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A study on the problems of resource use for low-carbon technologies and comparing methods to assess impacts

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A study on the problems of resource use for low-carbon technologies and comparing methods to assess impacts

"It is a service to society to reduce your supply risk, and reducing your critical raw material use will help others so that there is more for them." - Free citation of one of this study's interviewees

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Abstract

Throughout society a debate has been going on around the controversiality of using raw materials for renewable energy and electric transport, regarding environmental concerns but now also with socioeconomic an political issues. Most importantly there is a lot of vagueness around the concepts of depletion, scarcity and criticality as they are frequently used interchangeably. With this there is an ongoing discussion on how to measure different concerns and as to which methods to use to assess the impacts of resource use. The main aims of the research are to create a better understanding of ambiguous concepts used around resource use and to find out what role assessment methods and tools can play in addressing concerns around resource use.

By adopting a mixed methods approach we have come up with useful recommendations on the application and future developments of assessment methods for resource use in low-carbon technologies. From expert interviews we learned that the main problem related to the use of mineral resources is their accessibility, and more specifically criticality. One aspect of the problem with accessibility of a resource is its availability. In the literature review part of this study we found that availability of a resource can get affected by depletion or the rarity of a resource. When there is a low availability and a high demand then a resource can be considered scarce. Criticality of a material becomes a problem when it is difficult for an actor to access and this causes impacts to a social or economic system. By analyzing these concepts through the framework of the three dimensions of sustainability, we provided a strong terminological foundation to be used by assessment method developers and practitioners alike.

By answering the question of what are the most relevant methods to assess the identified problems with resource use we have found that there is a distinction between methods to assess circularity, LCA methods to assess depletion, scarcity or criticality and stand-alone methods to assess criticality. Most importantly, we found that criticality generally gets assessed by two dimensions being: supply risk and vulnerability to supply disruption. Supply risk is concerned with physical availability and socio-economic accessibility. Vulnerability to supply disruption gets measured by economic importance, with recycling and substitutability as mitigation factors. Criticality can be assessed through methods incorporated into the LCA methodology such as Essenz and GeoPolRisk, or by stand-alone methods such as the ones by the NRC, EU or Yale university. There are also methods considered within LCA to assess scarcity where the most prominent one is the Mineral resource scarcity indicator of ReCiPe. With the more in-depth literature research part of this study we analyzed selected methods in more detail by going into their operationalization and comparing them. Which method is the most appropriate to use then depends on the question to be answered by the researcher and the size of the project. The results of this in-depth literature research help to increase the transparency regarding methodologies and data sources used to assess criticality, this will contribute to the general trustworthiness of the results.

Finally, we performed a case study to practically test the applicability of the most relevant assessment methods to see how their results compare and whether they come to the same conclusions or not. The methods applied on the case of EV batteries were the ones by the EU, the GeoPolRisk method and the Mineral resource scarcity indicator. For the criticality of minerals used for the batteries the method by the EU and the GeoPolRisk method only agreed on Cobalt being the most critical. Furthermore, overall it would seem better to choose battery 2 over battery 1 in terms of criticality of the used minerals by both criticality methods. In terms of scarcity by the MRS indicator, both batteries scored just about the same. With this comes, that it can be taken that the mineral scarcity indicator is not directly linked to either one of the criticality methods. It then thus follows that when a mineral is scarce it does not always mean that it is critical, as was expected from theory. In addition, we found that that increasing recycling of the minerals will decrease criticality scores for both the EU criticality method and GeoPolRisk method.

The knowledge gained from this research can now be applied within future research on assessment methods focusing on impact of resource use in general and more specifically critical raw materials. Also It can be used to make more careful considerations on how to apply the assessment methods studied in this research in varying cases. Also this information can make it easier to specify certain trade-offs and to make better informed decisions.

To societal actors and stakeholders interested in or associated with criticality and its assessment, we would suggest the following. We recommend for researchers in the field of criticality and other academics to keeping in mind the concepts and terminology as defined within this research as a guide for any pursuits within the domain of criticality. Furthermore, we would insist on keeping data sources as well as methodologies and uncertainty in assumptions transparent within criticality assessment in general to promote cooperation and participation in this field. Knowing about these aspects as well as carefully considering the alignment of goals and scopes, are in the essence of anticipating any risks for national governments as well as corporate actors.

In conclusion, all in all, this research brings us closer to being able to reach the energy goals and transition to a net-zero economy while at the same time applying circular economy principles. For society to succeed in enabling more sustainable practices, it will be necessary to promote creating a more extensive knowledge base on material criticality and how to mitigate supply risk as well as limit the economy's vulnerability to it.

Preface

Dear reader,

Before you lies my final work for graduating from the master Innovation Sciences at the Eindhoven University of Technology, partly conducted at and supported by the TNO in Utrecht. This report has been a couple of months in the making, yet also required the knowledge gained from the investment of some years of studying at the TU/e. My path has not been as straight forward as others, but it has given me the opportunities and experiences to broaden my horizon and develop my character as well as many valuable skills.

At the end of this process of graduating, first and foremost I would like to express my gratitude to my main supervisor Arjan. Your knowledge and input has been immeasurably valuable and your enthusiasm from the start gave me a lot of energy and motivation. At times when I was struggling or my thoughts got clouded and I got stuck you have been greatly understanding and encouraging. Thank you for guiding me throughout this whole process and for always being available to help me.

Also, I would like to send my appreciation to Diana, for your input and guidance as well as support and understanding. With our weekly meetings at the TNO you provided me with the expertise and insights I needed to get a complete comprehension of the subject of criticality, and to work past some challenges. In addition, it gave me structure and some stimulation at times when I most needed it.

Next, I want to thank Mara, you have assisted me greatly with all of your suggestions and constructive criticism. Furthermore, I would like to thank my former colleagues at the TNO and interviewees for their interest and collaboration during this research. Moreover, I would also like to thank Heleen for being part of my graduation committee and providing me with valuable feedback.

Finally, a special note of heartfelt appreciation goes out to my friends and family for their emotional support during this whole journey. I want to sincerely thank you all for your support, distraction and patience.

Yorick Bakker
Utrecht, 22-03-2023

Contents

List of figures

List of tables

List of abbreviations

ADP:	Abiotic Depletion Potential
CF:	Characterization Factor
CI:	Circularity indicator
Co:	Cobalt
CRM:	Critical Raw Material
Cu:	Copper
DRC:	Democratic Republic of Congo
EC:	European Commission
EI:	Economic Importance
EOL-RIR:	End-of-life Recycling Input Rate
EU:	European Union
EV:	Electrical Vehicle
FAO:	Food and Agriculture Organization
GeoPolRisk:	Geo-Political Risk
HHI:	Herfindahl-Hirschman Index
IEA:	International Energy Agency
IRENA:	International Renewable Energy Agency
LCA:	Life Cycle Assessment
LCC:	Life Cycle Costing
LCIA:	Life Cycle Impact Assessment
LCO:	Lithium Cobalt Oxide
LCSA:	Life cycle sustainability assessment
LFP:	Lithium Iron Phosphate
Li:	Lithium
LiB:	Lithium-ion batteries
LMO:	Lithium Manganese Oxide
LREE:	Light Rare Earth Element
Mn:	Manganese
MRS:	Mineral Resource Scarcity
Ni:	Nickel
NiMH:	Nickel-metal hydride
NMC:	Nickel Manganese Cobalt
NRC:	National Research Council
OECD:	Organization for Economic Co-operation and Development
ReCiPe:	RIVM and Radboud University, CML, and PRé Consultants
REE's:	Rare Earth Elements
SCP:	Surplus Cost Potential
SI:	Substitution Index
S-LCA:	Social Life Cycle Assessment
SOP:	Surplus Ore Potential
SR:	Supply Risk
UN:	United Nations
USD:	United States Dollar
USGS:	United States Geological Survey
WGI:	World Governance Index

1. Introduction

1.1. The energy transition in a circular economy

Currently, the EU is facing a double sustainability challenge to reduce carbon emissions and do this resource-efficiently. In order to tackle climate and environmental challenges, the European Commission (EC) adopted the European Green Deal in 2019 (EC, 2019). The main goals are to have net zero emissions of greenhouse gases in 2050 and to decouple economic growth from resource use by creating a resource-efficient and competitive economy. In addition, in 2021, the EU adopted a package of policies to achieve its energy transition. This included an intermediate goal to reduce emissions by 55% by 2030 (EC, 2021). The energy transition means a transformation of the energy sector from fossil-based to zero-carbon. By this, the EU set concrete and ambitious targets for energy storage and conversion, including renewable energy and electric mobility. One target for energy use is to get 40% from renewable sources, indicating a significant increase in wind and solar power capacity. Another goal is to entirely stop gasoline-driven cars' sales by 2035 and, from then on, sell only electrical vehicles (EVs). One report by IRENA acknowledges that Solar photovoltaic (PV) and wind power generation, grid expansion and electromobility (motors and batteries) will be the main drivers of material demand in the energy transition in the coming years (Gielen, D., 2021). In a prognosis by the IEA, overall mineral requirements for clean energy technologies will almost triple between today and 2050 in one scenario, and multiply up to sixfold in another (IEA, 2021).
In the EC's 2020 circular economy action plan, a core policy initiative following the European Green Deal, they noted that half of total greenhouse gas emissions and more than 90% of biodiversity loss and water stress come from resource extraction and processing (EC, 2020a). Furthermore, they stated before that one of their main goals is to reduce resource consumption and that creating a circular economy is one of their core projects (EC, 2015). To be able to reach the energy goals and transition to a net-zero economy while at the same time applying circular economy principles will create opportunities but also challenges.

1.2. The present societal debate on criticality

To begin with, it will be most interesting to look at the current debate around the controversiality of using raw materials for renewable energy and electric transport. First, there is the question of how renewable so-called "zero-carbon technologies" are, as many mineral resources can be depleted. Here we need to be reminded of the "Limits of Growth" report by the Club of Rome (1972), saying that our planet is physically limited and that humanity cannot continue to use more physical resources than nature can supply. In addition, another principle point of discussion is how environmental friendly these technologies really are, considering pollution coming from the production of raw materials like Lithium, Cobalt and Nickel which are essential to electric cars and renewable energy technologies (Penn, I., Lipton, E., & Angotti-Jones, G., 2021). An article covered by the NOS reported: "*Europe wants to become less dependent on China for Lithium, an important raw material for making batteries.*", further explaining that "*The largest (EU) lithium reserves are in Serbia, and mining causes environmental problems in Serbia.*" (Godfroid, D. J., 2021). Environmental concerns have been rising in the EU as production processes are often ruinous to land, water, wildlife, and people. For example when mining Lithium all kinds of harmful substances are released, such as tar and mercury, and hydrochloric acid and sulfuric acid are used in the processing process, which can all end up in the air, soil, and water. Because of this, the introduction of a Lithium mine in Serbia was temporarily suspended after fierce protests by its citizens (NOS, 2022).

The British-Australian mining giant Rio Tinto carrying out the project argued that Lithium will play an essential role in the transition to a low-carbon economy. Furthermore they stated that the scale and high-grade nature of the Lithium deposits in Serbia provide the potential for a mine to supply lithium products into the electric vehicle value chain for decades, positioning Serbia as the European hub for green energy. Urging for the economic contribution of mining Lithium for the local economy and pointing out Europe's reliance on the materials' production.

A similar situation has occurred in Portugal as establishing a Lithium mine project in the rural area of Covas do Barroso has been contested by the local population (Menendez, S., 2022). Earlier, the region around Boticas and Montalegre was declared an Agricultural World Heritage Site by the UN Food and Agriculture Organization (FAO) in 2018 as an age-old form of traditional agriculture here is passed down from generation to generation producing famous kinds of beef and honey. Again, the mining company carrying out the project, here the London-based mining company Savannah Resources, argued in favor of the economic advantages of the project. They stated that the mine could generate €1.3 billion of revenue over the next fifteen years and that the ore's exploitation will create around 800 jobs for the residents. Thereby saying that these mines can largely contribute to Europe's economic stability and compensate the local population.

Besides the environmental concerns with mining Lithium, social concerns have been raised around the use of another essential mineral in EV batteries; Cobalt. An article from 2021 by The New Yorker headed "*The Dark Side of Congo's Cobalt Rush*" talked about the terrible worker conditions of Cobalt miners in the Democratic Republic of Congo (DRC) (Niarchos, N., 2021). Referring also to a report by Amnesty International from 2016, "*"This is what we die for": Human rights abuses in the Democratic Republic of the Congo power the global trade in cobalt.*". The report documented the hazardous conditions in which artisanal miners, including thousands of children, mine cobalt in the DRC. The report stated that miners dig out rocks from tunnels deep underground using basic hand tools, and that accidents are common. Despite the potentially fatal health effects of prolonged exposure to cobalt, adult and child miners work without even the most basic protective equipment (Amnesty International, 2016). Despite these terrible conditions, workers get almost none of the profit, they work for 30p (0,125£) an hour as was noted in an article by The Guardian (Pattison, P., 2021). The article further stated that Congolese workers describe a system of abuse, precarious employment, and paltry wages, all to power the green vehicle revolution.

One of the issues with the supply of Cobalt lies with its geographical distribution as nearly half of the minerals' reserves lay in the DRC, and the country accounts for around 70% of the world's production of the mineral (USGS, 2022). With this comes that China controls a large amount of the materials' international trade (Gulley, A.L., et al., 2019). Mining these ores more locally or recycling the materials are amongst the main possible contributors to decreasing Europe's dependency on external stakeholders like China in this example. Economically seen EV- and battery manufacturers also take part in the debate. On a corporate level, for example, it was reported that: *"VW and its US rivals (Ford & GM) face a struggle to source materials to power electric cars as China monopolizes supply"* in an article by the Financial Times headed *"Carmakers' battery plans in peril as raw material costs soar"*. These car-producing companies will have to innovate drastically to reduce their reliance on foreign suppliers.

Summarizing the debate, the problems that occur around using raw materials for low-carbon technologies are environmental, social, economic, and political, depending on the perspective taken. The issues here do not just present themselves on an academic or policy level but also practically, for example, on a corporate level and basically throughout our society. To be able to make decisions on what materials to use for low-carbon technologies and where best to get them from, a way of assessing the impacts of resource use would be necessary.

1.3. Problem statement: assessment of resource use

Assessment methods provide a unique opportunity to steer towards sustainable resource use and a circular economy. However, there is an ongoing debate on how to measure different concerns and as to which methods to use to assess the impacts of resource use (Lieberei & Gheewala, 2017; Northey et al., 2018; Ponomarenko et al., 2021). The United States National Research Council (NRC) first started studying the availability of materials and their importance to the country in their report “Minerals, Critical Minerals, and the U.S. Economy” (NRC, 2008). To address material availability problems in the EU, the EC has developed a methodology to create a list of Critical Raw Materials (CRMs) (European Commission, 2017). Besides this, there are also independent methods to assess

criticality, like the method developed by Yale University mainly for corporate applications (Graedel et al., 2011; 2015)
A tool widely used to measure and evaluate the environmental impact of a product or service is Life Cycle Assessment (LCA). LCA provides a systematic framework that helps to identify, quantify, interpret, and evaluate the impacts of a product, process, or service (Baumann & Tillman, 2004). LCA generally looks at a product from when materials are extracted to the use of a product until its disposal. This allows one to identify the impacts of different stages in the life cycle of a product/service to point out possibilities for improvement. LCA's can, for example, address environmental issues related to mineral mining/extraction, production processes, and waste treatment. The availability of materials now increasingly also gets considered in LCA methods. Generally, this has been done by including indicators for depletion or scarcity (Klinglmair et al., 2014; Huijbregts et al., 2017, Vieira et al., 2016, 2017). Methods assessing the depletion of mineral resources in the earth's crust are unintentionally incorrectly used by LCA practitioners who are actually interested in economic risks of raw material supply risks (Fraunhofer, 2018). Moreover, to address political and economic concerns, it could be helpful to introduce criticality indicators such as geopolitical risk to LCA methods (Sonnemann et al., 2015; Gemechu et al., 2016; 2017; Bach et al., 2016; Cimprich et al., 2017; 2019).
Criticality assessment methods have gained more and more attention since the US NRC, and the EU started to report on them. However, still, there is much discussion around the concept of criticality. From the literature now, it is found that it is to be discussed how criticality should best be assessed (Klinglmair et al., 2014; Berger et al., 2020; Sonderegger et al., 2020). With this comes the question of whether all problems get addressed well enough in the assessment of criticality. Most importantly, there is much vagueness around the concepts of criticality, scarcity and depletion, as they are frequently used interchangeably (André & Ljunggren, 2021). One very noteworthy article by Schrijvers et al., (2020) compared multiple types of criticality assessment methods and argued that for this area of research, two things are recommended. First, communication on critical raw materials should be more transparent regarding the methodology used, data sources, and uncertainty ranges, especially when criticality determinations have consequences on public decision-making (Schrijvers et al., 2020). Furthermore, A clear description of the goal and scope, including a description of the anticipated risks that are considered within the study, will help the readers of a study to evaluate whether a study fits their perception of criticality and to identify which studies are comparable. Therefore, this will be part of the aim of this study. To sum up, the main issues are that there is unclarity about what the impact of resource use for low-carbon technologies is and what methods or tools to use for assessing this.

1.4. Research goals and questions

Following the previously stated problems, this research contributes to solving these issues. The main goal of this research is to come up with useful recommendations on the application and future developments of assessment methods for resource use in low-carbon technologies. In order to do this, the first aim of the research is to create a better understanding of ambiguous concepts used around resource use. The second aim of this research is to find out what role assessment methods and tools can play in addressing concerns around resource use, which will be addressed theoretically as well as practically. Together these aims lead to the following research questions:

- RQ 1: What problems are related to the use of mineral resources for low-carbon technologies, and how are they linked to concepts commonly used around this subject?
- RQ 2:
  a) Which are the most relevant assessment methods and tools used to address the identified problems?
  b) What do selected methods entail, and how do these different assessment methods compare?
- RQ 3: What is the applicability of the most relevant methods, what conclusions do they lead to, and are these conclusions the same or different for the object of EV car batteries?

1.5. Methodology and research outline

This research adopts a mixed methods approach combining qualitative and quantitative research methods in which they complement each other. By incorporating both types of methods, they provide a more complete overview of the researched problems than each method alone, as when used in combination, they neutralize each other's biases and weaknesses (Creswell & Creswell, 2017). To begin with, the first research question will be answered qualitatively, employing an explorative literature review. After this, interviews will be carried out, the results are in part explorative of the concepts as well as more in-depth for the assessment methods and indicators. Next, the literature study will be continued by going into more detail to answer the second research question. By incorporating these qualitative methods in the research, the topic of this study can be most effectively and broadly explored, which is necessary to be able to answer the questions fully. Finally, the last research question will be answered quantitatively through a case study. By performing this case study, a more empirical understanding can be gained of selected assessment methods, and it will develop a comprehension of what it means to apply these methods in practice. An overview of the methods for each research question, together with their respective chapter in the report, is shown in figure 1.1 below. What can be found from this table is that the methods partially coincide as the literature study and interviews were formed by an iterative process. The next chapter will elaborate on the specific methods of the literature review and research, the interviews, and the case study.

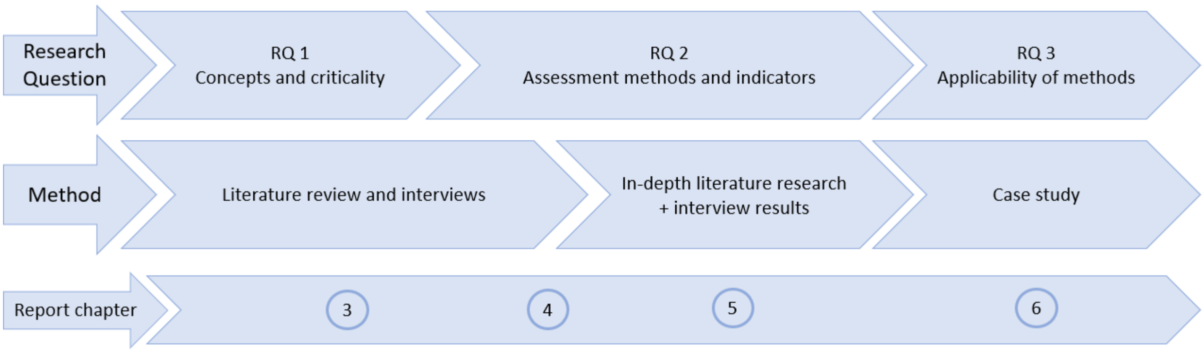

Figure 1.1. Overview of research questions, accompanying methods and report section.

2. Methodology

2.1. Literature Study

As noted before, to be able to partly answer the first research question an explorative review was made on existing literature. To answer the second research question, a more in-depth literary review was carried out on existing methods to assess criticality.

2.1.1 Literature review

An explorative method was applied to make an inventory of the concepts and clarify them. To find sources for this review, the search engines used were: Google and Google Scholar. These search engines were chosen because of their ease of use and broad data availability. To first explore the problems, searches were done containing the following words in the full text: “impact” AND (“mineral” OR “material”) AND “resource use”. From this, it was found that the concepts of criticality, scarcity, depletion, and rarity were the most relevant. To then go into detail on the concepts related to the found problems, they were each used in search queries containing: (“criticality” OR “scarcity” OR “depletion” OR “rarity”) AND (“mineral” OR “material”) AND “resources”. The types of publications selected to be included were scientific articles, research journals, books, and reports. Together with the publications found through this search on the different search engines, other relevant publications were found by cross-referencing from the reviewed articles. The found literature has led to clear formulations of chosen concepts which can be found in chapter 3. The concepts have been generally discussed and positioned against the problems found in the first search queries. Furthermore, it was considered what perspective they are based upon and how they relate to each other.

A more specific review was carried out to answer the first sub-question of the second research question about assessment methods for analyzing the found problems. To find academic literature for this part of the review, the search engines used were: Google scholar, Science Direct, and Web of Science. These search engines were chosen because of their ease of use, available data, and overall recognized performance. The priority was with Google Scholar and Web of Science as they directly show the number of citations for an article and short sentences containing the search words. The following searches were conducted: (“assessment methods” OR “indicators” OR “LCA”) AND (“circularity” OR “criticality” OR “scarcity” OR “depletion” OR “rarity”) AND (“mineral” OR “material”) AND “resources”. The publications were then sorted on relevance and selected on the number of citations, publication date, and amount of contained search words in the title. The types of publications selected to be included were primarily scientific articles and reports. After this, an overview of the selected articles was made in Microsoft Excel to more closely analyze the articles on their main idea, purpose, methodology, findings, and conclusions. This has resulted in an overview of methods and indicators given in the second section of chapter 3.

This section will start off by explaining indicators for circularity. Next, methods within the LCA methodology will be discussed. Here depletion methods will be generally covered, one method to assess scarcity will be explained in more detail as well as two methods for criticality. Finally, methods solely aimed at assessing criticality will be discussed.

2.1.2 Literature research

To answer the second research question, a more in-depth literature review was carried out on specifically selected assessment methods. In-depth research into their operationalization was performed by looking more closely at scientific articles, reports, and policy documents.

For this comparison, three LCA methods have been discussed; the GeoPolRisk method, ESSENZ method, and the ReCiPe mineral resource scarcity indicator. The methods of Essenz and GeoPolRisk have been selected as those are the most developed criticality assessments within LCA and are suggested for practical application (Berger et al., 2020).

Essenz is the most elaborate in this category and has the highest level of recommendation, however, it is not yet operational. GeoPolRisk, on the other hand, is operational, and its scope is product specific, which made this method the most interesting for the case study. The Mineral resource scarcity

indicator is the most widely accepted scarcity indicator in LCA and made operational in the ReCiPe LCA method (Goedkoop et al. 2009; Huijbregts et al., 2016; Huijbregts et al., 2017).
Next to this, three general criticality assessment methods have been considered; the ones by the NRC, the EU, and by Yale. These general methods were chosen for the following reasons. Firstly, the NRC criticality definition and method are on the base of many other methods as, for example, the ones in LCA and by the EU. Secondly, the EU method is most relevant within the found policy frameworks of the energy transition and circularity, making it relevant for the region studied in this research. Thirdly, the Yale method was the most elaborate on a methodological level and has been compared with the other methods before, as it was cited in a number of academic articles.
In the comparison of each method, its goal and scope were considered together with their level of integration, level of analysis, temporal scale, criticality parameters, and indicators. Next to that, the advantages and limitations of the methods used have been pointed out. In the end, the similarities and differences of each method have been discussed in more detail. The EU method, GeoPolRisk method, and Mineral resource scarcity method were also studied by their operationalization for the relevance of the case study later in this report.

2.2. Interviews: stakeholder perspectives

The main goal of conducting interviews was, to begin with, to partly answer the first research question in addition to the results gained from the literary review. Moreover, the interviews were performed to create a foundation for answering the second and third research questions on criticality assessment methods. The main aim of the interviews was to get a better understanding of the perspectives and opinions of experts involved with critical raw materials and criticality assessments. The decision was made to merely include experts on the topics of criticality and its assessment. By this it provides a valuable addition to the literature review because of the experts having state-of-the-art knowledge, which is also practically relevant for the case study later on. Here we were mostly interested to find out how different actors define and use the concept of criticality and related concepts, as well as their views on the applications of assessment methods and indicators. The results of the interviews have been presented in a narrative form to illustrate how a discussion could transpire emerged from varying views on the matters at hand. In a general discussion, the participants' answers were compared to each other to see how they matched or differed. The interviews' results also helped in guiding answers to the other parts of this study. Part of the results of the interviews has been used in the literature review and case study chapters. Still, the full results can only be understood after defining the concepts from the literature.

Data was collected through semi-structured interviews to create space for probing from the set questions with follow-up questions to be able to get more in-depth knowledge of the independent thoughts of each individual (Newcomer, K. E., 2015). A basic framework of questions was set up consisting of open-ended questions and sub-questions. The framework used was based on the three distinct aspects of this study, definitions and applications, assessment methods, and the case study. On this framework, for every aspect, questions were set up to guide the interview; the interview guide can be found in Appendix A. The set questions were slightly adapted when needed to fit the expertise of the interviewees. This type of interviewing also allowed for space for the interviewer to deviate from the interview guide and go into more detail with topics that come up during the conversation. Finally, the interviewees were asked for additional relevant papers in the field, the results of which are included in the literature study.

The interviewees have been selected in a way of expert sampling, which is a type of non-probability sampling (Etikan, I. & Bala, K., 2017). Sampling was based on a theoretical understanding of the topics and explorative reading to ensure the presence of individuals with unique and important perspectives on the topics in question. The participants have been chosen on the base of their knowledge on and experiences with criticality and methods for criticality assessment. The interviews were conducted with a range of expert actors involved with criticality, including mainly researchers of criticality assessment methods, one researcher of critical raw materials in the circular economy, and one energy expert. A list of the interviewees is provided in table 2.1 below. The participants for these interviews were approached by email and informed about the purpose of this study. The interviews were performed online via Microsoft Teams and lasted between 30 and 60 minutes. The interviews were recorded in consent with the interviewees after clarifying what would be done with the data. The interviews were then manually transcribed; transcriptions are provided in Appendix A.

To analyze the results, the data from the interviews were interpreted based on a method of qualitative in-vivo coding. By this, main themes could be identified in the data record by selecting codes based on the actual words of the interviewees (Saldaña, J.. 2014; Rowley, J., 2012). These themes could then be drawn together from different interviews and compared to get a proper understanding of what was said and to identify the most important quotes that had emerged. Eventually, notes were made on insights around possible new themes raised from the answers to the interviews.

Interviewee Nr.	Organization	Function and specialization
1	Dutch organization for applied science	Senior researcher: EU critical raw materials, circular economy, ESG and international trade
2	Dutch University	Professor, criticality researcher
3	French University	Professor, LCA expert
4	International organization for renewable energy	Industry expert, energy sector, criticality
5	German University	Senior researcher, criticality indicator in LCA

Table 2.1. List of interviewees

2.3. Case study on EV batteries: applicability of assessment methods

A case study was carried out to answer the last research question of the applicability of relevant methods. The goal of this case study was to practically test the applicability of different assessment methods to get a better understanding of how they compared and whether they came to the same or different conclusions. By this, it has been discussed whether they could be used as substitutes or if they complement each other because they tell different stories. The assessment methods chosen to be applied in this case study are the EU criticality method, GeoPolRisk indicator, and mineral resource scarcity indicator (ReCiPe).
In addition, part of this case study has as aim to test whether chosen methods provided more insight into the effects of using recycled materials on criticality. For this last part, the recycling rates of 5%, 10%, and 40% were tested for the following reasons; a recycling rate of 40% is the goal of the EU for 2050, 10% is the intermediate goal for 2035, and 5% is an intermediate and expected more realistic value. For practical reasons, it was assumed that the recycled materials could be directly used again in the production of new batteries, and there would be no material loss or reduction in ore grade.

The objects of this case study were two types of Nickel Manganese Cobalt (NMC) batteries, more specifically, the NMC (1:1:1) and NMC (8:1:1) batteries. The minerals contained in these batteries have been analyzed by applying different assessment methods.
The two batteries used in this case study were chosen for a couple of reasons. When looking at batteries for EV motors, varying types exist, such as Lead-acid, Nickel-metal hydride (NiMH), and Lithium-ion batteries (LiB) (EU, 2018). The most common type is the LiB, because of its high energy density to weight ratio (IEA, 2021). Other optional types of LiBs for EVs are Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), Lithium Iron Phosphate (LFP), and Nickel Manganese Cobalt (NMC) batteries. It is essential to notice that these batteries contain CRMs as defined by the EU (EU, 2020a). The LCO, LMO, and LFP batteries have a lower Cobalt content than NMC batteries, making them more appealing when taking into account criticality. Although the first three types have a lower Cobalt content, the NMC batteries are preferred for future application because of varying other considerations such as their stability (cycle life), energy density, or specific energy. Research also suggests that the expected battery market shares for specifically the NMC(8:1:1) batteries will be

higher in 2030 and 2050 compared with the shares of 2016 than that of NMC(1:1:1) batteries (which now are the most used NMC batteries) (Acatech, 2020).
The objects of this case study, therefore, were the NMC (1:1:1) and NMC (8:1:1) batteries, which were in the case study results referred to as battery 1 and battery 2. As noted before, NMC stands for Nickel, Manganese, and Cobalt, which are part of the contents of the batteries together with Copper, Lithium, Graphite and polymers. NMC (1:1:1) is a battery composed of equal amounts of Nickel, Cobalt, and Manganese respectfully (1:1:1). Similarly, the NMC (8:1:1) battery contains eight times more Nickel than Cobalt and Manganese. Shifting from NMC (1:1:1) to NMC (8:1:1) batteries will thus mean a lower Cobalt and Manganese use, but a higher amount of Nickel used. The masses (Kg) of the minerals used for both batteries can be found in table 2.2. Figure 2.1 presents the differences in minerals used between both types of batteries when considering the same battery weight. All minerals used for the two NMC batteries have been taken into account within the case study. Out of the used materials, Cobalt, Lithium, and Graphite are considered critical raw materials by the EU report of 2020 (EU, 2020a). One hypothesis followed from this is that it would be more beneficial to use the NMC (8:1:1) battery than the NMC (1:1:1) battery when considering criticality.

Battery type	Total mass of the battery	Li	Ni	Mn	Co	Cu	Others (mainly graphite and polymers)
NMC(1:1:1)	87.5	6.5	17.5	17.5	17.5	5.8	22.7
NMC(8:1:1)	66	5	32	4	4	4.4	16.6

Table 2.2. Typical composition of the NMC(1:1:1) and NMC(8:1:1) batteries, with masses in Kg. Sources: Li, Ni, Mn and Co (Acatech, 2020); Fe, Al and Cu (Buchert et al., 2011)

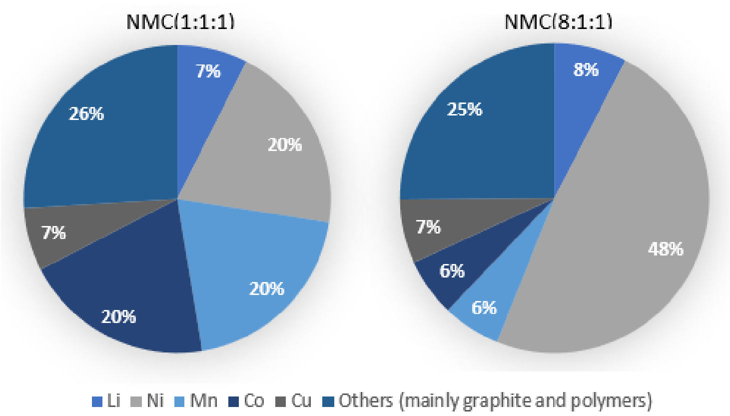

Figure 2.1. Mass composition of both battery types in percentages.

To acquire the results for the case study, the following approaches were adopted. The results of the EU criticality method were gathered from their 3-yearly reports (EC, 2011, 2014, 2017, 2020). For the EU method, the effect of different recycling rates was calculated by using the given End of Life Recycling Input Rate (EoL-RIR). The rates were converted by taking the results of the Supply Risk (SR) parameter and calculating the scenario where the EoL-RIR would be 0%.
The results of the GeoPolRisk indicator have been obtained from an online tool developed by The CyVi Group (available on http://geopolrisk.org/), based on the methods by (Sonnemann et al., 2015, Gemechu et al., 2016, Gemechu et al., 2017, Cimprich & Young, et al., 2017). Calculations have been based on raw material trade data from the United Nations (UN) Comtrade database (https://comtrade.un.org/data/, 2022). Characterization factors (CFs) have been calculated by the trade data of 2017 for the materials of NMC batteries; data for later years was not available. The characterization factors were then weighted by multiplying them with the material weights (Table

2.2). With calculating the effect of recycling for each rate two scenarios were calculated; a best-case scenario and a worst-case scenario. For the best-case scenario, it was assumed that the recycled material would be used as a substitute for materials traded from the countries scoring the lowest on the world governance index (WGI). For the worst-case scenario, this assumption was made for countries scoring the highest on the WGI. In the case study results, an average was taken of the best-case and worst-case scenarios. The mineral Manganese was left out of the recycling calculations because of a lack of data.

For the mineral resource scarcity indicator, the characterization factors were taken from the ReCiPe 2016 Endpoint (H) method (Huijbregts et al., 2017) included in OpenLCA, LCIA method package 2.1.2 (https://www.openlca.org/, 2022). The characterization factors were taken from the impact category of mineral resource scarcity. These characterization factors (in USD2013/kg) were then multiplied by the material weights, as shown in table 2.2.

