Critical Materials

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by

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Summary

As the world transitions to green energy and electrification, lithium has become indispensable in modern applications. It is used for energy storage in electric vehicles (EVs), stationary storage, and a wide range of other electricity storage needs. With the growing demand for lithium, more lithium enters Europe, and finally more lithium exits Europe (e.g. EVs leaving Europe after reaching their End of Life). Lithium is increasingly important but also scarce, which possibly leads to failure in meeting demand. This scarcity is due to limited supply and delivery risks from countries outside Europe.

As a result, the European Union has designated lithium as a critical material. Critical materials, as defined by the EU, are essential for the European (Net-Zero) industry but are available in limited quantities. To measure this scarcity and gain more autonomy over these important materials, the European Commission established the Critical Raw Material Act (CRMA) in 2024. The CRMA lists strategic raw materials and sets benchmarks both along the value chain of critical materials, and for diversifying EU critical material supplies. The benchmarks are stated as follows:

1. At least 10% of the EU's annual consumption for extraction
2. At least 40% of the EU's annual consumption for processing
3. At least 25% of the EU's annual consumption for recycling
4. No more than 65% of the EU's annual consumption from a single third country

This master thesis, titled ”What policies can influence the material flows of Lithium in Europe and have a positive impact on the CRMA benchmarks?”, examines how specific policies can affect the supply chain of lithium within Europe to better meet the CRMA benchmarks.

The study uses Material Flow Analysis (MFA) to model the entire European lithium supply chain, analysing how much lithium enters Europe, remains within the European system, and ultimately exits the European supply chain. The research creates a baseline scenario, evaluates current investments in the lithium supply chain and determines whether the CRMA benchmarks can be met. Additionally, delays inherent in the system are incorporated to provide a more realistic assessment of lithium flows over time.

MFA proves to be a useful tool for analysing the CRMA benchmarks, as it not only reflects the total consumption of lithium but also shows the amounts of lithium recycled, extracted, and processed within Europe. This research indicates that, under the conditions described, none of the benchmarks can be achieved by the target date of 2030.

The study examines potential policies that could influence the MFA and the benchmarks, allowing for the identification of effective policies to retain lithium within the European system, and thereby enhancing European autonomy. The policies investigated include:

1. Reducing the demand for imported Lithium batteries
2. Increasing Europe's battery manufacturing capacity
3. Increasing Europe's lithium recycling capacity
4. Increasing Europe's recycling capacity and incorporating small lithium products into the recycling circuit, such as mobile phones and small batteries (< 2 KWh)
5. Increasing Europe's recycling capacity, incorporating small lithium products, and accelerating the transition to hydrometallurgical recycling processes, thereby increasing recovery rates to 95%
6. Increasing Europe's lithium mining capacity
7. Increasing Europe's lithium processing capacity

The findings suggest that while increasing battery manufacturing in Europe boosts production (2), it has no effect on the CRMA benchmarks. Conversely, reducing imported battery demand (1) has an impact on the benchmarks, but the effect is limited. Enhancing recycling capacities (3) positively influences the benchmarks, particularly when small lithium products are incorporated into the recycling process (4). Accelerating recovery rates of black mass recycling is only useful with fast implementation (5), and expanding mining and refinery capacities (6, 7) also contribute to achieving the benchmarks but require significant time due to the duration it takes to build a mine and/or refinery.

Academically, this research demonstrates the use of dynamic Material Flow Analysis in policy analysis for critical materials and more specific the CRMA. The incorporation of delays in the MFA provides a more realistic and applicable model for future studies. This research also highlights areas for future investigation, including system dynamics modelling with incorporation of lithium prices and evaluating policy impacts on other critical raw materials, contributing to the broader body of knowledge in engineering, policy analysis, and industrial ecology.

This thesis is written for academic purposes but is also relevant for other stakeholders, such as industries involved in the lithium supply chain, as well as national governments and the European Union. Achieving European autonomy concerning lithium is challenging, and requires substantial increases in extraction, processing, and recycling capacities to meet CRMA benchmarks. Although the European Commission addresses this through legislation, it cannot achieve autonomy by itself. Comprehensive investment across the supply chain is crucial, with both processing and recycling being the most significant bottleneck. Industry involvement is essential for establishing a robust supply chain, mitigating foreign monopolistic risks, and ensuring sustainability through circularity. Collaboration between industry stakeholders and the European Commission is essential to enhance Europe's strategic autonomy and reduce dependency on third countries.

These conclusions highlight the necessity of strategic investments in mining, processing, and recycling infrastructure to meet CRMA benchmarks. Enhanced collaboration across the supply chain and coordinated policy implementation are essential for improving lithium flows and achieving increased European autonomy.

Contents

1

Introduction

In March 2023, the European Commission published the ”European Critical Raw Material Act” (CRMA) (European Commission, 2023a), aiming for a secure and sustainable supply of critical materials for the European industry. These critical materials constitute the starting point of many industrial supply chains for Net-Zero technologies, which are technologies that will make a significant contribution to decarbonisation (European Commission, 2023d), and the demand for them is on the rise. These materials are used in various applications, including, but not limited to, wind turbines, batteries, as well as smartphones, and they are all essential for the current green and digital transition that is underway. On top of the increasing need for these materials, they are scarce (possibly insufficient for the demand). The scarcity is attributed to the finite supply and delivery risks from countries such as China and the Democratic Republic of Congo (DRC) (Bille, 2024).

According to the International Energy Agency, achieving the 1.5-degree Celsius goal of the Paris Climate Agreement will necessitate a quadrupling of mineral requirements for clean energy technologies by 2040 (Vakulchuk & Overland, 2021). Nearly all technological advancements are, in one way or another, associated with critical materials. The absence of a comprehensive critical material autonomy strategy will be harmful to the European industry, leading to instability (Bille, 2024). Critical materials thus constitute a cornerstone for sustainable development. This aligns with several of the Sustainable Development Goals (SDGs) of the United Nations (Ministerie van Algemene Zaken, 2015): Affordable and Sustainable Energy (SDG 7), Sustainable Cities and Communities (SDG 11), and Climate Action (SDG 13).

The rapid increase in demand for materials such as lithium not only puts pressure on the environment but also gives rise to substantial societal and governmental implications (Lèbre et al., 2020). Mining critical materials affects miners, as well as the communities residing in the surrounding areas of the mines, and increases the likelihood of corruption, because of fast growing demand for the materials (Lèbre et al., 2020). Bringing lithium supply chains to Europe, a principle advocated by the European Commission in the CMRA, can help counteract corruption and overproduction. If the European Union takes a greater part in mining and processing lithium, then this can lead to better supervision of working conditions and overproduction, tackling this problem. This aligns with various Sustainable Development Goals, including Decent Work and Economic Growth (SDG 8), Industry, Innovation, and Infrastructure (SDG 9), and Responsible Consumption and Production (SDG 12).

The EU periodically assesses the criticality of materials through a systematic process that takes into account factors such as economic importance, supply risk, and the potential for substitution (European Commission, 2023a). The identification of critical materials is crucial for strategic planning, policy development, and the promotion of sustainable resource management practices within the European Union. It enables the EU to address potential vulnerabilities in the supply chain, reduce dependence on external sources, and implement measures to ensure the sustainable and secure access to these materials for the region’s industries. As of 2023, the European Union has a list of 34 Critical Raw Materials (CRMs) and 14 Strategic Raw Materials (SRMs) (European Commission, 2023a).

To enhance European strategic autonomy and ensure a steady supply of materials for the energy transition, the European Commission has introduced the Critical Raw Materials Act (CRMA). This Act establishes four key benchmarks aimed at measuring and enhancing strategic autonomy through the (i) extraction, (ii) processing, and (iii) recycling of critical materials within Europe, as well as (iv) reducing dependency on single third countries. These benchmarks are quantifiable metrics reflecting the European Union’s capacity to manage its own supply chains for critical materials. By achieving higher values in these benchmarks, the EU demonstrates greater self-sufficiency and reduced vulnerability to external supply disruptions. Each benchmark is calculated as a percentage of the total EU consumption of the critical material, comparing European capacity in extraction, processing, and recycling to total consumption. For instance, the extraction benchmark is derived by dividing the amount of a critical material extracted within the EU by its total consumption in the EU. Higher percentages indicate lower dependency on external sources and stronger strategic autonomy. Further details about the CRMA can be found in paragraph 2.

1.1. Research Problem and Objective

The CRMA and its benchmarks exhibit a strong correlation with material flows across Europe because adjustments in European consumption patterns, or increased recycling or extraction of a material within the EU, influence these benchmarks. While the significance of critical materials has been widely discussed, and the European Commission aims to reduce dependence on external sources, the specific policies that impact material flows within Europe are not straightforward.

This thesis is a preliminary research which seeks to illustrate the movement of one critical material, lithium, throughout Europe—whether as a raw material, semi-finished product, or finished product—creating a dynamic Material Flow Analysis (MFA). Furthermore, the thesis aims to identify which policies can influence these material flows and how they can positively affect CRMA benchmarks. By modeling the CRMA benchmarks embedded in the MFA, the research will evaluate the effectiveness of different policies, ultimately facilitating the development of more robust policies to achieve the CRMA benchmarks more quickly and accelerate the EU's sustainable transition. This thesis represents an initial exploration of combining multiple scenarios of MFA, both with and without the implementation of policies, specifically focusing on lithium flows through Europe.

Lithium was chosen not only because it is one of the critical materials, but also due to its significant value in the electrification of vehicles and its essential role in everyday items such as smartphones and other battery-powered devices. With the rise of grid electrification (IEA, 2023), batteries as storage systems are expected to play an increasingly important role, as emphasized by the European Commission in its policy document on Net-Zero technologies (European Commission, 2023d).

Although there is extensive information available on the global material flow of lithium in the current state-of-the-art, a knowledge gap exists within the European Union regarding a complete MFA of lithium (not only batteries) and how the CRMA benchmarks can be positively influenced by implemented policies. More information about this knowledge gap can be found in Chapter 2.5. This knowledge gap makes it challenging to assess the effectiveness of regulations on material flows, and thus difficult to measure their contribution to greater European autonomy.

Resulting from this knowledge gap, this thesis aims to address the following research question:

What policies can influence the material flows of lithium in Europe and have a positive impact on the CRMA benchmarks?

Answering this question will provide insights to the scientific field Engineering and Policy Analysis, Materials- and Industrial Ecology scientists and policymakers that operate in this field. To answer this main research question the following sub questions are proposed:

1. What are the key components of current European policy concerning lithium?
2. What are the key components of the European lithium supply chain, and which actors play pivotal roles?
3. What are the current lithium flows through Europe, and how do they influence the achievement of CRMA benchmarks?
4. Which policy effects could significantly influence the material flows of lithium in Europe?

By addressing these sub-questions and the main research question, this thesis aims to bridge the existing knowledge gap and provide a better understanding of material flows, particularly lithium, through

Europe. This enhanced understanding is expected to facilitate more informed decision-making in policy development. Additionally, this research is the first to present the CRMA benchmarks through a MFA. This research also incorporates delays, making use of a dynamic MFA over time (2020-2050) to visualize more realistic values. This methodological advancement can be applied to other critical materials, enhancing the generalizability and applicability of MFA for policy-making in the field of critical materials.

1.2. Overview of research

This thesis is structured into three core chapters, each including a methods and results section. This approach was chosen because the answers from one chapter are needed in the next, minimizing the need for the reader to constantly refer back and forth.

The first chapter **Understanding European lithium flows** addresses the sub-questions: What are the key components of current European policy concerning lithium? What are the key components of the European lithium supply chain, and which actors play pivotal roles? It includes a literature review on MFA, examines European lithium policies and supply chain stakeholders, identifies knowledge gaps, and justifies the use of MFA. This chapter combines methods and results.

The second chapter, **Material Flow Analysis**, presents a MFA with a baseline scenario, which is a MFA with input of the literature first chapter. It models lithium flows in Europe from 2020 to 2050, incorporating delays for more realistic projections.

The third chapter, **Policy Effect**, evaluates the impacts of different policy scenarios on the lithium supply chain. It also includes methods and results, comparing the baseline with policy scenarios to identify effective measures for sustainable and secure lithium supplies.

The **Conclusion and Discussion** synthesizes the findings, discusses broader implications, addresses study limitations, and suggests future research directions, providing a conclusion to the thesis. This structure ensures a logical progression from understanding current policies and supply chains, through detailed MFA analysis, to exploring the impacts of potential policy interventions.

2
Understanding European lithium Flows

This chapter answers sub-questions 1 and 2, which are related to European policies concerning lithium and lithium supply and its pivotal actors. Additionally, this chapter investigates the state-of-the-art in the field of Substance- and Material Flow Analysis (S/MFA). The combination of sub-question 1, 2 and the literature review into one chapter was chosen because all three components contribute to a better understanding of lithium flows. By clarifying European policies, actors, and the supply chain, and describing the existing literature on MFA, this chapter aims, beside answering the sub-questions, to justify the chosen approach of using MFA to answer the main question.

2.1. Methodology

This part of the research employs a mixed methods approach, combining qualitative and quantitative data to provide a comprehensive understanding of the actors involved, their motivations, and their interrelationships. This approach was chosen due to the complexity of the subject matter, which benefits from both empirical data and contextual insights. After explaining the methods used, this chapter is divided into three distinct results sections: one on European policies concerning lithium, one on the lithium supply chain, and lastly, a literature review on Material Flow Analyses. The chapter concludes by combining these sections into the knowledge gap and justifying the chosen approach.

