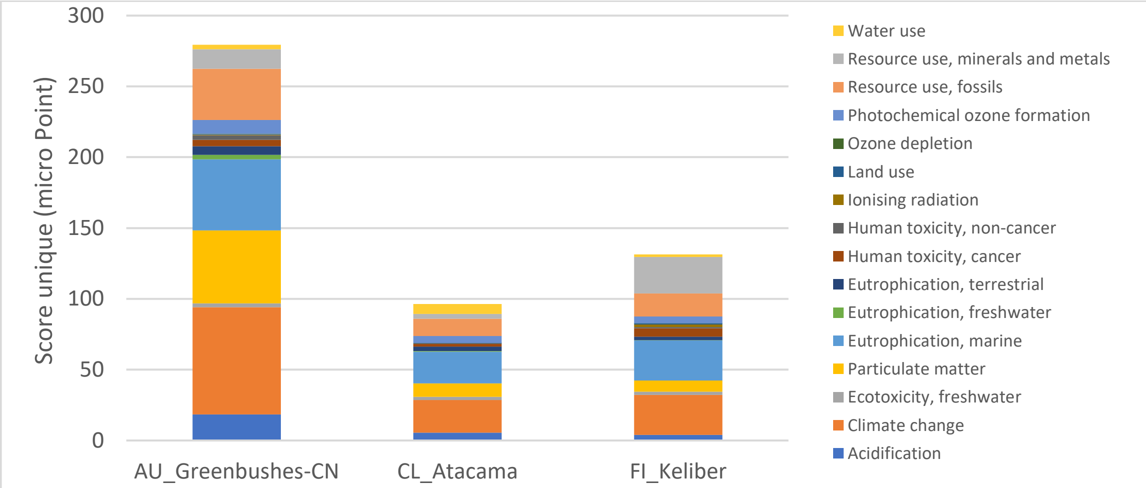


Figure 3 Results of the production of lithium hydroxide via 3 production routes presented in single score

The results (see Figure 3) show that European lithium production has a clear potential for reducing environmental impacts in most impact categories compared with the main processes currently in operation worldwide, as the Australia/China process, and is therefore in line with the criticality predictions. However, the environmental impacts remain higher than the Chilean case for some impact categories, particularly for mineral and metal resource use and marine eutrophication.

2.2.2. Case study 2: Environmental and criticality assessments of NMC811 and LFP batteries for electric vehicles

Since the second case study compares two batteries with different characteristics, the functional unit must be chosen to compare equivalent performance. An average electric car has an energy capacity of 65 kWh, which is used as the functional unit. According to LCI data, this corresponds to a mass of 562.3 kg for an LFP battery and 435.8 kg for an NMC811 battery.

The environmental assessments were carried out from cradle to gate using SimaPro software version 10.0.1.2 with the EF 3.1 life cycle impact assessment method, and the resource dissipation method to compare the results of the two methods. Resource depletion refers to the reduction in the mass of metals available in the earth's crust and is assessed using the $ADP_{ultimate\ reserves}$, indicator, while dissipation represents the reduction in the mass of metals available after their extraction.