To calculate the contributions of each material to the scores of each battery, the scores were weighted by calculating the share each material had in the end value, followed by the mass composition of the batteries. To calculate the results for different recycling rates, it was assumed that the recycled content had a CF of 0, meaning it did not contribute to the scarcity of a mineral. The masses of the remaining primary material input were then multiplied by the same CF as used before. This operation is the same as used in the method by the EU.

All of the calculations made for this case study were performed in Microsoft Excel, which can be found in the additional materials of this research. An explanation of the file has been written out in Appendix C.

Regarding the dimensions of the case study, for the temporal dimension of applying the assessment methods, it was chosen to use data from 2017. The reason for choosing this timeframe is that it is the most recent data available for most of the materials with the GeoPolRisk assessment method. Spatially the 28 EU countries of 2017 will be taken into account because of the relevance regarding the energy transition and the circular economy policy frameworks of this research.

The results for each method were first analyzed separately, after which a general comparison was made to test hypotheses and answer the research question. Within the comparison, the impact factors of all three methods have been put against each other by normalizing the scores to Copper. The EU criticality scores were based on average scores of the supply risk and economic importance parameters.

3. Resource use & criticality: concepts & assessment methods

Evidently, one of the possible limitations of low-carbon technologies is the general availability of needed minerals. Resource depletion can affect material availability, as minerals and metals are present in limited amounts on the earth, which decreases with the amount of it that is mined. One term often used is material scarcity; a resource is considered scarce when the demand for it is greater than the supply, as will be discussed in more detail in the following section. Within EU policy, materials can also fall under the term of critical raw materials (CRMs), whose availability gets affected by the vulnerability of their supply chains (EC, 2020b). CRMs are conceptualized as raw materials with high economic importance and whose supply is associated with high risk (EC, 2017).
As noted before, the concept which is being mentioned the most around resource use are depletion, rarity, scarcity, and criticality (André & Ljunggren, 2021). To be able to explore these concepts, it is necessary first to clear up the terminology involving resources. After this, the concepts of depletion, rarity, scarcity, and criticality will be explored to be able further to understand the confusion within the use of mentioned concepts. For this, each concept will be examined separately to clarify its definitions and conceptual differences. Most importantly, differences will be laid out on the three dimensions of sustainability the environment, social and economic dimensions (Purvis et al., 2019). The second part of this chapter will focus more on ways how to study and assess circularity and the criticality of materials. To begin with, an overview will be made of circularity indicators. Next, methods within the LCA framework will be discussed. Finally, separate methods to assess criticality will be covered.

3.1. Definitions of resources and circularity

To be able to produce products, obviously, resources are needed. Resources can be referred to in distinctive ways, and it will be helpful first to clear up definitions around resources. Resources, in general terms, refer to “an available supply of something that is valued because it can be used for a particular purpose, usually to satisfy particular human wants or desires” (Park & Allaby, 2007). Natural resources are materials and energy in nature that are essential or useful to humans (Miller & Spoolman, 2011). These resources are often classified as renewable (such as air, water, soil, plants, and wind) or non-renewable (such as copper, oil, and coal). For natural resources, a distinction can be made between biotic (living) and abiotic (non-living) resources (Klinglmair et al., 2014a). Abiotic resources can be divided into water, fuels, and minerals. Here metals fall under the section of minerals together with nuclear fuels. Metals are single elements, whereas minerals are compounds of various elements (Greenwood & Earnshaw, 2012). Metals rarely occur in their native form except for a few metals like Gold, Silver, Copper, and more. A mineral is an inorganic substance having definite chemical composition or atomic structure and naturally occur in the earth’s crust (Wenk & Bulakh, 2016). Ores are minerals that can be used to obtain metals profitably. For example, Lithium (Li) is a metal; Lithium occurs in nature in ores of, for example, petalite LiAl(Si2O5)2, spodumene LiAl(SiO3)2, and also in subsurface brines. These compounds can also be called minerals. A material, then, is a substance or mixture of substances that constitute an object.
Availability of resources has, in main lines, also been explained by one of the interviewees (Chapter 4), saying: “When it comes to availability, then we usually mean the physical availability to get these resources, and this is simply physical availability. That has to do with basically two components; one is the geological availability, how much we have in the earth. Moreover, the other would be the anthropogenic availability, which is how much is in societal use, for example, landfills and others.” The terms used here need to be explained in more detail. Anthropogenic means to originate from human activity; anthropogenic availability thus means whether it is possible to get material back from used products like electronic waste (Sonderegger et al., 2020). Other terms often used in this context are the ecosphere and technosphere. The ecosphere describes the natural environment, and the technosphere is the man-made environment. This man-made environment includes products made of natural resources.
Then a distinction can also be made between different kinds of material stocks or deposits. Natural stocks are what is present in the natural environment or ecosphere. In-use stocks are what has been extracted from the ecosphere and are presently in use by humans in the technosphere. Disposal stocks

are what are not in use but still in the technosphere in the form of, for example, landfills or stockpiles (Sonderegger et al., 2020).
From there, primary and secondary raw materials are defined as follows: primary raw materials are extracted from natural mineral resource stocks in the ecosphere, and secondary raw materials are extracted from anthropogenic mineral resources in the technosphere coming from disposal stocks.

3.1.1 Circularity, circular economy and product life cycle

For this research, it is necessary to understand what the concept of a circular economy means and how it opposes the linear economy, as it is one of the underlying principles of the LCA assessment methods. The Linear economy model follows a "take-make-dispose" structure of product use (MacArthur, E., 2013). The main problem with the linear model is that high amounts of resources are lost within the value chain. One of the main principles of the circular economy is to reduce harm to the environment (Prieto-Sandoval, et al., 2018). This means to reduce the energy use for production along the value chain to limit pollution and also reduce the amount of input materials taken from the environment. By this, circular economy thinking can be essential to solving part of the issues with material criticality. For example, materials can be recovered through the recycling of products or by separating waste such as for example plastic, paper, and glass so that it can be reused. This practice reduces the amount of needed materials by giving them a new purpose, but most of the time, the quality of products decreases. Besides reducing and recycling, another principle is to reuse products. Reusing products means maintaining or repairing products to be able to reuse them in their original form. To be able to understand the problems around resource use and the related concepts better, it is useful to know the different stages a product goes through, called its life cycle. The framework for the circular economy provides this overview, as it can basically be visualized as in figure 3.4.

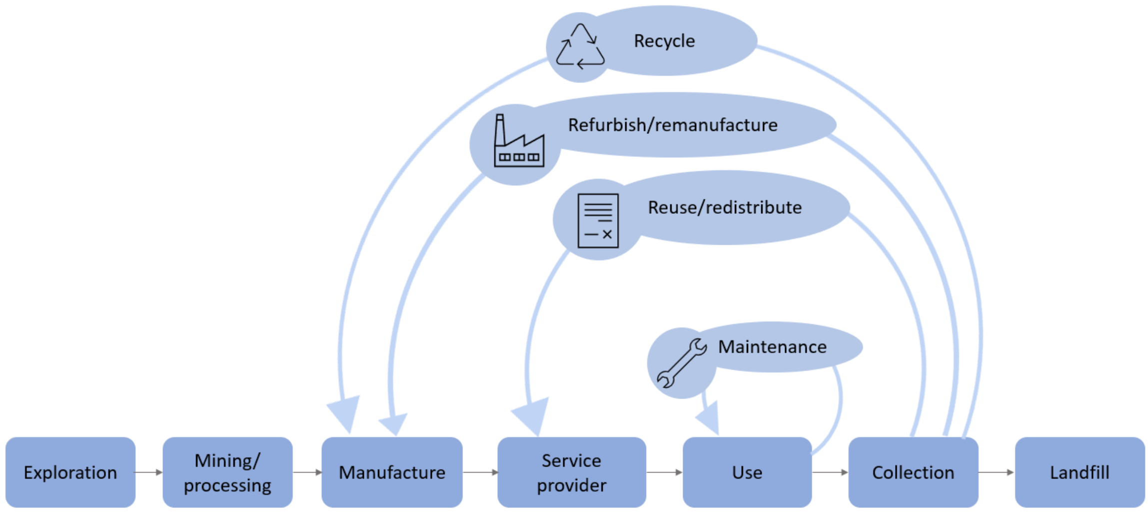

Figure 3.4. Adaptation of the circular economy model by the Ellen MacArthur foundation (Ellen MacArthur Foundation, 2015). It shows how circular economy principles can be applied within the life cycle of a product to make it more sustainable. The arrows indicate feedback loops showing how products can be recycled, refurbished or reused at the end of their life-cycle and how maintenance can extend the use phase.

3.2. Criticality and related concepts

In this section, the concepts of rarity, depletion, scarcity, and criticality will be explained and discussed on the before-mentioned dimensions of sustainability. In addition, the concept of circularity will be covered because of its relevance for further chapters and to the concept of criticality in general.
Before going into the concepts used around criticality, it is noteworthy to differentiate between the seemingly similar terms of availability and accessibility. The importance of this distinction has been mentioned in the interviews performed in this research, as can be found in chapter 5 of this report. It is essential to understand the differences between these two terms as it lays the foundation of what is seen as the main problem with resource use. The differentiation between availability and accessibility can be explained rather simply, but the differences are quite subtle. Literally speaking, availability means the physical presence of a resource, whereas accessibility is used to describe the direct possibility for people to make use of a resource (Schulze et al., 2020a). And as one of the interviewees said: “only because something is available doesn’t mean that you have access to it”. The ideas of availability and accessibility will be used to position the concepts of rarity, depletion, scarcity, and criticality towards each other as we evaluate them.

3.2.1 Rarity

When thinking about resources with low availability, an obvious link can be made to rare metals such as gold and silver and the concept of rarity. Rarity means that something is very unusual/uncommon (Cambridge dictionary) or cannot frequently be found (in nature).
The term rarity often refers to the limited availability of resources regardless of whether there is a demand or not (Ljunggren & Söderman et al., 2013). Interestingly, a group of 15 elements from the periodic table is known to be called Rare Earth Elements (REE), although they are relatively abundant in the earth’s crust (Figure 3.1). From figure 3.1 can be deduced that the REEs are not part of the rarest metals, with Cerium even being more abundant than Copper. REEs are being called rare because rare earth elements are typically widely dispersed due to their geochemical properties. This means they are not often found in clusters concentrated enough to make them feasible to be mined. It is also important to note the appearance of materials labeled as CRMs by the EU, such as Cobalt and Lithium. From figure 3.1 can be seen that Cobalt is present in almost the same quantities as Copper, and Lithium is even more abundant. The concept of rarity is thus most closely related to an environmental view on resource use.

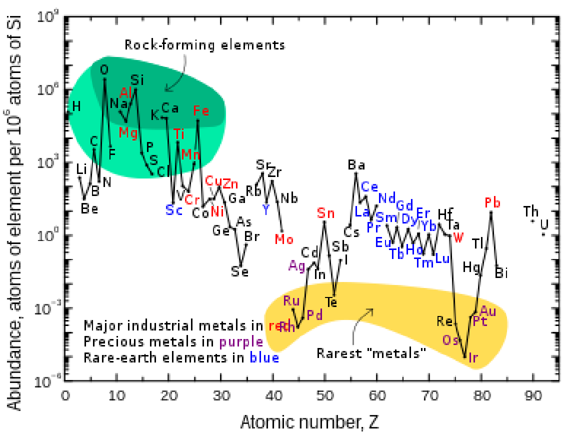

Figure 3.1. Abundance of various elements in the earth’s crust (USGS, 2002). Showing which metals are the rarest and the rarity of REE’s. One particularly interesting aspect to notice is the abundance of Cobalt and Lithium in comparison to Copper.

3.2.2 Depletion

The depletion concept is related to the reduction of a stock (or set of stocks) of a resource and to empty this stock. Depletion can occur due to a variety of factors, such as overconsumption, pollution, or degradation of the resource. This concept is often used as a proxy for the availability of mineral resources. It is assumed that the extraction of mineral resources from the ecosphere, that is the reduction of a resource from the earth by mining, causes the mineral resource to be less available (Sonderegger et al., 2020). Total depletion of a mineral would then mean no more of the resource would be available in the earth's crust. The concept of depletion is an issue of resource use that comes forth mainly associated with an environmental perspective as can also be found from the expert interviews in the next chapter of this research. Still, depletion of natural resources can have negative impacts on both the environment and human society. Depletion of natural resources can lead to pollution, habitat destruction, biodiversity decline, soil erosion and economic instability. Economically, depletion of abiotic natural resources such as minerals and metals can lead to increased mining costs, reduced supply, and higher prices for these metals.

3.2.3 Scarcity

Something is considered scarce when it is not easy to find or get (Cambridge dictionary). Scarcity is dependent on where the majority of a resource is located, also the concentration. It is then also associated with a more economic perspective on resource use; it connects availability to accessibility, as a resource is considered scarce when there is a difference in availability between different parties. By this, scarcity can thus be affected by depletion, as depletion would possibly decrease the supply of a resource when there is no stock. Another factor influencing mineral scarcity could be a decrease in general ore grade (Huijbregts et al., 2017, Vieira et al., 2016, 2017). What then differentiates scarcity from depletion is that scarcity also depends on another economic factor which is demand. A resource can be considered scarce when the demand for it is greater than the supply (Krautkraemer, 2005). A supply shortage thus can only exist when there is more need for a resource than how much is provided.

3.2.4 Criticality

Literally speaking, criticality means: "The fact of being extremely important" (Cambridge dictionary). In that way, the concept goes a step further than scarcity, as the term is used for a resource that is scarce and also crucial for society (Klinglmair et al., 2014b). Before the concept of criticality was used in the context of raw material accessibility, the term "strategic" raw materials was used in the domain of national security and defense, often with possible supply restrictions in mind (Ashby, 2016). The United States National Research Council (NRC) studied the availability of materials and their importance to the country in their report "Minerals, Critical Minerals, and the U.S. Economy" (NRC, 2008). In this report, they considered a material to be critical when a threat to the supply of that material from abroad could involve harm to the nation's economy (Evans, 1993, in DeYoung et al., 2006). The notion of criticality gained awareness due to an increase in demand for energy sources such as oil and nonfuel mineral resources caused by increasing industrialization and economic growth around the globe (U.S. National research Counsil, 2008). The increase in demand was not the only reason; another thing to initiate the increase of studies into criticality was export restrictions of REEs by the Chinese government. Together with the fact that China held a market share of 95% for these resources and there was a lack of local production, this caused high price increases and endangered economic growth around the world and especially in Europe (Dunham et al., 2017, Schrijvers et al., 2020). The European Commission defined materials to be seen as critical when: first, they have significant economic importance for key sectors, and second, the E.U. is faced with high supply risks. A high supply risk was then associated with very high import dependence and a high level of concentration in particular countries or a lack of substitutes (E.C., 2008). Sometimes supply risk is also referred to as "probability to supply disruption," and instead of economic importance, the term "vulnerability to supply restriction" might be used, as has been done in the criticality assessment method developed by Yale University (Graedel et al., 2015). Next to this, supply disruption probability and vulnerability have also been conceptualized as a function of "supply risk" as a single term for assessment methods to indicate criticality, like in the "GeoPolRisk" method developed for LCA (Cimprich et al. 2019).

Generally a supply shortage might be caused by general accessibility issues such as for example economic and technological limitations of exploration and extraction, environmental regulations, natural disasters, or even armed conflicts (Sonderegger et al., 2020). The probability to supply disruption then also gets measured by the risk of an actor not being able to get a material due to limitations such as a very concentrated production in a specific country, political instability, low governance quality or level of development, and trade barriers (Cimprich et al., 2019).
Vulnerability indicates the potential social or economic impacts on a system caused by supply disruption (Schrijvers et al., 2020). By this, vulnerability is a bit of a broader term than economic importance as the system can be functioning on different levels. Where economic importance will be specific to a region or country, vulnerability can also be used for a specific actor or company on a corporate level. Vulnerability often gets measured as how important the studied material is in what it is used for, how much profit is generated from it, or how competitiveness decreases with a supply disruption and the ability of the actor to use other substitutes for these applications or to innovate in this (Graedel et al., 2011).
To make all of the terms used in the discussion here more comprehensible, a schematic presentation has been made, as depicted in figure 3.2 below. It shows how the concept of criticality gets divided into supply risk and vulnerability to supply disruption. Here supply risk covers the availability and accessibility of resources due to their physical availability and socioeconomic accessibility. The physical availability gets affected by geological and environmental as well as technical factors. Socioeconomic accessibility is concerned with sociopolitical concerns. The vulnerability to supply disruption is involved with the economic importance of a material and the possibility to substitute.
Regarding criticality assessment methods, it can be said that there are then two main reasons for evaluating the criticality of materials (Schrijvers et al., 2020). Firstly, criticality studies are generally performed to raise the attention of decision-makers in government and industry towards issues related to raw materials supply and demand. This again shows the relation to scarcity, which in a way, is part of the concept of criticality. Secondly, criticality studies often aim to provide information to policymakers, industry, and consumers on how to mitigate criticality. Ways how to assess criticality will be examined in the next section of this chapter.

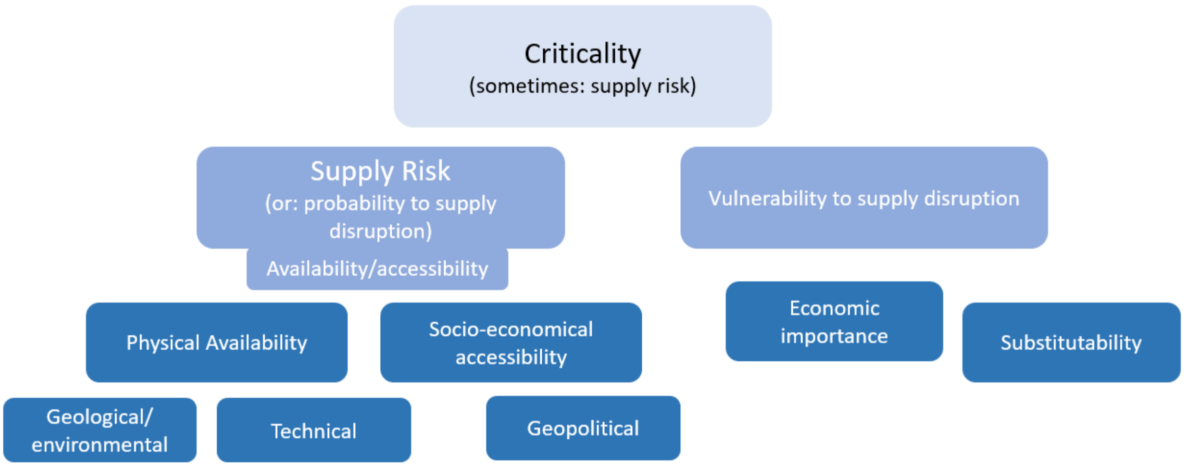

Figure 3.2. Schematic representation of the concept of criticality showing how the concept generally gets divided into two dimensions being: supply risk and vulnerability to supply disruption. Supply risk is concerned with physical availability and socio-economic accessibility. Physical availability includes geological/environmental and technical aspects, socio-economical accessibility includes geopolitical aspects. Vulnerability to supply disruption contains aspects of economic importance and substitutability.

3.3. Assessment methods and indicators

To be able to make decisions on what materials to use for low-carbon technologies and where best to get them from, a way of assessing the impacts of resource use would be necessary.
Assessment methods can provide a unique opportunity to navigate towards sustainable resource use and a circular economy. The following section discusses the most well-known examples of assessment methods related to the previously discussed concepts. The section will start off by exploring the idea of indicators for circularity. After this, assessment methods within the LCA methodology will be discussed: depletion, scarcity, and criticality methods, including Essenz and GeoPolRisk methods. Next, methods focusing purely on criticality assessment will be reviewed, including the NRC, Yale, and EU approach. This will all be followed by a general discussion and conclusion.

3.3.1 Circularity indicators

Circularity indicators (CI) show how much something is circular. Using these indicators can be helpful in measuring the progress of a transition toward a more circular economy (Saidani et al., 2019). One of the objectives of CIs are to measure progress in the form of resource efficiency and the effects of recycling and reusing products. Other measures include firm profitability, competitive advantage, or the number of new job opportunities (Linder et al., 2017).
The three most cited CIs are the Material Circularity Indicator (MCI) by the Ellen MacArthur Foundation and Granta Design (Ellen MacArthur Foundation, 2015), the Circular Economy Index (CEI) by (Di Maio et al., 2015) and the Reuse Potential Indicator (RPI) by (Park et al., 2014). The MCI has been regarded to be one of the most promising product-level CIs and is considered to be the most complete assessment method for circularity on a micro-level (Linder et al., 2017; Elia et al., 2017; Garza-Reyes et al., 2018). The method basically measures how restorative the material flows of a product or company are by incorporating many requirements for a CE. Based on this indicator also, a Product Circularity Indicator (PCI) was developed to measure the circularity performance of complex product supply chains (Bracquené et al., 2020). Although this gives a more detailed overview of materials' circularity, the thorough quantification of used parameters may be complex and make its operationalization difficult (ORIENTING, 2022).
The research on circularity indicators is extensive and can be done on multiple levels. For now, this subject is out of the scope of this study as the focus here is on resource availability and accessibility. These methods will thus not be included in the following chapters.

3.3.2 LCA methods

As noted before, LCA provides a systematic framework that helps to identify, quantify, interpret, and evaluate the impacts of a product, process, or service (Baumann & Tillman, 2004). LCA generally looks at a product from when materials are extracted to the use of a product until its disposal. In LCA, impacts are thus calculated by analyzing a product from the beginning to the end of its life cycle. This allows one to identify the impacts of different stages in the life cycle of a product/service to be able to point out possibilities for improvement. LCA's can, for example, address environmental issues like CO2 emissions related to mineral mining/extraction, production processes, and waste treatment.
The availability of materials now increasingly also gets considered in LCA methods. Generally, this has been done by including indicators for depletion or scarcity (Klinglmair et al., 2014; Vieira et al., 2017). Moreover, to address accessibility concerns such as political and economic issues, criticality indicators considering socio-economic factors are being introduced to LCA methods (Sonnemann et al., 2015; Gemechu et al., 2016, 2017, Bach et al., 2016, Cimprich et al., 2017, 2019). One key notion to make about criticality methods incorporated into LCA is that traditionally LCA covers the impacts of a product system on the environment, which can be called an "inside-out" perspective, whereas criticality methods are concerned more with an "outside-in" perspective by looking at the impacts of supply risks on a product system (Cimprich et al., 2019). This section has been divided into depletion methods, scarcity methods, and criticality methods.

Depletion methods

The main indicators considered in most LCA methods for analyzing the impacts of natural resource use are those for resource depletion, or more specifically, abiotic resource depletion (Klinglmair et al., 2014a). The main aim of depletion methods is to reflect that current resource use reduces resource availability which causes scarcity (André & Ljunggren, 2021). ADP (abiotic depletion potential) methods are generally based on the ratio between the yearly extraction of mineral resources and the square of an estimate of natural stocks (Guinée & Heijungs, 1995; Sonderegger et al., 2020). Current models are usually established on methods such as, among others, reserves of a resource, exergy consumption, and future consequences of resource extraction (the surplus energy approach) (Klinglmair et al., 2014a).

Reserves of a resource indicators are based on total reserves and directly assess the extracted mass of a given resource, usually in relation to its deposits. It shows, for example, a ratio between the annual extraction of mineral resources and the square of a natural stock estimate (Sonderegger et al., 2020). Examples of such methods are the CML 2002 method by Guinée et al. (2002) and van Oers et al. (2002) and the Environmental Design of Industrial Products (EDIP) methods by Hauschild and Wenzel (1998).

Exergy methods, or thermodynamic accounting methods, quantify the collective exergy used in a product system. The exergy of a system or resource is the maximum amount of work that can be obtained from this system or resource when it is brought to (thermodynamic) equilibrium with its environment (Perrot, 1998). For metals and minerals, examples of such methods are the methods of CEENE by Dewulf et al. (2007) and CExD by Bösch et al. (2007); they account for the difference in exergy of these resources compared with the reference state (Sonderegger et al., 2020).

Surplus energy approaches are based on the assumption that the quality of mineral deposits tends to decrease as more and more of a resource gets extracted (Klinglmair et al., 2014a). Each extraction of an amount of a resource from a deposit will mean that in the future, extraction must take place from lower-quality deposits, which will also be more energy-intensive. These methods get, for example, adopted in the Eco-Indicator 99 (EI99) by Goedkoop and Spriensma (2001) and the IMPACT 2002+ method by Jolliet et al. (2003). Because of the wide variety of depletion methods, it has not been practically possible to include this further in this research. Moreover, this research focusses more on the outside-in impact pathways of cause and effect as considered with scarcity and criticality assessments instead of the inside-out pathways of depletion methods (Cimprich et al., 2017).

Scarcity methods

Still, the methods described in the previous section focus mainly on the environmental implications of resource use, The first step towards integrating economic aspects is to model resource scarcity instead of depletion. Some examples of scarcity methods are the Swiss ecological scarcity method, the LIME2 method, and the Mineral resource scarcity (MRS) indicator (Frischknecht et al., 2006; Itsubo N & Inaba A, 2012; Itsubo N & Inaba A, 2014; Goedkoop et al., 2009; Huijbregts et al., 2017). To assess the importance of an increase in scarcity, the ReCiPe LCA method includes resource scarcity as an area of protection next to human health and ecosystem quality (Goedkoop et al., 2009; Huijbregts et al., 2017). To model the impacts on the resource scarcity area, the ReCiPe LCA method uses a mineral resource scarcity (MRS) indicator. One goal of the mineral scarcity indicator is to monetize the energy requirements of resource extraction (Huijbregts et al., 2016). The method used for this indicator corresponds to the surplus energy approach, though here, the extra costs necessary for future mineral and resource extraction gets represented (Klinglmair et al., 2014a). The main idea is that an increase in the extraction of primary metals results in an increase in mining costs because mines with lower operating costs get explored first (Vieira et al., 2016). The functional unit of scarcity in these models, therefore, is the United States Dollar (USD).

The model for mineral resource scarcity comes down to a couple of steps, which will be covered in more detail in chapter 5 of this report. The mineral resource scarcity indicator of the ReCiPe method is one LCA method that has already been widely accepted and used within LCA. For this reason, it will be interesting to also look at this indicator in more detail and compare them to other methods.

Criticality methods
For methods to assess criticality within the LCA framework, the following methods were found: the ESSENZ method by Bach et al. (2016) and the GeoPolRisk method by Sonnemann et al. (2015).

ESSENZ
As an extension and update of the ESP method, the ESSENZ method was developed to be an integrated method to assess resource efficiency (Bach et al., 2016). The main aim of the ESSENZ method is to analyze the restricted availability of resources due to physical as well as socio-economic factors compromising the productivity of companies (Schrijver et al., 2020). The eventual goal of performing the assessment is to inform material selection, product design, and supply chain management for companies. The analysis is thus meant for products on a corporate and global level for the short- and medium-term (<10 years).
The ESSENZ method essentially builds upon the criticality concepts as discussed before, as it includes multiple factors to assess supply distribution possibility as well as vulnerability factors (Sonderegger et al., 2020; Cimprich et al., 2019). The method has been regarded to be recommended as one of the best options for assessing accessibility issues related to geopolitical and socio-economic aspects partly due to its extensiveness (Berger et al., 2020).
Because of this reason, the operationalization of this method will be analyzed in more detail in chapter 5 of the research.
The model for mineral resource scarcity comes down to a couple of steps, which will be covered in more detail in chapter 5 of this report. The mineral resource scarcity indicator of the ReCiPe method is one LCA method that has already been widely accepted and used within LCA. For this reason, it will be interesting to also look at this indicator in more detail and compare them to other methods.

GeoPolRisk
The GeoPolRisk method has been developed to act as a complement to environmental indicators in LCA to be able to address concerns about the accessibility of raw materials (Sonnemann et al., 2015; Santillán-Saldivar et al., 2022). Its aim is to find out what the risk of supply is for product-manufacturing countries originating from their trade relationships with material-producing countries (Cimprich et al., 2019). This is done by calculating the proportion of mass at risk in the life cycle of a material, taking into account the production concentration at a global level and the import mix of the analyzed country or region for a material in a specific year (Cimprich, Young, et al., 2017). This indicates whether the import is distributed and comes from a range of trade partners or if the importing country is dependent on just a small amount of actors. The probability of supply disruption is then determined by the political (in)stability of the exporting countries. The amount of material produced domestically in the manufacturing country is here seen as a mediating factor for supply risk. With this, in the GeoPolRisk method, integrated factors influencing the vulnerability of an actor to supply disruption are substitutability and so-called product-level importance (Cimprich & Young et al., 2017; Cimprich & Karim et al., 2017). The GeoPolRisk method has been recommended to assess country-specific supply risks caused by the political instability of trade partners from which mineral resources are imported (Berger et al., 2020).
The operationalization of the GeoPolRisk method will be discussed in more detail in chapter 5 of this research, as this method of LCA fits the best to the application in the case study of chapter 6.

LCSA
As an improved version of traditional LCA, a method has been developed to be able to quantify aspects of sustainability (Kloepffer, 2008). Life cycle sustainability assessment (LCSA) is proposed to further complement the original environmental dimensions with the economic and social ones. The model of LCSA includes LCA together with Life Cycle Costing (LCC) as well as Social-LCA (S-LCA). As the LCSA method is much broader than resource availability and accessibility, it has been decided not to further include this method in the more in-depth research following in chapter 5.

3.3.3 Stand-alone criticality assessment methods

For stand-alone methods to assess criticality, the next methods were found…

NRC method

As noted before, the US National Research Council (NRC) defines materials as critical when a threat to the supply of a material from abroad could involve harm to the nation's economy (Evans, 1993, in DeYoung et al., 2006). To determine whether a material is critical, the NRC proposed a "criticality matrix" consisting of 2 dimensions (Figure 3.5) (US National Research Council, 2008). The first dimension is *importance in use,* measured by the impact of supply disruption, and the second is *availability*, measured by supply risk. Within this framework, minerals can be quite easily compared to each other as they are being set side by side on the matrix. How both the importance in use and the availability dimensions get measured through specific indicators will be covered in more detail in chapter 5.

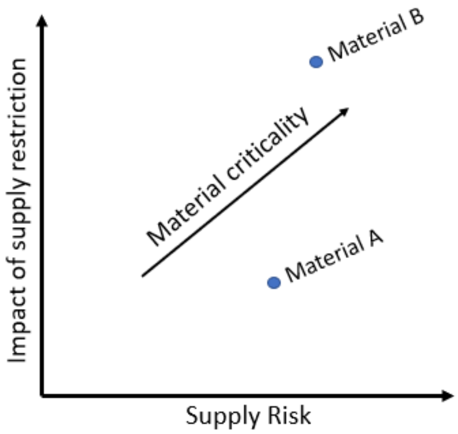

Figure 3.5. Adaptation of the NRC criticality matrix consisting of 2 axes; on the horizontal axis is the supply risk dimension and on the vertical axis is the impact of supply restriction (NRC, 2008).

Yale Method

As an enhancement of the US NRC template, another method for determining metal criticality was developed by the university of Yale (Graedel et al., 2011). The method was designed to help corporate, national, and global stakeholders conduct risk evaluation and to inform decision-making on resource use (Graedel et al., 2015). Their proposed methodology is based on three dimensions: supply risk, vulnerability to supply restriction, and environmental implications. Each of the dimensions represents an axis of their so-called "criticality space" (Figure 3.6). The criticality space is quite similar to the matrix proposed by the NRC, besides the fact that this method involves a third dimension of environmental implications. An analysis of what indicators these dimensions consist of will be given in chapter 5 of this research by looking at the operationalization of this method.

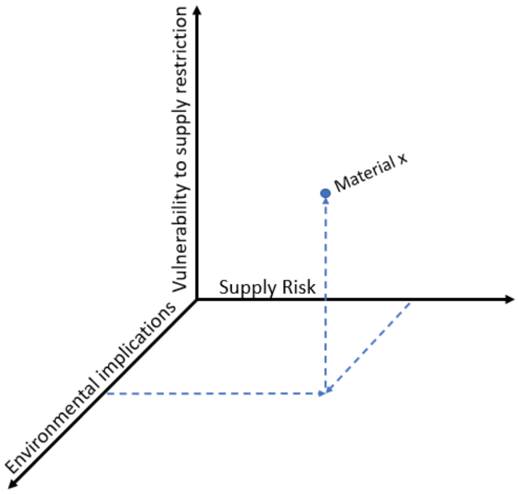

Figure 3.6. Adaptation of the criticality space as developed by the Yale university consisting of 3 axes; the x-axis shows the supply risk dimension, the y-axis shows the dimension of vulnerability to supply restriction and on the z-axis are the environmental implications (Graedel et al., 2011; Graedel et al., 2015). Materials can be shown against each other by placing them on the matrix, as an example "material x" is depicted.

EU method

To address the problems of material availability to the EU, the EC has developed a methodology in order to create a list of CRMs (European Commission, 2017). This list gets updated every three years to be able to analyze changes and trends for these materials. The goal of creating this list of critical raw materials is to increase the overall competitiveness of the EU economy (EC, 2020a). Another aim for the EC is to be able to make recommendations for key areas of work for the EU to reinforce its strategic approach towards more resilient raw materials value chains (EC, 2020b). To implement these strategies, it would be important for key stakeholders such as EU institutions, national and sub-national authorities as well as companies to know about the criticality aspects of materials. Therefore the EU measures criticality on an industry level by looking at complete sectors. Within their method, the EU measures the criticality of a material by assessing its economic importance (EI) and supply risk (SR).

3.4. Discussion/conclusion of the literature review

In this final section, we will come to a conclusion about the reviewed literature in answer to the first research question and part of the second research question. The questions were as follows:

- RQ 1: What problems are related to the use of mineral resources for low-carbon technologies, and how are they linked to concepts commonly used around this subject?
- RQ 2a: Which are the most relevant assessment methods and tools used to address the identified problems?

What now follows is a short conclusion about the main concepts and assessment methods. This will be started off with the terminology related to resource use and the definition of criticality together with its relation to circularity. After this, the assessment methods, such as the circularity indicators, LCA methods, and criticality assessment methods, will be covered.

Before it was stated that the most common concepts mentioned around the use of critical resources needed more clarification. The four concepts which are mentioned the most were rarity, depletion, scarcity, and criticality. Another noteworthy concept is that of circularity which was covered as well because of its relevance to the availability of resources.
It was also found that the main problems are both the availability as the accessibility of resources, although the terms get mixed up quite often. These two terms, together with the three dimensions of sustainability (environmental, social, economic), have been used as a framework to position the concepts against.