2.1.1. Data Collection

Literature

To answer the first sub-question about European Policy, various policy documents were used. The first and most important is the Critical Raw Material Act (CRMA), which serves as the primary motivation for this research. In addition to the CRMA, two other policy documents have been reviewed. These documents are listed in Table 2.1.

Table 2.1: European Legislation concerning lithium

Critical Raw Material Act	European Regulation 2024/1252 (European Commission, 2024)
Net Zero Industry Act	Working document NZIA (European Commission, 2023d)
EU Battery Regulations	European Regulation 2023/1542 (European Commission, 2023b)

The second sub-question about the Actors and Supply chain, is answered through the review of other literature. To gain an understanding of the existing landscape, the supply chain of lithium is first analysed. This involved an examination of academic articles, industry reports, and government publications pertaining to lithium production and consumption within Europe. The paper by Sun et al. (2017) was used to get an overview of the steps in the lithium supply chain.

After dividing the supply chain into its different parts, all the important actors are described. An overview of the literature used for the supply and actor analysis can be seen in Table 2.2.

Table 2.2: Literature Supply Chain lithium

Supply chain .	(Sun et al., 2017)
Stakeholders above and between supply chain	(Carrara et al., 2023); (Consilium, 2022)
Resource mining	(Mohr et al., 2012); (Matos et al., 2022); (Sun et al., 2017); (IEA, 2021); (Chaves et al., 2021); (Carballo-Cruz & Cerejeira, 2020); (Carrara et al., 2023) .
Chemical Production	(Sun et al., 2017); (Matos et al., 2022); (Volta Foundation, 2023); (IEA, 2021); (Carrara et al., 2023) .
Production Manufacturing .	(IEA, 2020); (Joint Research Centre, 2017); (Carrara et al., 2023)
Production use .	(Enserink et al., 2022); (Matos et al., 2022)
Waste Management	(Bille, 2024); (S. Liu & Patton, 2023); (Santillán-Saldivar et al., 2021); (Bruno & Fiore, 2023); (Zong et al., 2023)

Lastly, a literature review of current Material Flow Analyses (MFAs) is conducted. This review covers the state-of-the-art MFAs currently used in the context of lithium. The search strategy employed for this literature review is detailed in sub-chapter 2.4.

Interviews

For the sub-questions regarding European Policies and the Actor and Supply Chain Analysis, interviews were also conducted in addition to the literature review. This approach provides an additional validation step in the research while also highlighting the latest developments in both the policy field and the supply chain. These interviews were semi-structured, meaning that while the questions were predefined, there was room for additional optional questions. The questions were divided into two distinct sections: the Critical Raw Material Act and the Actor and Supply Chain of lithium. Since not all interviewees had expertise in both areas, some interviewees were specifically asked about only one of the two topics.

The interviewees, each with different areas of expertise, are listed in Table 2.3. An overview of the questions and complete anonymous summaries of these interviews can be found in Appendix C. Each interview lasted approximately 1 hour and were conducted either in person or via video call, allowing for flexibility and ensuring broad participation.

Table 2.3: Interviewees

Interviewee	**Specialization**
S1	Professor in Critical Materials
S2 and S3	Industry experts in Minerals Mining
S4	Policy Expert CRMA
S5	European Battery Expert
S6	Policy Expert CRMA - specialized in lithium

The interviewees are labelled from S1 to S6. For the European Policy section, only interviewees S1, S4, and S6 were included in the results due to their expert insights on European Policy. For the Actor and Supply Chain Analysis section, all interviewees were included in the results.

2.1.2. Data Analysis

European Policy

All three policy documents were thoroughly reviewed, and the key components relevant to lithium are summarized in the results section. This summary includes all regulations specifically important for lithium, although many rules apply to all Strategic Raw Materials, of which lithium is a part. Additionally, the interviewees provided supplementary information. This information is shared in the results by citing the interviewees with their anonymous interview codes S1, S4, or S6.

Actor and Supply Chain Analysis

To gain a comprehensive understanding of the European lithium landscape, a supply chain analysis was initially conducted, providing a clear depiction of the supply chain's operations and the identification of actors within each segment. Following this, key actors were identified and categorized based on supply chain and interview data into groups such as government bodies within and outside Europe, and industry players within the lithium supply chain. The system boundaries were then defined, focusing on a MFA of lithium within the EU, while also considering significant external actors influencing the system's inflows. Subsequently, an actor analysis was performed, outlining the predefined system boundaries, categorizing actors using a resource dependencies diagram, and creating a Power-vs-Interest Matrix to identify key players. All this information was consolidated into an aggregated overview of the lithium supply chain, distinguishing the main actors and serving as the foundation for addressing the next subquestion.In this section, additional information from the interviewees was also provided. This information is presented in the results by citing the interviewees with their anonymous interview codes, S1 through S6.

Literature Review M/SFA

The literature review of this study includes information about the general approaches to Substance and Material Flow Analysis, as well as System Dynamics. Following this, a justification is provided for choosing MFA as the analytical approach used in this thesis. Subsequently, Material Flow Analyses specifically for lithium and lithium-ion batteries are reviewed. This review aims to identify what has already been investigated and to pinpoint any potential knowledge gaps.

2.1.3. Limitations

European Policy

Both the CRMA and the EU Battery Regulations have been adopted by the European Council and Parliament. The Net-Zero Industry Act (NZIA), however, is currently a 'working document.' This means it is a proposal that has not yet been officially approved but has been published for review. Therefore, there is a possibility that some components of the NZIA may be modified before becoming official regulation.

Additionally, a translation has been made from the extensive regulations (ranging from 100 to 200 pages) to the current summary. Although minimal free translation was used and many points were further emphasized by the interviewees, it is possible that the interpretation provided by this research may not be entirely complete or accurate.

Actor and Supply Chain Analysis

The Actor Analysis in this study, while providing a comprehensive overview of the European lithium supply chain, is not without its limitations. Due to its broad aggregation at the European level, certain nuances may be lost, leading to a potential oversimplification of complex relationships. This large-scale aggregation might result in different aspects of the supply chain being treated uniformly, despite significant variations in operations, strategies, or impacts among actors. Such a generalized approach could obscure specific details, making the analysis less clear and potentially overlooking unique challenges or opportunities faced by individual actors. By acknowledging these limitations, we can better understand the context and constraints of the findings, and where further, more detailed investigations could be beneficial.

2.2. European Policy

To get a better understanding of what influences lithium flows on a European Policy level, different policy documents are analyzed, started with the European Green Deal. This in 2020 introduced set of overarching policy initiatives has the goal to reduce CO2 emmissions with 55% in 2030 and to make Europe climate-neutral by 2050. The initiatives focuses on industry and nature. In the context of critical materials and lithium, the three initiatives outlined in Figure 2.1 are particularly noteworthy because of the implications for this study. The Green Deal Industrial Plan consists of two distinct regulations: the Critical Raw Material Act (CRMA) of 2023, amended in 2024, and the Net Zero Industry Act proposal (NZIA) of 2023. Both regulations set benchmarks—the CRMA for Strategic Critical Materials, such as lithium, and the NZIA for European-based 'net-zero technologies' including batteries and storage solutions. This study also considers lithium manufacturing, which is why the NZIA is also relevant. As this study takes into account the future trend of increasing recyclability of lithium, the Battery Regulations is also discussed. This regulation address the recyclability of various strategic materials used in batteries. In the paragraphs below all three initiatives are discussed.

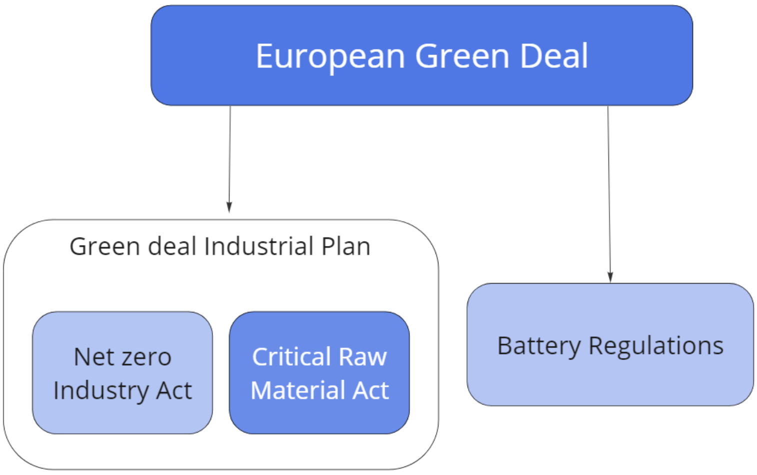


Figure 2.1: Overview European Legislation involving Critical Materials

2.2.1. CRMA

The Critical Raw Materials Act (CRMA) was first adopted in March 2023. The CRMA is a Regulation, which has direct effect on the member states and therefore does not need to be transposed into national legislation (as is required with an EU directive). A year later, the act was supplemented and amended, and as of April 11, 2024, the CRMA is in implemented. The act is divided into four distinct benchmarks which need to be realized in 2030.The benchmarks are as follows (Chapter 3, Section 1, Article 5):

- Union **extraction capacity** is capable of extracting the ores, minerals or concentrates needed to produce **at least 10% of the Union's annual consumption** of strategic raw materials, to the extent possible in light of the Union's reserves.
- Union **processing capacity**, including for all intermediate processing steps, is capable of producing **at least 40% of the Union's annual consumption** of strategic raw materials.
- Union **recycling capacity**, including for all intermediate recycling steps, is capable of **producing at least 25%* of the Union's annual consumption** of strategic raw materials and is capable of recycling significantly increasing amounts of each strategic raw material from waste.
- diversify the Union's imports of strategic raw materials with a view to ensuring that, by 2030, the Union's annual consumption of each strategic raw material at any relevant stage of processing can rely on imports from several third countries or from overseas countries or territories (OCTs) and that **no third country accounts for more than 65% of the Union's annual consumption of such a strategic raw material**.

(*): The recycling benchmark for End-of-Life Strategic Raw Materials (SRM), previously set at 15%, has been increased to 25% in the latest regulation adopted on April 11, 2024.

The benchmarks fall under EU Regulation 2021/1119, which sets the Union's climate and energy targets of the European Parliament and Council. It's important to note that, according to EU legislation, benchmarks and targets are not the same. According to interviewee S6 there is no legal penalty in not reaching these benchmarks. These regulations apply as a percentage for the entire European Union and are not subdivided by member states. All benchmarks will be monitored by a special "European Critical Raw Material Board" established by the Commission. If the benchmarks are not met, additional measures or legislation will follow, to be determined at a later stage, but earlier then 2030, as read in point 13 from the Regulation.

It is important to note that there is a difference between Critical Raw Materials and Strategic Raw Materials, also underlined by interviewee S4 and S6. Critical materials are those deemed critical by the European Union based on economic importance, supply risk, and import reliance (Annex 2, section 1). Strategic materials are assessed based on these factors of criticality, as well as the expected growth in demand relative to global annual production (Annex 1, section 1). That is why aluminium and copper are also listed as SRM. Although the act is titled the 'Critical Raw Materials Act', the benchmarks apply only to strategic raw materials. This is because the European Union anticipates that these materials will be crucial in sustaining a green economy as the materials are used in vital net-zero technologies.

The European Union is establishing new strategic partnerships to meet the 2030 benchmarks and minimize supply chain risks. This so-called 'CRM-club', mentioned in Chapter 6, Article 37 of the CRMA, describes a commitment between the Union and a third country or an overseas country or territory to increase cooperation related to the raw materials value chain. This commitment is established through a non-binding instrument that sets out actions of mutual interest, facilitating beneficial outcomes for both the Union and the relevant third country or overseas country or territory, this is also underlined by Interviewee S6.

Additionally, the European Union will focus on 'Strategic Projects'. These strategic projects relate to the extraction and processing/recycling of SRMs. The approval of such strategic projects falls under the European Commission mandate and must contribute to (Section 2, Article 6):

1. Meaningful contribution to the security of SRMs.
2. Technically feasible within a reasonable time frame.
3. Implement sustainability (Social License to Operate).
4. For project in the Union: Crossborder benefits beyond the member state (including downstream sectors).
5. For projects in third countries: mutually beneficial for the Union and the third country by adding value in that third country

If a project qualifies as a strategic project, the permit-granting process should not take longer than 27 months for a project involving extraction and 15 months for a project involving only processing or recycling (European Commission, 2023a). If the project is already in development and is only now considered strategic due to the introduction of the CRMA, the permit-granting process should last no longer than 24 months for extraction and 12 months for processing or recycling.

2.2.2. Net Zero Industry Act

The Net Zero Industry Act, along with the CRMA, is part of the Green Deal Industrial Plan. Together, these acts aim to establish Europe as an industrial base for net-zero technologies by increasing the EU's manufacturing capacity and achieving the EU's ambitious climate and energy targets. Unlike the CRMA, the Net Zero Industry Act provides a benchmark framework for technologies rather than materials. Since these initiatives are closely related, it is important to highlight both. As stated by interviewee S1, these two regulations cannot be viewed in isolation from each other, as together they focus on the entire supply chain of a Strategic Raw Material (SRM). The NZIA focuses on eight strategic net-zero technologies, namely:

1. Solar Photovoltaic and solar thermal
2. Electrolysers and fuel cells
3. onshore wind and offshore renewables
4. Sustainable biogas/methane
5. **Batteries and storage**
6. Carbon capture and storage
7. Heat pumps and geothermal energy
8. Grid technologies

Batteries and storage is the key technology in light of this research. Given that the demand for European lithium is highly dependent on the demand for batteries, it is important to focus on this area as well. The proposal for this act stipulates that by 2030, 610 GWh of batteries will be produced annually in Europe (page 15, working document NZIA).