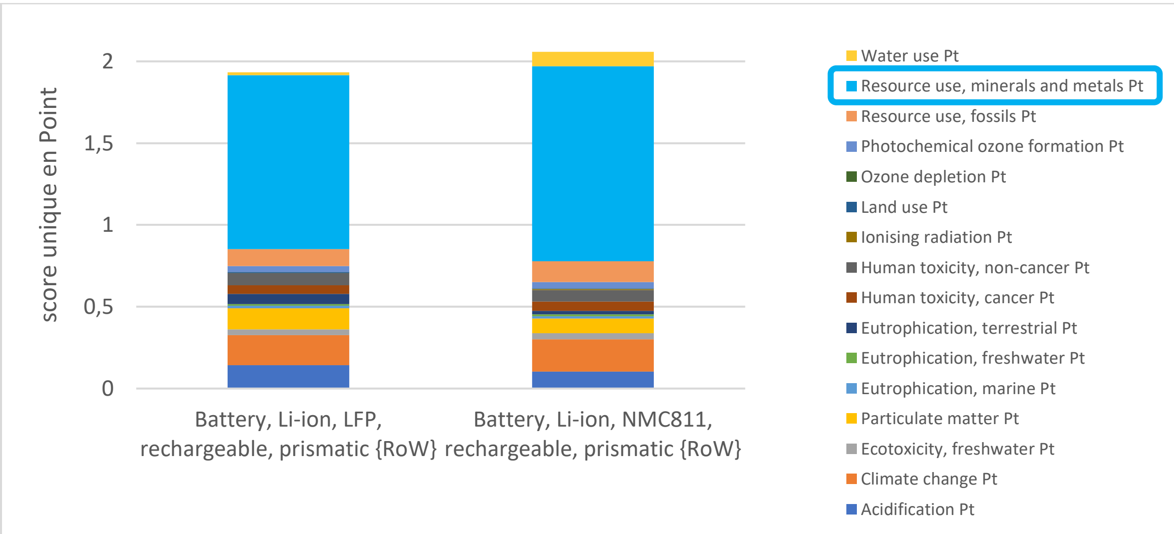


Figure 4 NMC811 and LFP batteries Single Score results

The LCA results, shown in Figure 4, demonstrate that an NMC811 battery has a slightly higher impact than an LFP battery and that the main impact category in both cases is 'resource use, minerals and metals' (see Figure 5) making it an appropriate case study for comparing the results with criticality studies.

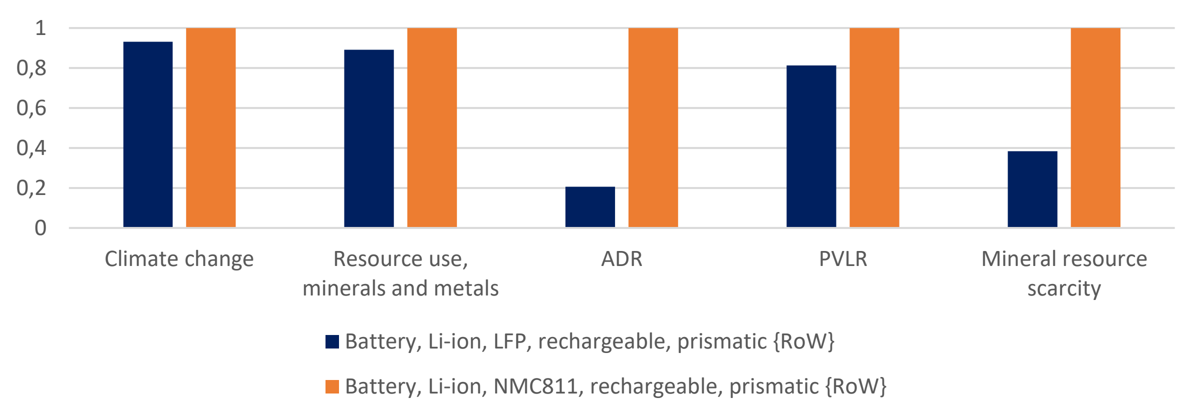


Figure 5 Results for NMC 811 and LFP battery for different indicators, with the highest value set at 100%

Two resource dissipation indicators are compared with the LCA results: the **ADR (Annual Dissipative Rate)**, an indicator measuring the quantity of metal lost irreversibly to the environment or in a non-recyclable form in relation to the estimated overall availability of the resource, thus reflecting the intensity of the dissipation of a resource and its criticality in terms of sustainability, and the **PVLR (Potential Value Loss Rate),** an indicator assessing the potential loss of economic value linked to the dissipation of a metal. As seen in Figure 5, the NMC811 battery has a higher scoring than the LFP battery for both indicators. Furthermore, the difference between the ADR values for the two batteries is significant, and greater than the difference for the LCA indicators studied.