The term rarity often refers to limited environmental availability of resources regardless of whether there is an economic demand or not (Ljunggren & Söderman et al., 2013). The concept of scarcity originates from more of an economic perspective. Plainly speaking, a resource is considered scarce when the demand for it is greater than the supply. It can also be said that scarcity connects availability to accessibility, as a resource is considered scarce when there is a difference in availability between different parties. Depletion is fundamental in the principle of availability, as the relation is quite straightforward. When anything gets depleted, it plainly means that it becomes less available. The concept of depletion directly comes from an environmental perspective on issues with resource use. The most urgent problem related to mineral resource use and the concept most relevant to the accessibility of minerals is criticality. Eventually, no matter which specific terms are used to describe criticality, either way, the principle of criticality stays the same: an actor gets affected by a supply shortage, which can originate from varying reasons. And the question then is what the impact of this shortage is and which options the actor has available to mitigate the impacts. In this research, the terms supply risk and vulnerability will be used when talking about criticality in general. Still, to be able to analyze specific methods, sometimes terms will be used as how the authors of those methods have conceptualized them.
The essence of one of the solutions to the problem of criticality is the concept of circularity and the idea of a circular economy. First of all, fundamentally, the concept of recycling is central to circularity and is seen as a potential answer to material criticality. Next to this, circularity and the theory of a product life cycle is one of the main underlying principles of the LCA assessment methods.

Traditionally the main indicators considered for analyzing the impacts of natural resource use in most LCA methods are those for resource depletion. The main aim of depletion methods is to reflect that current resource use reduces resource availability which causes scarcity (André & Ljunggren, 2021). Still, depletion methods focus mainly on the environmental implications of resource use. The first step towards integrating economic aspects is to model resource scarcity instead of depletion. One LCA method which has already been most widely accepted and used within LCA is the mineral resource scarcity indicator of the ReCiPe method (Goedkoop et al., 2009; Huijbregts et al., 2016; Huijbregts et al., 2017).
Assessment methods can also be useful in providing insights into the problem of criticality. Criticality assessments can be very valuable instruments for policymakers but also industrial actors to make

recommendations and choices in selecting materials to use for specific products (Graedel et al., 2015). Criticality assessment methods use many different indicators to reflect the criticality of a material, which type of indicators are used are dependent on the perspective or purpose for studying the criticality of a material. Criticality assessments can be carried out on different levels, such as on a product level but also on a corporate, national/regional, or global level (Graedel et al., 2011). Estimating material criticality then also is dependent on the timeframe taken into account, short-term (one or a couple of years), medium or long-term (one or multiple decades). With this, there are multiple methods of assessing criticality, many of which are regional-specific (Hackenhaar et al., 2022). As can be read in the next chapter, in the interviews, it was found that there are two types of criticality assessment. The first type are the methods focused purely on criticality, such as the NRC method, the EU method, and the Yale method. The latter are the methods integrated into the LCA methodology, such as the ESSENZ and GeoPolRisk methods. In the following chapters, it will be researched what is included in these methods and how they compare.

Concluding this chapter, it is sufficient to say that the confusion around ambiguous concepts has been cleared up, and the first research question has been answered adequately. In addition, the first part of the second research question has been covered in the part of this chapter on assessment methods. The second part of the second research question will be discussed more in-depth in chapter 5 after going through the results of the interviews.

4. Expert perspectives

As mentioned before, the results of the performed interviews are aimed at the exploration of the concept of criticality, the methods to assess it, and the applicability of those methods. The next chapter presents the perspectives of experts on the subjects studied in this research. Again, the framework used for carrying out the interviews was based on the three distinct aspects of this study, criticality and conceptual definitions, assessment methods, and the case study. For this reason, the results of the interviews have been divided into these three predefined categories as well and will be discussed in this order below. Parts of the answers to the questions asked have been selected and quoted to be discussed in the following paragraphs in the form of a narrative.

4.1. Definitions of criticality related concepts

The first questions in the interviews were focused on the definition of criticality and related concepts such as rarity, scarcity, depletion, and social impact. One of the interviewees (I4) responded to this with the statement that "*there is kind of no definition of criticality as far as we know.*", which is a bold statement but clearly shows that there exists confusion around the concept. This confusion was also noted by interviewee 1, who argued that "*Research questions related to criticality are usually poor. Most do not have a common view of what criticality is*", which is certainly a bit more of a nuanced view on the issue. This comment also reflects quite well on what has been found to be the main issue regarding academic research. Interviewee 1 further elaborated on this by saying that "*the questions being asked in criticality are not focused enough. People do not yet themselves know what they want to know.*". From this question then comes up to what are really the problems related to the use of resources and, more specifically, critical materials.

The impact of gathering and using natural abiotic resources can be seen in many different forms. About this, interviewee 2 states, "*when it is about impact, then we usually talk about environmental impacts, such as the carbon footprint, acidification, toxicity from mining activities, etc.*". From an environmental perspective, these are presumably the most important problems in relation to this topic, but these are definitely not the only issues. From this perspective, another problem that has come up is depletion which has been used mainly to indicate the availability of a resource. Interviewee 2 explained: "*When it comes to availability, then we usually mean the physical availability to get these resources, and this is simply physical availability. That has to do with basically two components; one is the geological availability, how much do we have in the earth. And the other would be the anthropogenic availability, which is how much is in societal use, for example, landfills and such.*". According to interviewee 3 this also has to do with the extraction of a resource as he states: "*and it is a question of technology for extraction, and a question of investment in exploration and new mines.*", to this he added examples of possible variables in this: "*how deep you are digging, how and which technology you have to lower concentration.*".

Besides the question of availability, another perspective could be gained from interviewee 3, who mentions that "*the whole move to criticality is to overcome, to me, the old limits to growth thinking of depletion.*". What can be taken from this is that the environmental perspective is not the main point in criticality. One could argue that criticality is more associated with an economic perspective. Economically the main problem could be said to be a mismatch in supply and demand; according to interviewee 1 saying, "*the market will not perfectly balance supply and demand*." and "*the market will not solve all of the problems*." which can be the cause for scarcity of a resource. Nevertheless, in contrast to this interviewee 3 sharply put forward that "*It is not about scarcity or depletion; it is about accessibility and not availability*". This can also be made clear by what was said by interviewee 2, who suggests, "*There is this dimension of criticality which is accessibility. Because only because something is there and its available does not mean that you have access to it, that is the idea of criticality.*". Correspondingly, interviewee 1 said the following: "*The main question that remains is, can we trust the supply or country of origin to deliver next year?*". About this, interviewee 2 said: "*Constraints can be monopolistic structures, political trade barriers, or that resources are too concentrated, or that there is a high price volatility*". Interviewee 5 argues, "*Political issues.., I think these are the most relevant ones*", elaborating by saying, "*in the end, availability and accessibility is mostly decided by some sort of trade barriers or political views certain countries have.*". Interviewee

4 was of the same opinion as she proposed: "*Actually, the whole discussion why we have CRMs is partially because of geopolitics*", together with: "*Which material or minerals will end up on the list is given by geography.*", and: "*But that is also geopolitical perception*.". What is meant by this is that a material is only critical to the party who is not able to acquire it, which is dependent on their location. So now it is possible to conclude that a part of what is criticality is the accessibility to a resource or the risk of supply. However, this is not the only part of criticality, according to interviewee 2, who argues, "*Very often criticality should have these two dimensions, on the one side on the x-axis you have the supply risk. But that by itself does not make a resource critical, its only critical if you are vulnerable to that, so if your economic growth or your production ability depends on this resource, that is usually the y-axis.*". With this the interviewee further explained: "*vulnerability depends on how easy or what share in your purchase is this resource, or can you easily substitute this or can you not, and do you have several suppliers of this resource. So that is your particular situation, supply risk is a global situation, and vulnerability is your particular situation, how dependent are you*.". As an example, the expert came with the following anecdote: "*You can be very dependent if you produce steel cups and you only rely on steel, and you have only one supplier, and you cannot substitute it, then you are highly vulnerable. When you produce cups in general from different materials, and you have 10 suppliers, then it's the same material were talking about but you're not as vulnerable*.". Interestingly, interviewee 1 concluded on the question with, "*in the end, criticality comes back to basic needs*", explaining that, "*generally people do not care about ores or Cobalt, they do not care about metals, they care about the eventual service or comfort provided by the products that contain the ores or metals, that is in the end what matters.*". Subsequently, interviewee 3 argued that, "*if we are moving into what we want to be a sustainable society with new technologies, it is hard to build this on countries where there is the possibility for them not to sell the raw materials anymore.*", which is an argument for both supply risk and vulnerability. When considering the topic of sustainability, the interviewees were also asked about the role of social impact in the criticality debate. Interviewee 2 then explained very well: "*There are two sides to the coin; one is the social impact caused by producing these materials. And that is something that does not belong to criticality methods, the same way that the carbon footprint and the water footprint do not belong to the criticality method, which is highly relevant but should be considered in other impact categories. And then the other way around, on how is the social impact influencing criticality. It can also be that it is critical because there are so many socially bad things happening to it that you cannot use it, even though it is physically available, it is not subject to barriers of trade, and there is no high price volatility, but really you lose the social license to operate if you're using these blood diamonds in your supply chain. It is not about the physical or economic availability, it is just that it is a bad thing to do, your customers won't buy your products anymore if you have these dirty things in your supply chain*.". Concludingly about the relation of social impact with criticality he said: "*Something people just don't accept, this can influence your supply risk*.".

Another curious point worth mentioning was made by interviewee 1, who noted the following about the dimensions of criticality: "*It can also be expressed in terms of time, something is critical if you need it in a week's time, but then also it may be costly, but it is only a week. It would be much more problematic or critical if you can only solve a problem in many months, years or decades*.". Interviewee 5 was in agreement with this as she said, "*I would say it is really mostly about the timeframe.*", arguing that "*most LCA methods focus on the long term perspectives*.", referring to the use of indicators for environmental availability such as depletion, and making clear the need for "*more of a short term or middle term perspective*" as argued by interviewee 5.

Altogether, this makes criticality not only an environmental or economic, but more of a socioeconomic or more generally a sustainability issue dependent on what perspective or point of view is taken and what timeframe is considered.

4.2. Assessment methods and indicators

A second set of questions were asked related to how indicators and methods can be used to evaluate criticality. According to interviewee 5, "*this is mostly about the accessibility, more on a short-term or middle-term perspective.*". When asked about the reason for stakeholders for doing criticality assessment, interviewee 2 answered that "*the most obvious benefit is that they can continue to operate; they are reducing their own risks by knowing what the criticality is*.". After answering the question of why to do a criticality assessment, it remains to go into how to do the assessment. In answer to the question of what would be the best way to measure criticality, interviewee 2 answered with: "*Most importantly, the method should fit your question*.", illustrating that "*it is a bit like asking what the best tool in your toolbox is, is it the hammer or the screwdriver, it depends very much on if your problem is a nail or a screw, it will be hard to answer.*". This means that in which way criticality assessment is performed is subjective to which stakeholder is carrying out the assessment. Then the question comes up as to what kind of criticality assessments are available. Interviewee 3 argued that "*we have to differentiate between independent criticality assessment tools*" and explained that "*Either you have to integrate at the methodological level and you get a sort of comparative risk assessment or you do it by integrating at the result level which means you do a risk assessment and an LCA independently and then you integrate at the results level*.". From this, it can be taken that the criticality methods by Yale, the NRC, and the EU are tools that integrate the assessment at the methodological level to be able to compare the criticality of materials to each other. Moreover, LCA methods such as GeoPolRisk and Essenz integrate at the results level, which means they can be compared to other indicators as well. Interviewee 3 also mentioned, "*For the purpose of having an ecodesign support method that is LCA, the integration (of criticality) provides huge advantages*." and followed up with an argument in favor of this approach, suggesting: "*The advantage of doing an integrated approach using LCA is that while you are doing a sustainability assessment on ecodesign questions of: 'I want to develop a storage device and I want it to have the lowest impact as possible', then the question still is you might have the lowest impact possible but you might use CRM's in the design.".* In conclusion interviewee 3 said, "*When you integrate into LCA you see the tradeoffs between carbon footprint and environmental impact in relation to these geopolitical criticality indicators.*". Although being an LCA expert, interviewee 3 might be subjective with this opinion, it is still a clear benefit of using the LCA criticality methods in contrast with other independent criticality assessment methods. Interviewee 1, who is more closely related to the EU criticality method, points out a disadvantage saying, "*LCA to the outside world, to a skeptic eye as you will, is sometimes still not clear or focused enough, and too uncertain to really make a point for criticality*.", and says: "*Pragmatically this method (EU) would be the most useful, why, because it is there it is accepted, and we can have it this year in our report*.", arguing in favor of the EU method for the use of policy making. Interviewee 2 gives a more nuanced view on the matter by also talking about the scale and level of analysis, stating: "*So if you want to analyze a product or a company, then the LCA-based approach usually works well enough. Mainly the Essenz method and the GeoPolRisk method, both have their pros and cons. The Essenz method is a bit more comprehensive in terms of supply risk dimensions, so you have many more dimensions which could lead to supply risk. GeoPolRisk is a bit more local/specific. So both are very good. If you want to assess it more from a large-scale perspective, so criticality of raw materials for a country or the EU, then these small-scale methods are not designed to answer these questions. Then I would rather go with methods like the Yale method or the European method.*".

After looking at the arguments for using various types of assessments, it is crucial to take into account limitations as well. When asked about this, interviewee 5 talked a bit about the operationalization of the methods starting with the Essenz method, stating:

"*What are the main limitations of Essenz, and that is that we're currently only looking at the materials themselves*.", and then explained further: "*A product itself, a microchip, has its own criticality. So these intermediate products are not considered; we are just looking at where this product is based, or even if there is a product that has a microchip in it, we break it down into materials, then we assume a global production. But this microchip is coming from China, and maybe another aspect of this product is coming from somewhere else. I think this is also an issue that Essenz had, but I also know the EU method for criticality has this as well; they are only looking at the imports of materials but not in part of intermediate products*.". From this, it can be taken that with the application of various methods, it is necessary to keep in mind which assumptions are being made about the products and their materials considered in the analysis. When talking about assumptions, one theme came forth quite dominantly with most of the interviewees, the data used within the assessment methods. When asked about the limitations of assessment methods, interviewee 1 straight answered with: "*Cons; a lack of data*" and "*you will eventually find that there is a data shortage*.". Interviewee 5 noted the same, arguing: "*data availability is always a challenge*.". A reason for the difficulties with this was given by interviewee 4, who argued that "*some of this data is from 2017/2018, which is old because the progress happens really fast*.". Then interviewee 4 also noted that "*the transparency of data is another issue*.", which was also noted by interviewee 5 saying, "*it is really hard to get some reliable data*.". Interviewee 4 then continued explaining, "*the market is not transparent that is why this is possible.*" and goes on by arguing: "*I always worry that you have the data in the hands of a couple of people and then they present to you aggregated outputs. How trustworthy is this, are they lobbied, and how transparent are they? And how many biases are in their work?*". This means that it always needs to be taken into account where the used data has come from. On more of a positive note on the data used, interviewee 4 said: "*we have quite some public data at least at the aggregated level.*", which was also argued to be a benefit according to interviewee 1 who said: "*Pros of current methods: public data, transparent data its clear, available for everybody to verify. Then next, it captures most of the initial problems like lack of recycling, export restrictions, poor social conditions, reputational damage*.". Still on more of a critical note, interviewee 1 explained about the data: "*why there also is insufficient data, because it is normally gathered for a different purpose*." and stated "*the data is not detailed enough*.". Furthermore he stated "*Well its better than nothing, but it can be improved by using better data, for example, verified by blockchain*." and "*there is a need of introducing ICT technologies, such as what is deployed in for example finance or health services, they deploy ICT techniques which are 10/20 years ahead of supply chain managers or environmental impact researchers or enforcing agencies.*". About the use of data, there is one thing we can conclude most certainly, which is that the data used should always be treated with care.

4.3. Applicability of assessment methods

The last part of the interviews was about applying assessment methods in a case study of EV batteries and which part is played by recycling.

About the application of these methods, interviewee 5 compared the LCA method Essenz to the general criticality method of the EU, arguing: "*If you are taking Essenz, which is a global assessment approach, and compare it on a very broad level with the EU method which is anyways a different level, because one is focusing globally and one is focusing on Europe, so there should be a difference. So the method which has different focusses like global or country level, there I would expect you get different results.*". By this, it can be said that the level of assessment plays a crucial role in the results you get when applying them. This makes sense as criticality is dependent on which stakeholder perspective is taken, as was discussed in the previous chapter. Another striking statement about the level of assessment was made by interviewee 2: "*The Essenz method, which again has a global approach, is more suitable for general assessments if you have a product which consists only of a few metals and you know the supply chain it might be more useful to use the GeoPolRisk*.". Which is an argument in support of using the GeoPolRisk LCA method. This is an interesting point to take into account in the case study on EV batteries. Interviewee 2 adds: "*Essenz, for instance, was designed to be really broad and to cover as many criticality aspects as possible. Others are more specific, like for example, the GeoPolRisk considering the specific supply chain situation for a country; this is more detailed. In general, it is always good to apply different methods, and in an ideal world they would all come to the same conclusion, and if not, then it is interesting to see why not*.". When asked whether it would be interesting to use multiple criticality methods, interviewee 2 answered by saying: "*So in general, take as many assessments as possible and combine and analyze them, but of course that is very unpractical if you are a practitioner and you just want to know by a click what is the result*.", and continued with: "*If you are a practitioner you would be overloaded with these kinds of information, and I would say rather pick one. For the LCA world, I think Essenz would have the highest level of recommendations because it is so broad and it has so many characterization factors*.". The last point could also be a limitation of the method, according to interviewee 5, who mentions: "*In Essenz we* *have like 11 indicators for supply risk which is a lot. I think most methods do not have this.*" and "*because now we have 11 indicators, they should be reduced*.". In addition, from a practical perspective and for the comparison of the Essenz and GeoPolRisk methods, interviewee 3 put forward, "*the difference between Essenz and GeoPolRisk is particular, especially with the webtool developed (for GeoPolRisk), it allows you to calculate, if you as a company, not as a country, or the world or Europe, you can develop your own procurement on your supply chain and make choices to make you more resilient*.".

This brings us to the next topic, which is the material supply and, more specifically, material supply by way of using recycled materials. With this, a warning was given by interviewee 4, who stated: "*Another form of supply can be scrap and recycling, but this is complicated*.". Why this is complicated partly gets explained by interviewee 2, who argues: "*With recycling, the tricky thing to get your head around is that there are two levels, so to say. One level is the product system that you are analyzing, and the other thing is recycling as a criticality dimension. So there are two dimensions; one is more related to your product system, and the other one is on a more macro scale of the materials, and both are relevant*.". This is a clear argument for the rationale of the importance of knowing what scale or level to take into account while assessing criticality, and also when considering recycled materials. Within the interviews also arguments were given clarifying the importance of taking into account recycled materials when assessing criticality, besides for the reason of mitigating the supply risk of a material. Just as Interviewee 2 explained: "*in general, you could say if this (recycling) is high, then the criticality is less because you can recycle, so you are not so dependent on the raw materials anymore.*" Interviewee 5 argued: "*Of course, if we think about recycling there are always costs associated with recycling, and it could also be an option to identify which material should be recycled not only from an economic point of view but also from a criticality point of view.*". Interviewee 4 interestingly looked at it from more of an environmental point of view saying: "*What would be very interesting is for policymakers and in general for everyone will be to see the type of recycling and the footprint of it. Because sometimes we see the footprint of recycling, emissions, and pollutions can be very high. So then it destroys the whole idea of sustainability that if you try to mine and process and do that very clean, up to the use, then the secondary use of recycling brings a big carbon footprint, then it kind of offsets all of the previous efforts*.". Although being very relevant, considering the scope of this research, this will not be very relevant for the case study, as the essence will be on the effect recycling has on the criticality of materials.

The next part will be on the topic of considerations regarding recycling in the case study and possible strategies for this. Interviewee 5 noted the following: "*We also did a case study where we included the recycling rate. We then assumed that everything which is recycled goes back into the same product system, which is not reality. So I think it would be very interesting to see if recycling really decreases criticality or supply risk.*". Another interesting point was made by interviewee 2, saying: "*if you have a high share of secondary material or a high recycling rate, this raises the question if you are using the recycling rate or the use of secondary materials.*". It is essential to notice the difference in this because different assessment methods might use other data inputs for this. About the use of secondary materials, interviewee 4 noticed that "*There are a couple of ways that need to be innovated in a way so we can recycle whatever and use it in whatever battery chemistry, so it will not be dependent on the chemistry*" further explaining: "*I am just thinking about high-grade ores which are needed for example for batteries. You might get Copper or Lithium in some form, but you might have a problem with having this high-grade ore which is needed for batteries for example. What we see is that we are able to recycle it, but the ore grade quality is not 99% but 95%, and the end users do not want that.*" She also said: "*There are a couple of ways that need to be innovated*.", arguing: "*I think the most important is transparency in design and probably some technical standardization around it*.". She then explained: "*I think because everything is such an early stage, it will take time and we know standards sometimes take ten years to develop and agree on, and they are also not binding at the same time. Let us say cathodes, and the chemistry is still evolving, so even if you get a cathode of NMC(1:1:1) batteries, in ten years, we still don't have processes to recycle and reuse the battery for a different chemical composition*.". Concludingly she said: "*I think it requires a lot of collaboration and coordination between the private and public sectors and academia to stabilize the whole*."

4.4. Discussion and conclusions

The results of the performed interviews provide a fundamental contribution to the exploration of the concepts related to criticality, the methods to assess it, and the applicability of those methods. As a result of performing the interviews in a semi-structured way, it was possible to identify themes within the different categories.

With the questions about the definitions of concepts related to criticality, what came up was the importance of what perspective is taken on the subject and the role of varying parameters.
Most commonly, when it is about the impact of gathering and using natural abiotic resources, people talk about environmental impacts, such as for example the carbon footprint, acidification, and toxicity from mining activities. From an environmental perspective, these are presumably the most essential problems in relation to this topic, but these are definitely not the only issues. From this perspective, depletion is one of the main problems which has been used to indicate the availability of a resource. What can be concluded is that the environmental perspective is not the main point in criticality. Initially, the interviewees argued that it was hard to define criticality. One could argue that criticality is more associated to an economic perspective than an environmental one. Economically the main problem could at first be said to be a mismatch in supply and demand. What eventually could be concluded was that criticality is mainly about the accessibility of resources instead of only their availability. Evidently, this was an essential conceptual difference to be used in the analysis of the concepts in the previous chapter. With the interviews, it can be confirmed that the biggest criticality concerns are supply risk, including geopolitical issues, and a system's vulnerability to this.
Social impact also has a part to play in criticality in two ways that are closely connected. The first is the social impact of using critical raw materials, and the second is the effect this has on the degree of criticality of a material. Another theme discovered in the interviews, which was said to be important to consider is the timescale of assessing criticality. The conclusion is that criticality has a short-/mid-term scale instead of long-term, like depletion.

The part of the interviews on assessment methods and indicators shed more light on their purpose and essence. The reasons for performing criticality assessments are closely linked with the problems around the use of critical materials and, with this, the definition of criticality. Principally the assessment method used should fit the question to be answered; the question inevitably depends on which stakeholder is asking it. Moreover, criticality assessment methods were discussed, and what came forth were similarities and differences between methods. Most notably, a difference was explained between the integration of criticality assessment on a result level (LCA methods) and on a methodological level (EU method). The main benefit of integrating on the results level was said to be able to point out tradeoffs between criticality and for instance environmental impacts. Knowing the theoretical difference between the two ways of assessing criticality will be necessary with comparing them, as will be done in the next chapter.
In addition to this, a number of advantages/benefits and disadvantages/limitations/challenges of the various methods could as well be recognized. One limitation of LCA methods pointed out was that it is at times still not clear or focused enough, and in cases, too uncertain to really make a point for criticality. The method by the EU would then be more useful because of its practical applicability and general acceptance, which is in favor of policymaking. Clarity and practicality of applied methods are therefore crucial considerations. Another vital consideration in deciding on what assessment method to use is the scale of assessment. On a small scale (product level) or medium scale (corporate level), LCA methods are supposed to be the most appropriate. However, on a large scale (country/economy level), the EU method is more fit to answer these questions. Nevertheless, the leading limitation of assessment, in general, is a lack of data which was mentioned by three out of the five interviewed experts.

The section about the application of different assessment methods for the case study went into more detail. Again, the emphasis was put on the importance of looking at the level of assessment, this time specifically for the EU method and Essenz method. The point was made that it was to be expected that the results of these methods would differ. On the other hand, the results of the GeoPolRisk would be more in line with the EU method. From this came a proposition of the first hypothesis to be tested in the case study. This will also be analyzed further in the next chapter, which evaluates the assessment methods more in-depth on their contents.

With this, differences between the GeoPolRisk and Essenz methods were pointed out together with reasons for using one or the other for the case study. From this also came more confirmation on which one to explore further and which to use in the case study and why. Firstly, although the Essenz method has a high recommendation, the method was said to be too broad as it uses a lot of indicators. The GeoPolRisk method, on the other hand, is a bit more specific and better suited for the application of a product like EV batteries. Secondly, from a practical perspective, the GeoPolRisk method is more useful because it has a web tool ready to be used. This makes the method also available for a company to make choices on its supply chain. The details of both methods will be further discussed in the next chapter.

Next, the topic of recycling was evaluated, and this came with strategies and policy suggestions by the interviewees. Most importantly, it could be concluded that, generally, a linear relation exists between recycling and criticality. If you are able to recycle materials, it means that you are less dependent on other actors, and the criticality of a material decreases. This, therefore, is also the main reason to take into account recycling with assessing criticality. From this also came the fourth hypothesis to be tested in the case study, as can be read in chapter 6 of this research.

5. Assessment methods and indicators in detail

In the previous chapters, the first part of the second research question has been answered. This next chapter will go into the second part. Based on chapters 3 and 4, we selected two groups of assessment methods to analyze in more detail. First, three LCA methods will be addressed: the mineral resource scarcity (MRS) indicator (ReCiPe), the Essenz criticality method, and the GeoPolRisk method. The MRS indicator and GeoPolRisk method will be explained by their midpoint and endpoint factors, for the Essenz method this was not available. The other assessment tools include the NRC, Yale, and EU criticality assessments.
In the last section, the selected methods will be compared to each other on their goal and scope, level of integration, level of analysis, temporal scale, criticality parameters, indicators, and data. Advantages and limitations, as well as similarities and differences, will be discussed here too.

5.1. LCA methods

This first section will go into three LCA methods: the mineral resource scarcity (MRS) indicator (ReCiPe), the Essenz criticality method, and the GeoPolRisk method. Firstly, the MRS indicator will be explained by its midpoint factor; surplus ore potential, and then its endpoint factor; surplus cost potential. Secondly, the Essenz method will be analyzed. Thirdly, the GeoPolRisk method will be discussed on its midpoint and endpoint characterization factors.

5.1.1 ReCiPe: mineral resource scarcity

As has been noted before, the model for mineral resource scarcity comes down to a few steps. First comes the extraction of a mineral resource, which in turn leads to a decrease in ore grade. This decrease in ore grade means that the concentration of this ore worldwide decreases, which then causes an increase in ores produced to extract the mineral (OP). Together with the expected resource extraction, it then causes a surplus ore potential (SOP), which is the midpoint characterization factor for this indicator (Vieira et al., 2016). The endpoint score is then calculated by the surplus cost potential (SCP) (Vieira et al., 2017). The detailed analysis will start off by considering the SOP and next look into the SCP.

Surplus Ore Potential (SOP)

The midpoint characterization factor for mineral resource scarcity thus is Surplus Ore Potential (SOP). This gets expressed in kg Cu equivalent as ore grades tend to decrease with the increase in copper extraction (Vieira et al., 2012). The primary extraction of a mineral resource will lead to an overall decrease in "ore grade" or the concentration of that resource in ores worldwide. This, in turn, will increase the amount of ore required per kilogram of mineral resource extracted. The SOP qualitatively expresses the average extra amount of ore mined per additional unit of resource extracted (Vieira et al., 2017). The SOP for a resource x is calculated as follows: first, the sum is taken of the ore mined (OM) for a certain amount of resource extracted (RE_x). This sum comes down to a current known cumulative tonnage of resource x extracted worldwide to the maximum amount to be extracted of that resource. Next, the sum gets divided by the estimated total global reserve of the resource x (R_x). These global reserves were estimated in two ways; the first reserves (R_R) are defined as "that part of a resource which could be economically extracted or produced at the time of determination," which means at current prices and state of technology (USGS, 2014). The second is the ultimate recoverable resource (R_{URR}), and refers to "the amount of available resource in the earth's upper crust that is ultimately recoverable." Finally, the URR, or extractable geological resource, is defined as 0.01% of the total amount of resources in the earth's crust to 3 km depth (UNEP, 2011; Vieira et al., 2017).

Surplus Cost Potential (SCP)

For the endpoint factor, the surplus ore gets converted to surplus costs, expressed in US Dollars (value of 2013), which represents the extra costs involved for future mineral resource extraction (Vieira et al., 2016). To calculate the overall surplus costs, the characterization factor as explained before gets multiplied by the potential future operating costs of a certain amount of extracted resources. To then calculate the endpoint impact score, this factor has to be multiplied by a certain amount of kg of a material.

5.1.2 ESSENZ

The ESSENZ method principally builds upon the criticality concepts as discussed before, as it includes multiple factors to assess supply distribution possibility as well as vulnerability factors (Sonderegger et al., 2020; Cimprich et al., 2019). The method has been recommended as one of the best options for assessing accessibility issues related to geopolitical and socioeconomic aspects partly due to its extensiveness (Berger et al., 2020).
The two criticality dimensions of probability to supply disruption and vulnerability consist of the following factors.
The probability of supply disruption is measured by: mining capacity, primary material used, the global concentration of reserves and production shares, feasibility of exploration projects, co-production, company concentration, price volatility, demand growth, trade barriers, and political stability (WGI: voice & accountability, political stability and lack of violence, government effectiveness, regulatory quality, rule of law, and control of corruption).
Vulnerability gets assessed by: the ratio of material used in a product, overall global production amount, and magnitude of inventory flow.
Although the method is quite thorough, it is not fully operational yet. Also, the method is not easily compared to the EU criticality method because of the level of assessment, so the decision was made not to consider it in the case study. Still, it can be theoretically analyzed and compared with other criticality methods, as will be done in the final section of this chapter.

5.1.3 GeoPolRisk

According to Cimprich et al. (2017), Geopolitical Supply Risk for a given unit process of material A and product P in country C ($GPSR_{APc}$) depends on the probability of supply disruption of the input commodity ($GeoPol_{Ac}$) as well as the vulnerability to supply disruption ($Vuln_{APc}$). For the operationalization of this method will be considered in detail how the characterization factor gets calculated, next a closer look will be taken at the calculation for the endpoint factor.

Midpoint characterization factor:

The GeoPolRisk indicator gets calculated by multiplying the mass of material A for product P in country C by a Characterization Factor (CF). This CF is calculated by multiplying the probability of supply disruption of an input material ($GeoPol_{Ac}$) by the vulnerability to supply disruption ($Vuln_{APc}$).
The vulnerability of a product system to supply disruption of a material depends on the importance of the material input to product performance and the potential for substitution (Cimprich et al., 2017).
The calculation for the economic importance is the same as applied in the CRM report of the EC (2014).
The probability of supply disruption gets calculated by first summing the geopolitical instability of a country i by the amount of imported material from country i to country c. This sum then gets divided by the domestic production of resource A in country C, adding the total imports of resource A to country C. The result then gets multiplied by the Herfindahl-Hirschman Index for resource A, representing a market's competitiveness. For this also, only publicly available data gets used so that it is transparent and reproducible.

Endpoint characterization factor:

For calculating the endpoint indicator of the GeoPolRisk method, a larger scale gets used then before which is necessary because metals are traded in a global market (Santillán-Saldivar et al., 2022). Here the OECD member states are used as a reference group. The endpoint indicator now comes down to multiplying the midpoint GeoPolRisk by the inverse price elasticity of resource a (ε_a) and the average price (p) of a resource a, in year t. The price elasticity is a proxy defined as the percentual price change of the concerned metal divided by the percentage of global mining volume affected by commodity specific disasters affecting production. In this way it accounts for identified associated short term impact measured by the inverse price elasticity of demand, specific to one material. Unfortunately the data needed for calculating the price elasticity to produce the endpoint indicator of GeoPolRisk was unavailable, meaning in the case study the midpoint CF will be used.

5.2. Stand-alone criticality assessment methods

In this section the three stand-alone methods to assess criticality as previously introduced in chapter 3 will be analyzed in more detail. The three methods we will talk about are the methods by the NRC, Yale university and the EU. For the EU method the supply risk (SR) parameter and the economic importance (EI) parameter will be discussed separately.

5.2.1 NRC method

As noted before, to determine whether a material is critical the NRC proposed a "criticality matrix" consisting of 2 dimensions (Figure 3.5) (US National Research Council, 2008). The first dimension is *importance in use*, measured by the impact of supply disruption, and the second is *availability*, measured by supply risk.
A material is considered important in use when the cost or impact of a restriction in supply is high, which also depends on the substitutability of the material. The importance in use of a material is measured in the amount of value-added and as a percentage of the total GDP of the US. The possible effects of supply restriction might include impacts on domestic production, domestic use or domestic employment. Availability equals the vulnerability to supply disruption of a material. For the materials, a distinction is made between primary materials, directly obtained from processing mined materials, and secondary materials, obtained from the recycling of scrap material. In the short and medium terms, availability is assessed by the degree of supply risk on a national level.
Factors affecting the degree of supply risk include the relation between demand and production, the size of the market, the concentration of production, the origin of production (main product or by-product), and the recovery of scrap materials. Two indicators taken into account for supply risk vulnerability are import dependence and the reserve-to-production ratio. Availability in the longer term here depends on many different factors in varying forms, such as; geological, technical, environmental, social, political, and economical. Geologic considerations are whether and where the material exists. Technical factors might be the possibility to extract and process any material. Environmental damage might cause availability issues in one way, for example socially, when society does not accept the effects extraction, and processing has on local communities. Other social considerations might include human rights violations. Politically availability can be affected by policies such as trade barriers and stockpiling. Economics might play a role as it needs to be taken into account whether mineral products costs are still on a level that consumers are willing to pay.