However, the European Battery Alliance (EBA), the alliance that is launched by the Commission and that wants to make Europe a global leader in sustainable battery production and usage, has even highter ambitions. The EBA has the political objective of ensuring that European manufacturers produce 90% of the EU's annual battery deployment needs by 2030, an objective that would be extremely difficult to achieve without the NZIA proposal. According to the EBA, the goal is to increase the EU's manufacturing capacity per annum for lithium-ion batteries from 75 GWh in 2022 to 885 GWh in 2030. The EBA, together with InnoEnergy, projects a battery demand in Europe of around 1000 GWh in 2030, which means that EU manufacturers of battery technologies would need to cover around 90% of the EU demand by 2030. Interviewee S1 highlights that when considering investment plans of battery manufacturers, one must be cautious about treating future projections as certainty. The golden rule to apply here as said by Interviewee S1 is the 70/70% rule, where 70% of the plans are executed and, most of the time, only at 70% of the projected capacity.

2.2.3. EU Battery regulations

In addition to the Green Deal Industrial Plan, another important regulation to mention is the EU Battery Regulation concerning batteries and waste batteries, which was implemented on July 12, 2023. This policy focuses on the circularity and recyclability of batteries and, as Interviewee S4 mentions, has potential implications for lithium flows throughout Europe.

From 2031 onwards, all batteries larger than 2 kWh must source 6% of their total lithium content from manufacturing or post-consumer waste. This percentage will increase to 12% from 2036 onwards. Furthermore, as described in Article 77 of the Battery Regulations, all batteries larger than 2 kWh must have an electronic record, known as a "Battery Passport." This passport must include the following information: Information accessible to the general public, information accessible to notified bodies, market surveillance authorities and the Commission and lastly information accessible to any natural or legal person with a legitimate interest in the information.

2.3. Actor and Supply Chain Analysis

In order to get a better understanding of how the lithium material flows look like, and what actors are involved in these flows, it is first necessary to determine how the lithium chain looks like and which actors play a significant role in influencing this chain. In the study by Sun et al. (2017), the lithium chain is described in five different steps. Figure 2.2 illustrates the five steps.

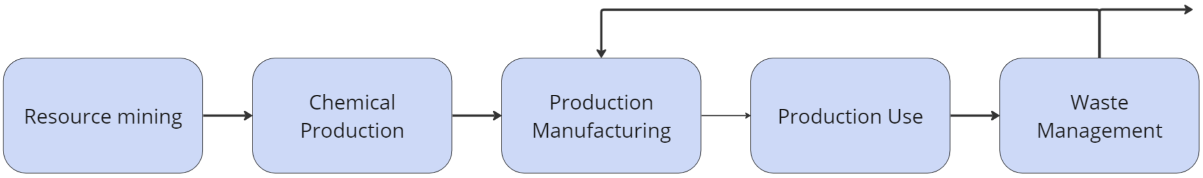


Figure 2.2: Five steps of the lithium supply chain (Sun et al., 2017).

The relevant stakeholders are situated along this chain. In addition, there are stakeholders positioned between the various chains, such as transportation companies. Lastly, there are stakeholders situated above the chain, yet of considerable significance, such as the European Member States, the European Commission, and the governments of lithium-producing countries. To enhance clarity, an examination of the principal actors is conducted within each segment of the chain, and described in the paragraphs below.

2.3.1. Supply chain Analysis

Lithium is an alkali metal with atomic number 3; it is the lightest metal, and has a high specific heat capacity (Mohr et al., 2012). Due to this high specific heat capacity, it an important metal for energy storage, such as batteries. There exist two distinct methodologies for lithium extraction. This can be achieved through lithium extraction from rocks and lithium extraction from brines. Due to uncertainties regarding the complete discovery of lithium and the usability of the identified lithium reserves, various scenarios have been formulated, each representing different total quantities of lithium. These scenarios include 19.3 Mt Li (Case 1), 55 Mt Li (Case 3), and 23.6 Mt Li (Case 2, Best Estimate) (Mohr et al., 2012).

As said before, after mining, lithium comes in two forms: ores and brines. It then moves on to chemical production, where it is transformed into materials essential for various end products. The four chemical derivatives stemming from the mining procedure are lithium Carbonate, lithium Hydroxide, lithium Chloride, and lithium concentrate. Notably, lithium Carbonate and lithium Hydroxide find application in the fabrication of lithium-Ion batteries, while lithium Chloride, lithium Concentrate and lithium Hydroxide serve a spectrum of alternative production purposes, spanning industries such as glasses & ceramics and lubricating greases. A more comprehensive overview of these material flows is presented in Figure 2.3, as documented by Sun et al. (2017) and Matos et al. (2022).

The manufacturing production is divided as two distinct domains: firstly, the use of lithium in lithium-Ion batteries, and secondly, its application in all other contexts. An overview of additional lithium applications is depicted in Figure 2.4. According to the International Energy Agency's (IEA) findings, during the period 2020-2025, 32% of the demand for lithium is attributed to these 'other' products, while the remaining 68% is allocated to lithium-Ion batteries in all its forms. This percentage of demand for other products is projected to decrease to 9% by 2050, as per IEA's forecasts.

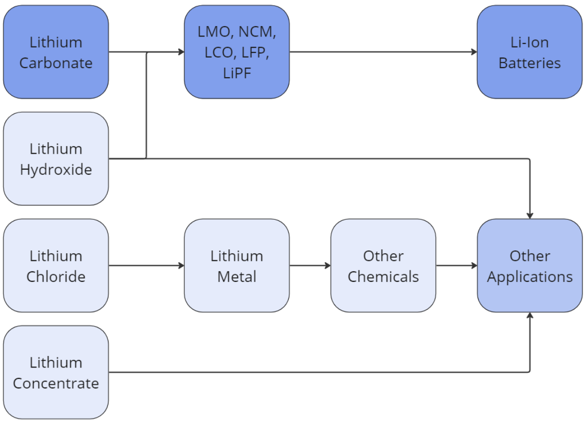


Figure 2.3: Chemical production divided by four main components.

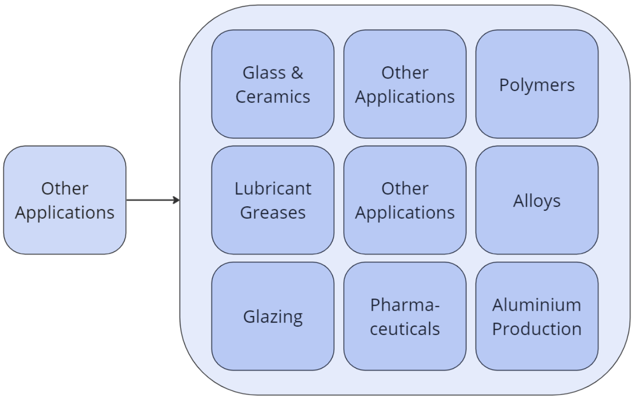


Figure 2.4: Other lithium applications besides Li-Ion batteries

lithium-ion battery manufacturing begins with preparing the cathode and anode materials. The cathode is typically made from a lithium metal oxide and coated onto aluminum foil, while the anode is usually composed of graphite coated onto copper foil (Battery University, 2010). The cathode material of a battery can very between different battery chemistry's such as LFP (lithium Iron Phosphate) or NCM (Nickel Cobalt Manganese). While NCM batteries are currently the market leader, LFP batteries are also on the rise, as noted by Interviewees S2 and S3. These components are then layered with a porous separator in between to prevent direct contact but allow ionic flow. The assembly is soaked in an electrolyte solution, enabling the movement of lithium ions between the electrodes during charging and discharging.

After products are manufactured, they are purchased by consumers. However, once these products reach their end-of-life (EoL) stage, they are frequently not returned to designated collection points for recycling, as said by Interviewee S5. This failure to recycle properly can occur either because the items are not disposed of correctly or because they are left 'hibernating' in storage. These so-called 'Hibernating products' (Matos et al., 2022; Zong et al., 2023) pose challenges in the recycling of batteries and, consequently, lithium. According to research by Matos et al. (2017), there were 321 kt LIB in this hibernating state (i.e., kept by the user after end-of-life) in 2016. Interviewee S1 mentions that in this supply chain, the user plays a pivotal role because recycling is one of the biggest bottlenecks in creating a circular supply chain.

The last stage of the lithium supply chain is the waste management of lithium. It comprises two main aspects. Firstly, there is the recycling of lithium into new batteries. Secondly, there is the recycling of lithium for 'end use,' such as recycling for Glass & Ceramics or other objects. Opting for recycling for end use removes lithium from the cycle of lithium usage, rendering it unavailable for subsequent battery production.

Various studies on the recycling of critical materials suggest significant potential in extracting value from recycling processes. Santillán-Saldivar et al. (2021) asserts that recycling can play a substantial role, emphasizing the importance of implementation at the national level to reintegrate recycled materials into domestic economies.

Upon reaching the end of their lifecycle, batteries are collected, fully discharged, and subsequently shredded, facilitating the separation of base metals in preparation for recycling. This resultant is a metallic mixture, commonly referred to as 'black mass,' encompasses all the valuable metals constituting battery anodes and cathodes—the most financially significant components of a battery. The distinctive black mass arises from the heightened concentrations of graphite present in battery anodes, imparting a deeply dark coloration. Comprising approximately 40-50% of the total weight of an electric vehicle (EV) battery, black mass plays a pivotal role in recycling efforts (Aqua Metals, 2023), also underlined by Interviewee S5. Global production of black mass reached around 0.5 million tonnes in 2023 (Volta Foundation, 2023). Once the batteries are transformed into black mass through shredding, the recycling process can start.

There are various methods to recycle lithium, namely pyrometallurgy, hydrometallurgy, and direct recycling. Pyrometallurgy and hydrometallurgy are two distinct methods employed in the extraction and processing of metals. Pyrometallurgy involves high-temperature processes, such as smelting or roasting, where heat is applied to ores or concentrates to extract metals. In contrast, hydrometallurgy uses liquid flowing solutions and involves chemical reactions at relatively lower temperatures to dissolve and recover metals from their ores. The key difference lies in the use of heat in pyrometallurgy and the use of liquid solvents in hydrometallurgy, each method tailored to specific ore types and metal extraction requirements. Direct (Cathode) recycling is in the early stage of development but holds high value for manufacturers due to low energy consumption and high recovery rates. According to the annual report of the Volta Foundation (2023), hydrometallurgy gains the most traction in the industry, because of the high recovery rates, which are between 95-99% (Quan et al., 2022). This is very high in comparison with pyrometallurgy, which has a recovery rate of around 40% (Matos et al., 2022).

2.3.2. Overview Actors

After the supply chain analysis, the actor analysis is conducted. This is divided into the different subdomains of the supply chain, as well as the stakeholders above or between the supply chian.

Actors in extraction of lithium

The predominant lithium producers are Chile, Australia, and China (IEA, 2020; Matos et al., 2022; Sun et al., 2017). Figure 2.5 illustrates the annual production of kilotons of lithium, if feasible, categorized between rock and brine sources. In addition to Chile, Bolivia has emerged as a significant player in the lithium market. A major discovery was made in the Salar de Uyuni, where approximately 5.4 million tonnes of lithium are estimated to be present (An et al., 2012). Although Bolivia's lithium reserves are substantial, it currently remains a smaller participant in lithium mining. However, it is expected that the country will play a larger role in the future (Carrara et al., 2023).

In Europe as well, a significant lithium discovery has been made. In the northern region of Portugal, nine distinct lithium-rich sites have been identified (Chaves et al., 2021). The total lithium content in these locations amounts to 60,000 t of lithium (0.4% of the world reserves) (Carballo-Cruz & Cerejeira, 2020). However, concerns have been raised regarding lithium mining in this Portuguese region, as outlined in the paper by Chaves et al. (2021). This paper highlights a crucial sustainability and low-carbon policy dichotomy: the tradeoff between global benefits, such as reduced greenhouse gas emissions, and the frequently observed negative impacts on local communities.

A significant lithium reserve has also been discovered in the Czech Republic. Located about 100 kilometers from Prague, near the German border, the Cinovec lithium Project has been underway since 2010. Interviewee S4 mentions that although mining operations have not yet commenced, this site is recognized as one of the largest lithium finds in Europe. The discovery underscores the potential for the Czech Republic to become a major player in the European lithium market.