The elements that contribute most to LCA impacts are:

- Copper (NMC811 and LFP), an element identified in the production hotspots for both batteries because it is present in the electronic components and the current collector.
- Gold (NMC811 and LFP), an element identified in the production hotspots of both batteries through its presence in electronic and electrical components.
- Silver (NMC811 and LFP), present in electronic compounds and in gold production.
- Sulphur (NMC811), necessary for the manufacture of cobalt and nickel sulphate, the active materials in the NMC811 battery.
- Tellurium (NMC811 and LFP), which is not used as a raw material but comes from the inventory limits explained in section 2.1 above. It is associated with the 'Copper concentrate, sulphide ore {RoW}| copper mine operation and beneficiation, sulphide ore | Cut-off, U' process, which is one of the most impacting processes in both batteries. With a high characterisation factor for the 'resource use, minerals and metals' indicator, Tellurium is the first element to emerge from the environmental analysis, despite its absence in the battery.

However, from the list of elements above, only copper is identified as a major contributor to impacts using the resource dissipation method. Other elements are highlighted in the dissipation results, like Gallium and Barium, which are present in electronics. There are also more elements actually present in batteries that stand out in the dissipation results and the 'mineral scarcity' indicator in the Recipe 2016 Midpoint (H) method. We can also see that iron has a greater impact on the results for the NMC811 battery than for the LFP battery, which may seem counter-intuitive but is also due to the limits of the inventory.

For the criticality studies, 3 methods were used: IRTC, GeoPolRisk and ESSENZ Plus. These methods have different scopes and different indicators, as shown in Table 1:

Tableau 1 Comparison of three criticality assessment methods, elements in bold are in common between at least two methods

	IRTC	GeoPolRisk	ESSENZ Plus
Number of metals	More than 50	56	48
Indicators	24	1	21
Scope (risks assessed)	Risks of accessibility, damage to reputation and price fluctuations	Geopolitical risk	Socio-economic risks and social acceptability
Data used	Complete LCI	Complete LCI but the results are presented to first level of aggregation	Complete LCI
Elements identified NMC811	**Cobalt**, **Tantalum**, Antimony, Graphite, Rhodium, **Magnesium**, Manganese, Silicon, Aluminium	**Nickel**, **Cobalt**, **Lithium**, **Iron,** Copper, Fluospar	**Iron,** Sulphur**, Nickel, Magnesium**, Gallium, **Lithium**, **Tantalum**
Elements identified LFP	**Tantalum**, Antimony, Graphite, Rhodium, **Aluminium**	**Lithium**, Copper, Fluospar	**Aluminium**, Iron, Selenium, Gallium, **Lithium**, **Tantalum**

The IRTC method is based on scores of all the elements of the inventory for the 24 indicators, where a threshold value for criticality is set for each indicator. The elements with the highest number of critical indicators are identified as critical and listed in table 1. Elements such as Rhodium, Magnesium or Antimony have been identified even though they are not in the batteries.

In the ESSENZ Plus method, characterisation factors for the 21 indicators are multiplied by the mass of each element in the inventory, so tantalum and selenium are not part of the battery but are present in the results. The results obtained for the societal acceptability indicators are unexpected for the NMC811 battery, but the major contribution to these indicators comes from iron. As previously stated, the large quantity of iron allocated to this part comes from the limits of the inventory. By weighting the characterisation factors by mass, iron stands out strongly for these indicators.

GeoPolRisk method is applied to full LCI but the results are presented to first level of aggregation. It uses characterization factors specific to a geographical region such as the EU. It focuses on the geopolitical risks associated with elements by considering the concentration of production of raw materials, their traded prices, and the instability of producing countries. This method accounts for all elements involved in both foreground and background processes, including primary raw materials and energetic raw materials. Despite allocation, the GeoPolRisk method identified nickel, cobalt, lithium, and copper as hotspots for NMC-type batteries making it more complementary to the results obtained by LCA.