5.2.2 Yale Method

The Yale methodology is based on three dimensions: supply risk, vulnerability to supply restriction, and environmental implications. A short summary will now be given of what indicators these dimensions consist of by looking at the operationalization of this method.
First, for supply risk, they take into consideration different temporal scales, being medium or long-term. On a medium-term scale, there are three components that might affect the supply risk; Geological/technological/economic, social/regulatory, and geopolitical, each evenly weighted. In the long term, only the geological/technological/economic component is taken into account. The first component has as its goal to measure the potential availability of a metal's supply, including both primary and secondary metals. The two others are aimed at the constrictions of supply. Each component, in its turn, is based on two indicators having the same weight. The geological/technological/economic dimension is based on indicators for depletion time and companion metal fraction. The social/regulatory dimension is based on a policy potential index and a human development index. The geopolitical dimension is based on the world governance indicator for political stability and an indicator for the global supply concentration of a resource.
Second, vulnerability to supply restriction varies with the organizational levels, which are global, national, and corporate. For the global level, what is taken into consideration is the economic importance and the substitutability of a resource. For the other levels, also the ability to innovate is taken into account. The indices of these levels are measured on slightly overlap, but also they are still specific to one level as they might not be appropriate to evaluate the others.
Third, environmental implications represent the potential environmental implications of utilizing a particular metal, such as for example toxicity, the use of energy and water in processing, or emissions

to air, water, or land. For this evaluation, the authors propose to use the inventory data from the ecoinvent database. From the ecoinvent inventory data, the damage categories of human health and ecosystems are calculated according to the ReCiPe endpoint method.

5.2.3 EU method

Within their method, the EU measures the criticality of a material by assessing its economic importance (EI) and supply risk (SR).
This part of the analysis will be started by looking at the EU its method of determining criticality, which is explained in detail in the EC report on the methodology for establishing the EU list of critical raw materials (2017). Within their method, the EU measures the criticality of a material by assessing its economic importance (EI) and supply risk (SR) (EU, 2011). For these calculations, publicly available data gets used so that it is transparent and reproducible. Whether a material is considered critical depends on if the scores for these parameters exceed a threshold defined by the EC. Since the revised methodology of 2017, the thresholds for the criticality assessment are set at 2.8 for economic importance and 1 for supply risk. The highest score for SR has been calculated for the Light Rare Earth Elements (LREEs), which is 6.0, and the lowest score is for Lead which has a score of 0.1 (EC, 2020a). The highest score for EI has been calculated for Tungsten which is 8.1, and the lowest score is for Sapele wood which has a score of 1.4. The reasons for these scores could differ based on what factors affect the calculation of these scores the most. To be able to assess the EI and SR scores, the operationalization of each parameter will be analyzed in more detail below. First, the supply risk gets considered, followed by the economic importance.

Supply Risk (SR)

The first step is to take a general look at how the supply risk parameter gets calculated, for a more detailed explanation we would like to refer to section 3 of the EC report on the methodology for establishing the EU list of critical raw materials (2017). As noted before, the supply risk (SR) of a material is defined as the risk of a disruption in the supply to the EU. It is based on the concentration of primary supply from countries producing a raw material, considering trade aspects and governance performance of these countries. For the country concentration the Herfindahl-Hirschman Index (HHI) is used, and the World Governance Index (WGI) is used as a measure for a country's governance. This gets calculated for global suppliers (GS) and the countries from which the EU is sourcing the raw materials as producing countries. The calculation then also depends on the import reliance (IR) which gets calculated as a fraction of the difference between import and export and the domestic production of a material. The HHI_{WGI} for global supplier country concentration and EU-28 actual sourcing country concentration gets calculated by summing up the square root of the share of country c in the global supply of the raw material multiplied by the scaled World Governance Index of country c (WGIc) times the trade parameter (t), adjusting the WGI. The trade parameter t is used for quantifying the trade contribution to increasing or diminishing the supply risk related to a specific country for a candidate raw material. This parameter takes into account the influence of export restrictions/taxes and trade agreements. It also considers a factor for EU sourcing of a material which represent the lowest supply risk for the EU. Data used for the trade parameter are the OECD's inventory of restrictions on exports of raw materials and the DG trade overview of trade agreements. All of the above then gets multiplied by the End-of-life recycling input rate (EOL-RIR), which gets calculated as the ratio of recycled material to the total demand of a material (primary and secondary input) (a more detailed explanation can be found in section 3.5 of the EU methodology report of 2017). One important thing to notice is that the EoL-RIR is not the total amount of recycled materials, but measures the quantity of end-of-life scrap contained within the total quantity of metal available to manufacturers. As can be deduced from the formula of SR (EU, 2017), the EoL-RIR is separately multiplied making this practically easy to use with calculating the effect of different recycling rates in Chapter 6 of this research. Finally a substitution index of the supply risk (SI_{SR}) is considered as a factor to possibly reduce the supply risk .

Economic Importance (EI)

The economic importance (EI) of a material to the EU economy is dependent on the share it has for an end-use application and amount of added value of the sector a material is used in. How important a material is also depends on the degree of substitutability of the material.
The score for this parameter gets calculated by summing up for a sector; the share of end use of a raw material in the sector times the sector's value added multiplied by the substitution index for EI (SI_{EI}).

5.3. Overview of dimensions, indicators and data

Following the in-depth analysis of the selected assessment methods, this section will give a schematic overview of all available indicators to assess criticality (Figure 5.1). Criticality here is defined as in chapter 3, by the two dimensions of supply risk and vulnerability to supply disruption. Supply risk is concerned with physical availability and socio-economic accessibility. Physical availability includes geological/environmental and technical aspects, socio-economical accessibility includes geopolitical aspects. Vulnerability to supply disruption contains aspects of economic importance and substitutability. Figure 5.1 shows the indicators divided into these classifications. It must be mentioned that it is difficult to classify the indicators because it depends on the system analyzed, the level of analysis and the time scale.

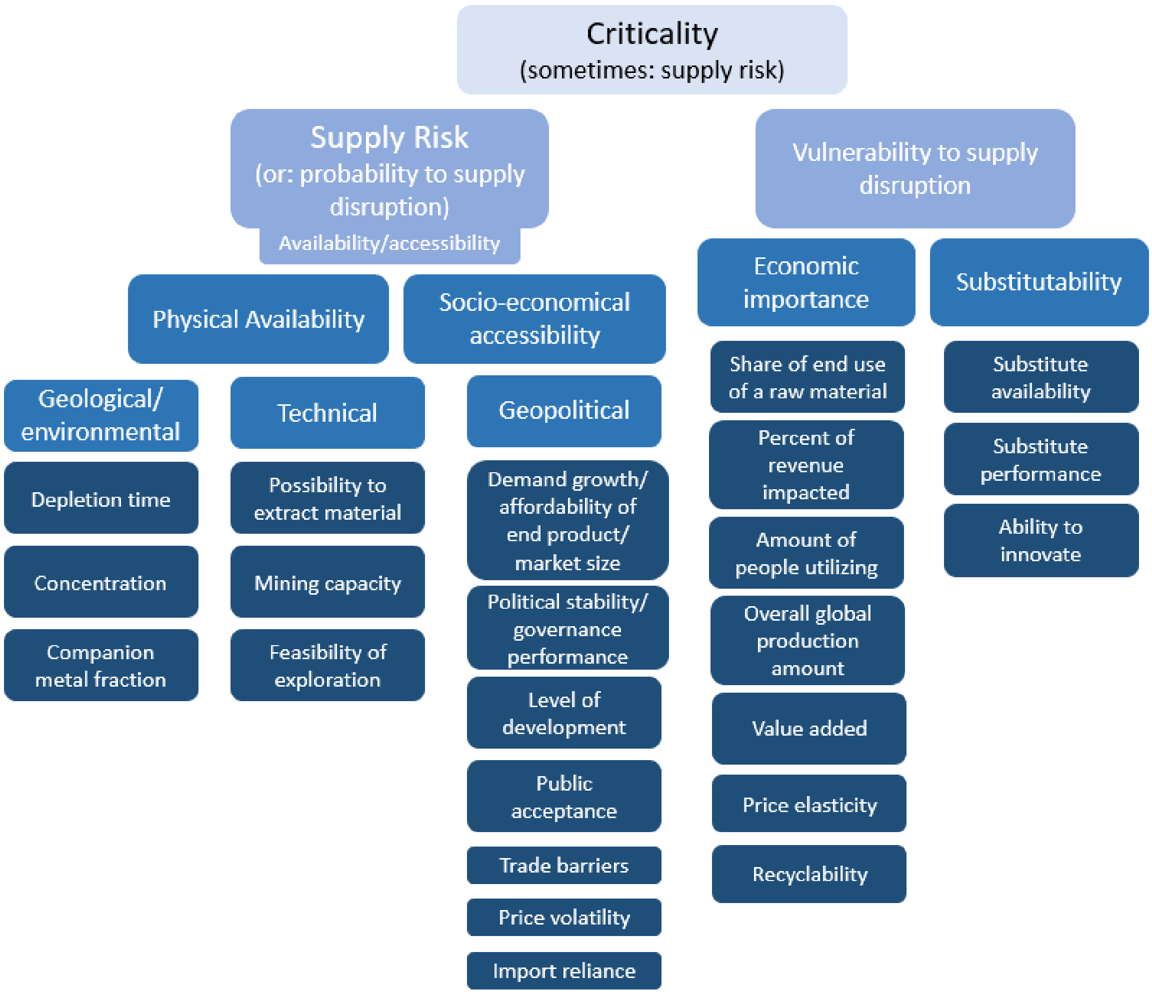

Figure 5.1. Schematic overview of criticality dimensions and associated indicators and data

5.4. Method comparison

Based on the last sections, this section aims to answer the last part of the second research question: what do selected methods entail, and how do these different assessment methods compare? The methods will be theoretically analyzed on their goal and scope, level of integration, level of analysis, temporal scale, criticality parameters, indicators and data. The results are shown in Table 5.1 below, which shows an overview of six assessment methods: Stand-alone criticality methods by Yale, the NRC, and the EU; LCA criticality methods Essenz and GeoPolRisk; LCA scarcity, the MRS method. For each method, the Goal and scope, level of integration, level of analysis, temporal scale, criticality parameters, indicators and data, advantages and limitations are shown. In the indicators and data column, the criticality parameters are shown in bold, the assessment levels are underlined, and dimensions are cursive.

Assessment method	Goal/scope	level of integration	Level of analysis	Temporal scale	Criticality parameters	Indicators and data	Advantages	Limitations
NRC (NRC, 2008)	Study the unavailability of materials disrupting economic activities and establish a general conceptual framework for evaluating material criticality, which specific users can customize to their own situations Identify (Schrijver et al., 2020)	Methodological	National economy	Long/Medium term (+-10 years)	Supply risk, Impact of supply disruption	**Supply risk** <u>Long term</u>: *Geologic*: Existence of a material *Technical*: Possibility to extract a material *Environmental and social*: Public acceptance of environmental damage level *Political*: How do policies affect its availability both positively and negatively? *Economic*: Affordability of end product to consumers <u>Medium/short term</u>: Relation between demand and production, size of the market, concentration of production, the origin of production (main-product or by-product), recovery of scrap materials, import dependence and the reserve-to-production ratio. **Importance in use** Substitutability, Impact on the US economy (levels: product, company, community, state, national), Impact on public well-being, Importance for National defense	Developed to be customized for specific users	Lack of accurate/reliable data
Yale (Graedel et al., 2015, 2012)	Study the reliability of material supply due to geological, technological, economic, social, regulatory, and geopolitical restrictions for materials that are important for the economy so policies can be developed for companies and governments (Schrijver et al., 2020)	Methodological	Company/ National/ Global	Long term (multiple decades) and medium term (unspecified)	Supply risk, Vulnerability to supply disruption, Environmental implications	**Supply risk** <u>Long term</u>: *Geological, technological, economic:* Depletion time, companion metal fraction <u>Medium term</u>: *Geological, technological, economic:* Depletion time, companion metal fraction *Social and regulatory:* Policy potential index, human development index *Geopolitical:* Political stability (WGI: voice & accountability, political stability and lack of violence, government effectiveness, regulatory quality, rule of law, and control of corruption), global supply concentration **Vulnerability to supply restrictions** <u>Corporate</u>: *Importance:* Percent of revenue impacted, ability	Corporate applicability Amount of details	Lack of accurate/reliable data Costs (monetary and time) of performing full assessment

						to pass-through cost increases, importance to corporate strategy. *Substitutability:* Substitute availability, substitute performance, price ratio, environmental impact ratio Ability to innovate: Corporate innovation National: *Importance*: National economic importance, percentage of population utilizing *Substitutability*: Substitute availability, substitute performance, net import reliance ratio, environmental impact ration *Susceptibility*: Net import reliance, global innovation index Global: *Importance:* Percentage of population utilizing *Substitutability:* Substitute availability, substitute performance, environmental impact ration		
EU (EC, 2017)	Analyze criticality of raw materials by looking at supply risks and economic importance to be able to make decisions to increase the EU's economic competitiveness such as: increase European production of a material by launching new mining or recycling activities, negotiating trade agreements, draft legislation, promote research and innovation (Schrijver et al., 2020)	Methodological	National economy	Medium/Long term (+-10 years)	Supply risk, Economic importance	**Supply risk** Import reliance, country concentration, country governance performance (WGI: voice & accountability, political stability and lack of violence, government effectiveness, regulatory quality, rule of law, and control of corruption), end-of-life recycling rate, substitution index **Economic importance** Share of end use of a raw material in the sector, the sector's value added and the substitution index.	Most suitable for long term plans, less sensitive to outlier events causing changes in the price Generally well accepted methodology	Lack of accurate/reliable data Does not consider intermediate products
Essenz (Bach et al., 2016)	Analyze restricted availability of resources due to physical as well as socio-economic factors compromising the productivity of companies to inform material selection, product design, and supply chain management (Schrijver et al., 2020)	Results level	Global/ Corporate/ Product	Short-/Medium term (<10 years)	Probability of supply disruption, Vulnerability to supply disruption	**Probability of supply disruption** Mining capacity, primary material use, global concentration of reserves and production shares, feasibility of exploration projects, co-production, company concentration, price volatility, demand growth, trade barriers, political stability (WGI: voice & accountability, political stability and lack of violence, government effectiveness, regulatory quality, rule of law, and control of corruption) **Vulnerability** Ratio of material used in a product, overall global production amount, magnitude of inventory flow	Within LCA methods considers the most broad range of indicators, including for example social impact Incorporation on a results level makes it easily comparable with other LCA indicators	Lack of accurate/reliable data Arguably too many indicators Equal weighting of characterization factors Not practically applicable yet Not well suited for a national level

								Does not consider intermediate products
GeoPolrisk (Gemechu et al., 2017; Cimprich et al., 2017, 2019)	Identify supply disruptions of materials to inform material selection, product design, and supply chain management (Schrijver et al., 2020)	Results level	Product/ National	Medium/Short-term (<10 years)	Probability of supply disruption, Vulnerability to supply disruption	**Probability of supply disruption** Political stability score (WGI: political stability and lack of violence/terrorism), country production concentration, import shares of trade partners in supply chain of importing countries, domestic production of importing country, market competitiveness **Vulnerability** Importance of material to product performance, potential for substitution, average price, price elasticity	More useful for short term decisions, because price values are considered for 1 year. Better suited for multinational industrial actors, because it looks in detail at the whole value chain of a commodity Incorporation on a results level makes it easily comparable with other LCA indicators Focus on supply risk coming from political instability	Lack of accurate/reliable data
Mineral resource scarcity (Huijbregts et al., 2017; Vieira et al., 2016, 2017)	Assess the importance of an increasing mineral scarcity through monetizing the energy requirements of resource extraction	Results level	Product	Long term (multiple decades)	Ore grade decrease	Surplus Cost Potential (SCP) (Vieira et al., 2016) Surplus Ore Potential (SOP) (Vieira et al., 2017)	Generally accepted within LCA methods and readily applicable Easy to be compared to other LCA indicators	Does not consider criticality indicators

Table 5.1. Overview of six assessment methods: Stand-alone criticality methods by Yale, the NRC and the EU; LCA criticality methods Essenz and GeoPolRisk; LCA scarcity, the MRS method. For each method the Goal and scope, level of integration, level of analysis, temporal scale, criticality parameters, indicators and data, advantages and limitations are shown. In the indicators and data column the criticality parameters are shown in bold, the assessment levels are underlined and dimensions are cursive.

5.5. Discussion/conclusion of the assessment methods and indicators

This section will be a discussion of table 5.1 to come to a conclusion on the second research question. The first part will compare the three stand-alone criticality assessment methods by the NRC, Yale, and the EU. The second subsection will go into the LCA methods of Essenz, GeoPolRisk, and mineral resource scarcity. Third will be a comparison between the stand-alone methods and LCA methods. In the end, a schematic representation is given on the selection criteria for the evaluation of the chosen assessment methods for this research.

Stand-alone criticality assessment methods

First of all, the NRC method was the first method to assess criticality and introduced the criticality matrix. This method has two parameters being the supply risk and the impact of supply disruption. The supply risk parameter can be assessed on a long- or medium-term (+- 10 years) time scale. It has been developed to assess criticality on a national scale and, more specifically, for the USA. Still, an advantage is that it was also developed to be customized for specific users. Moreover, as was discussed before, its parameters established a basis for the other methods by Yale University and the EU. With this method, the main limitation is a lack of accurate and reliable data.
Secondly, the Yale method consists of three parameters being supply risk, vulnerability to a supply disruption, and environmental implications. The method assesses criticality on long-term (multiple decades) and medium-term temporal scales. The method can be applied on the global, national, and corporate levels. The corporate applicability of this method is one of its main advantages. This method takes into account many indicators and uses a lot of data making this method the most specific of the three stand-alone criticality methods. Limitations of this method are a lack of accurate and reliable data and the high costs (monetary and time) of performing a full assessment.
Thirdly, the EU method again has two criticality parameters which are supply risk and economic importance, which is based on the NRC method. The level of analysis and the temporal scale is the same as that of the NRC method. The method was developed to assess criticality on the national economy scale and for long or medium-term time periods. The advantages of the method are that it has generally been well-accepted, and the results are available for anyone to use. Together with the appropriate scale, that makes this method the best option to use for the case study in the next chapter. With this, this method is less sensitive to outlier events causing changes in the price, making the results very robust. One limitation of the method is that it looks only at individual materials, and intermediate products are not considered (Matos, 2017). A product can have its own specific criticality, which could be different from the combined criticality of materials. Still, in the case study, product criticality will be calculated by weighting of the materials contained in the products. Another limitation of the method again is a lack of accurate and reliable data, just like the other methods. One example is the data used for the recycling rates in the EU report on critical raw materials, which is partly outdated. The rates are based on a material system analysis (MSA) from 2015, and when this data is not available, data from a report by UNEP, 'recycling rate of metals' from 2011, is used (Mathieux et al., 2017; EC, 2017).

LCA methods

Two LCA integrated criticality methods taken into account in this comparison are the Essenz and GeoPolRisk methods.
To begin with, the Essenz method assesses criticality by the two parameters probability of supply disruption and vulnerability to supply disruption. The method can be used to assess criticality on a global, corporate, and product-level for a short or medium (<10 years) time scale. The Essenz method is the most extensive method and considers more indicators to assess criticality than the GeoPolRisk method. One example is the inclusion of social impact indicators. Still, it was argued by an expert in the interviews that a limitation of the method is that it is too broad, and the number of indicators needs to be reduced to make the assessment more specific for selected impacts. It was also pointed out by this expert that the normalization and weighting of the characterization factors in this method are questionable. All impacts are weighted equally, but possibly not all impacts are equally important to criticality. In addition, the Essenz method has a similar limitation to the EU method because it focuses on the supply risk of primary resources only (Berger et al., 2020). Moreover, from the same study,

another limitation was mentioned being that the Essenz method does not consider the country-specific import situation. Furthermore, the Essenz method is not yet fully practically applicable, making it unsuitable to be used in the case study. With this, the method is unfit for assessing criticality on a product level, as is needed for the object of our case study.
Next, the GeoPolRisk method too measures criticality by the two parameters of probability of supply disruption and vulnerability to supply disruption. The GeoPolRisk method focuses on supply risk coming from political instability, meaning it uses fewer indicators than the Essenz method. The GeoPolRisk method measures criticality on a national or product level, as it aims to show the differences in supply risk between countries based on trading relations (Sonderegger et al., 2020). Where the Essenz method calculates a global average WGI index using country-specific production shares of raw materials, the GeoPolRisk method weights WGI values of material-producing countries by their import shares to product manufacturing countries. This property in particular makes this method the most suitable method for the case study as the scope can be narrowed down to the EU, which makes for a better comparison with the method by the EU. In addition, the method is more useful than the Essenz method for short-term decisions because price values are considered for 1 year, making the method better suited for industry actors. A limitation of this method is, again, the lack of accurate and reliable data, as uncertainty information is typically missing from commodity trade data coming from the UN Comtrade database (Cimprich et al., 2019). Together with this, it shares the limitation of Essenz and the EU method in that it focuses only on the supply risk of primary resources (Berger et al., 2020).
The scarcity method taken into consideration is the mineral resource scarcity indicator (ReCiPe). As discussed before, it does not assess criticality but measures scarcity through ore grade decrease by surplus ore potential (SOP) and surplus cost potential (SCP) of a material. The method is generally well accepted within LCA methods and is readily applicable. Still, there are also limitations to this method, for example, looking at the assumptions made. Ore grade–related methods rely on the assumption that mining takes place from the highest to the lowest grade, although different ore grades are mined in parallel, making the method questionable in the long run (Sonderegger et al., 2020). Regardless it was found that the SOP method has the most solid data foundation. In the same study, it was noted that the SCP methods rely on data from a period with substantial growth in mineral demand and prices, which is a reason for questioning the assumption of a causal relationship. The main advantage of the MRS method for this research is that the results can easily be compared to other LCA methods and is thus suitable for the case study.

Stand-alone criticality against LCA methods

Then the methods can further be theoretically compared by looking at the contrasts between stand-alone criticality assessment methods and the LCA methods. The most significant difference is in the level of integration, as was mentioned in the interviews. Where the stand-alone methods integrate criticality assessment on the methodological levels, the LCA methods integrate on the results level. This makes it possible for the LCA methods to be compared more easily against each other to reveal tradeoffs between other impacts besides criticality. Another difference can be seen in the temporal scale of assessment. The LCA criticality methods can be used for medium or even short-term assessments, whereas the stand-alone criticality methods are designed to look at long-term impacts. This makes the stand-alone methods better suited for long-term governance strategies, and the LCA methods are generally more fit for individual actors. This theoretical comparison will be complimented by the practical comparison in the next chapter, where the methods are applied in a case study.

Overview of criteria for the selection of assessment methodologies

Figure 5.2 gives an overview of criteria for the selection of assessment methodologies to be taken for detailed evaluation in this chapter and for the application in the case study. First of all, a distinction was made between LCA methods (blue) and no-LCA methods (purple) so that they can be compared to each other. Next, the choice was made to specifically go into methods which incorporate the outside-in cause-and-effect mechanisms which meant depletion methods had to be left out. With this, circularity methods were left out as well because they did not fit within the research scope of evaluating material impact assessments. Furthermore, the BGS and NEDO methodologies were left out because of considerations with the geological relevancy and policy framework taken into account for this research. Moreover, it was decided to focus more on criticality assessment than on scarcity methods causing the Swiss ecological scarcity and LIME2 methods to be excluded from the detailed evaluation as well. Eventually, the ReCiPe, GeoPolRisk, and EU methods were selected to be applied with the case study in the next chapter because of their practical operationality.

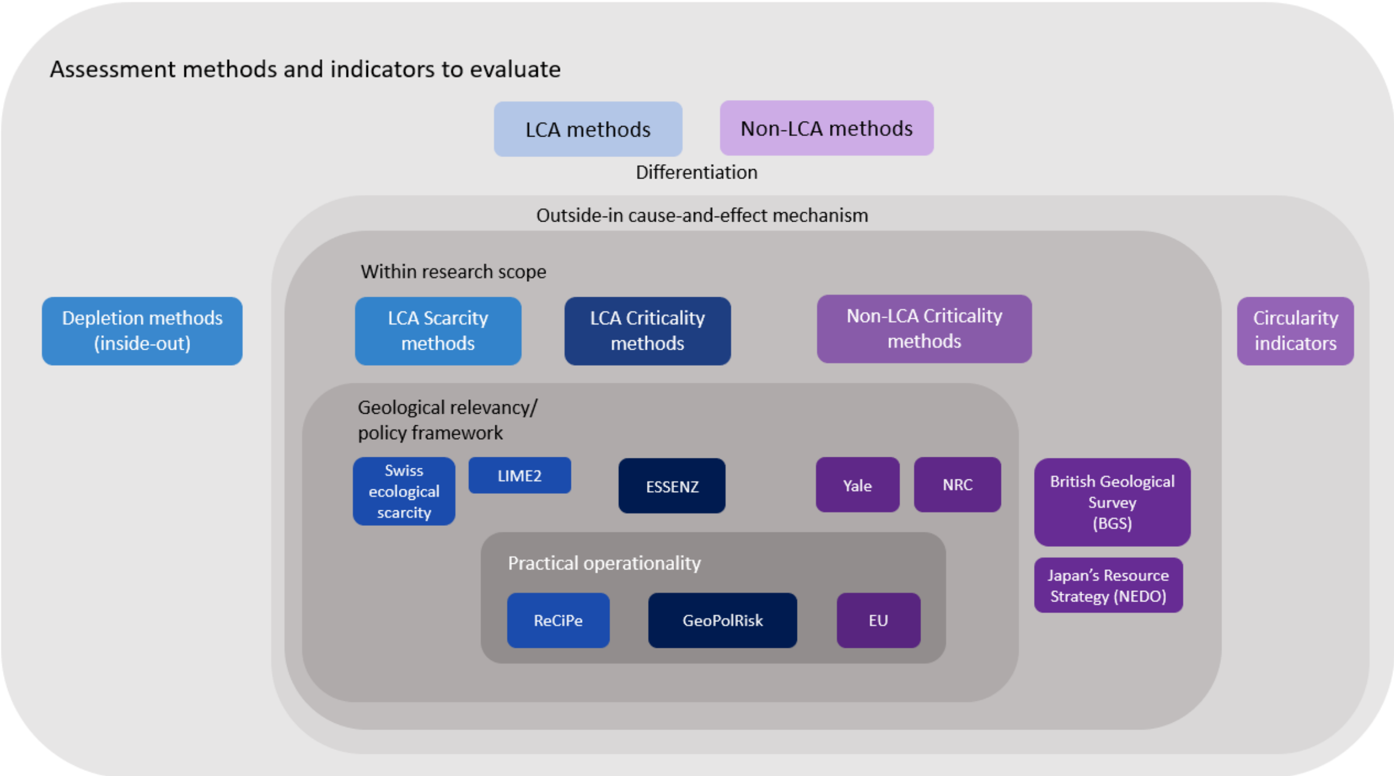

Figure 5.2. Overview of criteria for the selection of assessment methodologies to be taken for detailed evaluation in this chapter and for the application in the case study. With non-LCA methods in purple and LCA methods in blue, where LCA scarcity methods are of a lighter blue than LCA criticality methods

6. Case study on practical implications of assessment methods

To answer the question of what conclusions different assessment methods come to, this case study was carried out to test the applicability of relevant assessment methods. By carrying out this case study, a better understanding will be gained of selected assessment methods, and it will develop a comprehension of what it means to apply these methods in practice.
The aim of this case study is to practically test the applicability of the EU criticality method, the GeoPolRisk indicator in LCA, and the mineral resource scarcity indicator (ReCiPe). These methods will be applied to the minerals within the objects of this case study. The objects are the NMC(1:1:1) and NMC(8:1:1) batteries, further referred to as battery 1 and battery 2, respectively. As explained before, the life cycle of a product can be divided into five stages. For this case study, the most relevant stages are the raw material acquisition and the end-of-life stages. The production, distribution, and use stages of the product are mainly interesting when looking at energy input and emissions, which are outside the focus of this study. As noted before, recycling can be a supply risk mitigating factor for criticality. Therefore, in this case study, it will also be tested whether chosen methods provide more insight into the effects of using recycled materials on criticality. For this, recycling rates of 5%, 10%, and 40% will be tested, as was stated in the methods chapter.

What we want to get out of this case study is an answer to the third research question by testing hypotheses following from earlier chapters. The following hypotheses will be tested:

- The EU method and GePolRisk method will show the same minerals as being critical, because of similar input data.
- In terms of criticality, it would be better to use battery 1 instead of battery 2, because of lower CRM contents.
- Scarcity is not directionally proportional to criticality because criticality depends on many other variables.
- Increasing recycling of the minerals will decrease criticality and scarcity scores.

The results for each method will first be analyzed separately, after which a general comparison will be made. To test the first and third hypothesis, all of the materials used in both batteries will be assessed. In the discussion, GeoPolRisk data will be compared to the data from the EU, and both will be compared to the Mineral resource scarcity indicator scores. To test the second hypothesis, for all methods, a differentiation will be made between the two batteries, and for each a weighted score will be calculated. To test the last hypothesis, the effects of varying previously specified recycling rates will be evaluated for each method.

6.1. Results & discussion

The results are split up in 3 sections; first the results of the EU criticality method are shown, second will be the results of the GeoPolRisk LCA method and at last the Mineral resource scarcity indicator results will be depicted.

EU criticality method results

It was noted before that from the EU report of 2020 it followed that out of the minerals used for the assessed batteries Cobalt, Lithium and Graphite were considered to be critical. In the results from the 2017 report of the EU only Cobalt and Graphite were considered critical (Table 1, Appendix C). In Figure (6.1) the results from the EU report of 2017 have been put in a criticality matrix showing for the used materials their SR and EI values as well as the thresholds. It can be seen that Lithium was just non-critical as the EI parameter was just below the threshold of 2.6 with a score of 2.4. The SR value of Lithium was at a value of 1.0 which was above the criticality threshold. About Manganese it has to be noted that it is not critical although it is highly economically imortant and has a supply risk just a tenth below the threshold. Nickel also has a considerably high EI, but is not critical as the SR is lower than its threshold.

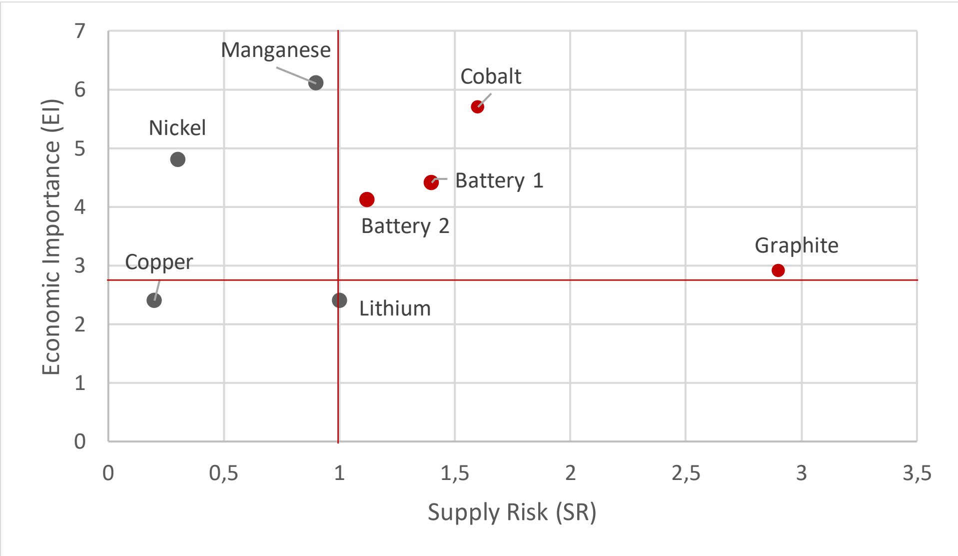

Figure 6.1. Criticality scores by the EU method for each material used within both types of batteries. Together with the weighted scores for each battery, calculated by the share of each material followed from the mass composition of the batteries. Depicted on the criticality matrix with the SR parameter on the x-axis and the EI parameter on the Y-axis. Red lines indicate the threshold values for each parameter, being 1.0 for SR and 2.6 for EI. The scores were taken from the final report of the EU's list of Critical Raw Materials of 2017 (EU, 2017).

After weighting and calculating the SR and EI parameters for each battery based on the input shares of each material, the criticality of both batteries can be discussed. When put on the criticality matrix it becomes clear that shares of materials in battery 1 makes the product more critical than battery 2.

When comparing the input materials of both batteries, the effect shares for each parameter can be discussed. It can be concluded that the most significant difference for the SR would be the smaller amount of Cobalt input in battery 2, which makes its share in criticality drop with 14% (Figure 6.2, a & b). Next to this, what stands out are the larger parts for Graphite and Nickel (+11%, +9%). For Nickel this can be explained by its higher material share for battery 2 compared to battery 1 (Figure 2.2). Another thing to notice is the lower share of Manganese (-8%), which has a supply risk just a tenth below the threshold (Figure 1).
For the variation in value of the EI parameter between both batteries differences can be seen. Here the biggest difference in share of materials between batteries can be seen for Manganese (-17%), closely followed by Cobalt (-16%). What immediately stands out is the higher share of Nickel in battery

2(+35%), again caused by the increase in share of this material. Nontheless, the EI value of battery 2 is still slightly lower than that of battery 1.