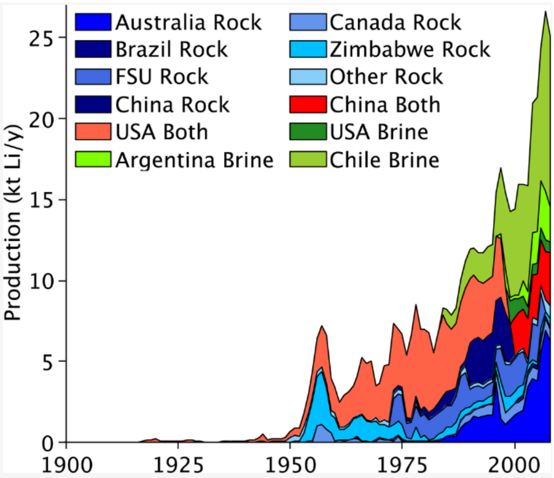


Figure 2.5: World production of lithium by country and mineral type (blue colours are rock, green colours are brines and red colours contain both rock and brine (Mohr et al., 2012).

Actors in Chemical Production

The largest companies in mining and processing lithium into raw materials are Albemarle (US), Sociedad Química y Minera de Chile (Chile), Ganfeng lithium (China), Tianqi lithium (China), and Yahua (China) (Volta Foundation, 2023)). Between 2023 and 2030, geographically, approximately 49% of the refining projects for lithium chemicals are undertaken in China (European Commission, 2023c). Following this, Argentina accounts for 16%, Australia for 11%, Chile for 9%, and all other countries collectively contribute 15%.

In 2024, only one company in Europe engages in lithium processing. The American company Albemarle operates a production plant in Langelsheim, Germany, where it processes lithium into products such as lithium carbonate and hydroxide. Beyond this facility, the lithium processing industry in Europe is currently non-existent, a fact emphasized by interviewees S4 and S6. This highlights a significant gap in the regional value chain for this critical raw material.

Actors in Production Manufacturing

In the domain of lithium manufacturing, the primary actors are situated in China, South Korea, and Japan. These three countries collectively hold an 88% share of the total production (Carrara et al., 2023; Joint Research Centre, 2017). In the field of batteries, until 2018, Europe witnessed limited indigenous battery production. However, post this period, significant manufacturing facilities were initiated in several European countries. Particularly noteworthy are Sweden and Germany, where substantial producers have emerged. Prominent players in the field include NortVolt and Tesla, with planned capacities of 100 GWh (expected to be finalized by 2024) and 100 GWh (projected completion by 2028) respectively (Carrara et al., 2023; Volta Foundation, 2023). Additionally, PowerCo (a Volkswagen group corporation) is noteworthy, as it is set to establish a capacity of 120 GWh split between Germany and Spain (60 GWh each). Furthermore, Poland is poised to host a substantial Gigafactory by LGES, scheduled to achieve a capacity of 115 GWh. A more comprehensive overview of European Gigafactories is shown in Appendix A.

Users of lithium Products

Although users are incorporated in the supply chian of lithium, normally in an actor analysis they are typically not included as actors, except when united into a civic initiative or movement (Enserink et al., 2022).

Actors in Waste Management

Until 2022, little progress had been made in Europe regarding the recycling of lithium. This was primarily due to the extended period during which the market price of lithium remained considerably lower than the cost of recycling lithium (Bille, 2024). However, since 2022, the market price of lithium has experienced a significant increase (S. Liu & Patton, 2023), leading to increased consideration of recycled lithium.

Additionally, the European Parliament and Council approved regulations on batteries and battery waste in 2023.

According to these regulations, by 2031, 6% of the lithium used in all batteries larger than 2 GWh must be recycled, with this target increasing to 12% in 2036. Furthermore, by 2025, 65% of the average weight of lithium-based batteries must be recycled, rising to 70% by 2030. Finally, by 2027, a minimum of 50% of lithium must be recovered in the recycling process, with this target increasing to 80% by 2031. This will create streams of recycled lithium within Europe, most likely also coming from outside of Europe. Interviewees S2, S3 and S5 mention that it is uncertain whether the European Union can achieve the target of 6% recycled lithium for new batteries solely through its own recycling circuit (Bruno & Fiore, 2023).

Important players in the recycling world at the moment include HydroVolt (a collaboration between NorthVolt and Hydro), where a total of 12 kilotons of batteries have been recycled so far. Other significant players are Bas-F, Stena, TES and Umicore (Volta Foundation, 2023).

Other stakeholders

In addition to the various actors in the lithium supply chain, there are also entities that play a role within the supply chain, but do not directly fall within any of the chains. Foremost among these is the European Commission, which has established the Critical Raw Material Act (CRMA). Operating at the supranational level, the European Commission holds a crucial role in shaping policies, legislation, and regulations. Moreover, within the European Union, individual countries have their own governments. These are considered in the actor analysis as part of the European Council, where a qualified majority voting system is in place (Consilium, 2022). The European Council has the authority to reverse regulations imposed by the Commission.

Countries involved in lithium mining and processing exert influence on lithium flows throughout Europe, making their inclusion in the actor analysis essential. Consequently, these nations are considered and examined in detail in Section 2.3.4. Their impact on the European lithium landscape is a crucial aspect to be observed, emphasizing the complex interplay between global lithium-producing nations and the dynamics within the European context.

Lastly, transport companies and ports within the European Union play a pivotal role as channel for the transit of lithium in Europe. Understanding the involvement of these transport entities and ports is essential not only for tracking the physical movement of lithium but also for establishing a clear understanding of the logistical pathways through which lithium travels within the European landscape.

2.3.3. System boundaries

The MFA spans across all 27 member states of the European Union, resulting in the categorization of certain actors as external factors despite their substantial roles. Notably, lithium mines and processing facilities are predominantly situated abroad, with key players located in countries such as Australia, China, and Chile. Although geographically distant, these entities significantly influence the boundaries of the European Union's system. As a result, they are incorporated as sources of uncertainty in both the entry and exit stages of the system. Recognizing them as uncertainties acknowledges the inherent complexities introduced by these foreign actors, ensuring a more nuanced understanding of how their activities impact the overall dynamics and constraints within the European context.

2.3.4. Actor Analysis

Based on the system boundaries and sources, various actors have been identified. This is crucial for the MFA to gain a comprehensive understanding of how flows traverse through Europe. Despite the boundaries being defined by the European Union, various actors outside the EU are also described to provide a clearer picture of how lithium inflows and outflows reach the European domain.

Outside System Boundaries

The various companies listed in table 2.4 are ranked based on their total size in the domain where they operate (US Dollars) (Volta Foundation, 2023). Additionally, it describes which governments are relevant. These are considered due to potential import/export agreements with the European Union or, conversely, bans on lithium to the European Union. Some countries (China and Chile) are engaged in both mining and processing, whereas, for example, Australia and Argentina are primarily involved in mining. Furthermore, Japan and South Korea are included because they are significant players in battery production. Lastly, the United States, although not directly involved in mining or processing domestically, holds a substantial portion of the chain through entities like Albemarle. It's important to highlight that, while the European Battery production from table 2.5 may appear larger, the total delivered capacity from Chinese suppliers stands at 2293.5 GWh, surpassing that of European suppliers at 1897 GWh. This consideration includes the capacities of scheduled European factories.

Table 2.4: Actors outside boundaries

	Who?	**Sources**
lithium Mines	Albemarle SQM Allkem Livent Tianqi lithium Pilbara Minerals Mineral Resources Ganfeng lithium	CRU Group as cited by Volta Foundation (2023)
lithium Processing	SQM Albermarle Ganfeng lithium Yahua Allkem Livent CanMax Tianqi lithium	CRU Group as cited by Volta Foundation (2023)
Battery Industry	Jiangsu China (55 GWh) Zhejiang China (31 GWh) Guangdong China (28 GWh) LGES South Korea (35 GWh) Envision Japan (20.6 GWh)	CRU Group as cited by Volta Foundation (2023), (Carrara et al., 2023)
Governments	Australia Chile China Argentina Japan South-Korea United States	(Joint Research Centre, 2017), (Matos et al., 2022), (Rossi et al., 2023)

Inside system boundaries

Within the boundaries of this MFA, the following 8 main actors are considered: the European Commission, European Council, Seaports, lithium mines, Transportation Companies, Industry (both batteries and other), and Waste management. These actors are sometimes further divided into individual entities, as, for example, the industry sector encompasses multiple companies. For a complete overview of gigafactory plants and recycling companies in Europe, see Appendix A. However, throughout the progression of this actor analysis, only the 8 main actors are specifically addressed, assuming that actors within the same class will generally share similar perspectives. In this actor analysis, the inclusion of various member states is facilitated by their representation in the European Council. Although this representation simplifies the complexity of the situation, the presence of a veto right for each individual member state ensures that all countries can be adequately represented.

Table 2.5: Actors inside boundaries

	Who?	Sources
Government	European Commission European Council	
Seaports	Antwerpen Rotterdam Hamburg Valencia Pireus	(Bille, 2024), (Shiphub, 2019)
lithium Mines	Barroso - Alvão (PT) Vulcan Project (DE) Cinovec Project (CZ) The EMILI Project (FR) Wolfgang project (AT)	(Chaves et al., 2021) (Sterba et al., 2020)
Transportation Companies	MSC A.P. Moller-Maersk CMA CMG Group Cosco Evergreen	
Industry (Batteries)	PowerCo (60+60 GWh) LGES (115 GWh) Tesla (100 GWh) CATL (100 GWh) NorthVolt (60+40 GWh) ITAVOLT (70 GWh) Verkor/Renault (50 GWh)	CRU Group as cited by Volta Foundation (2023), (Carrara et al., 2023), (Joint Research Centre, 2017)
Industry (Other)	Albemarle	Interviewee S4 and S6
Waste Management	HydroVolt Bas-F Umicore Stena TES	CRU Group as cited by Volta Foundation (2023)

Resource dependency

After determining the actors, the resource dependency diagram of this thesis was created. A resource dependency diagram is a visual representation that illustrates the relationships and dependencies among various resources within a system or organization. The resource dependency of one actor in relation to a second actor depends on the importance of the resources held by the second actor and the degree to which these resources can be replaced by other resources (Enserink et al., 2022). All actors that draw an arrow to another actor exhibit a lower dependency relative to the recipient of the arrow.

In this diagram, it can be observed that the European Council and Commission have the highest dependency compared to the other groups. It is chosen that the European Council has more influence than the European Commission, because of the veto right of the Council. In reality, this situation is more complex, but for the purposes of this diagram, it is chosen this way due to the Council's ability to obstruct decisions. Outside boundaries, such as countries that extract or process lithium also have lower dependency on the commission, but are only illustrated for extra information. These actors are excluded from the stakeholder analysis. Although there is no visible arrow from the European Commission to transport companies in the diagram, an influence does exist. This thesis assumes that the Commission impacts both but opts not to display too many arrows for the sake of clarity.

Both the lithium industries, as well as waste management and lithium mines, have less dependency on transport companies and seaports compared to the other way around. This lower dependency is due to the availability of multiple companies and ports, which reduces pressure on supply security. However, waste management and European mines hold more influence over the battery industry. This is because, starting in 2031, batteries must contain at least 6% recycled lithium, and companies are keen to invest in European mines to reduce global lithium monopolies.

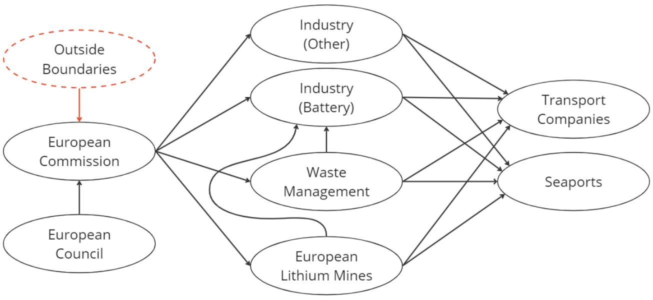


Figure 2.6: Resource interdependency diagram

Power-vs-interest matrix

The Power-Interest Matrix is a strategic tool used in stakeholder analysis to categorize stakeholders based on their level of power and interest in a given project or initiative (Bryson, 2004; Eden & Ackermann, 1998 as cited by Enserink et al. (2022)). Divided into four quadrants, it helps identify key stakeholders by assessing the combination of their influence and interest. Stakeholders with high power and high interest require close management, those with high power and low interest should be kept informed, those with low power and high interest need to be kept satisfied, and those with low power and low interest can be monitored with minimal engagement. This matrix aids organizations in tailoring their engagement strategies to effectively address the concerns and expectations of different stakeholder groups.

As depicted in the Power-vs-Interest Matrix in Figure 2.7, the EU Council, the Commission, Waste Management, lithium Mines, and the European lithium Industry are identified as key players requiring close management. This classification is based on the resource dependency diagram, highlighting that all these stakeholders collectively have significant influence—or potential influence—on the supply chain. In contrast, transportation companies and seaports are positioned with less power and interest in the matrix. This is largely because lithium constitutes only a part of their diverse product and supply chain portfolios, thus granting them less direct influence on the lithium supply chain.