Interestingly, as in the environmental assessments, GeoPolRisk and ESSENZ Plus identified iron as a hotspot in NMC811 rather than in LFP, and copper was only identified in GeoPolRisk.

At the identified critical elements level, the IRTC method results differ from those of other criticality methods and LCA. This is likely due to the way the method is applied and the limitations of the LCA inventories. However, it does provide risk mitigation measures for the elements identified *via* the decision support tool [Decision Tool – IRTC].

In order to compare the overall criticality and environmental results, overall scores by indicator were calculated for each battery by setting the highest overall value per battery and per indicator to 100%.

Figure 6 shows that although the differences between the values for the two batteries differ for all the methods, the NMC811 battery consistently has higher environmental impact, criticality and dissipation.

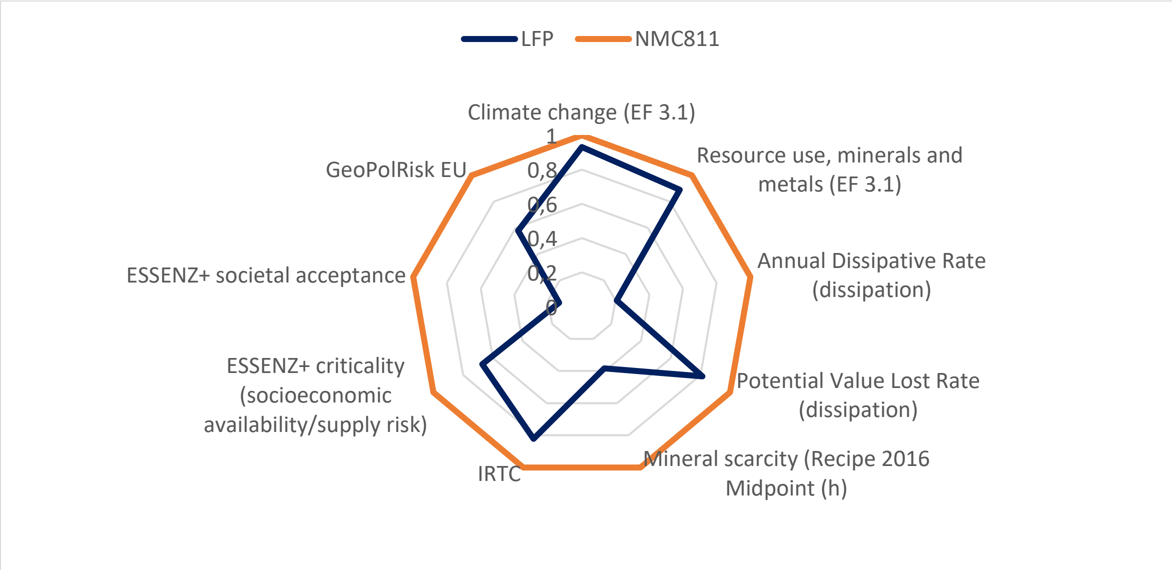
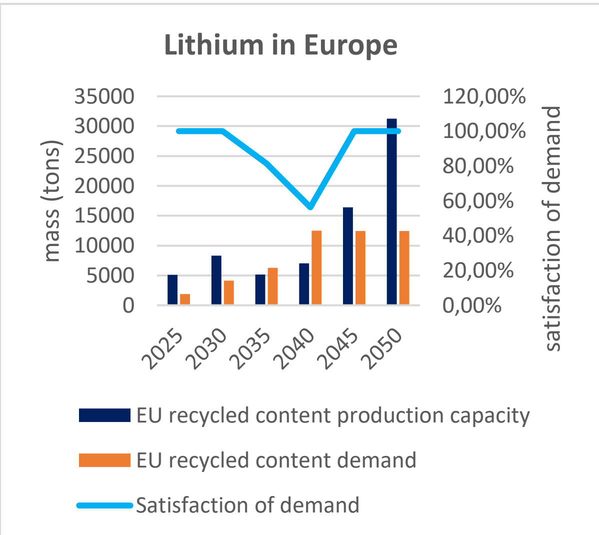
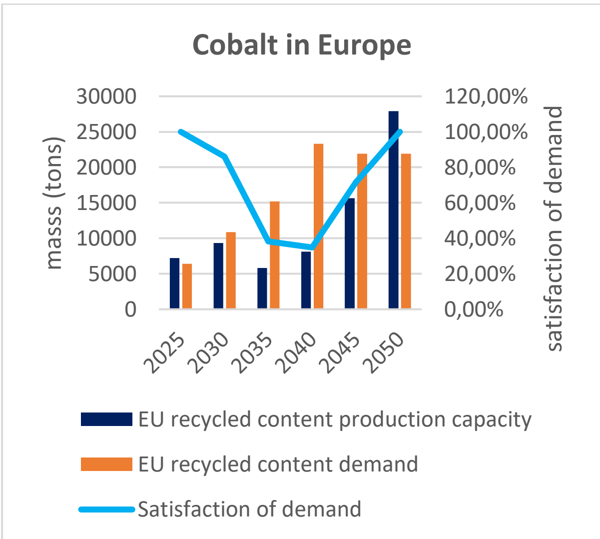