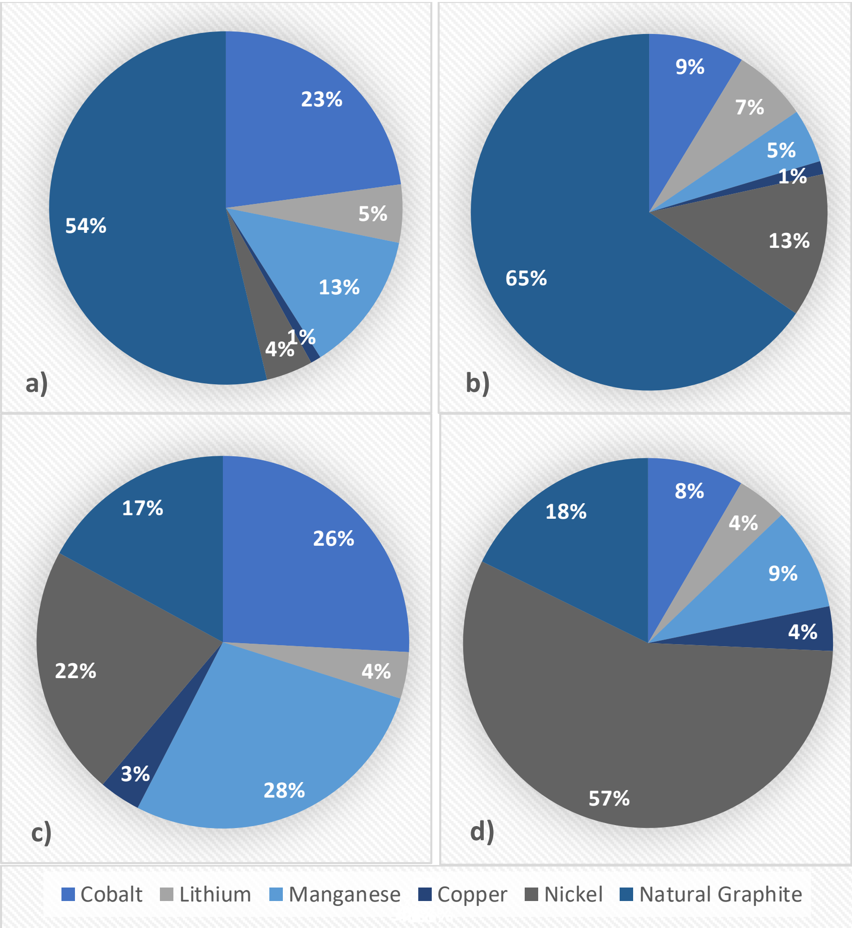

Figure 6.2 (a, b, c, d). Contribution of different materials to SR and EI scores: a) SR for Battery 1; b) SR for Battery 2; c) EI for Battery 1; d) EI for Battery 2. Calculated by multiplying the parameter scores with the mineral masses in Kg used per battery

Out of the parameters for SR, what is of importance for this case study is the percentage of End of life recycling input rate (EoL-RIR). From 2017 to 2020 the EoL-RIR increased for Cobalt and went down for Manganese, Copper and Nickel (Table 2, Appendix C). Figure 6.3 shows the results of calculations made on the EoL-RIR, including the SR for the predetermined recycling rates and its value when EoL-RIR is converted back to a percentage of 0. Here it can be seen that an EoL-RIR of 5% is enough to get the SR of Manganese below the threshold. Only with an EoL-RIR of 40% the SR parameter of Cobalt goes below the threshold of 1.0. Graphite still exceeds the threshold for this highest recycling rate.
To know what rate of recycling was needed to reach non-criticality the EoL-RIR values were coverted to where the SR would be 1.0. It shows that the EoL-RIR needed for Cobalt, Manganese and Graphite would have to be 38%, 2% and 67% respectively (Figure 6.3).

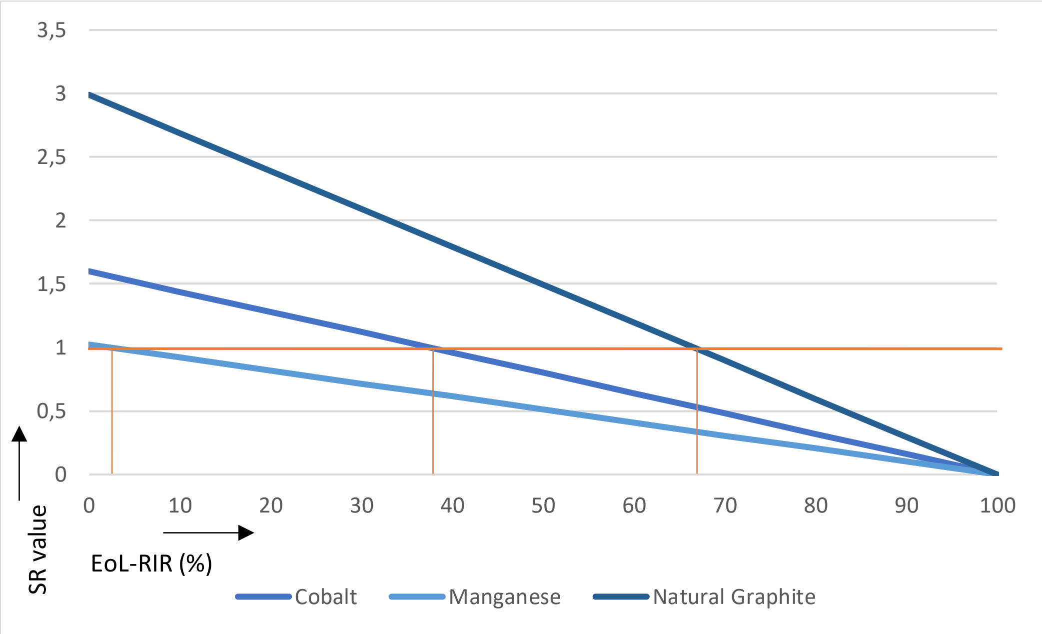

Figure 6.3. SR parameter scores for Cobalt, Lithium and Graphite with recycling rates from 0 to 100. Showing the threshold of 1.0 and lines indicating for each material the recycling rate needed for the SR parameter to even the determined threshold. End of Life Recycling Input Rate (EoL-RIR) follows a linear relation to supply risk as deduced from the EU methodology for establishing the list of CRM's.

GeoPolRisk results

Figure 6.4 shows the GeoPolRisk impact scores for the battery materials in USD/kg. It is plain to see that the scores of Cobalt by far exceed the scores of the other minerals, making it necessary to put these against a different value range on the vertical axis. For battery 1 the score of Cobalt is more than 20 times higher than the second highest scoring mineral (Graphite). After Cobalt, Nickel and Lithium have the next highest scores and Manganese has the lowest value.

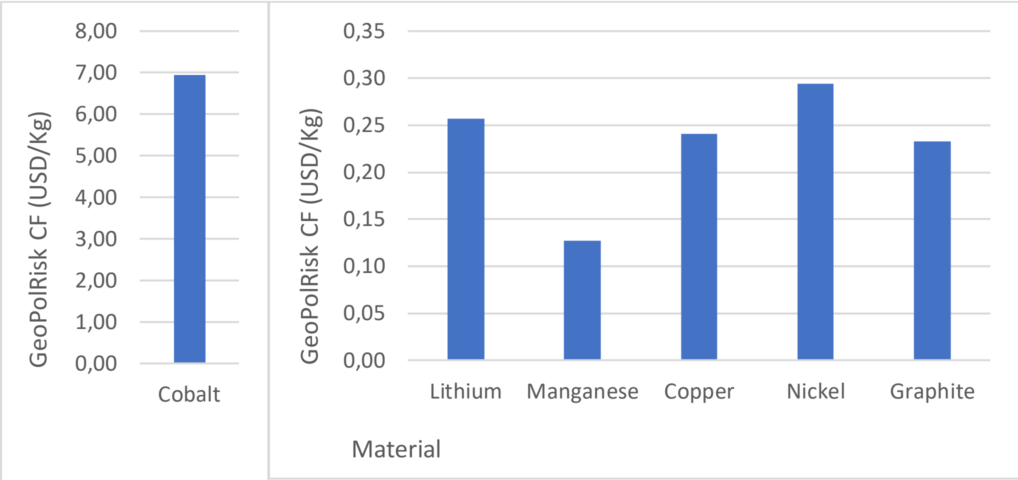

Figure 6.4. GeoPolRisk Characterization Factors (USD/Kg) per material. Taken from the online tool by The CyVi Group (available on http://geopolrisk.org/).

In Figure 6.5, the GeoPolRisk in USD per material used for the NMC(1:1:1) and NMC(8:1:1) batteries is shown. From Figure 6.5 it can be taken that Cobalt has the highest GeoPolRisk for both types of batteries. For Cobalt, Lithium, Manganese, Copper and Graphite the values for battery 2 are lower than those of battery 1. Meaning that only Nickel has a higher value for battery 2 than for battery 1. Even as the value of Nickel is higher and the value of Cobalt is considerably lower for battery 2 than for battery 1, Cobalt still has a value almost three times higher than that of Nickel. For both batteries the values for Lithium are similar to those of Copper, with Lithium having just a bit higher values.

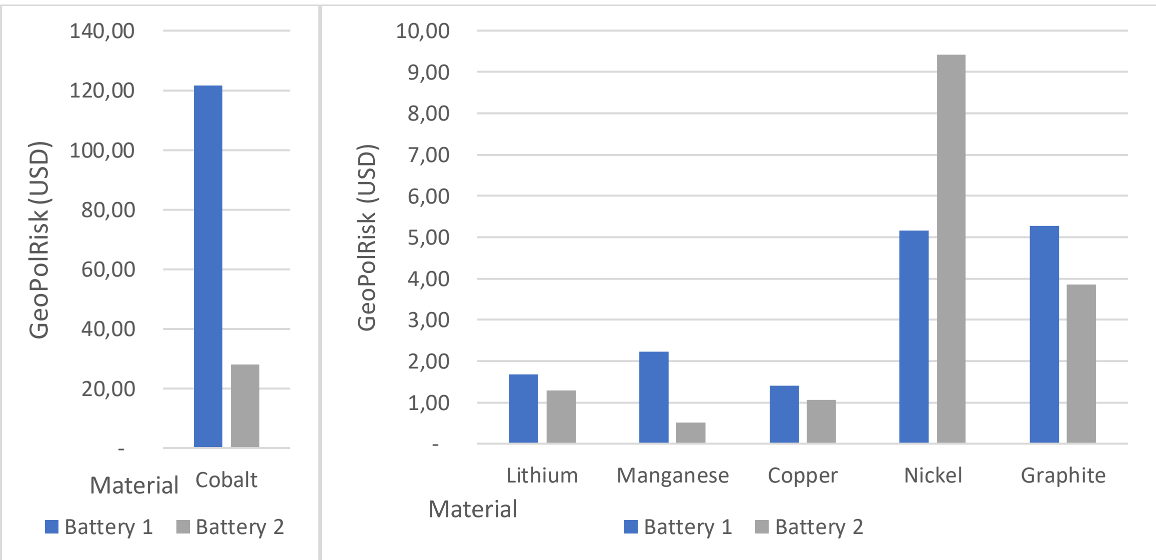

Figure 6.5. GeoPolRisk in USD per material used for battery 1 and battery 2. Calculated by multiplying the characterization factors by the material weights used per battery.

Figure 6.6 below shows weighted GeoPolRisk values for the materials per battery. Calculated by the share of each material followed from the mass composition of the batteries. When looking at the values weighted against each other for both batteries, it shows that the share of Cobalt goes down from 88% to 63%. The shares of Nickel and Graphite increase the most with 18% and 5% respectively.

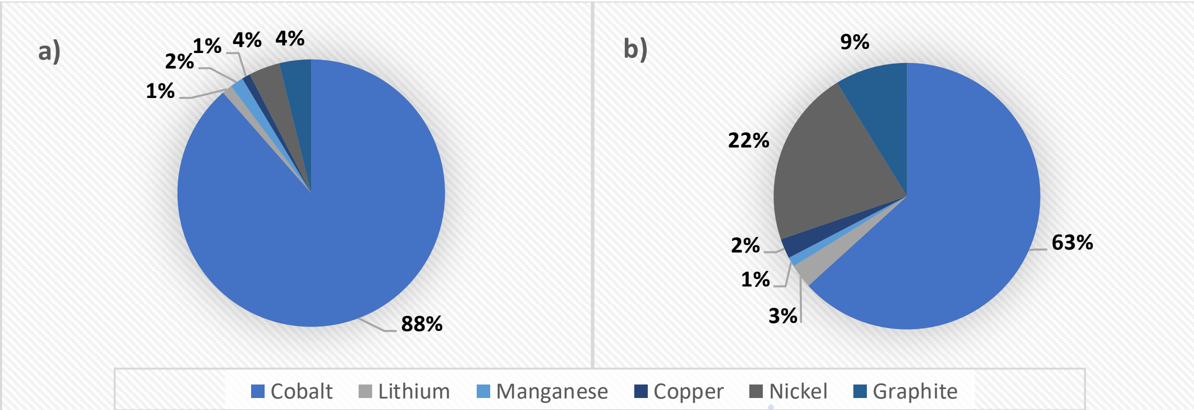

Figure 6.6. Weighted GeoPolRisk values for the materials per battery. Calculated by the share of each material followed from the mass composition of the batteries. a) shows battery 1, b) shows battery 2.

In Figure 6.7, GeoPolRisk impact factors are depicted per material in USD for both batteries (B1 & B2), showing the predefined recycling scenarios ranging from no recycling to a rate of 40%. From figure 6.7 it is clear to see that the GeoPolRisk values go down as the recycling rate goes up for each material and in both batteries.

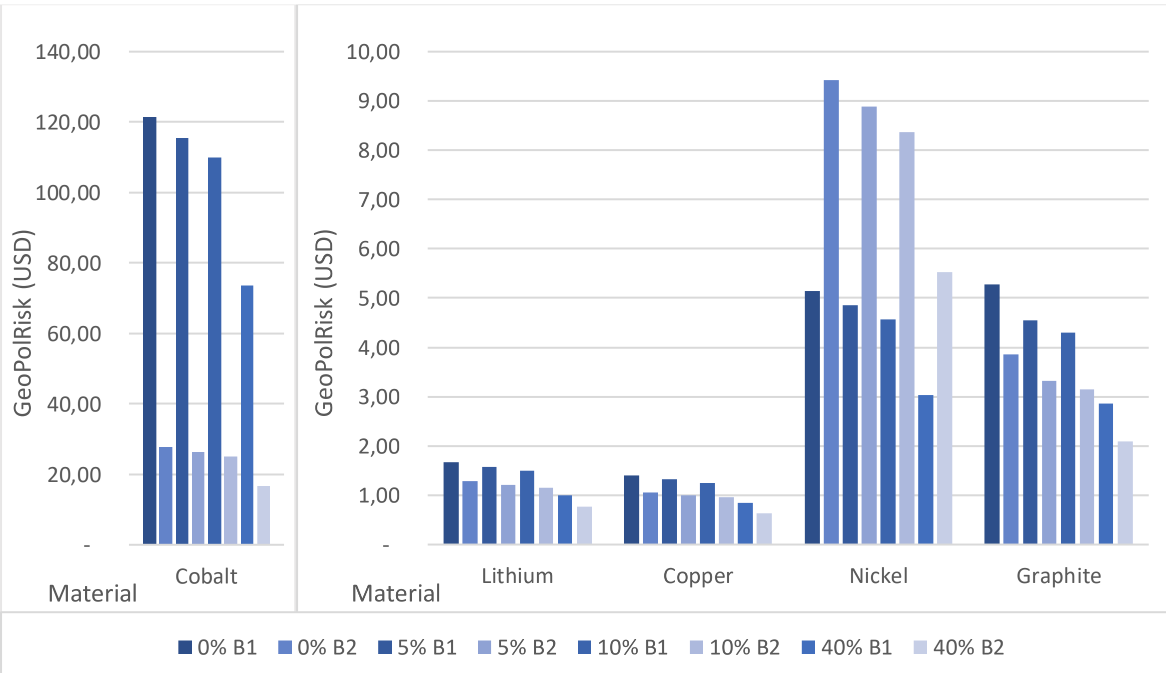

Figure 6.7. GeoPolRisk impact factors per material in USD for the NMC(1:1:1) and NMC(8:1:1) batteries (B1 & B2), for the predefined recycling scenarios ranging from no recycling to a rate of 40%. Calculation was based on the average of a best-case and worst-case scenario.

Mineral resource scarcity (MRS, ReCiPe) results
Figure 6.8 shows MRS impact factors in USD (with the value of 2013) per Kg. From Figure 6.8 it can be taken that Nickel has the highest score for this indicator, followed by Cobalt and Lithium. Nickel, Cobalt and Lithium score considerably higher than the other minerals for this indicator.

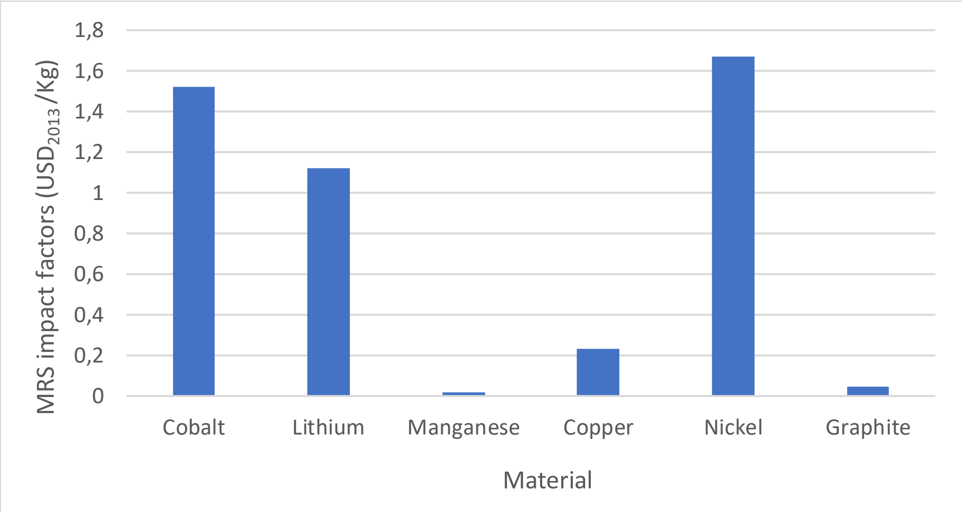

Figure 6.8. Mineral resource scarcity impact factors in USD (with the value of 2013) per Kg. Taken from OpenLCA LCIA method package 2.1.2, ReCiPe 2016 Endpoint (H), Impact factors.

In Figure 6.9, MRS (USD_{2013}), for battery 1 and battery 2 are shown. For both battery types Nickel has the highest value followed by Cobalt. For battery 1 the values of Nickel and Cobalt are much closer together than for battery 2. For battery 2 the value of Nickel exceeds that of Cobalt by about 9 times. Cobalt there has a value almost the same as Lithium, both still have a higher value than the other remaining minerals. For Cobalt, Lithium, Copper, Manganese and Graphite the values are lower for the second battery then those of the first battery, only for Nickel its value is higher.

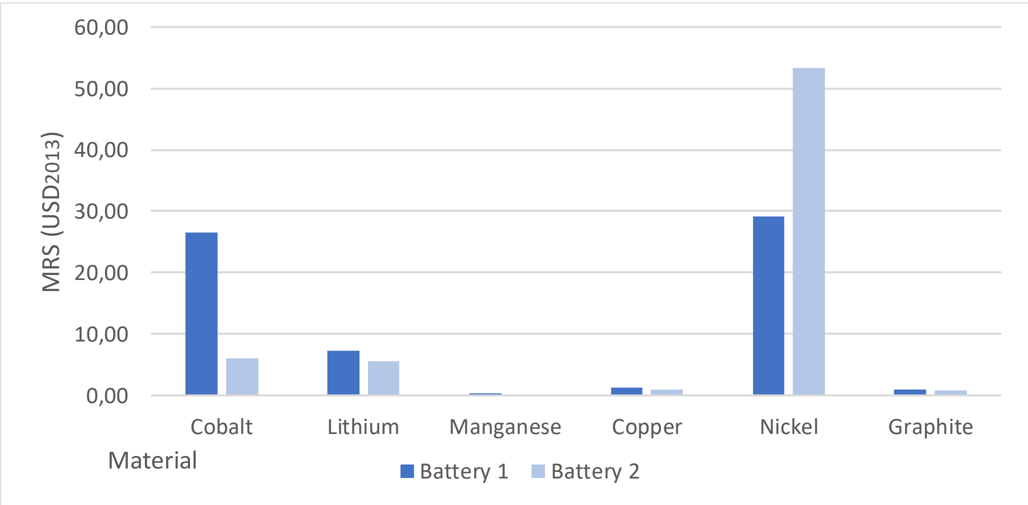

Figure 6.9. Mineral resource scarcity in USD (with the value of 2013), for battery 1 and battery 2. Calculated by multiplying the endpoint impact factors with the material weights per material for each battery.

Figure 6.10 shows the share of materials in MRS values for both batteries. Here it becomes clear to see that the share of Nickel is almost twice as high in the second battery than in the first. The share of Cobalt decreases by a fourth, making the share about the same as Lithium's. The shares of Manganese, Copper and Graphite are next to neglectable, all being under 2%.

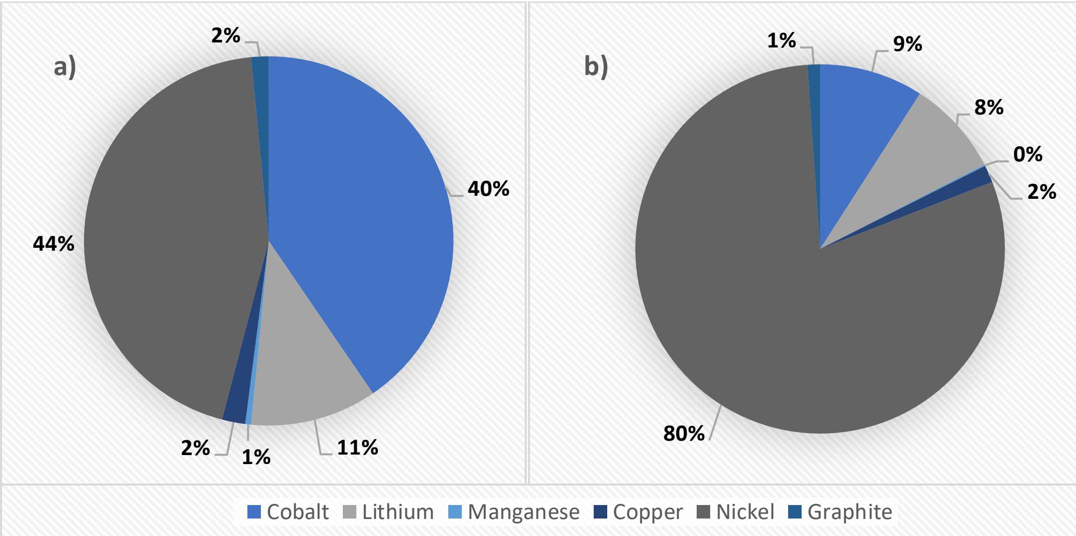

Figure 6.10. Share of materials in Mineral resource scarcity values for both batteries. With the share of each material based on the mass composition of the batteries. a) shows battery 1, b) shows battery 2.

In Figure 6.11, the MRS impact factors (USD_{2013}) are shown for both battery types for the predefined recycling rates of 0%, 5%, 10% and 40%. For the MRS indicator all of the values for all minerals go down as the recycling rate goes up for both batteries (Figure 6.11).

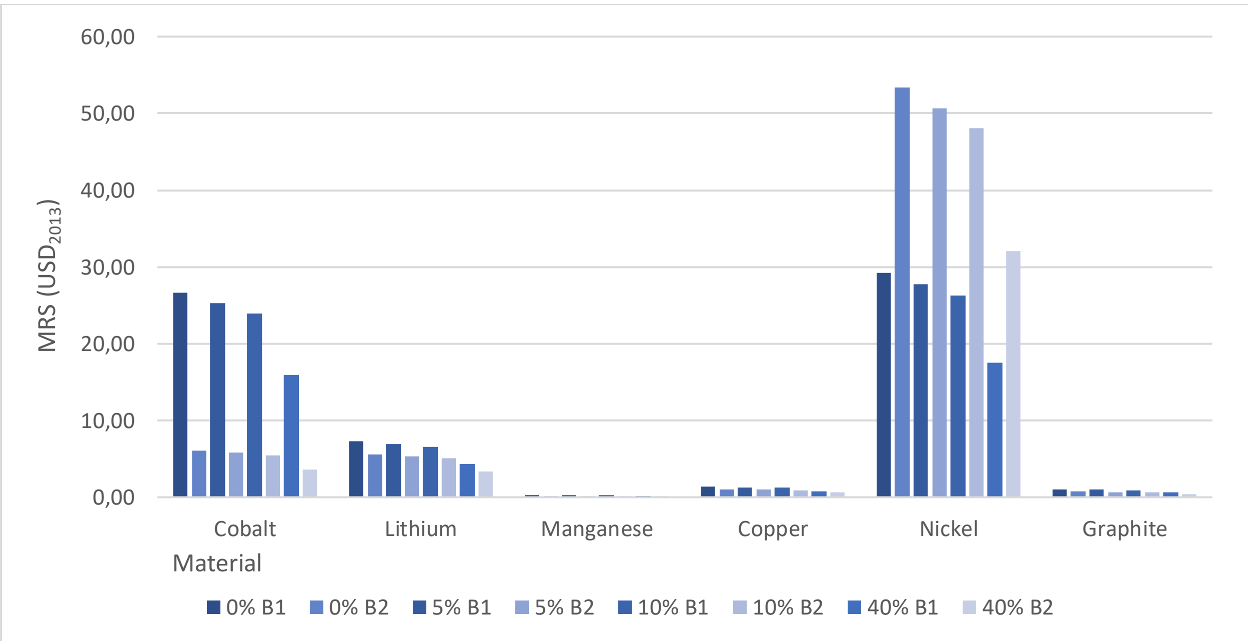

Figure 6.11. Mineral resource scarcity impact factors in USD_{2013}, for the NMC(1:1:1) and NMC(8:1:1) batteries (B1 & B2), for the predefined recycling rates of 0%, 5%, 10% and 40%. To calculate the results for different recycling rates, it is assumed that the recycled content has a CF of 0 meaning that it does not contribute to the scarcity of a mineral. The masses of the remaining primary material input were then multiplied by the same CF as used before.

6.2. Conclusion: Comparing the results

For this discussion, the hypotheses as proposed before will be evaluated by comparing the results of the three methods applied in this case study.

The first thing to look into is whether the EU criticality method and the GeoPolRisk method would show the same minerals as being critical. Although for the GeoPolRisk method no threshold has been defined for which values are considered critical, still the minerals can be put in contrast against each other. From figure 6.2, it can be concluded that for the GeoPolRisk method the minerals Cobalt, Nickel and Lithium can be considered the most critical for both battery types. For the EU method, the same conclusion holds for Cobalt and Graphite, which out of the analyzed materials, are the only ones being critical in 2017. Nickel is not considered critical by the EU method for the reason being that the SR parameter does not surpass the defined threshold. Still, the EI parameter is the second highest and even exceeds Graphite. This means that the material is quite essential but not critical as long as there is no risk to its supply. Within the EU method, Lithium is considered just non-critical, whereas the SR parameter is on the value of its threshold of 1.0, the EI parameter is just 0.1 below its threshold of 2.4. By the 2020 results of the EU method, Lithium does get considered critical, meaning it would be very interesting for a follow-up research to test the EU results of 2020 to the GeoPolRisk method if data for this would become available. For now, it can be concluded that only Cobalt is considered critical by both criticality methods tested within this case study.

Next, it was expected that it would be better to use battery 2 instead of battery 1 because of the amount of input materials. It was expected to hold true for all three methods mainly because of the considerable decrease in Cobalt use. As said before, one important thing to notice is that the amount of Nickel used increases.
As shown in the criticality matrix for the EU results (Figure 6.1), it becomes clear that following this method, the shares of materials in battery 1 make the product more critical than battery 2. The main reason for this is the decrease in Cobalt, having a big effect on both SR and EI parameters. Based on the results of the GeoPolRisk methods can also be concluded that the proposed hypothesis is true and battery 2 would be preferred over battery 1. When summing the criticality values of all materials for both batteries, the total value of battery 1 becomes 137 USD, whereas the value of battery 2 becomes 44 USD. Again, the main reason is the decrease in Cobalt which shares on criticality of battery 1 is 25% lower than for battery 1. Even as the amount of Nickel is higher and the amount of Cobalt is considerably lower for battery 2 than for battery 1, Cobalt still has a value almost three times higher than that of Nickel for battery 2. The share of Nickel increases the most when comparing battery 2 to battery 1, as its share on the criticality of battery 2 is 18% higher compared to that of battery 1. Meaning that overall as for now, it would seem better to choose battery 2 over battery 1 in terms of criticality of the used minerals by both criticality methods. In terms of scarcity by the MRS indicator, both batteries score just about the same, where battery 1 comes to a sum of 66 USD_{2013}, and battery 2 comes to a sum of 67 USD_{2013}.
One essential thing can be observed when comparing the EU data of 2017 to that of 2020. This would be the increasing SR parameter of Nickel from 0.3 to 0.5 from 2017 to 2020 (Table 1, appendix C). This means that if it further increases beyond the threshold, in the future, the use of Nickel might create issues for the criticality of battery 2. With this, an increase of the use of this material might also increase its economic importance. In follow-up research, it could be tested what the effect of using battery 2 instead of battery 1 is over a timescale of a couple of years.
The next conclusion to be made is about hypothesis 2, being that scarcity is not directionally proportional to criticality. This can be done by placing the values of each method against each other. To be able to make a fair comparison, the impact scores of all methods were normalized to Copper. For the EU method, an average score of the SR and EI parameters was calculated (Figure 6.12). The goal of this is to be able to make a better comparison between the different indicators as they are not expressed in equivalent quantities. From this comparison, it can be taken that the mineral scarcity indicator is not directly linked to either one of the criticality methods. It then thus follows that when a mineral is scarce, it does not always mean that it is critical, as was expected from theory.

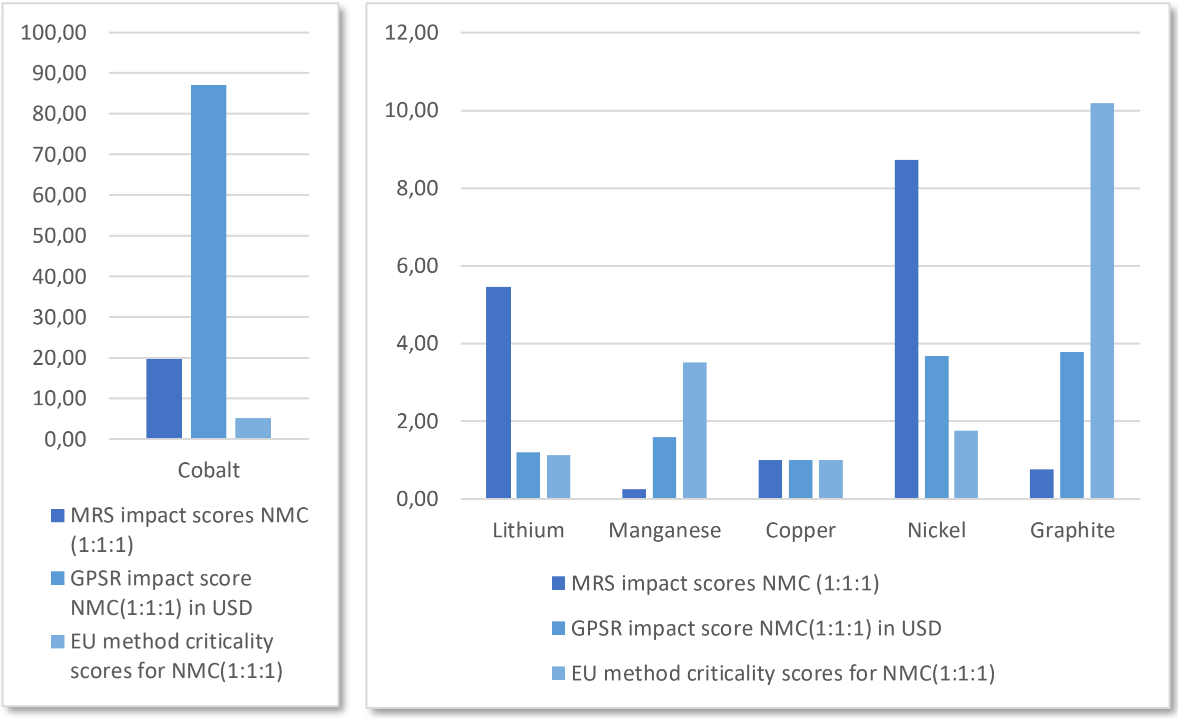

Figure 6.12. Impact factors of all three methods normalized to Copper. The EU criticality scores are based on average scores of the SR and EI parameters.

To conclude on the last hypothesis the figures 6.3 (EU method), 6.7 (GeoPolRisk method) and 6.11 (MRS indicator) will be considered. From these figures it follows that increasing recycling of the minerals will decrease criticality scores for both the EU criticality method and GeoPolRisk method. Also scarcity decreases following the MRS indicator. From the EU method follows that the focus of increasing recycling should be on Cobalt, then Graphite and Manganese respectively. It could also be concluded that to reach non-criticality the EoL-RIR values needed for Graphite, Cobalt and Manganese would have to be 67%, 38% and 2% respectively (Figure 6.3). For GeoPolRisk in battery 2 Nickel becomes more critical and Cobalt becomes less critical, still even for a recycling rate of 40% Cobalt is more critical than Nickel without recycling considered (figure 6.7). This means that following GeoPolRisk the focus of recycling should be on Cobalt. For the mineral resource scarcity indicator the same conclusion can be drawn but then for Nickel (figure 6.11).

7. Conclusion & Discussion

As mentioned in the introduction, the primary motivation for performing this study was the challenges and opportunities in reaching energy goals and transitioning to a net-zero economy while at the same time applying circular economy principles. The subject of impacts caused by the use of mineral resources has been a topic of persistent debate throughout society. In particular, the issues of criticality have been a concern amongst policymakers and researchers. This has raised confusion about how to define this concept as well as how to assess it, given the variety of methods to choose from, to be able to make decisions in mineral resource use. Based on the stated problems, the goals of this research were clear, and the questions to be answered were as follows:

- RQ 1: What problems are related to the use of mineral resources for low-carbon technologies, and how are they linked to concepts commonly used around this subject?
- RQ 2:
  a) Which are the most relevant assessment methods and tools used to address the identified problems?
  b) What do selected methods entail, and how do these different assessment methods compare?
- RQ 3: What is the applicability of the most relevant methods, what conclusions do they lead to, and are these conclusions the same or different for the object of EV car batteries?

Based on the literature study, expert interviews, and a case study accomplished in the previous chapters, this study has provided clear answers to these set-up questions. This chapter provides a reflection on the research process of this study. The implications for the interpretation of the results are discussed, as well as the limitations and potential consequences of the research design. The chapter ends by going through recommendations for future research.

7.1. Interpretation

The outcomes of this study provide plain answers to the set-up research questions. To answer the first research question, we explored problems associated with the use of mineral resources and related concepts through a literature review and expert interviews. From the expert interviews of this research, we learned that the main problem related to the use of mineral resources is their accessibility and, more specifically, criticality. One aspect of the problem with the accessibility of a resource is its availability. In the literature review part of this study, we found that the availability of a resource can get affected by depletion or the rarity of a resource. When there is low availability and high demand, a resource can be considered scarce. The criticality of a material becomes a problem when it is difficult for an actor to access, and this causes impacts on a social or economic system. These findings help to clear up de vagueness about the ambiguous concepts of depletion, rarity, scarcity, and criticality, as was suggested by André & Ljunggren (2021). By analyzing these concepts through the framework of the three dimensions of sustainability, we provided a solid terminological foundation to be used by assessment method developers and practitioners alike.