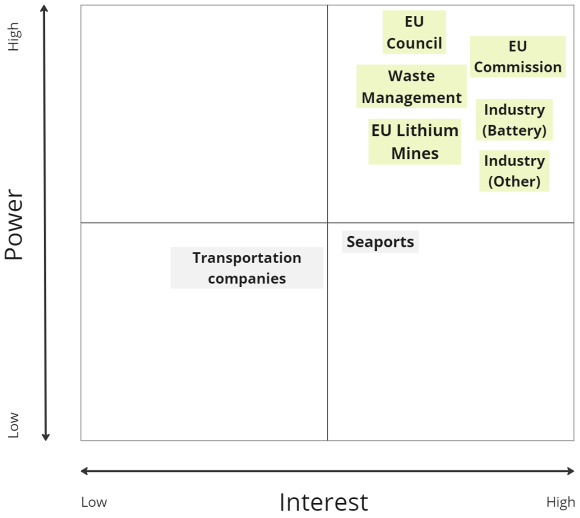


Figure 2.7: Power-vs-Interest Matrix

2.3.5. Aggregated Overview

This aggregated overview of the lithium supply chain, seen in Figure 2.8, includes all key players involved, and has been developed through a combination of supply chain analysis and actor analysis. The European Commission and Council have not been included in the diagram, as they operate across the supply chain by introducing various regulations. In the overview, a distinction is made between two lithium industries, specifically those involved with small lithium products (batteries smaller than 2 kWh and other applications) and batteries larger than 2 kWh. Seaports are not included in the overview because they are not considered 'key players' in this actor analysis. However, they still play an indirect role, as they are major entry points for the inflow of materials. The overview is highly aggregated, and therefore, it does not differentiate between individual ports.Transport companies have not been explicitly highlighted in the overview because they are not classified as key players. However, they do play an indirect role as goods are transported, and thus, their contribution is included, although in a consolidated manner within the overall analysis.

This aggregated overview of the lithium supply chain will be used as the basis for the MFA model to simulate lithium flows. By using this actor and supply chain analysis, the MFA model can more accurately represent and analyze the dynamics of lithium movements within the European context, providing valuable insights for policy development and strategic decision-making.

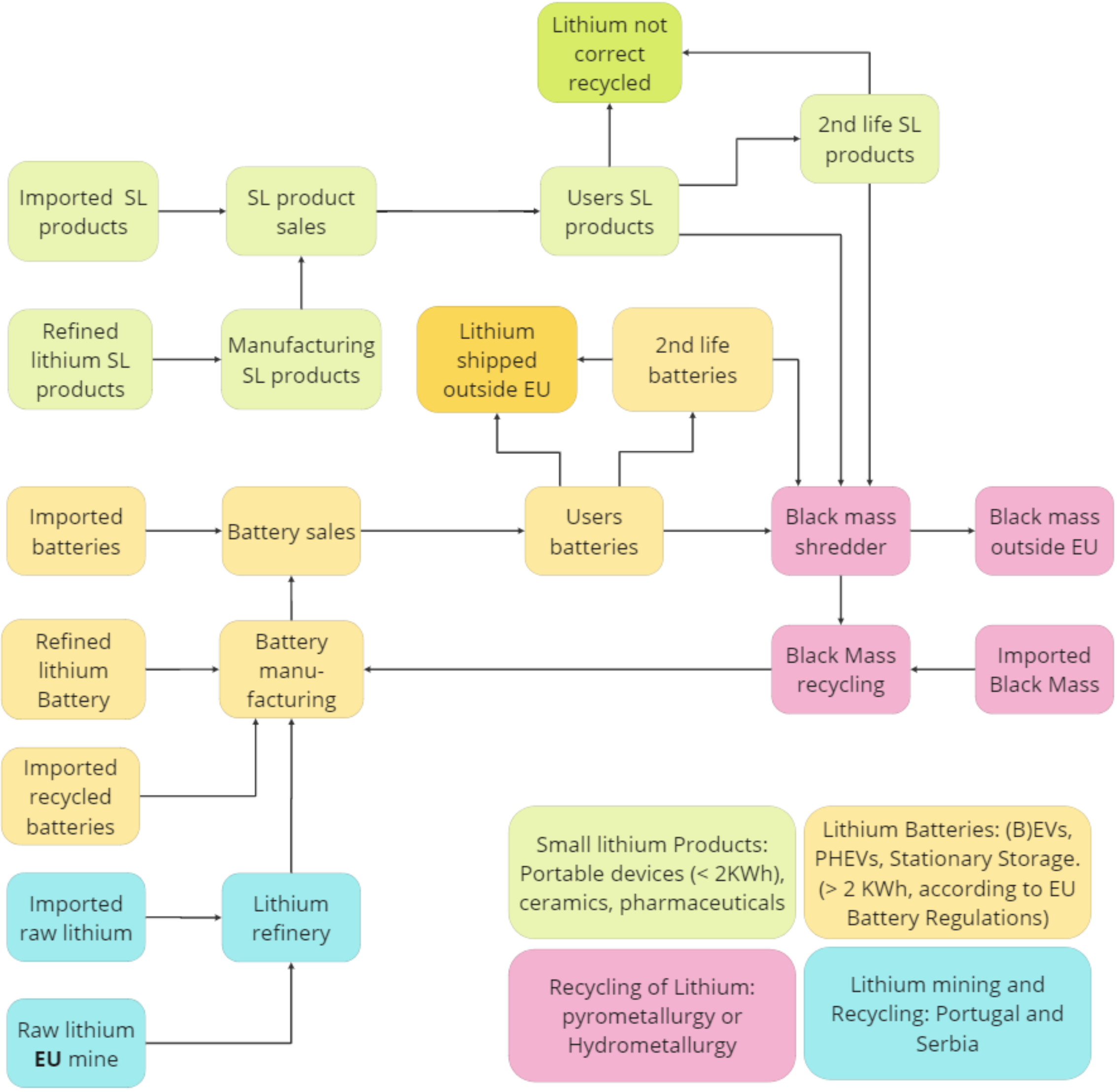


Figure 2.8: Aggregated Overview of Supply Chain lithium with key players

2.4. Literature Review

To answer the main research question, it is important not only to investigate policy and the supply chain/actors but also to determine the most suitable analytical method to use. Given the analytical nature of this research, various types of analyses, such as Material Flow Analysis (MFA) and Substance Flow Analysis (SFA), emerged as the most appropriate approaches. These methodologies are particularly effective because they provide a comprehensive view of the entire supply chain, capturing all stages of material flow, including production, usage, recycling, and disposal.

Additionally, the analytical approach of System Dynamics is considered due to its ability to incorporate delays within a system and its use of feedback loops. This method allows for the modeling of dynamic behaviors and interactions within the supply chain, providing further insights into the complexities and potential bottlenecks in material flows.

2.4.1. Modelling techniques

Material and Substance Flow Analysis

To monitor various material pathways, Material or Substance Flow Analysis (M/SFA) serves as a frequently employed tool for decision-making in material management. Both material and substance flow analyses use mass balance principles (Huang et al., 2012; Müller et al., 2014; Stanisavljevic & Brunner, 2014). Material Flow Analysis or Substance Flow Analysis (M/SFA) stands as a well-established methodology for evaluating the sustainability of socioeconomic development and environmental changes, with a particular focus on enhancing efficiency in material/substance flows (Huang et al., 2012).

The distinction between MFA and Substance Flow Analysis lies in the fact that Substance Flow Analysis monitors the flows of individual substances that obtain specific concerns related to environmental and health risks associated with their production and consumption operating on a higher aggregated level. In contrast, Material Flow Analysis purely tracks the flows of chosen raw materials or semi-finished products that raise concerns regarding the sustainability of their usage, the security of their supply to major economic sectors, and/or the environmental implications of their production and consumption (Huang et al., 2012).

The study by Stanisavljevic and Brunner (2014) demonstrates that the integration of these two analyses holds significant potential for enhancing research. This is primarily because MFA/SFA modeling, grounded in the law of conservation of matter, represents a replicable procedure: no substance flows can be lost. This attribute is particularly pertinent in decision-making processes involving stakeholders from diverse disciplines (Stanisavljevic & Brunner, 2014). Additionally, it finds extensive application in monitoring (critical) metal fluxes (Müller et al., 2014; Peiró et al., 2013; Zimmermann, 2013).

The fundamental steps of an M/SFA process encompass six key stages (Bringezu et al., (1997), Brunner and Rechberger, (2004), as cited in Huang et al. (2012)). Initially, it is crucial to establish a clear research objective and define various monitoring indicators. Subsequently, attention is directed towards scoping, outlining the boundaries, and examining the timeframe, known as system definitions. The third step involves the identification of diverse flows, processes, and stocks. Following this, the creation of a material/substance flow chart ensues. Second to last, mass balancing is applied, representing the foundational principle of this analysis. Finally, it is imperative to attain a clear visualization and interpretation of the results, drawing insightful conclusions.

Material and substance flow analysis can also incorporate scenario development (Huang et al., 2012; Stanisavljevic & Brunner, 2014). This involves, for instance, the incorporation of recycling practices into the flow analyses. Additionally, it allows for the inclusion of the impact of national or European laws and regulations on material flows.

System Dynamics

As argued in the introduction, the lithium flows through Europe are a dynamic material flow over time. To model these flows different modelling techniques can be used. One modelling technique which is considered is System Dynamics (SD). This technique was created by MIT Professor Jay W. Forrester (Forrester, 1961). System Dynamics Models uses integral techniques to simulate complex systems over time, focusing on the interactions among various elements through stocks, flows, and feedback loops.

Stocks represent accumulated resources or quantities, and flows indicate the rate at which these change. Feedback loops are critical in SD, as they can either reinforce or balance changes within the system, influencing its behavior and outcomes. This modeling approach helps in analyzing the dynamic nature of systems, making it valuable for policy analysis. The use of System Dynamics in Critical Material studies is also not new.

For example, the study by Sato and Nakata (2020) presents a model to forecast the recoverability of critical materials from electric vehicle lithium-ion batteries (LiB) in Japan. The research employs a system dynamics modeling approach to predict the volume of materials recoverable from end-of-life electric vehicles (EVs). Key findings indicate that by 2050, the volume of scrapped electric vehicle batteries will increase significantly, allowing for substantial recovery of lithium (Li), cobalt (Co), nickel (Ni), and manganese (Mn). The study highlights the importance of efficient recycling processes to minimize raw material supply risks and economic impacts, and it identifies current limitations to achieving closed-loop production in Japan. This approach underscores the potential for recycled materials to meet a significant portion of the demand for new battery production, contributing to a more sustainable and circular economy.

And the study of Keilhacker and Minner (2017) presents a system dynamics model to analyze and manage supply chain risks associated with rare earth elements (REEs), which are vital for high-tech and clean energy applications. The model simulates the dynamics of REE supply chains, including production, demand, and market fluctuations, to identify potential vulnerabilities and mitigation strategies. The research highlights key supply chain vulnerabilities such as geopolitical risks and production concentration in specific countries. It evaluates various risk mitigation strategies, including diversification of supply sources, development of alternative materials, and investment in recycling technologies. The findings provide insights for policymakers on reducing dependence on REE imports through strategic stockpiling, supporting domestic production, and fostering international cooperation, demonstrating the effectiveness of system dynamics modeling in enhancing supply chain resilience.

2.4.2. Justification MFA

After investigating all three methods, MFA is chosen to answer the main question of this research: What policies can influence the material flows of lithium in Europe and have a positive impact on the CRMA benchmarks? MFA provides a comprehensive and systematic method to quantify and map the flows and stocks of lithium throughout its life cycle. This includes stages such as extraction, processing, usage, recycling, and disposal. By offering a detailed overview of these stages, MFA helps in understanding the current state of lithium flows in Europe and assessing the impact of various policies on each stage of the supply chain. Furthermore, MFA is essential for identifying bottlenecks and inefficiencies within the supply chain, which is crucial for developing targeted policies to enhance efficiency and resilience. The aggregated implementation of MFA allows for a thorough examination of the entire supply chain, integrating data from diverse sources to provide a detailed picture of material flows. This research focuses on the material aspects of policy impacts and does not delve into financial stimulants.

A MFA is chosen over the the other techniques because of its ability to create a structured overview of all flows of lithium over time. The use of a Substance Flow Analysis is taken into account, however because this research is purely focusing on the change in flows and not in the potential environmental impacts, MFA is chosen over SFA. However, investigating environmental impact of lithium mining could interesting to investigate in the future.

System Dynamics is also not chosen because a system dynamics model also takes into account possible feedback loops and the use of non-material variables, such as consumer behaviour. This research requires detailed material flow information and direct policy application without the need for dynamic system behavior modeling, making SD the more complicated version. However, delay times, which are a crucial part of SD can be beneficial for the MFA. That is why this research incorporates delays in the system. This because delays in the lithium supply chain would give a more comprehensive idea of how the system would work.

2.4.3. State of the Art MFA lithium

To gain a understanding of MFA and the research that has employed this methodology, this section presents a literature review on the state-of-the-art in MFA of lithium. The review aims to identify previous applications of MFA, particularly in the context of the critical material lithium, and lastly to highlight any gaps in the current body of knowledge.

A more in-depth search is conducted to explore Material Flow Analysis (MFA) in Europe for lithium and MFA with policy scenarios. The search queries are: ”Material Flow Analysis lithium Europe” OR ”Material Flow Analysis Policy Scenarios lithium” OR ”Material Flow Analysis Policy Scenarios”. The latter to get a better understanding of implementation of policy scenarios in MFA. To exclude non-relevant articles, a search criterion was added to consider papers published from 2000 until now. This is to prevent significant lithium discoveries from being excluded in the literature review. The approach was used in all search procedures, using the search engines Scopus and Google Scholar.