Figure 6 Results for an NMC811 and LFP battery for different indicators of environmental and criticality assessment methods, where the highest impact for each indicator is set to 100%

2.3. Sensitivity analysis: Recycled content

The Critical Raw Materials Act (CRMA) is a European Union legislative framework aimed at securing supplies of strategic materials, essential for key sectors such as electric mobility, renewable energies and digital technologies. Faced with Europe's reliance on imports of critical materials such as **lithium** and **cobalt**, the CRMA was proposed in September 2023 and adopted in May 2024, to achieve a **25% recycling rate for critical materials** to reuse them as recycled content by 2030. Therefore, this sensitivity analysis aims to assess the recycling capacity of lithium-ion batteries in Europe to comply with the CRMA and meet the objectives of regulation (EU)2023/1542 on the rate of recycled materials. The calculations are based on a study carried out by WeLOOP during the BATTERS project.





Figures 7 Demand satisfaction for recycled lithium and cobalt for lithium-ion batteries in Europe

The results in Figure 7 indicate that Europe can meet the demand for recycled materials over certain periods (2025-2030 and 2045-2050); however, significant gaps remain between 2030 and 2040, necessitating reliance on imports. The continued dependence on cobalt, due to the absence of local production, contrasts with the potential progress in lithium supply through the exploitation of European resources. However, the efficiency and capacity of recycling are closely tied to the rates imposed by regulations. While increasing these rates supports sustainability, it may also limit Europe's ability to meet future demand for recycled materials.

The sensitivity analysis highlights the challenges of **incorporating recycling and recycled materials into assessment methods**. In LCA approaches, recycled content can be modelled and contributes to reducing a product's environmental impact. However, in criticality assessments, there are few established methods or characterisation factors to evaluate the influence of recycled content on criticality results. We therefore recommend conducting a **dedicated study** on developing criticality methods for recycled materials to address these gaps in a field that is expected to gain increasing importance in the coming years.

3. Recommendations for the joint use of environmental and criticality analyses

3.1. Integrating an environmental dimension into criticality for short-term decision-making

Criticality assessments are well suited for decision-making with a short-term impact, because they evaluate the vulnerability of a resource (e.g. metals, minerals) in terms of supply risks and its economic importance, which vary due to factors that are often dynamic and can change rapidly (e.g. new regulations, geopolitical tensions, technological innovations). The target audience for the results of criticality assessments is primarily limited to the 'economic stakeholder at risk' and associated stakeholders with similar interests. The results of the criticality assessment are less likely to be of interest to the general consumer, who is more flexible in the use of substitutes when certain products become inaccessible or too expensive. However, the public may need to be made aware of the risks associated with businesses, where these form the basis for policy intervention.