Additionally, with this research, we answered the question of what are the most relevant methods to assess the identified problems with resource use. We have found that there is a distinction between methods to assess circularity, LCA methods to assess depletion, scarcity, or criticality, and stand-alone methods to assess criticality. Each method looks at distinct aspects of using mineral resources and prioritizes different impacts of the activities around it.

Most importantly, we found that criticality generally gets assessed by two dimensions: supply risk and vulnerability to supply disruption. Supply risk is concerned with physical availability and socio-economic accessibility. Physical availability includes geological or environmental and technical aspects, and socio-economical accessibility includes geopolitical aspects. Vulnerability to supply disruption gets measured by economic importance, with recycling and substitutability as mitigation factors. Criticality can be assessed through methods incorporated into the LCA methodology, such as Essenz and GeoPolRisk, or by stand-alone methods, such as the ones by the NRC, EU, or Yale university. There are also methods considered within LCA to assess scarcity, where the most prominent one is the Mineral resource scarcity indicator of ReCiPe. By this, the results of this research contribute to resolving the ongoing debate on how to measure different concerns and as to which methods to use to assess the impacts of resource use (Lieberei & Gheewala, 2017; Northey et al., 2018; Ponomarenko et al., 2021).

With the more in-depth literature research part of this study, we analyzed selected methods in more detail by going into their operationalization and comparing them. When comparing the methods, it was suggested in the expert interviews that the key difference is their level of integration. Where the stand-alone methods integrate criticality assessment on the methodological levels, the LCA methods integrate on the results level. This makes it possible for the LCA methods to be compared more easily against each other to reveal tradeoffs between other impacts besides criticality. Next to this, we found that the methods principally differ in their goal and scope, level of analysis, temporal scale, indicators, and data. A clear description of how these elements are considered within a study will help the readers of the study to evaluate whether a study fits their perception of criticality and to identify which studies are comparable (Schrijvers et al., 2020). Which method is the most appropriate to use then depends on the question to be answered by the researcher and the size of the project. The results of this in-depth literature research help to increase the transparency regarding methodologies and data sources used to assess criticality. This will contribute to the general trustworthiness of the results.

Finally, we performed a case study to practically test the applicability of the most relevant assessment methods to see how their results compare and whether they come to the same conclusions or not. The methods applied in the case of EV batteries were the ones by the EU, the GeoPolRisk method, and the Mineral resource scarcity indicator. For the criticality of minerals used for the batteries, the method by the EU and the GeoPolRisk method only agreed on Cobalt being the most critical. Furthermore, overall it is better to choose battery 2 over battery 1 in terms of the criticality of the used minerals by both criticality methods. In terms of scarcity by the MRS indicator, both batteries scored just about the same. With this comes that it can be taken that the mineral scarcity indicator is not directly linked to either one of the criticality methods. It then thus follows that when a mineral is scarce, it does not always mean that it is critical, as was expected from theory. In addition, we found that increasing the recycling of the minerals will decrease criticality scores for both the EU criticality method and the GeoPolRisk method. Now with these results, the question of how criticality should best be assessed, as found in existing academic literature (Klinglmair et al., 2014; Berger et al., 2020; Sonderegger et al., 2020), has also largely been answered with our research.

7.2. Limitations

However, the results should be interpreted with caution due to limitations of our current research. To begin with, this study has incorporated a mixed method approach which came with advantages but also drawbacks. The methods involved a qualitative part, including a literature review and research, together with interviews, in combination with a quantitative part in the form of a case study. Because of this big spread in types of methods, each has provided us with different insights, yet it took away of the thoroughness of each method.

For example, in the literature study, we made a choice to focus mainly on the concept of criticality and the problems around it. Because of this, the assessment methods used to study depletion and scarcity were less extensively covered. This could have provided a better understanding of the relations between environmental impacts and socio-economic issues regarding criticality. With this, as this research considered the effects of supply risks on an economic system, the social impacts of using mineral resources from an inside-out perspective have been left out of this research to be able to narrow the scope.

In addition, because the field of study on criticality and criticality assessment is relatively contemporary, not a lot of research has yet been done on this subject. This has made it fairly difficult to find significantly relevant academic research on these matters.

Furthermore, with the interviews, limitations can be pointed out as well. First of all, only selected experts were interviewed based on their experience with and contributions to the use and research done on methods for criticality assessment. Different points of view could have been gained by including other actors as, for example, practitioners of criticality assessment such as corporate actors like EV battery producers, policymakers, or other societal stakeholders. Moreover, only 5 experts

were interviewed, which limited the number of perspectives and made it more difficult to find patterns of correspondence or disagreements among different actors.
Finally, for the case study, there are two main points of discussion that need attention. Firstly, as was indicated in the interviews and the method comparison parts of our research, the primary adversity to doing criticality assessments is data availability. Within the case study, this was no different, and the data we used can be considered reasonably outdated. The most recent data found from EU criticality studies was that of their study from 2020, which is still relatively recent. The latest data used for the GeoPolRisk criticality calculations, however came from 2017, making it necessary to use also the EU data from their report of 2017. Secondly, it could have been interesting to compare more than the three chosen assessment methods to each. For our case study, it was decided to compare the criticality scores of the EU and GeoPolRisk scores to the scarcity scores of the MRS indicator. Next to these methods, it might have been interesting also to consider depletion methods to dig deeper into how socio-economic issues compare to environmental issues.

7.3. Recommendations

The limitations, as pointed out, then bring us to the recommendations for further research and to stakeholders and society in general.
For further research, we would first suggest considering doing research focusing on either carrying out interviews or a case study separately. This would allow the researcher to more extensively study one or the other. For the interviews, for example, it would be most worthwhile to expand the number of interviews and, with this, include other actors such as corporate actors, policymakers, or other societal stakeholders. By making the examination more thorough, it would be possible to get more insights into the perspectives of practitioners and their experiences with the use of the concept of criticality and ways to assess it. It may allow the researcher to distinguish conceptual categories of interest, clarify relationships between them, and identify variations in processes (Dworkin, 2012).
For the case study, following the before mentioned limitations, we would propose to apply a broader set of assessment methods. This could include, for example, depletion methods as well as other scarcity and criticality assessment methods. Depletion methods could include abiotic depletion potential (ADP) methods such as CEENE, or IMPACT 2002+ (Guinée & Heijungs, 1995; Sonderegger et al., 2020; Dewulf et al., 2007; Jolliet et al., 2003). Scarcity methods could include, for example, the LIME2 method by Itsubo N and Inaba A (2012, 2014), or the more recent economic product importance (EPI) indicator (Lütkehaus et al., 2022). For criticality methods, there are two which we would propose could benefit from studying their practical application; the ESSENZ method (Bach et al., 2016) and the one by Yale university Yale (Graedel et al., 2011; Graedel et al., 2015). This, of course, would only be possible provided there are enough resources available to the party performing the research. To include these methods could provide an understanding of their practical applicability as well as to study tradeoffs between other impacts besides criticality more closely.
More broadly, to societal actors and other stakeholders who are interested in or associated with criticality and its assessment, we would suggest the following. We recommend starting by keeping in mind the concepts and terminology as defined within this research as a guide for any pursuits within the domain of criticality. Furthermore, we would insist on keeping data sources as well as methodologies and uncertainty in assumptions transparent within criticality assessment in general to promote cooperation and participation in this field. Knowing about these aspects as well as carefully considering the alignment of goals and scopes, are in the essence of anticipating any risks. In conclusion, all in all, this research brings us closer to being able to reach the energy goals and transition to a net-zero economy while at the same time applying circular economy principles. For society to succeed in enabling more sustainable practices, it will be necessary to promote creating a more extensive knowledge base on material criticality and how to mitigate supply risk as well as limit the economy’s vulnerability to it.

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9. Appendices

9.1. Appendix A: Interview guide

General framework
Hi (interviewee name), thank you for meeting me for this interview. Are you okay with me recording this?

[Start recording on Teams and phone]

Right now I am doing my graduation thesis at the University of Eindhoven together with an internship for the TNO in Utrecht, for my thesis I am studying material availability, the definition of criticality and methods to analyse it. Therefore I would like to ask you questions about definitions of criticality, assessment methods, and expectations of a case study.

<u>Definitions:</u>
Q1a (ice breaker question): What are from your point of view the main problems/impacts related to the use of critical raw materials? For example how does it relate to rarity, scarcity, depletion and social impact?

Q1b: In the literature I found that the EC defines critical raw materials as materials which are economically important for key sectors and which supply is associated with high risk. In your experience, is this the definition which is most worked with in practice? And do you agree with this definition?

<u>Assessment methods:</u>
Q2a: What methods/indicators (LCA or non-LCA) do you think are the best ones to measure criticality, and what are the criteria to select these?

Q2b: In your opinion, what are the pro's and con's of using LCA methods such as GeoPolRisk and EZZENZ? Which aspects do you think could be improved, maybe by using a different method of analysis?

Q2c: Do you think it would be useful to have different types of methods used in combination with each other, for example can methods such as LCA scarcity and criticality methods and non-LCA methods be complementary to each other?

Q2d: Do you think social aspects/impacts of using CRM's (such as: human right violations of workers, forced labor, child labor, health and safety of workers) or the effect of social impacts on supply risk (public acceptance, strikes, conflict) have been considered well enough in criticality analysis?

<u>Case study:</u>
As a case study we study how different criticality assessment methods include the effect of recycling and whether the methods come to the same or different conclusions, by looking at the recycling of EV batteries.

Q3a: In terms of material criticality/supply risk/scarcity/material depletion/social impacts, what outcomes would be interesting to get out of such a case study? Which interesting research gaps could be filled with this kind of case study?

Q3b: In what way can actors and stakeholders of the EV battery industry benefit from criticality assessments? (consumers, private/public companies, policy makers, researchers) And do you think it can support decision making?

9.2. Appendix B: Interview transcripts and coding

Transcripts of records interview 1.

Questions and answers	**Coding**
Definition:	
Q1: For my graduation thesis I have studied the definition of criticality, in the literature I found that the EC defines critical raw materials as materials which are economically important for key sectors and which supply is associated with high risk. In your experience, is this the definition which is most worked with in practice? And do you agree with this definition?	
Criticality for me best expressed maybe in time and also in mathematical expressions, and what do I mean with that. I know the European definition and we are working with the EC on the actual methods, for me it's okay, like 5.5 out of 10 for that definition. But for one, they only focus on raw materials. And so getting back to my original answer what for me in criticality what is most important is its relation to safety, food and shelter. This sounds like very basic needs but if you think about it starting from buildings and your safety in forms of food, and I would say this even before 2022 but even more right now, the military, criticality is related to the most basic needs for human beings in terms of information and entertainment but in the end criticality it comes back to basic needs, things that mattered 10 thousand years ago. It can also be expressed in terms of time, something is critical if you need it in a week time, but then also it may be costly but it's only a week. It would be much more problematic or critical if you can only solve a problem in many moths, years or decades. So two important things in criticality, the finite thing is one and the relation to basic human needs. To be more concrete in the EU definition, raw materials go into products, products are made by sectors, sectors relate to innovation, labor conditions and societal goals. It's like a pyramid, raw materials, products, sectors, societal goals. The EU definition is okay, it's a good start, but for me the scope has to be wider, you have to paint the complete picture to be able to see where it hurts, generally people don't care about ores or cobalt, they don't care about metals, they care about the eventual service or comfort provided by the products that contain the ores or metals, that's in the end what matters.	"The European definition, it's okay, 5.5 out of 10 for that definition" – *criticality definition* "For one, they only focus on raw materials." – *criticality definition* "For me in criticality what is most important is its relation to safety, food and shelter." - *criticality, issues, definition* "in the end criticality it comes back to basic needs" – *criticality, issues, definition* "It can also be expressed in terms of time, something is critical if you need it in a week time, but then also it may be costly but it's only a week. It would be much more problematic or critical if you can only solve a problem in many moths, years or decades." – *criticality, issues, definition* "So two important things in criticality, the finite thing is one and the relation to basic human needs." – *criticality, issues, definition* "The EU definition is okay, it's a good start, but for me the scope has to be wider, you have to paint the complete picture to be able to see where it hurts" – *criticality definition* "generally people don't care about ores or cobalt, they don't care about metals, they

	care about the eventual service or comfort provided by the products that contain the ores or metals, that's in the end what matters." – *criticality, issues, definition*
Q2: What methods/indicators do you normally use to measure criticality, and what are the criteria to select these?	
The conventional way is to use public statistics, expressing the world economy in countries, statistics from mining data which are provided by certain geological surveys around the world, US, UK, Austria. And public statistics from different sectors, employment high/low, performance statistics in the form of corporate social responsibility, innovations. So the data that you use is strictly public, oriented on either a product sector of that of a raw materials. But if you do criticality studies for a couple of years, you will eventually find that there is a data shortage or lack of data. *And until the time you feel comfortable and according to the Yale university method by Graedel, or OECD or the world bank, if you speak of public statistics, for raw materials, products or sectors and countries you're doing an okay job, you get a 6/10 grade if you will.* *This works best on a global economy level, when you want to do assessments on a corporate level it's another different story, because they have their own data.*	"The conventional way is to use public statistics" – *assessment data* "strictly public" – *assessment data* "you will eventually find that there is a data shortage or lack of data" – *assessment data* "This works best on a global economy level, when you want to do assessments on a corporate level it's another different story, because they have their own data." – *assessment level*
Q3: To what purpose do you normally apply these methods? Are you looking at specific products/processes or do you look more at industry sectors/ supply chains on a macro scale?	

<u>The scale of criticality, let's start with what it's not about, it's not about supply chain issues</u> like everybody is talking about. Why not, because there is no real data, there are some economic models which are very coercive, very aggregated, and wont suffice to do supply chains. So <u>it's a relationship between products and the size of a sector in a certain country.</u> And also <u>to answer the question, it's about sectors and countries mostly, but all determined by the available data</u>. *As an example, the whole world economy captures in maybe 5000-8000 product groups, which is quite a good data source, considering a lot of studies only cover 50-100 products as data source. This makes 5000 quite a detailed data source, so you have the opportunity to go with a certain level needed to do a good assessment. And then when you look at how does the data get there, there is international trade measure import subsidies, or export subsidies. That's why the data is there, not because of criticality<u>. So why do you do a criticality study, well to prove that the market will not solve all of the problems.</u> If you engage in criticality studies, you must have some sense of that <u>the market will not perfectly balance supply and demand.</u> The funny thing is that an economist will say it always will, but you only study criticality because you assume that it is not so, that's <u>why there also is insufficient data, because it is normally gathered for a different purpose.</u> Because traditionally an economist would say why care about the environmental impact. This is a prejudice you have to face, because before the rise of criticality studies the consensus was that the free market would solve the problems.*	"The scale of criticality, let's start with what it's not about, it's not about supply chain issues" – *assessment scale* "it's a relationship between products and the size of a sector in a certain country." – *assessment scale* "it's about sectors and countries mostly, but all determined by the available data." – *assessment scale and data* "So why do you do a criticality study, well to prove that the market will not solve all of the problems." – *assessment purpose* "the market will not perfectly balance supply and demand." – *assessment reason* "why there also is insufficient data, because it is normally gathered for a different purpose." – *assessment data*
Colleague attending the interview: I was also wondering because also of course because you're employed by the TNO, it is dependent on what kind of projects or questions come in to what kind of scale you're looking at? Do you find that the government for example wants to know mainly about the sector scale, or if it comes from a company it comes down to a product scale. What type of questions do certain projects raise?	
<u>Research questions related to criticality are usually poor. Most do not have a common view of what criticality is</u>, that's why I had to try to explain the first	"Research questions related to criticality are usually poor. Most do not have a

answer in 5 minutes. Because when people will ask what is criticality, is it materials or products, is it electronics or specifically a smartphone or one with a specific innovation, those are already some widely distinctive detail levels we speak about. So questions are varied, but the main question that remains is, can we trust the supply or country of origin to deliver next year? Also dependent on export restrictions or how they treat their labour force, what is the recycling level of raw materials in the products we find important. Which is subjective too, what is important, depends on the size of a sector, why is it for some materials more painful when it disappears in your supply? Network effects are for one, the level of tacit knowledge, being build up in many decades, which will be lost in an instant when a company moves offshore. Normally they just want to know about the amount of car manufacturers and how many materials they use, but this is not the most important. This means questions around criticality are nowhere near detailed enough.	common view of what criticality is" – *criticality definition* "The main question that remains is, can we trust the supply or country of origin to deliver next year?" – *assessment reason* "what is important, depends on the size of a sector, why is it for some materials more painful when it disappears in your supply? Network effects are for one, the level of tacit knowledge, being build up in many decades, which will be lost in an instant when a company moves offshore." – *Economic importance* "questions around criticality are nowhere near detailed enough." – *criticality assessment*
Assessment methods:	
Q4: In your opinion, what are the pros and cons of the method you're using? Which aspects do you think could be improved, maybe by using a different method of analysis	

Pros of current methods: public data, transparent data its clear, available for everybody to verify. Then next, it captures most of the initial problems like lack of recycling, export restrictions, poor social conditions, reputational damage. *Cons: lack of data, the data is not detailed enough. Secondly, the absence of societal goals which will not be addressed by just the function of a market, current methods do not account for societal drivers, like the EU saying we do not want Russian imported materials, or no matter what we want to have renewable electricity even by violating some market rules because it is so important. Non market forces can be left out of the picture.* *How to improve: to introduce the wonders of ICT by developing a system of product passport, this might be a silver bullet to improve the ability of governments and institutions and NGOs to assess criticality. But what they entail is a different study entirely.* *And companies are actually the drivers for such a development, for their customers, for their business customers downstream suppliers, they want to know where a material is coming from, they want to know that their carbon footprint is lower than that of their competitors.* *Frans Timmermans EU, CAM, Carbon Accounting Measures.* *How can the con's be improved? For example to accept that for major societal changes we can't rely on markets, but that's an institutional challenge, not a methodological challenge for researchers, it's for politicians and leaders.*	"Pros of current methods: public data, transparent data its clear, available for everybody to verify. Then next, it captures most of the initial problems like lack of recycling, export restrictions, poor social conditions, reputational damage." – *assessment methods advantages* "Cons: lack of data, the data is not detailed enough. Secondly, the absence of societal goals which will not be addressed by just the function of a market, current methods do not account for societal drivers" – *assessment methods disadvantages* "How can the con's be improved? For example to accept that for major societal changes we can't rely on markets, but that's an institutional challenge, not a methodological challenge for researchers, it's for politicians and leaders." - *policy*
Q5: Does the criticality method you're using take into account social aspects/impacts of using CRM's (such as: human right violations of workers, forced labour, child labour, health and safety of workers) or the effect of social impacts on supply risk (public acceptance, strikes, conflict), or how do you think it is best taken into account?	

Now it's taken into account by the WGI, it's a quality label for all countries in the world. For example the UK took a huge dive after the Brexit. It's very general and very aggregated, it incorporates the social impacts in your methodology. Another one is the Human Development Index, its one index comprised of 30 other indicators. They represent 6/10, but at least it's there. *Just to give you a story that sticks to mind; you are ABN ambro bank, for some reason they want to do due diligence on their gold supply. What do they do, they hire a helicopter, fly someone over in Ecuador, and they say "ah yes this looks good" and they fly home and say this is a responsible source of gold. And you think how can that be, is this really the level of investigation what they put in their social responsibility. Well its better than nothing but it can be improved by using better data, for example verified by blockchain. And then there is the product passport element, which is my darling solution to all the problems here. If you want to know the social conditions in your supply chain are okay, and remember that criticality is not assessed at the supply chain, because there is no data. But as a company, Philips for example, they want to prove to their customer that their problems come from a low supply risk. To do this there is a need of introducing ICT technologies, such as what is deployed in for example finance or health services, they deploy ICT techniques which are 10/20 years ahead of supply chain managers or environmental impact researchers or enforcing agencies. So that is how social responsibility can be improved, ICT technologies, rather than letting a company fill in another form, because they are too busy.*	"the WGI, it's a quality label for all countries in the world." – *input data/ indicator* "It's very general and very aggregated, it incorporates the social impacts in your methodology." – *input data/ indicator* "Another one is the Human Development Index, its one index comprised of 30 other indicators. They represent 6/10, but at least it's there." – *input data/ indicator* "Well its better than nothing but it can be improved by using better data, for example verified by blockchain." – *data improvement* "there is a need of introducing ICT technologies, such as what is deployed in for example finance or health services, they deploy ICT techniques which are 10/20 years ahead of supply chain managers or environmental impact researchers or enforcing agencies. So that is how social responsibility can be improved, ICT technologies, rather than letting a company fill in another form, because they are too busy." – *data improvement*
Q6: Do you think it would be useful to combine criticality methods with LCA methods? *Maybe through the use of an indicator developed for that purpose such as (GeoPolRisk) or should we assess product life cycles and material criticality separately?*	

Let me give you a provocative answer and say, no. Although they will be useful inevitably in the long term, because I dearly appreciate the field of LCA, and they make/lead the way in terms of data, it was the first way of looking at impact along the supply chain, and to be quantitative about it like an accountant. And criticality clearly needs that, so in that way I would have to say yes. But why do I say no, because there is no drivers within LCA to improve data which LCA uses themselves. And this is not the fault of people at Ecovent or other LCA databases like Simapro, these people want to make progess and take meaningful steps within the LCA data as well. But for example to use depletion as an environmental impact, this is total rubbish, it's not useful. *I would say, wait 2 or 5 years, and they criticality can really pick up LCA elements.* *And another way to answer your question is, well look at social impact in criticality, it's there, environmental impact, it was taken out of the criticality method by the EU, they say carbon footprint forget it, we don't want that in criticality assessment. And that was the year 2013/2014, this was all before the Paris agreement. And now criticality assessment still bares the legacy of that decision, to really forget about environmental impact all together. So therefore it makes even more sense to look at criticality from an LCA point of view. Criticality needs to be solid and verifiable and LCA to the outside world, to a sceptic eye as you will, is sometimes still not clear or focussed enough, and to uncertain to really make a point for criticality and go to the likes of Glencore or Shell, then you really have to be certain about your criticality assessment, so if you use LCA you better have really good data.* *That's why I stick to my no, even though there are many ways to use LCA.*	"I dearly appreciate the field of LCA, and they make/lead the way in terms of data, it was the first way of looking at impact along the supply chain, and to be quantitative about it like an accountant. And criticality clearly needs that, so in that way I would have to say yes." – *LCA data* "But for example to use depletion as an environmental impact, this is total rubbish, it's not useful."- *LCA indicators* "Environmental impact, it was taken out of the criticality method by the EU" – *Criticality parameters* "And now criticality assessment still bares the legacy of that decision, to really forget about environmental impact all together. So therefore it makes even more sense to look at criticality from an LCA point of view." – *Criticality parameters* "LCA to the outside world, to a sceptic eye as you will, is sometimes still not clear or focussed enough, and to uncertain to really make a point for criticality" – *criticality in LCA*
Case study:	
Q7: What actors and stakeholders are you targeting with your assessments? (consumers, private/public companies, policy makers, researchers) And does the method you apply support their decision making?	

I can give you a clear answer, its policy makers and researchers, definitely not the final consumer, they don't care at all, and it's to a minor extend companies. Companies do care about it but then they operate through branch organisations, these are interesting for criticality. Big organisations, either they have criticality assessment for themselves, like big internationals do, constantly monitoring every hour of the day their supply chain and disruptions. Or they don't have a clue and say they trust in the working of the market. *So researchers, policy makers, and to a lesser extend the branch organisations, those are the type of stakeholders interested in criticality.* *It is not yet used in decision making, because the questions being asked in criticality are not focused enough, people do not yet themselves know what they want to know. This wat people get confused on how to act on criticality, because a mandate is missing.*	"I can give you a clear answer, its policy makers and researchers, definitely not the final consumer, they don't care at all, and it's to a minor extend companies." – *criticality stakeholders* "the questions being asked in criticality are not focused enough, people do not yet themselves know what they want to know." – *criticality assessment purpose*
Q8: For the case of analyzing the effects of recycling EV batteries, how would you approach this assessment? What methods/indicators would you recommend to use and why?	
For EV, they are important for societal goals, and even though the data is not sufficient, EVs are the exception to the rule, usually criticality assessment doesn't provide clear policy advice, but for EV's it just might. And that is to organize the supply chain in Europe, organize it and scale up. Provide yourself with the option, to have a supply chain at scale for EV batteries in Europe, that option is not present right now.	"usually criticality assessment doesn't provide clear policy advice, but for EV's it just might." – *EV batteries/ policy* "And that is to organize the supply chain in Europe, organize it and scale up. Provide yourself with the option, to have a supply chain at scale for EV batteries in Europe, that option is not present right now." – *criticality strategy*
Colleague attending the interview: What would be a useful indicator? Would the EU method be the most useful?	

Pragmatically this method would be the most useful, why, because it's there its accepted and we can have it this year in our report. *To be able to say why this project matters.* *If you really want to get into time and Maslow, the need for society to provide for itself, especially ours, our society is used to be a frontrunner on high-tech in the world, to be able to have a share in your own supply chain. If you want to express that message with current criticality measures then that's not possible. But there's no other method that's out there and ready to deliver that message. Hopefully in 5 years' time when people will support this point of criticality and the need to not only look at raw materials but also in terms of entire sectors and knowledge base, tacit knowledge, then you will apply that method.* *But until then the EU is the most clear to use and linked to policy advice*	"Pragmatically this method would be the most useful, why, because it's there its accepted and we can have it this year in our report." – *criticality method EU advantage* "Hopefully in 5 years' time when people will support this point of criticality and the need to not only look at raw materials but also in terms of entire sectors and knowledge base, tacit knowledge" – *criticality parameters*
Final takeaway: Imagine yourself having all the money in the world and all the information and all the energy, until recently you would be regarded as the most powerful person in the world. Now we move towards a future where energy is coming from renewable sources, so having oil and coal creates not that much power. Money is another story of its own, there's now governments who create money out of thin air, they say they still account for it. But let's assume money is ambiguous since 2009, the financial crisis, there's lots of money going around everywhere. And information, well, we have the internet, I mentioned this tacit knowledge, which are things you cannot convey through the internet, things you can only learn by being close to other people. Then still information, money and energy is tending to get less scarce, but what of course is tending to be more scarce is our molecules, our ores our natural resources, and that's the major shift that lies behind this inability of people to expect the market to solve our problems, and this shift of scarcity is what we're witnessing in the long term, it's a long term driver. For me this tells the story about some of the problems that criticality methods are facing, because people still don't understand that this is happening. This shift is causing this need for criticality methods.	"Then still information, money and energy is tending to get less scarce, but what of course is tending to be more scarce is our molecules, our ores our natural resources, and that's the major shift that lies behind this inability of people to expect the market to solve our problems, and this shift of scarcity is what we're witnessing in the long term, it's a long term driver. For me this tells the story about some of the problems that criticality methods are facing, because people still don't understand that this is happening. This shift is causing this need for criticality methods." – *criticality assessment reason*

Transcripts of records interview 2.

Questions and answers	**Coding**
Definition:	
Q1: For my graduation thesis I have studied material availability, the definition of criticality and methods to analyze it, what are from your point of view the main problems/impacts related to the use of critical raw materials? For example how does it relate to scarcity, depletion and social impact?	
Okay, these are quite a few terms already which you have in your question, which is availability, criticality and impact. These are things we try to separate a bit from each other in the LCA world. So when it's about impact, then we usually talk about environmental impacts, such as the carbon footprint, acidification, toxicity from mining activities etc. And this is usually captured in the traditional LCA impact categories. That's not the issue of the resource categories. Then when it comes to availability, then we usually mean the physical availability to get these resources and this is simply physical availability. That has to do with basically two components, one is the geological availability, how much do we have in the earth. And the other would be the anthropogenic availability, which is how much is in societal use, for example landfills etc, and what can you get out of it. And then there's this third dimension of criticality which is accessibility. Because only because something is there and its available doesn't mean that you have access to it, that's the idea of criticality. And there can be different constraints, this can be that you have monopolistic structures and they are very high at price or that there are political barriers of trade so you can't get certain materials. Or that the resources are too concentrated in a country that can be problematic. Or that there is a high price volatility, these are all things which can make a resource critical. So in a short term and social economic way they can be critical, and this is what these criticality methods try to assess	"availability, criticality and impact. These are things we try to separate a bit from each other in the LCA world." – *definitions* "when it's about impact, then we usually talk about environmental impacts, such as the carbon footprint, acidification, toxicity from mining activities etc." – *definitions, environmental impact* "when it comes to availability, then we usually mean the physical availability to get these resources and this is simply physical availability. That has to do with basically two components, one is the geological availability, how much do we have in the earth. And the other would be the anthropogenic availability, which is how much is in societal use, for example landfills etc." – *definitions, availability* "And then there's this third dimension of criticality which is accessibility. Because only because something is there and its available doesn't mean that you have access to it, that's the idea of criticality." - *definitions, accessibility and criticality* "constraints can be monopolistic structures, political trade barriers, or that resources are too concentrated, or that there is a high price volatility" – *criticality, issues, parameters* "So in a short term and social economic way they can be critical, and this is what these criticality methods try to assess." – *criticality assessment, purpose*

Q1b: In the literature I found that the EC defines critical raw materials as materials which are economically important for key sectors and which supply is associated with high risk. In your experience, is this the definition which is most worked with in practice? And do you agree with this definition?	
Yes, now we go into the details. Very often criticality should have these two dimensions, on the one side on the x-axis you have the supply risk, which are all the things I just mentioned. But that by itself doesn't make a resource critical, its only critical if you are vulnerable to that, so if your economic growth or your production ability depends on this resource, that's usually the y-axis. And then the highest critical things are in the top right corner. The other ones should be more precise, also my own terminology in the first question that is rather supply risk assessment, and not really criticality assessment. Criticality the common definition is the combination of vulnerability and supply risk. Vulnerability depends on how easy or what share in your purchase is this resource or can you easily substitute this or can you not, and do you have several suppliers of this resource. So that's your particular situation, supply risk is a global situation and vulnerability is your particular situation, how dependent are you. You can be very dependent if you produce steel cups and you only rely on steel and you have only one supplier and you cannot substitute it, then you are highly vulnerable. And when you produce cups in general from different materials and you have 10 suppliers then it's the same material were talking about but you're not as vulnerable.	"Very often criticality should have these two dimensions, on the one side on the x-axis you have the supply risk, which are all the things I just mentioned. But that by itself doesn't make a resource critical, its only critical if you are vulnerable to that, so if your economic growth or your production ability depends on this resource, that's usually the y-axis." - *criticality parameters* "my own terminology in the first question that is rather supply risk assessment, and not really criticality assessment." – *criticality assessment* "Criticality the common definition is the combination of vulnerability and supply risk." – *criticality definition* "Vulnerability depends on how easy or what share in your purchase is this resource or can you easily substitute this or can you not, and do you have several suppliers of this resource. So that's your particular situation, supply risk is a global situation and vulnerability is your particular situation, how dependent are you." – *criticality parameters* "You can be very dependent if you produce steel cups and you only rely on steel and you have only one supplier and you cannot substitute it, then you are highly vulnerable." – *criticality parameters* "When you produce cups in general from different materials and you have 10 suppliers then it's the same material were talking about but you're not as vulnerable." – *criticality parameters*
Assessment methods:	

Q2: What methods/indicators (LCA or non-LCA) do you think are the best ones to measure criticality, and what are the criteria to select these?	
Most importantly, the method should fit to your question. So if you want to analyse a product or a company then the LCA based approach usually works well enough. Manly the Essenz method and the GeoPolRisk method, both have their pros and cons. The Essenz method is a bit more comprehensive in terms of supply risk dimensions, so you have many more dimensions which could lead to supply risk. GeoPolRisk is a bit more local/specific. So both are very good. If you want to assess it more from a large scale perspective, so criticality of raw materials for a country or the EU, then these small scale methods are not designed to answer these question. Then I would rather go with the greater methods like the Yale method or the European method which are out there. So I'm hesitating to say use this one or this one because it depends on the question. *If you have a specific supply chain that you want to analyse, of course it makes sense to have it very specific for your supply chain. If you have a complex product system like a smart phone or an EV and you have dozens of supply chains then of course you also get a bit of a limit if you want to analyse every supply chain individually, and there the Essenz method which again has a global approach is more suitable for these general assessments, if you have a product which consists only of a few methods and you know the supply chain it might be more useful to use the GeoPolRisk. It's a bit like asking what is the best tool in your toolbox, is it the hammer or the screwdriver, it depends very much on if your problem is a nail or a screw, it will be hard to answer.*	"Most importantly, the method should fit to your question." – *criticality assessment* "So if you want to analyse a product or a company then the LCA based approach usually works well enough. Manly the Essenz method and the GeoPolRisk method, both have their pros and cons. The Essenz method is a bit more comprehensive in terms of supply risk dimensions, so you have many more dimensions which could lead to supply risk. GeoPolRisk is a bit more local/specific. So both are very good. If you want to assess it more from a large scale perspective, so criticality of raw materials for a country or the EU, then these small scale methods are not designed to answer these question. Then I would rather go with the greater methods like the Yale method or the European method which are out there." – *criticality assessment, LCA, Essenz, GeoPolRisk, EU, Yale* "the Essenz method which again has a global approach is more suitable for these general assessments, if you have a product which consists only of a few methods and you know the supply chain it might be more useful to use the GeoPolRisk." – *criticality assessment, Essenz, GeoPolRisk* "It's a bit like asking what is the best tool in your toolbox, is it the hammer or the screwdriver, it depends very much on if your problem is a nail or a screw, it will be hard to answer." – *criticality assessment*
Q3: In your opinion, what are the pro's and con's of using LCA methods such as GeoPolRisk and EZZENZ? Which aspects do you think could be improved, maybe by using a different method of analysis?	
The idea of Essenz or GeoPolRisk is basically to integrate this supply risk assessment into the LCA analysis. At least the traditional criticality analysis	"The idea of Essenz or GeoPolRisk is basically to integrate this supply risk

from Graedel and others, they were the first, and the idea was to look at the country scale or an economy scale. And the idea then was, hey couldn't we somehow get this in LCA, so that we can do this by one click, for example Essenz is also implemented into some software such as the Gabi software where you can implement it there. And then it really helps as in the same way you can analyse your carbon footprint or your water footprint and your geological resource depletion, and then you can also analyse your criticality and see instantly, what materials are worth to have a closer look at. So it's also the intention, it's more to be a screening tool, for example if you're producing a smartphone what other things do you need to worry about and look into in more detail. It doesn't replace this other initiatives, its rather an idea to get the criticality aspects into the LCA world. And in that I think they make sense and they are quite far developed, and even they go beyond aspects of the traditional criticality analyses, so in that way it is a good complement.	assessment into the LCA analysis." – *criticality in LCA* "At least the traditional criticality analysis from Graedel and others, they were the first, and the idea was to look at the country scale or an economy scale." – *criticality assessment scale* "And the idea then was, hey couldn't we somehow get this in LCA, so that we can do this by one click" – *criticality in LCA* "And then it really helps as in the same way you can analyse your carbon footprint or your water footprint and your geological resource depletion, and then you can also analyse your criticality and see instantly, what materials are worth to have a closer look at." – *criticality in LCA* "And in that I think they make sense and they are quite far developed, and even they go beyond aspects of the traditional criticality analyses, so in that way it is a good complement." – *criticality in LCA*
Q4: Do you think it would be useful to have different types of methods used in combination with each other, for example can methods such as LCA scarcity and criticality methods and non-LCA methods be complementary to each other?	
Then you would have to really go into the details of the methods, and look at what are the indicators that they are assessing. Essenz for instance was designed to be really broad and to cover as many criticality aspects as possible, so there in theory you should not have missed anything I would say. Others are a bit more specific, like for example the GeoPolRisk considering the specific supply chain situation for a country, this is more detailed. In general it is always good to apply different methods and in an ideal world they would all come to the same conclusion and if not then it is interesting to see why not. Then you look at what is behind these results, what is showing up here and there, and also the analysis of the results you gain from different methods usually make you know your product better, and also the criticality constraints can be identified better because you have to think about the results. So in general yes, take as many assessments as possible and combine and analyse them, but of course that is very unpractical if you're a practitioner and you	"Essenz for instance was designed to be really broad and to cover as many criticality aspects as possible" – *criticality in LCA, Essenz* "Others are a bit more specific, like for example the GeoPolRisk considering the specific supply chain situation for a country, this is more detailed. In general it is always good to apply different methods and in an ideal world they would all come to the same conclusion and if not then it is interesting to see why not." – *criticality in LCA, GeoPolRisk* "Criticality constraints can be identified better" – *criticality assessment*

just want to know by a click what is the result. But you could do this with everything, if you are analysing the carbon footprint you could do the global warming potential for 20 years, 100 years, 500 years, and you could use midpoint and endpoint models and you could use temperature models and you will get different results and it would be really interesting to see why methane is more relevant in the short term then in the long term because the atmospheric life time is not as long as compared to CO2, and all these analyses give you a lot of insights, but on the other hand it is not very practical. So if you have the time and this is an academic exercise then yes do as much as you can, if you're a practitioner you would be overloaded with these kinds of information and I would say rather pick one. For the LCA world I think Essenz would have the highest level of recommendations, because it has is so broad and it has so many characterization factors. Because in our recommendations group we were asking ourselves the same questions, if we have to recommend one, we always write use as many as possible of course . But if you want to use one then based on what is out there then which one to use, and in several papers it was written why this one was best for this purpose. And sometimes you have to be brave, this is the best what we have right now for this question, go for it.	"So in general yes, take as many assessments as possible and combine and analyse them, but of course that is very unpractical if you're a practitioner and you just want to know by a click what is the result." – *criticality assessment* "If you're a practitioner you would be overloaded with these kinds of information and I would say rather pick one. For the LCA world I think Essenz would have the highest level of recommendations, because it has is so broad and it has so many characterization factors." – *criticality in LCA, Essenz*
Q5: Do you think social aspects/impacts of using CRM's (such as: human right violations of workers, forced labor, child labor, health and safety of workers) or the effect of social impacts on supply risk (public acceptance, strikes, conflict) have been considered well enough in criticality analysis?	