Material Flow Analysis of lithium

When searching for Material Flow Analysis for lithium in Europe there are material flow analyses available about lithium in general. In 2012, Zieman et al. conducted an initial study on a global material flow analysis for lithium. This was further developed by Sun et al. (2017), who examined a trade-linked material flow analysis for global lithium flow. It describes lithium carbonate, ore, and concentrate, constituting 67% of the total trade volume. Europe has the largest international trade proportion at 15.51%. It is also emphasized that an improved recycling system is of significant necessity in this context.

Material Flow Analysis of lithium-Ion Batteries

When searching for Material Flow Analysis for lithium in Europe, numerous sources related to lithium that emerge are specifically focused on lithium-Ion Batteries. This is unsurprising. The International Energy Agency (IEA) estimates that by 2030, 82% of the total demand for lithium will be directed towards battery storage (IEA, 2020), with the majority allocated to electric vehicles (EVs). Additionally, the transportation sector contributes to 30% of the greenhouse gas emissions at the European level (Rossi et al., 2023).

The study of Bruno and Fiore (2023) focuses on Material Flow Analysis (MFA) for the recycling of lithium-Ion batteries in Electric Vehicles (EVs) in Europe. The study of Bruno and Fiore assumes in their study a 42% recycling rate for lithium in the batteries. This is mainly based on the assumption of pyro-metallurgic treatment instead of hydro-metallurgic. However, in newer recycling studies the potential of hydro-metallurgic treatment is underlined. The recovery rates of this treatment lies around 95-99% (J. Liu et al., 2020; Quan et al., 2022). The biggest bottleneck found in the study of Bruno and Fiore (2023) is that a significant portion of waste is not being classified as ’waste,’ the primary challenge in recycling lies in investing in a larger waste collection system. This issue is not unique to Europe. The paper of Song et al. (2019) also describe a 40% lithium recycling rate in China, with usage of pyrometallurgic threatment. However, this paper highlights the absence of proper waste management there as well. Zong et al. (2023) describe in another study a scenario analysis with MFA under the framework of China’s recycling policies. China has issued a series of laws and regulations to manage spent power on lithium-Ion batteries (Zong et al., 2023). These regulations have been used as input for the MFA.

Rossi et al. (2023) describe an optimization model for European batteries using Material Flow Analysis and a Life Cycle Assessment (LCA). Here, the new goals of the European Green Deal are mentioned, but the focus is solely on batteries. Attention is given to recycling, which has significant potential to make the European Union self-sufficient. In the Reference Scenario, designed to mirror European policies, the results indicate that Europe would attain high self-sufficiency from external producers (Rossi et al., 2023). This study did not scope that additional possibilities have emerged since then, such as mining on European territory, which is one of the main pillars of the CRMA.

Matos et al. (2022) describes in their research a Material Flow Analysis of lithium-Ion batteries in Europe, including the raw materials required. The study identifies the major operating facilities in the European Union producing Li-Ion batteries, with Li-ion cells currently located in Hungary, France, Germany, Poland, and Sweden (Roskill, 2019; Steen et al., 2017 as cited in Matos et al. (2022)). Recent projections indicate that Europe is set to increase its installed lithium-Ion Battery (LIB) manufacturing capacity from 48 GWh in 2020 to 670 GWh in 2030, eventually reaching 1100 GWh in 2040 (Fraser et al., 2021; Tsiropoulos et al., 2018 as cited in Matos et al. (2022)). These assumptions are also underlined in the European Net Zero Industry Act (NZIA), as seen in paragraph 2.2.2.

Source:	MFA of:	Boundaries:
Zieman et al. (2012)	lithium	Global
Sun et al. (2017)	Traded lithium	Global
Bruno and Fiore (2023)	Li-Ion Battery recycling	Europe
Song et al. (2019)	Li-Ion Batteries	China
Zong et al. (2023)	Li-Ion Battery recycling	China
Rossi et al. (2023)	Environmental optimization for Li-Ion batteries (Combination MFA and LCA)	Europe
Matos et al. (2023)	Li-Ion batteries	Europe

Table 2.6: Summary of MFA Studies

2.5. Knowledge gap

Since the introduction of the Green Deal in 2020, there has been a growing recognition of the importance of Net-Zero technologies for the green transition. Policies such as the Critical Raw Materials Act (CRMA), the Net-Zero Industry Act (NZIA), and the Battery Regulations are clear responses to this, aiming to increase autonomy in materials critical for these Net-Zero technologies. Moreover, the European supply chain for lithium has significantly expanded and transformed in recent years, driven by the growing demand for technologies like Electric Vehicles (EVs).

The implementation of MFA for materials like lithium is not new. MFA has proven to be a valuable tool, as evidenced by the literature, chosen over Substance Flow Analysis (SFA) due to its ability to track flows of raw materials and semi-finished products. While SFA focuses on measuring environmental and health risks, this research centers on the material aspects, making MFA the more suitable approach. Various MFAs have been conducted on global lithium flows and lithium batteries within the European Union, as seen in Figure 2.6. However, there is a notable knowledge gap in a complete MFA of all lithium flows in Europe, encompassing both batteries and other products. Additionally, the CRMA benchmarks have never been integrated into an MFA.

This research does not use System Dynamics to analyze the main question. However, the added value of considering delay times is acknowledged, even in a MFA. Although this is not typically done in an MFA, this study employs a dynamic MFA over time. Introducing delays, such as from the factory to the user or from the user to the recycling plant, provides a more realistic picture of how lithium moves through Europe. Therefore, the decision was made to model the MFA using the System Dynamics program Vensim. This program is an excellent tool for incorporating delays while still adhering to the MFA framework, focusing solely on material movements over time.

This preliminary research hypothesizes that implementing an MFA for these lithium flows, combined with the latest information from the supply chain and actors, could be a valuable contribution to the scientific community. This implementation could potentially aid in better tracking lithium flows and thus support the CRMA benchmarks. By providing a detailed and systematic understanding of lithium material flows, this research aims to enhance strategic decision-making and contribute to achieving the goals of increased autonomy and sustainability in the European lithium supply chain.

3
Material Flow Analysis

To address the subquestion, ”What are the current lithium flows through Europe, and how do they influence the achievement of CRMA benchmarks?” a Material Flow Analysis (MFA) has been developed. This MFA is constructed without incorporating the benchmarks established by the CRMA, allowing it to serve as baseline scenarios. The section is structured to first outline the methodology used in the analysis, followed by a presentation of the results.

3.1. Methodology

This section provides a detailed overview of the data collection methods, modeling techniques, and the conceptual MFA baseline model used in the study. Additionally, it delves into each of the sub models, describing them in greater depth. This thorough explanation ensures a clear understanding of how the data was gathered, the assumptions made during modeling, and the specific methodology employed to analyze the lithium flows through Europe. By outlining each component, the section aims to offer transparency and insight into the study's analytical framework.

3.1.1. Data Collection

Literature

In Chapter 2.3, a comprehensive Actor and supply chain analysis has been conducted. This analysis serves as the foundation for the subsequent MFA as the aggregated overview of Figure 2.8 is used as the basis for the supply chain. To enhance our understanding of the system's dynamics additional literature has been reviewed, such as transportation and manufacturing times and about battery chemistry's. An overview of all the literature utilized in the MFA is presented in Table 3.1.

Table 3.1: Literature on Modeling Techniques and Conceptual Models

Modeling techniques	(Forrester, 1961); (Müller et al., 2014); (Huang et al., 2012)
Conceptual Model	(Ventana Systems, 2010); (European Commission, 2024); (Xu et al., 2020); (IEA, 2020); (Volta Foundation, 2023)
Conventions	(Ventana Systems, 2010)
Submodels	(Xu et al., 2020); (Rossi et al., 2023); (Matos et al., 2022); (Joint Research Centre et al., 2020); (Zong et al., 2023); (European Commission, 2023c); (Barboza, 2016); (Polák & Drápalová, 2012); (IEA, 2020); (European Commission, 2023b)

Interviews

To complement and verify the findings from the literature review, semi-structured interviews were conducted with various stakeholders. These stakeholders included policymakers and industry representatives. The interviews were designed to gather diverse perspectives and insights, enhancing the robustness of the model by incorporating firsthand accounts and experiences from key figures directly involved in the lithium market. This approach ensured that the study not only relied on published sources but also included current, real-world viewpoints from influential participants in the policy and industrial sectors. In Table 3.2 an overview of interviewees is displayed. Anonymous summaries of the interviews can be found in Appendix C.

Table 3.2: Interviewees MFA

Interviewee	Specialization
S1	Professor in Critical Materials
S2 and S3	Industry experts in Minerals Mining
S5	European Battery Expert

3.1.2. Core Assumptions

A highly aggregated conceptualisation of the model is shown in Figure 2.8 in the previous chapter. The MFA is created in the modelling software Vensim (Ventana Systems, 2010). Using Vensim for MFA provides several key advantages. It excels in dynamic modeling, allowing for accurate simulation of material flows over time and the incorporation of delays, such as from production to recycling, for a more realistic depiction. Vensim's powerful visualization tools enhance understanding and communication of the system's material flows. Additionally, its user-friendly interface simplifies model building and analysis, making it accessible even for those not expert in system dynamics. These features make Vensim a valuable tool for conducting detailed and insightful MFA. More about the modelling conventions of Vensim in Paragraph 3.1.4.

This MFA is based on the work of the International Energy Agency (IEA) scenarios of Stated Policy Scenario (STEP) and Sustainable development Scenario (SD). As described on the website of the IEA, The STEPS scenario provides a more conservative benchmark for the future by not taking for granted that governments will reach all announced goals. Full implementation cannot be taken for granted, so the prospects and timing for their realisation are based upon our assessment of countries' relevant regulatory, market, infrastructure and financial circumstances. The Sustainable Development Scenario describes the broad evolution of the energy sector that would be required to reach the key energy-related goals of the United Nations, including the climate goal of the Paris Agreement (SDG 13), universal access to modern energy by 2030 (SDG 7), and a dramatic reduction in energy-related air pollution and the associated impacts on public health (SDG 3.9). Both scenarios describe different amounts of lithium used in the worldly market for batteries, which mainly focuses on different amount electrification of the market.

In combination with the two different IEA scenarios, also two different battery chemistries are discussed as possible 'market leaders'. Xu et al. (2020) identify three leading battery chemistries in the market: LFP batteries, NCX batteries (combination of both NCM and NCA battery types), and Li-Air/S batteries, which can be seen in Figure 3.1. Although Li-Air/S batteries are still in development, interviews with Interviewees S1, S2, S3, and S5 indicate that Li-Air batteries are unlikely to play a significant role in the future due to a decline in investment. Consequently, this research does not consider Li-Air batteries in its analysis.

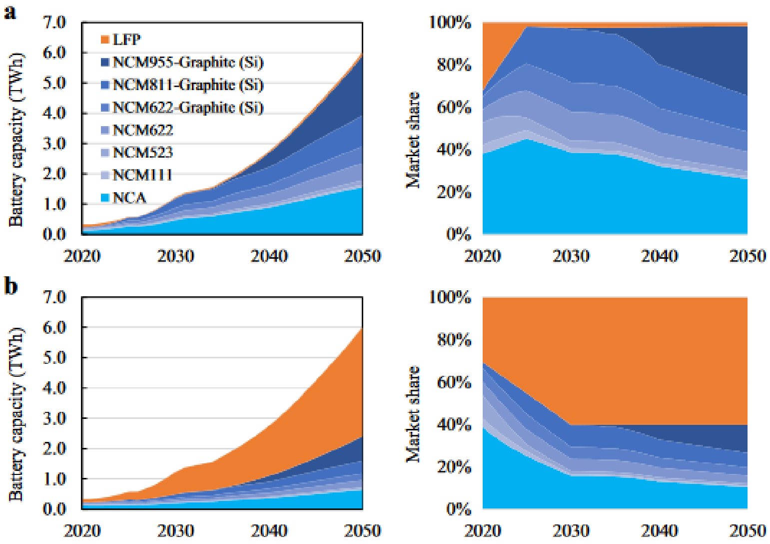


Figure 3.1: Percentages of battery chemistries related to total demand of battery, as cited by Xu et al. (2020). **a** NCX scenario, **b** LFP scenario.

The scenarios described in Xu et al. (2020) creates different market leaders (NCX or LFP) but does not say that there will be a 100% market monopoly by one of the two chemistries. This overview of the predictions of percentages of total battery capacity (TWh) of wordly demand per battery chemistry can also be seen in Figure 3.1.

All calculations are made with the unit kilotonnes lithium Carbonate Equivalent (LCE). In the lithium sector this is an standardization of all different lithium chemistry's such as lithium Hydroxide, lithium Carbonate and lithium Oxide. The report of Volta Foundation (2023) describes the different conversion rates which apply for the different chemistry's to LCE. Not only is it the standardized way of calculating lithium equivalents, it also creates standardization of units within the material flow.

Table 3.3: Lithium Conversion rates as described in Volta battery report (2023)

Convert from		Convert to Li	Convert to Li2O	Convert to Li2CO3	Convert to LiOH
Lithium	Li	1.000	2.153	5.323	3.448
Lithium Oxide	Li2O	0.464	1.000	2.473	1.601
Lithium Carbonate	Li2CO3	0.188	0.404	1.000	0.648
Lithium Hydroxide	LiOH	0.290	10.625	1.544	1.000

The system boundaries of this model are bounded by the CRMA. This, because of that the regulations only apply for the 27 member state of the Union and without its overseas territories, as they are not part of the European Union's internal market (European Commission, 2024).