However, regulations such as the CRMA advocate sustainability and circularity by empowering the European Commission to regulate the environmental footprint of critical raw materials, specifying that the environmental footprint must be based on scientific methods and established life-cycle assessment standards, including a verification process. It is therefore necessary to integrate an environmental dimension into assessments for a short-term effect.

To achieve this, it is recommended that criticality methods incorporating environmental indicators be used, such as ESSENZ, which includes five indicators: climate change, acidification, eutrophication, particulate emissions and water scarcity, or IRTC, which considers high environmental impacts as a 'warning signal' or a critical point in a criticality assessment. It therefore takes environmental indicators into account, using cradle-to-gate LCA or Environmental Performance Indicators.

For short-term supply risk assessment, the GeoPolRisk method provides a more detailed and complementary perspective, focusing specifically on the "economic stakeholder," in contrast to the global perspective offered by other criticality methods. When using GeoPolRisk or other criticality methods, it is recommended to use it in conjunction with environmental impacts categories that are relevant to specific case studies, such as the one involving lithium hydroxide. The choice of indicators should be made according to the purpose of the study. For example, the first case study of lithium hydroxide revealed high water consumption during salt production, so a related environmental impact category would be relevant to complete the criticality assessment.

3.2. Integrating criticality into LCA for medium- to long-term decision-making

For decision-making with a medium- to long-term effect, LCA is more suitable, as it involves an environmental assessment throughout a product's life cycle, including extraction, production, use and end of life. In terms of audience for resource assessment methods, since LCA resource assessment methods (including ADP) consider the potential loss of value to users beyond the value chain, a high score in this impact category means that others will suffer damage from this product system. Therefore, it is worth communicating the results to a wide audience.

However, LCA is based on averages and stable scenarios and does not take account of short-term economic or political fluctuations. The use of critical and strategic materials in strategic technologies such as electronic equipment or batteries also implies a link with CRMA. It is therefore preferable to include criticality assessments in environmental studies.

The second case study showed that the IRTC method, GeoPolRisk and ESSENZ Plus can be adapted to LCIs. However, the inventories used in LCA are not necessarily suitable for this purpose, and introduce limitations that influence the results, as seen in section 2.1. Using the Bill of Materials (BoM) is not sufficient, as it does not include data on intermediate processes. It is therefore advisable to combine the BoM and the LCI to obtain an inventory that is true to the product and complete. This could be done by carrying out an in-depth analysis of the LCI to identify the elements actually used in a product's value chain. Then, inventories could be built from the quantities declared in intermediate LCIs rather than from elementary flows, so as to obtain more accurate and relevant data. However, this approach requires time and in-depth expertise in the processes concerned and cannot be carried out directly using LCA software.

Moreover, criticality methods and indicators do not have the same characteristics as LCA in terms of time (LCA: long/short term, criticality: short term), method (LCA: inside-out, criticality: outside-in) and geography (LCA: global, criticality: local). It is therefore recommended that the environmental and criticality methods be conducted separately or combined with an in-depth analysis of the inventory and the messages given by each of the methods.

Given the different tool availability and the varied materials and perimeters covered by the methods, GeoPolRisk is a criticality method that aligns with LCA. It can be used as an initial screening tool to identify raw material hotspots that are specific to the economic stakeholder. Also, GeoPolRisk includes characterisation factors similar to those used in LCA, making it compatible with LCA software for seamless integration. ESSENZ Plus can also be used; meanwhile, the assessment should be conducted using BoM and LCI for criticality indicators. Note that the LCA part of ESSENZ may deviate from the default LCA impact categories to cover a wider range and more recent LCIA methods and impacts (environmental impacts categories that are relevant to specific case studies).