You already mentioned that there are two sides of the coin, one is the social impact caused by producing these materials. And that is something that does not belong to criticality methods, the same way that the carbon footprint and the water footprint don't belong to the criticality method, that is highly relevant but it should be considered in other impact categories. So if you're doing the total sustainability analysis of methods, then you should analyse the water footprint and the carbon footprint and the incidents of child labour and the accidents and all these social environmental impacts. But the criticality indicators in that orchestra of indicators should assess how critical is this material, and there we talked about several of these dimensions already and one of them can also be it is critical because there are so many socially bad things happening to it that you cannot use it, even though it is physically available and it is not subject to barriers of trade and there is not a high price volatility but really you lose the social license to operate if you're using these blood diamonds in your supply chain. It is not about the physical or economically availability, it is just that it is a bad thing to do, your customers won't buy your products anymore if you have these dirty things in your supply chain. *And then the other way around, on how is the social impact influencing the criticality and that is something that has at least in a rough way been considered in the Essenz method by a means of a few indicators of the SHDB, I don't recall really, that's something you have to ask Vanessa. I think it is something like child labour or accidents, something people just don't accept, this can influence your supply risk.*	"You already mentioned that there are two sides of the coin, one is the social impact caused by producing these materials. And that is something that does not belong to criticality methods, the same way that the carbon footprint and the water footprint don't belong to the criticality method, that is highly relevant but it should be considered in other impact categories." – *social impact in criticality assessment* "But the criticality indicators in that orchestra of indicators should assess how critical is this material, and there we talked about several of these dimensions already and one of them can also be it is critical because there are so many socially bad things happening to it that you cannot use it, even though it is physically available and it is not subject to barriers of trade and there is not a high price volatility but really you lose the social license to operate if you're using these blood diamonds in your supply chain. It is not about the physical or economically availability, it is just that it is a bad thing to do, your customers won't buy your products anymore if you have these dirty things in your supply chain." – *social impact in criticality assessment* "And then the other way around, on how is the social impact influencing the criticality and that is something that has at least in a rough way been considered in the Essenz method by a means of a few indicators of the SHDB." – *social impact in criticality assessment, LCA, Essenz* "Something people just don't accept, this can influence your supply risk." – *social impact on criticality*
Case study:	
As a case study we have studied how different criticality assessment methods include the effect of recycling and whether the methods come to the same or different conclusions, by looking at the recycling of EV batteries.	

Q6: In terms of material criticality/supply risk/scarcity/material depletion/social impacts, what outcomes would be interesting to get out of such a case study? Which interesting research gaps could be filled with this kind of case study?	

<u>*With recycling, the tricky thing to get your head around is that there are two levels so to say*</u>*.* <u>*One level is your product system that you are analysing*</u>*, your electrical vehicle for instance. And there it might be that you recycle something and that instead of using one Kg because you have a closed loop of 90% you're only using 100grams effectively. And then the recycling is already reflected in your LCA inventory, so you say you only use 100grams of a material instead of 1 Kg, but that is dependent on your specific product system. In another product system with another manufacturer it might be 500grams or it might be no recycling and they use a full Kg. That is reflected in the amount of primary material you use in your product system. That is very direct, if you use only half of it or you use 10% of that material because you're recycling so much and you have a closed-loop then that is a positive thing in all other impact categories, your carbon footprint goes down, your water footprint goes down, because you're using only a fracture of that which is actually required.* <u>*The other thing is recycling as a criticality dimension*</u>*, and there we are away of the specific product system we are analysing and we take this whole pool of analyses, so there you could say, on global average there is a 30% of recycled content share for a material. Then of course it can reduce,* <u>*if you have a high share of secondary material, or a high recycling rate, this raises the question if your using the recycling rate or the use of secondary materials. And in general you could say if this is high then the criticality is less, because you can recycle so you're not so dependent on the raw materials anymore.*</u> *And that is something which is independent of your individual product system, whether your individual recycling rate is then 100% it does not influence the overall recycling rate of that material is.* <u>*So there are 2 dimensions, one is more related to your product system and the other one is on a more macro scale of the materials. And both are relevant*</u>*, so if you have the same recycling rates in your product systems and you're using 2 materials, one with the higher recycled content and the other with a lower one, the one with a high rate will be less critical. But vice versa, if they have the same recycled content, and you have a product system where you can recycle 90% and another where you don't recycle then it is also relevant.* <u>*And these are 2 dimensions, one is your product system and the other is the overall criticality.*</u>	"With recycling, the tricky thing to get your head around is that there are two levels so to say." – *recycling and criticality* "One level is your product system that you are analyzing" – *recycling and criticality* "The other thing is recycling as a criticality dimension." – *recycling and criticality* "if you have a high share of secondary material, or a high recycling rate, this raises the question if your using the recycling rate or the use of secondary materials. And in general you could say if this is high then the criticality is less, because you can recycle so you're not so dependent on the raw materials anymore." – *recycling and criticality* "So there are 2 dimensions, one is more related to your product system and the other one is on a more macro scale of the materials. And both are relevant." – *recycling and criticality* "And these are 2 dimensions, one is your product system and the other is the overall criticality." – *recycling and criticality*

Q7: In what way can actors and stakeholders of the EV battery industry benefit from criticality assessments? (consumers, private/public companies, policy makers, researchers) And do you think it can support decision making?	
The most obvious benefit is that they can continue to operate, they are reducing their own risks by knowing what the criticality is. So then when you do this kind of analysis, let's say you take the 2 dimensions of supply risk and vulnerability. Then you know okay these are my top 3 materials with a high supply risk and for which I'm highly vulnerable. Then you can of course try to see what to do with these results, maybe you can't change the supply risk but maybe you can change your vulnerability by looking for alternatives/substitutes, looking for a more diverse supplier structure, these kind of things. So you can reduce your individual vulnerability to a certain supply risk. And that is where these methods can help you, to know what is there because if you have a complex product of 50 materials it is hard to focus, and then this kind of analysis can help you. So that's a direct benefit for a company. And then in general it is also a service to society, so by reducing your supply risk and reducing your critical raw materials, will help others so that there is more for them.	"The most obvious benefit is that they can continue to operate, they are reducing their own risks by knowing what the criticality is." – *benefits of criticality assessment* "Maybe you can't change the supply risk but maybe you can change your vulnerability by looking for alternatives/substitutes, looking for a more diverse supplier structure." – *criticality assessment parameters* "So you can reduce your individual vulnerability to a certain supply risk." – *criticality assessment parameters* "If you have a complex product of 50 materials it is hard to focus, and then this kind of analysis can help you." – *criticality assessment benefits* "And then in general it is also a service to society, so by reducing your supply risk and reducing your critical raw materials, will help others so that there is more for them." – *criticality assessment benefits*

Transcripts of records interview 3.

Questions and answers	**Coding**
Definitions	
Q1: For my graduation thesis I have studied material availability, the definition of criticality and methods to analyze it, what are from your point of view the main problems/impacts related to the use of critical raw materials? For example how does it relate to scarcity, depletion and social impact?	
First of all, the whole move to criticality is to overcome, to me, the old limits to growth thinking of depletion. About depletion, there might be depletion, for example with Brine, for Lithium, it depletes, but that does not mean that Lithium depletes, this only means that the easily extractable resource to get lithium depletes. Then we can go to speromine(?) or water that's in Germany now discussed. So we are not faced with depletion you see, the path normally for Copper, depletion was always 50 years away. But this has been done since I know the topic when I started in the beginning of the 90s. There are some issues for Phosphorus for example, but for most of the metals it's not the case. It's more a question of, and then you will have to find a report which is not yet published by the university of Yale, on that it is hard to show that there are limits for these methods on availability, so it's rather a question of accessibility of course. And of technology, how deep you are digging, how and which technology you have to lower concentration. But for most metals we are not at a low concentration like we are for gold, and we are still able to find gold and extract gold. Also the environmental impact is increasing, much higher for gold, but that's a whole different story. That's a story of environmental impact and not a question of scarcity. And it's a question of technology for extraction, and a question of investment in exploration and new mines. But for this the most important issue for lithium what happened is that the European Parliament and the ministers and in California they decided that in 2035 most cars have to drive on 0 emissions in the use phase. Then most probably they will have to run on batteries, and most likely Lithium batteries. And in order to have those, then the mining industry needs to have a sort of security of investment in new mines. And we work with one of the refining companies to move to the next level of Lithium, to get out of brine. So that's the issue, it's not about scarcity or depletion, it is about accessibility and not availability. So if you go back to the 2015 paper of Graedel, the geological availability	"First of all, the whole move to criticality is to overcome, to me, the old limits to growth thinking of depletion." – *criticality definition* "There are limits for these methods on availability, so it's rather a question of accessibility of course." – *criticality definition* "And of technology, how deep you are digging, how and which technology you have to lower concentration." – *criticality, issues, parameters* "But for most metals we are not at a low concentration like we are for gold, and we are still able to find gold and extract gold " – *criticality, issues, parameters* "And it's a question of technology for extraction, and a question of investment in exploration and new mines." – *criticality parameters* "So that's the issue, it's not about scarcity or depletion, it is about accessibility and not availability" – *criticality definition* "The geological availability is one element among multiple other, like economy, like technology, like social, for example strikes on PMG in Africa, the topic of GeoPol." – *criticality parameters* "And if were moving into what we want to be a sustainable society with new technologies, it is hard to build this on countries where there is the possibility for them to not sell the raw materials anymore." – *criticality parameters*

is one element among multiple other, like economy, like technology, like social, for example strikes on PMG in Africa, the topic of GeoPol. We discussed the issue of raw earths with China and Japan. But now we see that for the old world technologies it was oil but it means GeoPol, that for example Russia is not delivering any natural gas. And if were moving into what we want to be a sustainable society with new technologies, it is hard to build this on countries where there is the possibility for them to not sell the raw materials anymore. Particular there is an issue of not sending the raw materials, but selling you instead the raw earth elements or selling instead of Graphite they sell the whole battery or a magnet. So that means it's a question of competition or even GeoPols in the classical way as we saw in Europe with wars. And then you have the environmental impact, and then the question for the evaluation of criticality you have the whole vulnerability and substitutability and economic importance, as the European method tells it. But don't start with me on scarcity and depletion, because then you clearly are on the wrong side and not rightly briefed. Dave Peck was a strong opinion leader on that.	"And then the question for the evaluation of criticality you have the whole vulnerability and substitutability and economic importance, as the European method tells it." – *criticality parameters* "But don't start with me on scarcity and depletion, because then you clearly are on the wrong side and not rightly briefed." – *criticality definition*
Q2: What methods/indicators do you think are the best to measure criticality, and what are the criteria to select these?	

I don't know what is the best, but I can tell you we are referring to the method of Graedel from 2015 on criticality assessment. We don't really apply this but we refer to it and I am including this in my teaching and so on. And then you have the one most relevant in Europe, which is the European commission method from 2014/17/20. And then if you only want to look into criticality… I am looking at what is the best method… the ones integrated into LCA that's another story. <u>"A review of methods and data to determine raw material criticality -Dieuwertje Schrijvers" This paper gives a good overview and its much cited, on criticality method which are not integrated into LCA.</u> And then there are the ones integrated into LCA and that is where we come into play, we have developed the GeoPolRisk that you might have looked at. And then you have the method that is developed by the group of TU Berlin, and that is Essenz. So these are the ones that you know. GeoPolRisk has now its own website, geopolrisk.org where you can use it. We are now writing the paper with characterization factors for every country, so that's where we are currently working on. You can calculate also for other regions and other constellations your own. So that is what you have currently. *This is what you know, <u>we have to differentiate between independent criticality assessment tools and then in LCA we talk about integration on the results level because you have LCA and risk assessment for criticality of raw materials independent</u> and then you <u>integrate at the results level or you integrate at the methodological level</u>, <u>which means you integrate criticality as one additional indicator into the LCA method.</u> So these are really the two different approaches that you can choose.*	""A review of methods and data to determine raw material criticality - Dieuwertje Schrijvers" This paper gives a good overview and its much cited, on criticality method which are not integrated into LCA." – *criticality research* "We have to differentiate between independent criticality assessment tools and then in LCA we talk about integration on the results level because you have LCA and risk assessment for criticality of raw materials independent." – *criticality assessment* "Then you integrate at the results level or you integrate at the methodological level, which means you integrate criticality as one additional indicator into the LCA method." – *criticality in LCA*
Q3: What are the pros and cons of using LCA vs non-LCA methods?	
That's what I'm telling you, you have to choose, it's the same issue that we have in environmental risk assessment and LCA, this is a long discussion and there have been PHD's on this and part of the book of mine, integrated LCA risk assessment and so on. <u>So you have either integrating at the methodological level and you get a sort of comparative risk assessment or you do it by integrating at the result</u>	"So you have either integrating at the methodological level and you get a sort of comparative risk assessment or you do it by integrating at the result level which means you do independently a risk assessment and an LCA and then you integrate at the results level. The advantage of doing an integrated approach

level which means you do independently a risk assessment and an LCA and then you integrate at the results level. The advantage of doing an integrated approach using LCA is that while you are doing a sustainability assessment on ecodesign questions of you know, I want to develop a storage device and I want it to have the lowest impact as possible, then the question still is you might have the lowest impact possible but you might use CRM's in the design. And when you do an independent assessment you make it totally different, you don't get this for the designer as a result integrate into LCA that is already prepared for ecodesign. But if you want to do it as a whole country or as a huge company, I know Renault and Volkswagen they have a whole own team on raw materials, they can pay for an sophisticated much more detailed raw material assessment on their accessibility and the risks. And also the TNO, or who is doing the geological survey for the Netherlands, they have enough resources to do an independent assessment and it does not have to be linked to LCA, this is another question, they can be much more detailed. But for the purpose of having an ecodesign support method that is LCA, the integration provides huge advantages. And the difference between Essenz and GeoPolRisk is particular, especially with the webtool that we have developed, it allows you to calculate, if you as a company, not as a country, or the world or Europe, you can develop your own procurement on you supply chain and make choices to make you more resilient.	using LCA is that while you are doing a sustainability assessment on ecodesign questions of you know, I want to develop a storage device and I want it to have the lowest impact as possible, then the question still is you might have the lowest impact possible but you might use CRM's in the design." – *criticality assessment* "But for the purpose of having an ecodesign support method that is LCA, the integration provides huge advantages. And the difference between Essenz and GeoPolRisk is particular, especially with the webtool that we have developed, it allows you to calculate, if you as a company, not as a country, or the world or Europe, you can develop your own procurement on you supply chain and make choices to make you more resilient." – *criticality in LCA*
Q4: In terms of material criticality what outcomes would be interesting to get out of the case study we are working on with EV batteries and recycling, what do you think are interesting research gaps that could be filled with such a case study?	
Well first of all you of course see which metals in the method are critical more or less, and you are not only looking at the EU list of CRMs in which a material either is critical or not. We are providing with a continuous system with a range of how big the risk is and not just critical or not. So this you will get for the batteries first of all and then in particular you get it for the processes of recycling and you can see if actually the metals which are more or less critical can be recycled or they are lost. In recycling for example the REE are going in the steel or are not able to be recovered if you do certain refiner processes. So you see this, do you get these critical metals recycled or not and you get this not only on a yes no, but on a sort of scale like you get it for any other impacts so you don't have 0 or 1 but a range and you know which	"We are providing with a continuous system with a range of how big the risk is and not just critical or not." – *criticality in LCA* "Then in particular you get it for the processes of recycling and you can see if actually the metals which are more or less critical can be recycled or they are lost." – *criticality and recycling* "And related, when you integrate into LCA you see the tradeoffs between carbon footprint and environmental impact in relation to these geopolitical criticality

ones are more interesting to keep or not. And related, when you integrate into LCA you see the tradeoffs between carbon footprint and environmental impact in relation to these geopolitical criticality indicators.	indicators." – *LCA criticality assessment advantages*

Transcripts of records interview 4

Questions and answers	**Coding**
Definition:	
Q1a: For my graduation thesis I have studied material availability, the definition of criticality and methods to analyze it, what are from your point of view the main problems/impacts related to the use of critical raw materials? For example how does it relate to scarcity, depletion and social impact?	
Okay when it comes to a definition, there is kind of no definition of criticality as far as we know. But it is more linked to the fact whether you have a reliable supply, an available timely supply. And this can change in relation to demand, and also to resources and reserves and the quality of ores, so there are many factors which play a role in it. I think in one of our reports we even in bullet points pointed out these factors, but I cannot reach the internet right now. We put down like six or seven bullet points of what can affect criticality, or what can be a broader definition of scarcity or criticality. So as an example if you think about Copper or Lithium which are needed for batteries or Rare earths needed for permanent magnets or mobility or wind turbines or even for cooling. Right now many policy makers do not feel like there is any scarcity because the demand is not so high, but the demand is projected to go 10 or 20 fold up in 30 years. And because all the mining and processes take a long time to open and operationalize, this can become a reason of scarcity as well. And also another scarcity can be the sustainability and environmental considerations, because the end users can opt for, and it is not only the end users but also the government and CO2 footprint and … in Europe, they can all play a role in the fact if you can have a reliable supply. Because the supply can come from China, or Myanmar for rare earths or Cobalt from Congo, and they are not so sustainable then they might not be a choice for the producers of magnets for example, or might not be able to opt for that source in the future.	"Okay when it comes to a definition, there is kind of no definition of criticality as far as we know. But it is more linked to the fact whether you have a reliable supply, an available timely supply. And this can change in relation to demand, and also to resources and reserves and the quality of ores." – *criticality definition* "I think in one of our reports we even in bullet points pointed out these factors." – *criticality research* "And because all the mining and processes take a long time to open and operationalize, this can become a reason of scarcity as well." - *scarcity*
Q1b: In the literature I found that the EC defines critical raw materials as materials which are	

economically important for key sectors and which supply is associated with high risk. In your experience, is this the definition which is most worked with in practice? And do you agree with this definition?	
In principle I do, even though I'm thinking whether this works the other way around, because not all materials are critical for any sector. But in principle I agree with that yes.	"I'm thinking whether this works the other way around, because not all materials are critical for any sector." – *criticality level*
Interviewer: What do you mean with it doesn't work for every sector?	
Well I'm just thinking whether all critical materials are critical for each sector. I'm just thinking about high grade ores which are needed for example for batteries. You might get Copper or Lithium in some form but you might have the problem to have this high grade ore which is needed for batteries for example. And I'm just wondering if for example we have a lot of resources for.. What is the question again?	"I'm just thinking about high grade ores which are needed for example for batteries. You might get Copper or Lithium in some form but you might have the problem to have this high grade ore which is needed for batteries for example." – *metals criticality*
Interviewer repeats question.	
Yes then I agree.	
Q2: What methods/indicators do you think are the best ones to measure criticality, and what are the criteria to select these?	
Well that's a very broad question, so criticality of course is about the resources, the reserves, the quality of the ores, but also about geographical concentration, so who mines, who processes, refining processes, the whole value chain. So where is the concentration, this is another factor, this is the primary supply. Another form of supply can be the scrap and recycling but this is complicated because whether we talk about batteries or magnets or anything, because A, we don't have a stockpile to do that, and the second, there is a big problem with the design, there is no harmonization of design of batteries or for let's say cathodes, and the chemistry is still evolving, so even if you get a cathode of NMC(1:1:1) batteries, in ten years we still don't have processes to recycle and reuse the battery for a different chemical composition. Like we learned that the NMC(1:1:1) always have to be used in electrical vehicles, at least that's how it is now. So the design and technical standards of the final product or medium product has also come into play in order to assess the future supply.	"So criticality of course is about the resources, the reserves, the quality of the ores, but also about geographical concentration, so who mines, who processes, refining processes, the whole value chain." – *criticality definition* "Another form of supply can be the scrap and recycling but this is complicated." – *criticality parameters* "Let's say cathodes, and the chemistry is still evolving, so even if you get a cathode of NMC(1:1:1) batteries, in ten years we still don't have processes to recycle and reuse the battery for a different chemical composition." – *criticality and recycling* "There is a big problem with the design, there is no harmonization of design of batteries." – *batteries, design*

	"So the design and technical standards of the final product or medium product has also come into play in order to assess the future supply." – *criticality parameters*
Q3: The EU has a method to assess criticality, there is also one from the Yale university, but there are also LCA methods being developed, what do you think about this?	
I don't have enough knowledge to answer such a question, because we only look at criticality for particular, we don't do the whole LCA, we only look at the supply and whether there is enough primary supply and processing and which countries are offering it and if we can scale it up quicky. But it's a very narrow view of it, and who assesses it, we know that the US has their own list of criticality, Japan has and Australia has one. So I know there are more views on it from a government perspective, but that's also geopolitical perception. There is some definition of course but then which material or minerals will end up on the list is given by geography.	"We only look at the supply and whether there is enough primary supply and processing and which countries are offering it and if we can scale it up quicky." – *criticality parameters* "I know there are more views on it from a government perspective, but that's also geopolitical perception." – *criticality perspective* "Which material or minerals will end up on the list is given by geography." – *criticality perspective*
Interviewer: So does this mean that the way you are viewing it is from the European perspective?	
No because we're a global organization so we don't. We look on where is the biggest demand, so for example for EV's the big demand is in China, the sale. Let's say we assess demand by how many cars were sold last year in different geographies, then the largest one was in China, the second largest in the EU and then the US or that region. So the criticality you can say like "oh there is enough Lithium in China and we can process it easily", but then it doesn't hold the truth for the EU or for the US.	"We look on where is the biggest demand" – *criticality perspective*
Interviewer: Okay so you look at different regions, then do you look at a specific product, industry or sector?	
We look on the energy sector and then we look at which energy technology or energy related technologies rely on critical materials, they are not plentiful, so there are solar PVs we haven't analysed yet, what we did for now are permanent magnets for wind turbines and EV motors. And then we looked on where you are dependent on rare earths, and then we look on batteries for EVs or for transport. And that's not rare earths but the other ones, and then there is also, we haven't yet assessed it but for electrolysers so we still don't know which electrolyser will be the	"We look on the energy sector and then we look at which energy technology or energy related technologies rely on critical materials." – *criticality perspective* "It also applies for the batteries so it's very difficult to assess in which situation we will be in 10 years for now." – *criticality timeframe*

future choice. <u>It also applies for the batteries so it's very difficult to assess in which situation we will be in 10 years for now</u>, because we don't see, we have no clarity and we don't really feel that even producers have clarity on which battery will prevail. So we look on those, wind, EVs, not yet solar and not yet electrolysers. Because our members are global governments so we have 168 member countries, 167 plus the EU, so when we talk about risking the supply we can, <u>what we are trying to do but we are in the early process, we are trying to develop a roadmap to assess criticality</u>, so basically what you are doing and I would be very interesting to see your final dissertation because it could even be helpful to us. <u>And then when we talk about the risk then we will have to do a couple of different pathway strategies because it really depends on where you are and what region you are because then you see which countries have access to ore and its mining and whether it's able to go more downstream towards refining processes and so on, and then its geographically different.</u>	"What we are trying to do but we are in the early process, we are trying to develop a roadmap to assess criticality." – *criticality assessment* "And then when we talk about the risk then we will have to do a couple of different pathway strategies because it really depends on where you are and what region you are because then you see which countries have access to ore and its mining and whether it's able to go more downstream towards refining processes and so on, and then its geographically different." – *criticality perspective*
Interviewer: So if I understand correctly <u>it is about making a preparation for the future, what based on the criticality of materials right now what products or processes are preferred for different applications</u>, is that right?	
Yes, that's one part, then the second is also where the demand is coming from and whether those countries are able to have these applications ready. So whether the supply in the region can meet the demand.	
Q: So you mentioned EV batteries, and in a case study we studied how different assessment methods for criticality include recycling and what conclusions they come to. I would want to ask you, in terms of criticality and scarcity and supply risk, what outcomes would be interesting to get out of a case study like this?	
<u>What would be very interesting is for policy makers and in general for everyone will be to see the type of recycling and the footprint of it. Because sometimes we see the footprint of recycling, emissions and pollutions can be very high.</u> I am not saying about only EV batteries but also motors<u>, so then it destroys the whole idea of sustainability that if you try to mine and process and do that very clean, up to the use then the secondary use of recycling brings a big carbon footprint then it kind of offsets all of the previous efforts.</u> So LCA assessment are one thing and the big unknown is more on the technology side is to develop	"What would be very interesting is for policy makers and in general for everyone will be to see the type of recycling and the footprint of it. Because sometimes we see the footprint of recycling, emissions and pollutions can be very high." – *recycling impact* "So then it destroys the whole idea of sustainability that if you try to mine and process and do that very clean, up to the use then the secondary use of recycling

the way and not just develop but there are a couple of ways that needs to be innovated in a way so we can recycle whatever and use it in whatever battery chemistry, so it won't be dependent on the chemistry, at least when it comes to Nickel rich cathodes. For example when you recycle LFP batteries there are also issues because not every LFP battery is equal to every LFP battery, but at least there is some kind of similar composition, they might be a bit heavier or lighter, so there is this variable. But if you look on Nickel rich cathodes, some have a lot of Cobalt, some have little Cobalt, so what impact does that have on recycling and can we recycle NMC(811) or (111) and then use it later by extracting the materials and use them to produce cathodes such as NMC(622) and then how much losses do we have in the process and what is the quality of it, do we have a high grade quality. And this is not about batteries but permanent magnets for example, which goes into motors, what we see is that we are able to recycle it but the grade quality is not 99% but 95% and the end users don't want that. So you put all this effort into recycling and then you don't have offtake. So do we need to educate or show the quality of the end product performance stays the same. So there are all these unknowns for us when we assess future supply.	brings a big carbon footprint then it kind of offsets all of the previous efforts." – *recycling impact* "There are a couple of ways that needs to be innovated in a way so we can recycle whatever and use it in whatever battery chemistry, so it won't be dependent on the chemistry, at least when it comes to Nickel rich cathodes." – *battery recycling* "What we see is that we are able to recycle it but the grade quality is not 99% but 95% and the end users don't want that." – *battery recycling*
So another option would be to do something in the design phase of the product?	
I think the most important is transparency in design and probably some technical standardization around it. But I think because everything is so early stage it will take time and we know standards sometimes take 10 years to develop and agree on, and they're also not binding at the same time. But at least something to have clarity, even when we do assessment, when we talk to producers of cathodes they cannot even tell us the real specifications of their cathodes. We don't know how heavy the battery is and how much of what does it have. We are using the Argon lab model, "batcap" and there is another one on the composition, but you know some of this data is from 2017/2018, which is old because the progress happens really fast. So the transparency of data is another issue. But design and probably for the policy perspective, policy will push for some clarification and transparency of design would be very helpful.	"I think the most important is transparency in design and probably some technical standardization around it." – *battery recycling, policy* "I think because everything is so early stage it will take time and we know standards sometimes take 10 years to develop and agree on, and they're also not binding at the same time." – *recycling policy* "But you know some of this data is from 2017/2018, which is old because the progress happens really fast." – *criticality data validity* "So the transparency of data is another issue." - *criticality data transparency*
This thing about data transparency I have heard before.	

Yes, because there is a lot of steel secrecy and confidentiality and nobody wants to say what they are working on, they just want to show you the final perfected product. So you really don't know, so when you go to peer review documents, if they are older than 1 year old they are no longer relevant. Like when they are published last year you know they are probably written 3 years ago. For example we published a report on rare earths beginning this year which means writing was finished writing about half a year before. So a report published in February, finished writing in October/November, so almost a year ago, and I just came back from the rare earths conference and I came to the conclusion that everything already has to be updated with our information.	"When you go to peer review documents, if they are older than 1 year old they are no longer relevant. Like when they are published last year you know they are probably written 3 years ago." – *criticality research*
So there are a couple of things now that come up to me. First I wanted to ask you about an assessment method you just mentioned and couldn't find the name.	
So it is not really an assessment method but it is more like which points to consider, and if you go to the IRENA website, then you have on the top this education tab and there are our 3 reports. CRMS for the energy transition, CRMS rare earth and lithium, and I think in the first one we put a couple of points about criticality, I think it is somewhere in the introduction or the summary. And now we're working on the battery report but it is being peer reviewed now so it will take time. It's on page 10 I think. *""WHAT ARE CRITICAL MATERIALS? For a start, there is the question of what determines criticality. Generally, attention has focused on minerals and metals that require a significant extraction effort, where the production is concentrated in a few countries, where the quality of natural resources is declining, where a massive ramp-up of supply will be needed and where prices have shown large fluctuations that reflect supply-demand imbalances."" (IRENA, 2021)*	""WHAT ARE CRITICAL MATERIALS? For a start, there is the question of what determines criticality. Generally, attention has focused on minerals and metals that require a significant extraction effort, where the production is concentrated in a few countries, where the quality of natural resources is declining, where a massive ramp-up of supply will be needed and where prices have shown large fluctuations that reflect supply-demand imbalances."" (IRENA, 2021) – *criticality research*
And you mentioned a method they used to assess criticality.	