The timeframe selected for this system spans from 2020 to 2050. This period aligns with both scenarios from the International Energy Agency (IEA)—the STEP and SD scenarios—which project estimates up to 2050. Additionally, the battery chemistries described by Xu et al. (2020) only extend their market leader projections to 2050. Beyond 2050, data becomes scarce, and market forecasts are increasingly uncertain due to potential technological advancements that have not yet been realized.

The initial values of the system are based on 2019 data of the IEA and literature. All initial values are described in appendix A.

The MFA is divided into four different sub models which interact with each other. The first two sub models are 'Small lithium products' and 'lithium batteries'. There is a difference between these two due to a lifetime variation between big batteries, for instance batteries inside EVs, and other uses, such as portable devices but also ceramics and pharmaceuticals. Not only the lifetime is different, also different legislation applies to them. Because of the EU Battery Regulations (seen in paragraph 2.1), batteries with a higher capacity than 2 KWh need to have 6% of recycled lithium of total lithium of the batteries from 2031 onwards. Because of this variation of lifetime and regulations, small lithium products and batteries are divided into two different sub models. After lithium products (both batteries as smaller products) reach End of Life (EoL) the recycling submodel comes into play. This submodel describes how lithium is recycled in Europe. The last submodel is the mining and refinery facilities in the European Union. Currently, almost every lithium chemical is imported from elsewhere in the world. However, in the CRMA the benchmark 10% of extraction of lithium inside the European union is adopted, creating a boost in mining and refinery industry in the upcoming years. All different sub models are discussed more in depth in the next paragraph, paragraph 3.1.5.

3.1.3. Experimental Design

The scenarios from the IEA and the battery chemistries described in Chapter 3.1.2 are combined in this research into four different scenarios. This approach aims to clearly describe the uncertainty in both government intervention and the dominance of battery chemistry's. By running these different scenarios, the research addresses this uncertainty. Table 3.4 provides a description of all four scenarios.

Table 3.4: Description of the Scenarios

Run Name	Explanation
NCX - STEP	Combination of the Stated Policy Scenario from the IEA and NCX as dominant battery chemistry
NCX - SD	Combination of the Sustainable Development Scenario of the IEA and NCX as dominant battery chemistry
LFP - STEP	Combination of the Stated Policy Scenario from the IEA and LFP as dominant battery chemistry
LFP - SD	Combination of the Sustainable Development Scenario of the IEA and LFP as dominant battery chemistry

3.1.4. Modelling conventions

Since the System Dynamics program Vensim (Ventana Systems, 2010) is used, it is useful to briefly explain the conventions associated with it. Utilizing Vensim allows us to easily manage the stocks and flows that play a significant role in SD, but also in MFAs. This facilitation aids in effectively modeling and simulating complex systems by visualizing the various components and their interactions.

The key component of MFA is the stocks that are connected to flows. This connection results in the accumulation of material in a stock when the inflow exceeds the outflow, or conversely, the stock depletes if the outflow exceeds the inflow. The behavior of a stock is mathematically defined by an integral equation, which calculates the total amount of material $s(t)$ within the stock over time, factoring in both inputs $f(t)$ and outputs $g(t)$, and the initial value $s(t_0)$:

$$s(t) = s(t_0) + \int_{t_0}^{t} f(t) - g(t)dt \tag{3.1}$$

Given the complexity of a large model, which involves numerous calculations, the program Vensim uses numerical integration to manage these computations. Specifically, this model employs Euler Integration because the derivatives of some variables within the model are discontinuous. Euler Integration is a straightforward method that calculates the next value of a variable by taking the current value and adding the product of the derivative and the time step, making it suitable for dealing with abrupt changes in models.

Since a MFA solely focuses on inflows and outflows without incorporating feedback loops, it cannot be classified as a traditional system dynamics model. However, the use of delays is implemented, which can lead to the accumulation of material in a stock. This is reflective of real-world scenarios, such as the lifespan of batteries, where not all material immediately exits the system. These delays model the temporal distribution of material throughput and storage, capturing the time-lag effects that are critical for accurately representing system behavior over time.

In this analysis, we specifically use 3rd order and pipeline delays, as they best represent the dynamics within our system. 3rd order delays involve three sequential stages, adding inertia to the system and smoothing out fluctuations in flows, which is useful for processes where delays naturally occur, such as in production. Pipeline delays, on the other hand, model continuous, uninterrupted flows through a system, like material moving through a manufacturing line. While first order delays were considered, they were ultimately not used as they oversimplify the system dynamics. First order delays assume immediate and uniform mixing of inputs, which does not adequately capture the layered and sequential nature of the processes we are modeling.

3.1.5. Sub models

In this section, all different sub models are described. To maintain clarity and focus on the narrative, not all formulas have been included in the text. A comprehensive overview of the formulas used in the model is available in appendix A. This approach ensures that the main text remains readable while providing detailed technical information for those interested in the specific calculations behind the model.

European battery demand

The European Battery Demand is a small submodel within the overall model that accounts for a portion of the inflow streams. This demand is determined based on the global demand for batteries as described in Xu et al. (2020), which provides annual demand projections for four scenarios (NCX STEP, NCX SD, LFP STEP, and LFP SD) from 2020 to 2050. Rossi et al. (2023) further detail the specific portion of this demand attributed to Europe, which is 6% in 2020, increasing to 16% by 2030. Rossi's paper assumes that this demand will continue to grow at the same linear trend beyond 2030. In this study, we assume a growth rate that is half as rapid. Additionally, the value of lithium metal is converted to LCE using the 'Li Metal Converter' to standardize the input data for our analysis.

Small lithium products

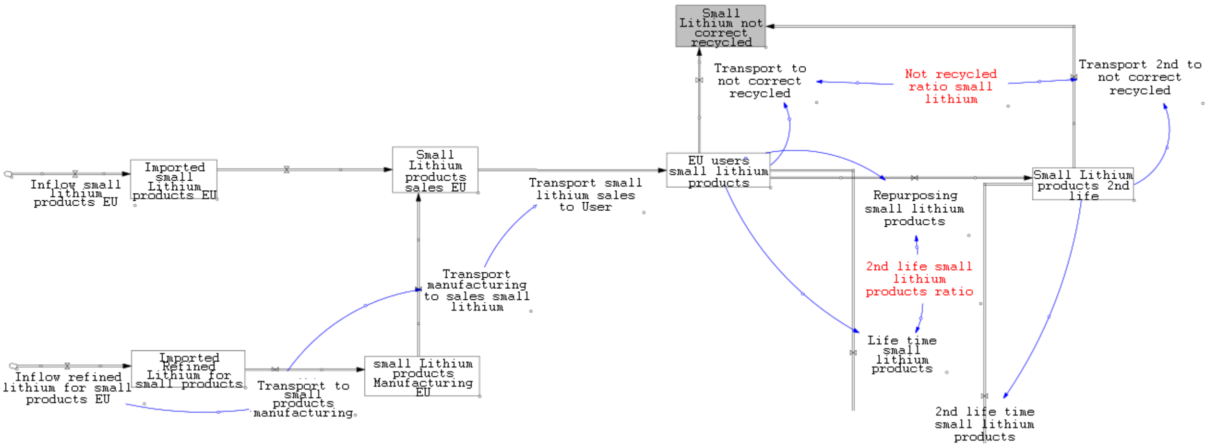


Figure 3.2: Submodel: Small lithium Products

In the 'Small lithium Products' framework, there are two distinct inflows contributing to the flow of LCE. These are imported small lithium products and inflow of refined 'lithium for small products'. Both ultimately contribute to 'small lithium product sales in the EU'. The route is divided into two different flows because one (Imported small lithium products) involves importing finished small lithium products into Europe, while the other flow includes lithium chemistries that are first processed into products before entering the European consumer circuit. Both inflows are based on the European Battery Demand and the percentages allocated to small lithium products according to the IEA. These are divided into percentages for the STEP and SD scenarios. Additionally, the inflows are split between imported small lithium products and products manufactured locally. The products made locally account for only a small portion (20%) of the total. Comparable values can be seen in the report of Joint Research Centre et al. (2020). This is underscored by interviewee S4, who also observes that small lithium products, such as portable devices, are predominantly manufactured abroad.

Although small lithium products include more than just batteries smaller than 2 kWh, such as lithium in ceramics or pharmaceuticals, the decision was made to base the delay time of this entire submodel on the production process of portable devices (like mobile phones). This choice is supported by the interviewed battery expert S4, who noted that the majority of 'small' lithium products (approximately 70%) are portable devices.

The production time for making a portable device varies but generally peaks at around one month, as noted by Barboza (2016). Taking the iPhone as an example, the production process involves several steps: manufacturing the iPhone, then transporting it to a storage facility near an airport, followed by shipping it to a distribution center in the country of sale, and finally delivering it to the retail store where it is purchased by the customer. Part of this chain occurs outside Europe, which shortens the actual delay time in the system to three weeks. However, the various steps that still fall within the system's boundaries (landing of the product and customs clearance, moving to the distribution center, and transporting to the sales point) justify the decision to implement a 3rd order delay in the system.

For the production of 'small lithium products' within the European Union, lithium chemicals are imported into Europe, where products are subsequently manufactured. The production of these products in Europe takes longer than if the products were to arrive finished on the European mainland. A 3rd order delay has also been selected for the transportation of lithium to the manufacturer. This is the same for the the transport from EU manufacturing to sales. The production itself could be seen as a pipeline delay, however, more steps are involved, so modeling it in a pipeline delay would be sufficient.

After the sales process, the product is transferred to its owner. The average lifespan of a mobile phone is four years (Polák & Drápalová, 2012), after which it faces three possible outcomes within this system. First, the phone may not be properly recycled, which can occur if it is thrown away with regular waste. This is a relatively big proportion as almost 80% of small lithium products are thrown away after use (J. Liu et al., 2020). Alternatively, the phone can be given a second life, extending its lifespan with approximately 3 years through measures such as the addition of a new battery. It may also be directly recycled. Even after a potential second life, there is still a chance that the phone will not be properly recycled. This model assumes that the order of delay for usage of small lithium products is a 1st order delay, assuming that the products stays with its first owner.

An overview of all used variables in the system with its sources can be seen in appendix A.

Lithium Batteries

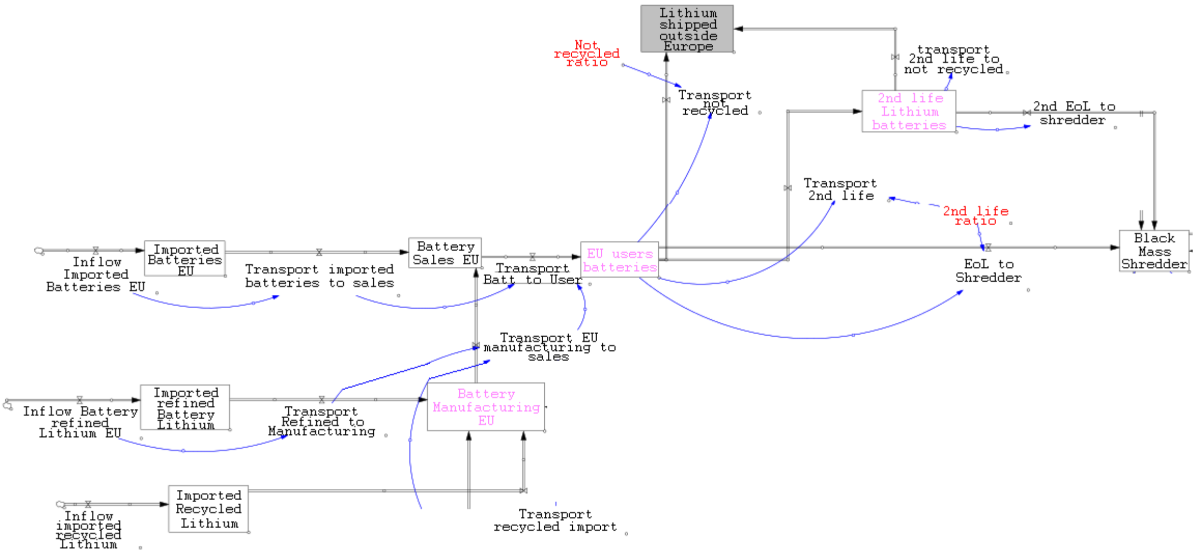


Figure 3.3: Submodel: Lithium Batteries

This sub model of the MFA has three distinct inputs. Firstly, there is an inflow of imported batteries manufactured elsewhere in the world. Secondly, similar to the case with 'small lithium products', refined lithium is also imported. This lithium is used for the production of batteries within Europe. Lastly, there is an inflow of recycled lithium, which, starting from 2031, can be used if the EU does not have enough recycled lithium. The inflow of refined lithium is based on the capacity of Gigafactories in the EU, measured in GWh. Additionally, scenarios are made depending on which technology is the market leader. The inflow of imported batteries is based upon the difference between the European demand for batteries and the total amount of LCE in batteries produced within the EU.

The time it takes to manufacture a battery varies depending on the type of battery and the product in which it will be used. For this MFA, the production time of a battery for an Electric Vehicle (EV) is considered as the actual production time. This is because the vast majority of batteries, approximately 85% (Interviewee S4), are used for this application. Manufacturing time for self-configured cars are around the 3 till 6 months (Gellendin, 2021), which is also underlined by Interviewee S4. As in other sub models, some steps are combined here as well, and higher-order (3rd order) delays are employed.