3.3. Risk mitigation measures

Risk mitigation is fundamental to criticality assessment, whose aim is to identify elements at risk and their associated supply risks, unlike LCA, which focuses more on obtaining quantified results. The aim of risk mitigation in criticality studies is to reduce vulnerability to critical resources. It is based on several strategies, which may be technological, economic, political or environmental.

A non-exhaustive list of mitigation measures is included in Appendix 6 of this report. They should be assessed according to their **relevance** to the type of risk associated with the raw material concerned, following an interpretation of the risks identified. This is necessary with ESSENZ, GeoPolRisk and other criticality methods.

The **IRTC decision tool**, on the other hand, is designed to propose tailored mitigation measures in two sectors: Energy and Transport. **Other sectors** are targeted for future development of the tool.

4. Conclusion

Criticality and LCA present two different approaches. Criticality has an 'outside-in' approach and is not directly concerned with the environmental impacts of a given material, but rather with the economic and industrial risks associated with the availability of resources. On the other hand, LCA offers an 'inside-out' approach centred around environmental impacts. While LCA and criticality 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 Figure 8.

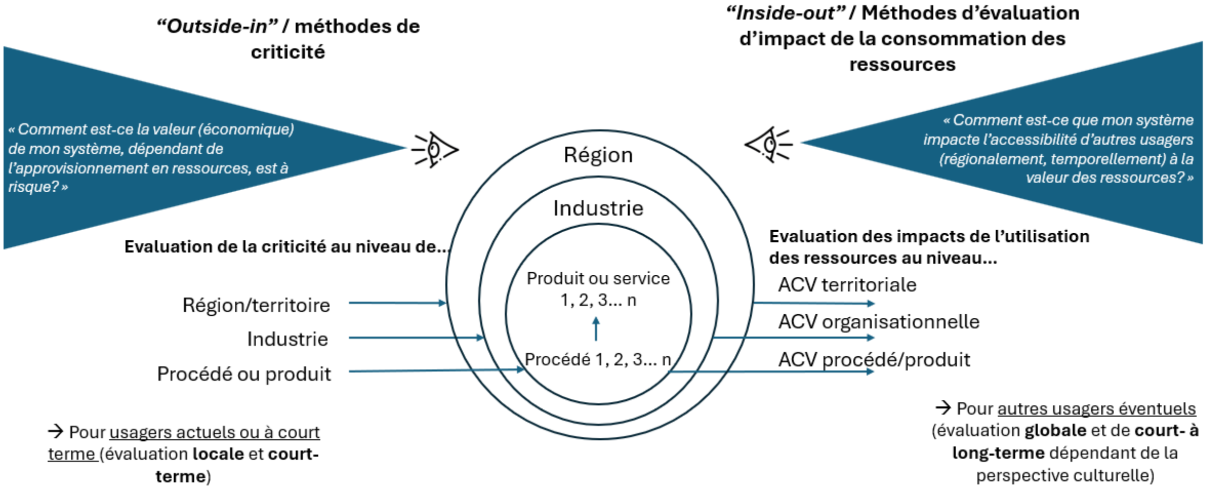


Figure 8 The 'outside-in' approach to criticality and the 'inside-out' approach to assessing the impact of resource consumption in LCA

For example, environmental impacts (assessed via LCA or other indicators, such as the Environmental Performance Indicator) can be used as an indicator in criticality assessment methods, to assess risks related to regulation, price, or reputation. At the same time, a disruption in the supply of raw materials can have environmental impacts (assessed by LCA), as is the case for raw materials used in low-carbon technologies.

In conclusion, in order to optimise the joint use of environmental and criticality studies, this study has shown that it is recommended to carry out a combination of BoM and ICV analysed in depth in order to have relevant inventories to use for the criticality assessment, given that ICV may have limitations. This combined inventory can be integrated with the GeoPolRisk/ESSENZ method to identify raw material hotspots that are specific to the economic player. This assessment can be followed by a more in-depth assessment using the IRTC method and the IRTC decision-making tool to develop mitigation strategies.