So it is not really the method, we are still trying to introduce, we first did it now for the batteries, it's a simple model. *<u>What we look at is in general globally we projected demand for batteries, we looked on how much of what minerals you have in the world, we looked on how much is mined, we look on quality although there we don't have the greatest transparency so there are a lot of assumptions there, even in demand we do this.</u>* *And then we did a scenario, for example 50/50 LFP battery or NMC battery, which will be prevailing. Then we look at EVs and we look on how much of what mineral you will need by 2030 or 2050, and then we look on how much production is there and how much is it possible to ramp up the project in the pipeline. Then we also looked on SNP database to see about their assessment of risks, political and so on, so we also know that if you have a visibility study of 10 mines then only about 1 mine will open. So we little bit factored that in and we look at how much we are able to produce of Nickel, Cobalt, Lithium, Graphite and so on, then we look at where are the gaps. But there are so many assumptions because nobody can tell us which chemistry will prevail. For example when you look 3 years back, LFP was dead and nobody was talking about LFP batteries, and now probably it will be a huge dominant battery in some geographies and maybe for heavier cars or particular EVs.* *<u>And also the other problem which we don't have when we do the demand part is that the consumers don't have usually a good understanding,</u>* *they look on range and costs basically. But the range is dependent on so many things, for example when it is 600km it might not really be, because you don't know if the person will use it in the city or not, if it is hilly or flat and so on. So the consumers are also not per se interested, they don't know what batteries they have in their cars, so we don't know when they will start to become interesting and they will start to play a role in the future.* *<u>We are just playing with so many assumptions in our models.</u>*	"What we look at is in general globally we projected demand for batteries, we looked on how much of what minerals you have in the world, we looked on how much is mined, we look on quality although there we don't have the greatest transparency so there are a lot of assumptions there, even in demand we do this." – *criticality perspective* "And also the other problem which we don't have when we do the demand part is that the consumers don't have usually a good understanding." – *criticality public knowledge* "We are just playing with so many assumptions in our models." – *criticality data*
Interesting that you talk about the demand, because the EU mostly looks at the supply side of criticality. Also with the supply side there are problems of risk with political relations or restrictions on certain materials do you also look at this?	
Yes, but it is in an very early stage, we have started working on geopolitics. We have in IRENA a collaborative framework, with this we are bringing different countries which are interested in the topic together. Because not all countries are interested in	"And actually the whole discussion why we have CRMs is partially because of geopolitics" – *criticality reason*

all topics, for example in some countries it is more important to look at a particular product which is not that important to another. So we have a collaborative framework on CRMs, we have just started it and we are working on more programs, so for the last 5 months we were discussing with countries what were their worries and we have the same thing for geopolitics and we did one global one on any energy technologies. We did one on hydrogen and now we are in an very early stage of CRMs, and this will take probably another half a year to develop maybe a little more because we have a very strict peer review process which takes time. So yea we do look at it and actually the whole discussion why we have CRMs is partially because of geopolitics and I know you are talking a lot about batteries, but there is a very good example of how geopolitics play a big role in criticality and that is with rare earths. For example in 2008, China holds 56% of all mines for rare earths in the world, or resources/reserves, or they mine this amount, and then they process about 88% of all CRMs. And also countries stockpile, and we think this stockpiling is important but it is a big political weapon. We saw what China did with it, they basically pretended for a period that there is not enough of CRMs of rare earths, the prices went up like crazy. Because of this a lot of things started to develop, for example to look at where we can open mines and so on, and when they saw, they were also trying to map China and what was going on in the world, what are the capabilities, where is money, are countries able to ramp up the supply. When they saw that actually there is money to ramp it up they dropped the prices because they control the whole supply chain if I can say it like this. Not the production of magnets, but more the refined/processed product. And when they dropped the price, of course the whole interest of those who hold the money went away, because they are not going to open mines when the price of the minerals is low. So again they really checked what was going on in the world, and this really scared EU a lot. So the EU is trying to work, what EU is doing, is also through the batteries it is a bit more obvious, but also a bit more different, because also geopolitically it is different, because the Chinese are processing a lot of Lithium and mining but they have very low grade of a lot of batteries, the ore required for them, they really rely on import of ore. So they hold the power in processing but not in mining, so it also makes them vulnerable, countries are trying to catch up on processing, it is just very dirty. It is very different the technologies you are discussing, so you know this vertical integration thing which is becoming a big thing of policy making and they are trying to	"Are countries able to ramp up the supply." – *criticality parameters* "They hold the power in processing but not in mining." – *criticality parameter* "This vertical integration thing which is becoming a big thing of policy making and they are trying to encourage the whole value chain." – *criticality strategies* "You see this in batteries a lot, the producers of EVs for example create joint ventures of battery producers with cathode or anode producers, and then you go down the chain, or up the chain" – *criticality strategies* "What they are trying to do is all of these offtake agreements between the producers of EVs, of batteries, of cathodes/anodes, processing and mining. So you have the whole value chain and there is some guarantee in between." – *criticality strategies*

encourage the whole value chain. So this is that, you see this in batteries a lot, the producers of EVs for example create joint ventures of battery producers with cathode or anode producers, and then you go down the chain, or up the chain, so for example that Volkswagen wants to ensure that when they have half a million of cars demanded but they can only produce 300k because they don't have enough battery materials, then what they are trying to do is all of these offtake agreements between the producers of EVs, of batteries, of cathodes/anodes, processing and mining. So you have the whole value chain and there is some guarantee in between. And we have seen it happening in batteries, because also when it comes to China and batteries, the government owns everything, but the competition is a bit better when it comes to batteries, so you see Chinese cathode producers doing this joint ventures with the US, Canada, Europe, this is what we see. When you look at permanent magnets which are also used for cars you don't see it because the competition within China and their control of rare earth processing is not as "free" as you see in EV batteries. And therefore it is the bigger geopolitical issue.	
You said something about the EU got scared about the power which China holds over these products. Don't you think that by setting the goals of the EU for EVs to be the only vehicles sold by 2035, don't you think they have put a mark on themselves, other supplying countries now know that EU needs the materials, wont this increase the price of it?	
Price is only influenced when the supply cannot meet the demand, and also there is a lot of speculation as well so sometimes the supply and demand remains and then you see a huge price volatility. So there is a lot of speculation behind this, like you saw the Nickel speculation in the beginning of the year where even the London metal exchange has to spend the Chinese Nickel, miner or processing, the price went up like crazy and then dropped or the other way around. So you have a lot of speculation around this. The market is not transparent that's why this is possible. But at the same time when you have these goals there is a 2 way sword, it can hurt you but it can also not hurt you because when you need to ramp up supply which is both mining and processing, you need money and you have a lot of junior miners who are inexperienced who are raising money and there is a lot of joint ventures and equity possible for that. So but if you don't have clear goals that this is needed, the investors do not have a clear signal, so if you know that by 2035 we need this and that, then there is a clear political signal in one direction which also helps. Of course at the	"Price is only influenced when the supply cannot meet the demand, and also there is a lot of speculation as well so sometimes the supply and demand remains and then you see a huge price volatility." – *criticality parameter* "The market is not transparent that's why this is possible." – *criticality data transparency* "What hurts the most is that who can pay the most for something for the end product, which consumers will be able to pay the premium price for more expensive battery cathodes or permanent magnets." – *criticality parameter*

same time there are all these games of who holds the power with mines and processing, the game can hurt but I don't think western countries will really do that. What hurts the most is that who can pay the most for something for the end product, which consumers will be able to pay the premium price for more expensive battery cathodes or permanent magnets. We don't know which consumers are willing to pay 10% more, we just don't know this. But the signals are important, always.	
I have heard someone else say that there was a conviction in the west that the free market will solve the problems of supply and demand, but that now there is more steering needed. Would you agree with this?	
I studied economics and I don't believe in the free market and we see it over and over again when you look on the energy crisis or CRMs, because we don't have the same level of, not the same competition in all countries. For example in China everything is government owned and there is no laws to control the supply whether it is sustainable, there are no labour laws for example, there was a big scandal for a while with Myanmar and mining so you don't have the same level playing field basically, so you are comparing different supplies with demand. So I think it requires a lot of collaboration and coordination between the private and public sectors and academia to stabilize the whole. But this is my personal view, we don't at IRENA discuss these things so we don't have any line at IRENA, so this is more my personal perspective. But I have never seen in my life a completely free market. And even when you study it is always like in the free market consumers are perfectly informed. But show me one consumer, I am an energy expert and I still am not perfectly informed about how the electricity market are done or how the supply of CRMs is done, so how can you expect this from your parents for example if they studied something else. And then you have also all the lobbies and so on, so I think it really requires better coordination and collaboration between different players to bring stability to the market.	"I studied economics and I don't believe in the free market and we see it over and over again when you look on the energy crisis or CRMs, because we don't have the same level of, not the same competition in all countries." – *criticality perspective* "There was a big scandal for a while with Myanmar and mining so you don't have the same level playing field basically, so you are comparing different supplies with demand." – *criticality level comparability* "I think it requires a lot of collaboration and coordination between the private and public sectors and academia to stabilize the whole." – *criticality policy* "I have never seen in my life a completely free market. And even when you study it is always like in the free market consumers are perfectly informed. But show me one consumer, I am an energy expert and I still am not perfectly informed about how the electricity market are done or how the supply of CRMs is done, so how can you expect this from your parents for example if they studied something else." – *criticality public knowledge* "So I think it really requires better coordination and collaboration between different players to bring stability to the market." – *criticality policy*

This also reminds me of the last thing I wanted to ask you. We talked about data and it not being available enough, and I have heard someone talk about a product passport, what do you think of this?	
You mean battery passport for example, yes this is one part of the issue, but when you create strategies for policy makers, for criticality you need much more than that. This helps but <u>what we need is in the whole supply chain, where are resources, how much is being mined, and we have some of this from the US geological survey but we need more about the quality, the fluctuation in prices and when you need information you have to pay a lot of money for them</u>. So in a big market you gain, those people, <u>I always worry that you have the data in the hands of a couple of people and then they present to you aggregated outputs. How trustworthy is this, are they lobbied, how transparent are they? And how much biases are in their work, I think unless we have a lot of information out here in a public way and we have universities and public organizations taking the same data and working with them and modelling and using different assumption</u>, until we reach that we kind of reach it with the energy balances so we have that, <u>we have quite some public data at least at the aggregated level, at the country level what is being produced, what is the LCOI price. Until we have this with CRMs I worry that we just rely on postings in social media for example like who said what, and then you have to go behind the source whether there are lobbies</u> or, like we have a big problem when, if I can be honest with you, we are working on this battery report and we send it to reviewers to Universities and we are like we have this data but we cannot really check what this organization is, and one reviewer came back to us and was like "yea don't trust this because they are lobbied of combustion motor vehicles, so be careful of what they say about this thing". So data transparency is one of the big problems that some countries are fighting against, you can probably guess which. So what IRENA is trying to do also there is also a lot of secrecy of the chemistry of things, but a t least some aggregated data we are trying to get and our efforts at IRENA is to create factsheets and overviews of different data from mining and we will be incorporating data from the US geological survey and trade of the WTO and cleaning data, so the long term goal is to create a database, at least with aggregated data.	"What we need is in the whole supply chain, where are resources, how much is being mined, and we have some of this from the US geological survey but we need more about the quality, the fluctuation in prices and when you need information you have to pay a lot of money for them." – *criticality data* "I always worry that you have the data in the hands of a couple of people and then they present to you aggregated outputs. How trustworthy is this, are they lobbied, how transparent are they? And how much biases are in their work, I think unless we have a lot of information out here in a public way and we have universities and public organizations taking the same data and working with them and modelling and using different assumption." – *criticality data* "We have quite some public data at least at the aggregated level, at the country level what is being produced, what is the LCOI price. Until we have this with CRMs I worry that we just rely on postings in social media for example like who said what, and then you have to go behind the source whether there are lobbies." – *criticality data* "So data transparency is one of the big problems that some countries are fighting against, you can probably guess which. So what IRENA is trying to do also there is also a lot of secrecy of the chemistry of things, but a t least some aggregated data we are trying to get and our efforts at IRENA is to create factsheets and overviews of different data from mining and we will be incorporating data from the US geological survey and trade of the WTO and cleaning data, so the long term goal is to create a database, at least with aggregated data." – *criticality data*
I have ran out of questions by now.	

Let me know if there is something more you need to know, and I would more than like to review your work for you if you need it and I really would want to read it when it is ready.	

Transcripts of records interview 5

Questions and answers	Coding
Definition:	
Q1a: For my graduation thesis I have studied material availability, the definition of criticality and methods to analyze it, what are from your point of view the main problems/impacts related to the use of critical raw materials? For example how does it relate to scarcity, depletion and social impact?	
So yea as you said it is mostly the accessibility and the availability more on a short term or middle term perspective, and I think that the main difference compared to the classical LCA indicators for resource use like ADP for example are really focussed on which resources are available now and in the foreseen future. And of course this is then determined through a couple of factors, and in Essenz we try to kind of reflect these different factors like political or geopolitical factors, maybe even social and environmental issues, but probably not as much as political issues and I think these are the most relevant ones, because in the end availability and accessibility is mostly decided by some sort of trade barriers or some political views certain countries have. And then of course if I have a material which is available in almost all countries then of course this is a little bit outweighed by that. These are the main issues.	"It is mostly the accessibility and the availability more on a short term or middle term perspective" – *criticality definition, perspective* "Political issues.., I think these are the most relevant ones" – *criticality parameters* "In the end availability and accessibility is mostly decided by some sort of trade barriers or some political views certain countries have." – *criticality parameters*
Q1b: In the literature I found that the EC defines critical raw materials as materials which are economically important for key sectors and which supply is associated with high risk. In your experience, is this the definition which is most worked with in practice? And do you agree with this definition?	
I think it is one of the most common definitions, but I do not fully agree with that. Because I think that vulnerability should be more than just EI. In the end you could argue other factors as well play into EI, but it also depends a bit on how is a country or company able to maybe navigate this. For example if one material is important from an economic point of view, they might still be able to navigate that. Or maybe it is	"Because I think that vulnerability should be more than just EI." – *criticality definition* "I think just focussing on the EI is a bit short-sighted, however I think it is one of the most relevant issues regarding availability." – *criticality definition*

important for one certain industry which in the long run should be out phased or there is a strategy to out phase it. So I think just focussing on the EI is a bit short-sighted, however I think it is one of the most relevant issues regarding availability. In Essenz we have a few more, but there we are also discussing here and there if in the end at least most of them are indirectly correlated with EI, so I wouldn't also state that you need all of these we have in Essenz, but I personally think it should be more that EI. However it is a good indicator to measure, and then again it comes to what is part of the vulnerability and what of the SR. For example in Essenz we have substitutability as a part of vulnerability however in many other methods it is part of SR and if I see it as SR then I don't need it in vulnerability, and then it is not as important for the vulnerability indicator and then maybe at some point EI is enough. However I still think there should be other factors considered, maybe in the SR. But I mean in the end you want to measure how a company or country is able to navigate around certain restriction or access to certain materials and of course the EI but also if the country is rather rich or poor plays a role.	"However it is a good indicator to measure, and then again it comes to what is part of the vulnerability and what of the SR" – *criticality parameter, indicator* "In the end you want to measure how a company or country is able to navigate around certain restriction or access to certain materials." – *criticality assessment goal*
I wanted to talk about substitutability as well, because I think the EU incorporated into the EI, so it is maybe about the terms they use. And in the assessment method it comes forward but it is definitely good to look at it from a broad perspective.	
Q2: We know there are different types of criticality assessment, for example the EU method, the Yale method or LCA methods like ESSENZ and GeoPolRisk, what are the criteria to select a type of criticality assessment?	
To give a broad answer, relevant aspects are of course that most issues are reflected somehow and on the other hand that there is data available, so these 2 points. Data availability is always a challenge, and in the end every method relies on the USGF, so on the WGS, anyway it is a bit challenging, because of all this data. But I would say this on a broad level. And then you could argue, there are discussions on which aspects are relevant, which are not, what should be part of vulnerability, what should be part of SR. I personally rather think it is better to consider more aspects than less, but I think there the methods differentiate quite a lot. As you know in Essenz we have like 11 indicators for supply risk which is kind of a lot. I think most methods don't have this. Also we look at the correlation between those aspects, I mean there are no correlations that is why we keep them in	"Data availability is always a challenge." – *criticality data availability* "In the end every method relies on the USGF, so on the WGS." – *criticality assessment, data* "There are discussions on which aspects are relevant, which are not, what should be part of vulnerability, what should be part of SR." – *criticality parameter* "In Essenz we have like 11 indicators for supply risk which is kind of a lot. I think most methods don't have this. Also we look at the correlation between those aspects." – *criticality assessment*

but one could still argue that there are too much or it is too challenging to interpret, and maybe there are correlations we don't see, and maybe there are qualitative correlations and so on. So I think it is very hard to define a right or wrong, but in the end I would say that most aspects should be considered and I think these are the geopolitical ones, and I would for example expect political stability, trade barriers, some sort of concentration of the production, at least these three should be taken into account.	
Q2b: would it be different if you would look at a while sector or product, and what would be the consideration?	
I don't think there should be anything different, because in the end the same aspects apply. Also in the end even if it is differentiated between product level, company level or country level, in the end it all comes together. Like if I have a company in Germany of course I am profiting or have a negative influence that my company is located there, and if a company has some certain kind of contracts with certain countries regarding specific materials then my company is produced in a different location it could be an advantage or disadvantage if such trade contracts exist or not. So in the end product level, company level or country level, they all kind of belong together, however from a methodological level for example Essenz is only on a product level and there are other methods for a company or country level. So <u>for a methodological point of view to assess it I think it also kind of makes sense to look at all these different levels in a different way but in the end they all belong together so in the and more or less the same aspects should be considered</u>. I think it is a bit more tricky with regards to vulnerability because of course EI is one of the relevant factors but <u>to really measure EI for a product is more challenging than for a country level for example but for SR it should be the same.</u>	"For a methodological point of view to assess it I think it also kind of makes sense to look at all these different levels in a different way but in the end they all belong together so in the and more or less the same aspects should be considered." – *criticality assessment level* "To really measure EI for a product is more challenging than for a country level for example but for SR it should be the same." – *criticality, level, scale*
Q2c: how do ESSENZ and GeoPolRisk compare to each other?	
First of all these are the only two method to assess on a product level so for as an add on to LCA, and I think the overall idea behind it is very similar to have these different indicators which are connected to each other and to a material or inventory of a product you are considering. Also similar is that similar indicators or aspects are used like for example the concentration and WGI, which is used in a different way but I think the idea behind it to measure criticality on a product level is very similar but then of course how the	"One of the big differences is that Essenz is looking on a global production level and the GeoPolRisk is looking on more like an import pattern approach and I think in the end to get a full picture both aspects are equally important to consider." – *criticality in LCA*

methods are implemented is a bit different and for example <u>*one of the big differences is that Essenz is looking on a global production level and the GeoPolRisk is looking on more like an import pattern approach and I think in the end to get a full picture both aspects are equally important to consider.*</u>	
<u>Assessment methods:</u>	
Q4: In your opinion, what are the pro's and con's of using LCA methods such as GeoPolRisk and EZZENZ?	
Which aspects do you think could be improved, maybe by using a different method of analysis?	
<u>*Cons, I would say is the complexity, because if you would do for example a full LCA it is complex enough and with criticality as an additional indicator could be more complex.*</u> <u>*On the other hand it is also a pro because you have one more aspect to take into account as you can consider trade and so on.*</u> *Also I think a difference is also that we are talking more about, especially compared to other resource indicators which are more long term and, we're talking about more middle term aspects, however if we compare that with the environmental impact then* <u>*we should also consider the middle term*</u>*, and that is also what we're doing, we are not looking at the global warming potential in 2000 years but more in like 100. I think one of the biggest cons I would see is that for me LCA should focus on the environment and not on economic aspects so this is similar to I have a social-LCA for social aspects, and of course LCA also includes social aspects but it could also be discussed that they should be excluded because* <u>*I think it is better to have one method focussing on the environment, one focussing on social aspects and one on economic aspects.*</u> *But to include criticality assessment for example in LCC, I also don't think it fits there so we say it should be an addition to LCA and not LCC. But in the end LCA should be focussing on environment only.*	"Cons, I would say is the complexity, because if you would do for example a full LCA it is complex enough and with criticality as an additional indicator could be more complex. On the other hand it is also a pro because you have one more aspect to take into account as you can consider trade and so on." – *criticality in LCA, problem, benefit* "We should also consider the middle term" – *criticality timeframe* "I think it is better to have one method focussing on the environment, one focussing on social aspects and one on economic aspects." – *criticality assessment*
So why not include it in LCC, is it too difficult?	
First I am not an expert in LCC to make that clear and for me, with the conventional LCC you focus on monetary values only, so how much do different production steps cost. And then I feel like it would be difficult, I do think you could make an add on to LCA, but I barely do LCCs, and if we go a step further by looking at how can we internalize these external costs then it could become very complex and I think internalizing costs with monetarization factors is	

complex enough, we shouldn't put in criticality issues. This would be my main argument, but as I said I barely have done any LCC case studies myself.	
I read that Essenz is based on the ESP indicator, there is also in the ReCiPe method an indicator for mineral resource scarcity, how do you think it is related to scarcity in that way?	
I currently don't know how ReCePe does the scarcity approach for resources to be honest. Is it middle term or long term?	
They have SOP and SCP, as midpoint and endpoint indicator in that way.	
I do remember because at one point I looked at all of them, the thing is I don't know where the SCP is based on because for what I remember <u>most LCA methods focus on the long term perspectives</u>, like okay there is an additional cost because the ore grade is declining, and because of that then we have additional efforts which leads to additional costs, and I do think this is still a relevant factor, but to me I would still be, at least for most minerals and metals, looking more at the long term. And of course there are some minerals or metals for which it is clear that in 10, 20, 30 years there might be already additional costs, but for Copper, Aluminium and so on this will be 100 of years for the ore grade to decline, and that ore grade would be an additional cost. So then I would really see it more in the long term and as scarcity. However to fully answer this question I think I would need to understand again how ReCiPe works and then I would more easily be able to say how Essenz relates to it, but for now <u>I would say it is really mostly about the timeframe</u>.	"Most LCA methods focus on the long term perspectives." – *criticality perspective* "I would say it is really mostly about the timeframe." – *criticality dimensions, timeframe*
Q4b: What are the limitations of the ESSENZ method, what can be improved?	
<u>Data for sure</u>, but I mean data is hard to improve because to really improve that the data of UGFS and WGS have to be improved but I don't feel like this is our job to improve because we don't have the expertise. But what could be improved definitely is to include these different points of view as I mentioned before with GeoPolRisk basically has that they are looking on the import because <u>looking on a global perspective I think still gives you a certain amount of information but only to a certain point and then you have to consider where is your product produced, in which country is your company, to also maybe even set some hotspots.</u> So I think this is something which	"Data for sure." – *criticality data* "Looking on a global perspective I think still gives you a certain amount of information but only to a certain point and then you have to consider where is your product produced, in which country is your company, to also maybe even set some hotspots." – *criticality perspective*

definitely should be included in Essenz another factor is that there might or there should be, because now we have 11 indicators, they should be reduced. We should connect them in a way so that there would be only about 5, the best way of course is to only have 1 but at least reducing that. And then one very methodological point of view but I think it is super relevant is the whole part about the weighting, because right now both normalization and weighting and also scaling we're doing that so we can compare the different materials over the different indicators, but in the end we weigh them all equally. And that's a choice to do and that's a choice which is also hard to criticize because no one knows how to do that but I would like to come up with an approach where we don't have such an equal weighting because I feel like that's not the best way to go but however for now we don't have a better solution but this is definitely a weak spot in Essenz.	"Because now we have 11 indicators, they should be reduced." – *criticality assessment in LCA, indicators* "And then one very methodological point of view but I think it is super relevant is the whole part about the weighting, because right now both normalization and weighting and also scaling we're doing that so we can compare the different materials over the different indicators, but in the end we weigh them all equally." – *criticality assessment in LCA*
Q6: Do you think social aspects/impacts of using CRM's (such as: human right violations of workers, forced labor, child labor, health and safety of workers) or the effect of social impacts on supply risk (public acceptance, strikes, conflict) have been considered well enough in criticality analysis?	
I think it is not considered well enough also because it is really hard to get some reliable data, because every, well maybe not every but almost every criticality method uses some sort of WGI which kind of reflects something political and therefore also how people and the countries are treated. But this is only to a certain amount and of course also depending from sustainability point of view of course it would be the best to also consider human rights violations on every scale. From a criticality point of view I think it is still relevant to consider the ones which can actually lead to a reduction in availability. Because on the one hand from a sustainability perspective it is super important that everyone is paid a certain amount of money so that people can live, no question about it, but for me it is more of like a sustainability issue than a criticality issue and it just becomes a criticality issue the moment they are paid so low that they might go on strike or something like that. And I think that there should definitely be a different, not in overall because overall we want sustainability, but if we really focus on criticality then only certain aspects should be considered and only these aspects which potentially could lead to supply restrictions. And that's in my opinion just certain aspects, also it is hard to define which aspects these are and I don't know how we could quantify them in the end. But I wouldn't just say	"It is really hard to get some reliable data." – *criticality data* "From a criticality point of view I think it is still relevant to consider the ones which can actually lead to a reduction in availability" – *criticality parameter* "For me it is more of like a sustainability issue than a criticality issue and it just becomes a criticality issue the moment they are paid so low that they might go on strike or something like that." – *criticality problems* "But if we really focus on criticality then only certain aspects should be considered and only these aspects which potentially could lead to supply restrictions." – *criticality parameter, SR*

okay let's do an S-LCA, it has its own challenges, but theoretically if you could just do an S-LCA, wouldn't say every criticality assessment should come with a S-LCA. From a sustainability point of view yes but not from a criticality point of view.	
Case study:	
As a case study we have studied how different criticality assessment methods include the effect of recycling and whether the methods come to the same or different conclusions, by looking at the recycling of EV batteries.	
Q8: In terms of material criticality/supply risk/scarcity/material depletion, what outcomes would be interesting to get out of such a case study? Which interesting research gaps could be filled with this kind of case study?	
I think most interesting would be to really see how recycling could reduce criticality, but this is also challenging I think because I don't know how to approach this fully because we also did a case study, you probably saw this in one of our publications, where we included the recycling rate. But of course we then assumed that everything which is recycled goes back into the same product system, which is not reality. So I think it would be very interesting to see if recycling really decreases criticality or supply risk. Because right now we are talking about really minor amounts and if I recycle 10 batteries that's good and from an environmental perspective probably even better. But I'm not sure if considering the amount of resources a country needs, this is really tangible. I mean of course on a product level it could be, but it is dependent on what kind of perspective is taken and what you really assume like everything which is recycled goes back into the same product system or when it is recycled it goes into the market how does that even influence the market if we are talking about really small amounts. So I think that could be interesting but maybe it goes a bit beyond the focus on product assessment and criticality, but from a methodological point of view the question is also what we kind of discussed with how would you implement it because on the one hand this is what we did, we basically said okay then secondary materials or recycled contents we are using in our battery or some sort of recycling material then doesn't really get any criticality value. That's the easy option, but in the end that is not even correct because also recycled material will have some sort of criticality aspect just a completely different one than maybe political stability	"We also did a case study, you probably saw this in one of our publications, where we included the recycling rate." – *criticality research, recycling* "We then assumed that everything which is recycled goes back into the same product system, which is not reality. So I think it would be very interesting to see if recycling really decreases criticality or supply risk." – *criticality recycling, data assumptions* "But I'm not sure if considering the amount of resources a country needs, this is really tangible. I mean of course on a product level it could be, but it is dependent on what kind of perspective is taken." – *criticality perspective, level* "What you really assume like everything which is recycled goes back into the same product system or when it is recycled it goes into the market how does that even influence the market if we are talking about really small amounts." – *recycling, assumptions*

could be but I don't know other relevant factors which are more relevant and concentration of mining and concentration of research or political stability, and I think some sort of concentration might be relevant but maybe not from a European point of view. Right now every country is setting up these recycling facilities to have access to these resources which makes sense and then from a European point of view probably in 20 years there's no supply restriction because of concentration of these recycled materials. But there might be if Germany has most of that and then the Netherlands only has one then maybe for the Netherlands it is something negative, these aspects would be interesting to see, also from a methodological point of view, do you need then a complete GeoPol or Essenz only for recycled materials or how could you address that. And as we did in one of these case studies we just assumed 0 but of course this is not reality, so I think this would be interesting to see. And also but I'm not an expert for the recycling market I think it would also be interesting to talk maybe with some expert which are having a better understanding on the recycling market and can identify better what are the aspects currently and which could be the ones potentially for the future which would then decrease the availability of recycled materials	
Actually we are comparing assessment methods, so what do you think would be the conclusions of different methods, would they be different when considering recycling?	
I think that the results of course overall will be different because the methodological basis is different, but I think the trend, like not focussing too much on specific numbers but more focussing on the overarching outcome, it shouldn't be too different. <u>If you are now taking Essenz, which is a global assessment approach, and compare it on a very broad level with the EU method which is anyways a different level, but still there might be differences because one is focussing globally and one is focussing on Europe so there should be a difference. So the method which have different focusses like global or country level, there I would expect you get different results.</u> But for example the GeoPolRisk which is also focussing on the import, if you compare these results with European for example <u>I would expect that the results shouldn't differ too much because the underlying approach is similar</u>. But it would be interesting to see if the same or different results emerge.	"If you are now taking Essenz, which is a global assessment approach, and compare it on a very broad level with the EU method which is anyways a different level, but still there might be differences because one is focussing globally and one is focussing on Europe so there should be a difference. So the method which have different focusses like global or country level, there I would expect you get different results." – *criticality assessment, level* "I would expect that the results shouldn't differ too much because the underlying approach is similar." – *criticality assessment methods results*

Q9: In what way can actors and stakeholders of the EV battery industry benefit from criticality assessments? (consumers, private/public companies, policy makers, researchers) And do you think it can support decision making?	
I think how they benefit most is that from a production point of view they can analyse or identify the materials which are the most critical to them. I think they are already doing this, and they might not use Essenz or the GeoPolRisk, but they are looking at every material they are buying from this angle already. And <u>of course if we think about recycling there are always costs associated with recycling, and it could also be an option to identify which material should be recycled not only from an economic point of view but also from a criticality point of view.</u> For example with rare earths it is now done because, the problem has been solved a bit but let's stick with it, <u>if China decided again to not trade it anymore, the US also don't want to trade it then Europe would have a problem. And then it might make sense to get these materials back and I think this is something which could definitely help if you would apply a criticality assessment on your product level. And maybe also if you see this is a material which is really critical, that you from a company perspective then start to initiate for example some trade agreements with other companies or countries or maybe even motivate on a political level that these trade contracts will be set up, so that you as a company would have access to that.</u> So I think that this is quite relevant but this is also what the EU assessment is about a bit. To see which materials are relevant and then in the end this is where the EU focusses on setting up some trade agreements. But I think it is relevant for companies to also be aware, I mean it also depends on what kind of companies and so on, but in the end I think it is important for companies to understand where their bottlenecks are. And then to add to that, because I forgot, <u>what are the main limitations of Essenz, and that is that we're currently only looking at the materials themselves</u>, so we're looking at Copper and Aluminium and so on but we are not considering for example that if we would import for example a microchip, this microchip is produced in China and therefore this <u>product itself, a microchip, has its own criticality. So these intermediate products are not considered in Essenz, we're just looking if this product is based, or even if there's a product that has a microchip in it, we break it down into materials and then we assume a global production, but this microchip is coming from China and maybe another aspect of this product is coming from somewhere else. I think this is also an issue that</u>	"Of course if we think about recycling there are always costs associated with recycling, and it could also be an option to identify which material should be recycled not only from an economic point of view but also from a criticality point of view." - *recycling* "If China decided again to not trade it anymore, the US also don't want to trade it then Europe would have a problem. And then it might make sense to get these materials back and I think this is something which could definitely help if you would apply a criticality assessment on your product level. And maybe also if you see this is a material which is really critical, that you from a company perspective then start to initiate for example some trade agreements with other companies or countries or maybe even motivate on a political level that these trade contracts will be set up, so that you as a company would have access to that." – *criticality level* "What are the main limitations of Essenz, and that is that we're currently only looking at the materials themselves." – *criticality in LCA, Essenz* "Product itself, a microchip, has its own criticality. So these intermediate products are not considered in Essenz, we're just looking if this product is based, or even if there's a product that has a microchip in it, we break it down into materials and then we assume a global production, but this microchip is coming from China and maybe another aspect of this product is coming from somewhere else. I think this is also an issue that Essenz had but I know also the EU method for criticality has this as well, they are only looking at the imports of materials but not in part of intermediate products." – *criticality assessment in LCA, Essenz, assumptions*

Essenz had but I know also the EU method for criticality has this as well, they are only looking at the imports of materials but not in part of intermediate products. And one more shortcoming, I think this we have seen this now with the entire war in the Ukraine and how this influences resource availability of resources from Russia but also Ukraine, this is something that no method could ever predict, because Essenz and I think most of the criticality methods they rely on what we are doing is basically we are using data from the last 5 years and then extrapolate it and say okay this is how the future will look even though we don't know. But it is also challenging because what other way is there, we could also focus on similar to what the IPCC is doing and look at trajectories and say okay this is how the world will develop, but in the end I think no one saw this coming. And now within for example our scarce method, we could say okay gas was always a critical material, but of course not so much on the agenda as it is right now. And I think this is one of the biggest challenges but every method has it, because no one can see in the future.	"One more shortcoming, I think this we have seen this now with the entire war in the Ukraine and how this influences resource availability of resources from Russia but also Ukraine, this is something that no method could ever predict, because Essenz and I think most of the criticality methods they rely on what we are doing is basically we are using data from the last 5 years and then extrapolate it and say okay this is how the future will look even though we don't know." – *criticality assessment, cons, shortcoming* "This is one of the biggest challenges but every method has it, because no one can see in the future." – *criticality assessment challenge*

9.3. Appendix C: Case study figures and calculations

Case study extra figures

EU method

Material	SR (2017)	EI (2017)	EoL-RIR (%)(2017)	SR (2020)	EI (2020)	EoL-RIR (%)(2020)
Cobalt	1.6	5.7	0	2.5	5.9	22
Lithium	1.0	2.4	0	1.6	3.1	0
Manganese	0.9	6.1	12	0.9	6.7	8
Copper	0.2	2.4	55	0.3	5.3	17
Nickel	0.3	4.8	34	0.5	4.9	17
Natural Graphite	2.9	2.9	3	2.3	3.2	3

Table 1. Criticality parameters EU (2017 & 2020). Showing the SR (Supply Risk), Economic Importance (EI) and End of Life Recycling Input Rate (EoL-RIR) for the years 2017 and 2020.

Material	0%	5%	10%	40%
Cobalt	1,60	1,52	1,44	0,96
Lithium	1,00	0,95	0,90	0,60
Manganese	1,02	0,97	0,92	0,61
Copper	0,44	0,42	0,40	0,27
Nickel	0,45	0,43	0,41	0,27
Natural Graphite	2,99	2,84	2,69	1,79

Table 2. SR parameter scores for selected materials considering varying EoL-RIR in percentages, EU method 2020.

Material	EoL-RIR (%) if SR = 1
Cobalt	38
Manganese	2
Natural Graphite	67

Table 3. Recycling rates for Cobalt, Lithium and Graphite needed for the SR parameter to even the determined threshold of 1.0. Volgende zin: nuancering van EoL-RIR

Explanation of the Microsoft Excel file "all calculations"

- The sheet "mineral masses per battery" contains the masses of minerals contained by the NMC(1:1:1) and NMC(8:1:1) batteries, also converted to when both batteries are of the same mass.
- The sheet "EU method values" are taken from the EC "Study on the review of the list of critical raw materials" (2017)
- The sheet "EU method values (2020+2017)" contains the SR and EI values from the EU method for the two years.
- The sheet "GeoPolRisk values (2016+2017)" contains values calculated with Excel for 2016 and for 2017 data taken from the geopolrisk.org online tool .
- The sheet "GPRS (2017)" contains the values taken from geopolrisk.org online tool.
- The sheet "GPRS (2016+2017)" is a combination of sheet 4 and 5, together with some visualizations.
- "Trade Calculation", "Raw trade data", "WGI normalized", are calculations and data provided by the University of Bordaux.
- The sheet "Mineral Resource Scarcity", are calculations following from the ReCiPe method data.
- "Results comparison" is a combination of previous sheets and visualizations