The recycling inflow is directly linked to the inflow of recycled black mass within the EU, governed by the Battery Regulations Act. By the year 2031, the Act requires that batteries must contain at least 6% recycled lithium, a percentage that is double in 2036. If the internal European recycling efforts fail to meet this demand, imported recycled lithium will be utilized to fill the shortfall. This regulatory requirement ensures a minimum threshold for the inclusion of recycled materials in battery production.

Once manufactured, the batteries are directed to ’Battery Sales EU’. After a 3rd order selling delay of three months, they are distributed to EU users. Post-consumption, the used batteries have three potential outflows: they can be shipped outside of Europe, given a second life, or sent to the recycling submodel of this MFA. If the lithium receives a second life, it still may eventually be either shipped outside of Europe or sent to the recycling submodel. All lithium that is not correctly recycled becomes part of the ‘shipped outside of Europe’ outflow. According to Battery Expert S4, this is around one third of all cars reaching EoL.

An overview of all used variables in the system with its sources can be seen in Appendix A.

Recycling

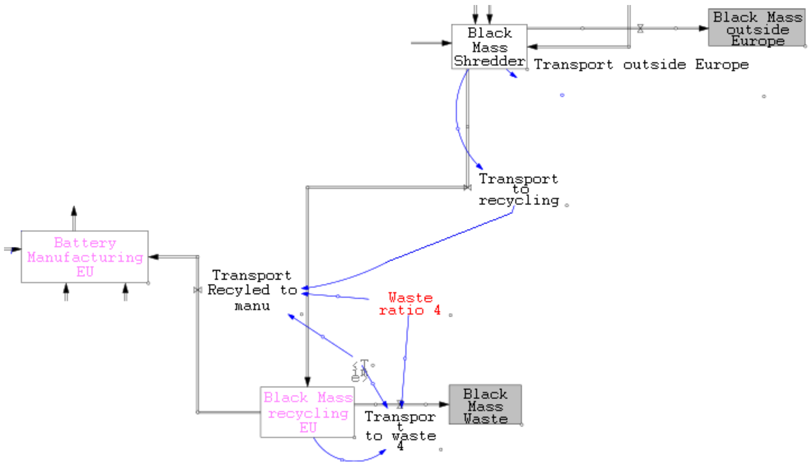


Figure 3.4: Submodel: Recycling

Once all the lithium is accounted for—assuming it has been correctly recycled and not exported—the material is processed into what’s known as black mass at the ’Black Mass Shredder’ in this model. The inflow of this stock are all flows from the sub models ’small lithium products’ and ’batteries’. However, this stage doesn’t guarantee that the material will stay within European borders. The amount of black mass that goes to European recyclers after shredding depends on the capacity of European recycling facilities. According to the Joint Research Centre et al. (2020), there has been no significant progress in establishing new recycling facilities for lithium. However, the Report of the Volta Foundation (2023) and Battery News (2023) indicate that the number of these facilities are expected to increase in the near future. The remainder of the black mass is moved out of Europe to be recycled in other locations outside of Europe.

If the black mass remains in Europe, it’s taken to ’black mass recycling EU’ facilities, where it undergoes a recycling process to convert it back into a form usable for battery production. The rate of waste from this process is expected to decline significantly between 2030 to 2050. Currently, pyrometallurgy, which has a recovery rate of 40-45%, is the predominant technology in use. However, projections indicate a shift towards hydrometallurgy and direct recycling techniques by 2030-2040, which boast an impressive 95-99% recovery rate (Matos et al., 2022; Zong et al., 2023). The reason this has not yet occurred is due to the high costs of constructing new recycling facilities combined with an insufficient supply of recyclable lithium.

As the recycled black mass is reintroduced into the production cycle, it enters back into ’Battery Manufacturing EU’. There is also potential 2nd inflow for ’Imported Black Mass’ to enter the system in the future. This depends also on the capacity to recycle in Europe. While this pathway is not currently active, it stands as a prospective alternative should the need arise to supplement the European supply, ensuring that the battery manufacturing industry has a steady stream of materials.

This sub model features two distinct inflows: the inflow from lithium mining within Europe, and the inflow of raw lithium sourced from outside Europe, which could potentially be refined in Europe. The refining stock exclusively supplies to the battery manufacturing sector and not to small lithium product manufacturers. This specification aligns with the stipulations of the CRMA, which designates only battery-grade lithium as a SRM. Consequently, if this industry segment is to expand, it will specifically increase the production of battery-grade lithium.

An overview of all used variables in the system with its sources can be seen in Appendix A.

Refining

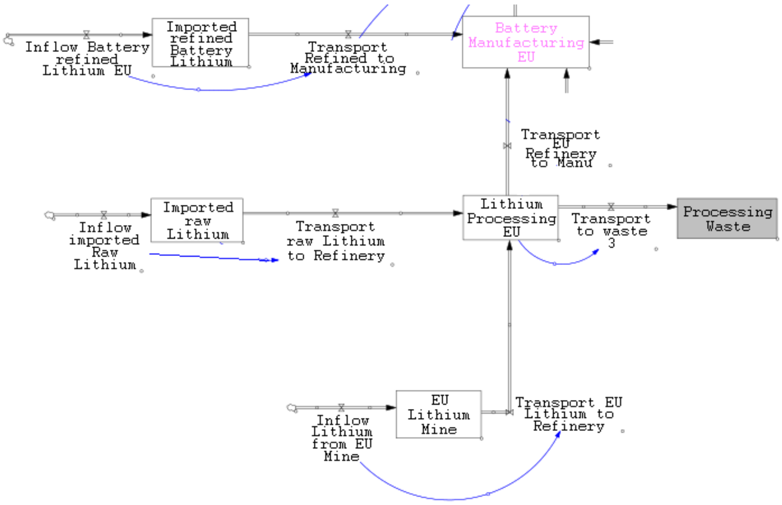


Figure 3.5: Submodel: Mining and refineries

The final sub model of this MFA focuses on mining and refining. In all base line scenarios, this sub model will have minimal impact on the system due to the very limited amount of lithium mined in Europe. According to the European Raw Materials Information System (RMIS) (European Commission, 2023c), currently, only 1.5 kT of LCE is mined (2019). However, this sub model is a crucial component of implementation of CRMA regulation, where benchmarks for processing and extracting will need to be integrated.

The same applies to the refinery, or processing, segment of this sub model. In 2019, there were almost no facilities processing battery-grade lithium, and to date, no plans have been made to establish lithium refineries in the EU. There is one facility operated by Albemarle (US) in Langelsheim, Germany; however, this facility is mainly used for processing lithium for ceramics, placing its biggest proportion within the small lithium products sub model.

An overview of all used variables in the system with its sources can be seen in Appendix A.

CRMA Benchmarks

The benchmarks for the CRMA are calculated by dividing the total inflow of demand from users (including both batteries and small lithium products) by the specific flows that pertain to the benchmarks. These flows include extraction, processing, and recycling. This method allows for the calculation of benchmark percentages for all three aspects, providing a clear measurement framework to assess the effectiveness in each area.

The final benchmark, which pertains to the diversification of third-country suppliers, cannot be calculated through this MFA. This limitation arises because the scope of this research focuses on flows that pass through Europe, resulting in foreign suppliers falling outside the system boundaries. Consequently, this aspect of the benchmark remains unaddressed within the boundaries of the current study parameters.

3.2. Verification and Validation of the model

To ensure that the model operates without errors within its boundaries, a verification was conducted. A unit consistency test was performed by checking that Vensim does not report any unit errors, and this was also mentally verified. Additionally, the time step was checked and set to 0.015625 to ensure model stability without being unnecessarily small, thus avoiding excessive computational demands. Finally, a structure-verification test was conducted to ensure that no material is lost in the MFA. All three tests are detailed in Appendix B.

The validation of this model consists of four different tests designed to ensure its fitness for purpose. A model can be invalid or incorrect in various ways, and is always a simplification of reality. However, by checking its fitness for purpose, this research can better determine if the model can properly analyze the main question.

First, the structure-verification test checks whether the model accurately reflects other models and whether it has support. Next, a boundary adequacy test is conducted to ensure that all relationships and variables necessary for accurately describing how the system works are included in the model. It is crucial to assess the level of aggregation to ensure no important components are missing. The extreme values test examines whether the system still produces real-world outcomes when subjected to nearly impossible values. For example, it tests the system's response to a total stop in lithium imports. Lastly, a sensitivity analysis is conducted to identify potential critical points in the system. This involves adjusting certain values by 10% to observe the system's response. The goal is to ensure that the model exhibits only numerical sensitivity, not behavioral sensitivity, to prevent excessive sensitivity.

Making a model fit for purpose does not mean that the model is completely accurate. As mentioned earlier, a model is never the exact reality but merely attempts to replicate it. According to this research and the various tests conducted, this model appears to be fit for purpose. Based on this validation, the model should answer the research question. A more detailed report of all the tests can be found in Appendix B.

3.3. Results

3.3.1. CRMA Benchmarks

Figure 3.6 shows the benchmark for extraction over time. The different scenarios are based on the battery chemistry (NCX/LFP) and the demand scenarios (STEP/SD) as described the methodology of this chapter. The CRMA benchmark for extraction starts at a relatively high percentage. This is because the input of lithium from Europe (specifically from the Portuguese mine) is relatively high compared to the small European demand in the early years of the timeframe of this model. However, this demand grows exponentially over the years, and under current policies, no new mines are being developed. This leads to a steep decline in the extraction percentage.

The difference between the SD and STEP scenarios is greater than the differences between the battery chemistry's. This is because European extraction is divided by total European consumption. The total consumption for SD is higher than for STEP, creating this disparity. In none of the scenarios, according to the Figure, the Extraction benchmark to produce at least 10% of the Union's annual consumption after 2030 seems to be met.

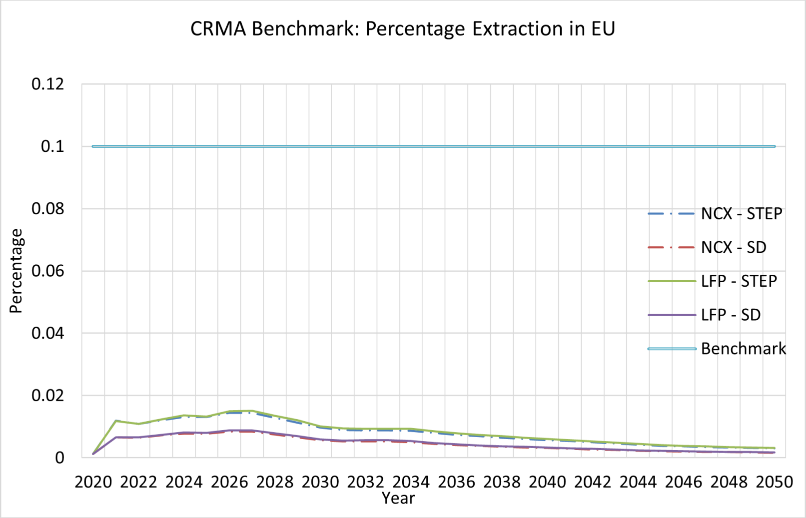


Figure 3.6: CRMA Benchmark: Extracted

The same reasoning applies to a small increase in the CRMA benchmark for processing lithium. However, as seen in Figure 3.7, the percentage is very low compared to the CRMA benchmark and degrades over time, but is never zero.

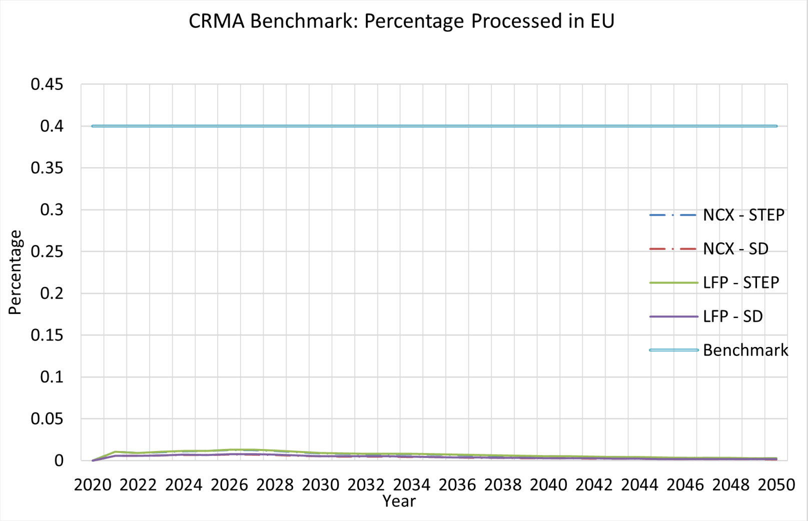


Figure 3.7: CRMA Benchmark: Processed

In Figure 3.8, the recycling benchmark over time is shown. It is evident that the percentages are zero until 2022 because no lithium recycling existed in the European Union before that year. After 2022, there is a gradual increase in recycling capacity. The slow growth of the benchmark can be attributed to the lifespan of batteries, including the potential for an extended lifespan through a second life. This also explains why LFP batteries emerge later but grow faster. LFP batteries have a longer lifespan, and the amount of lithium in these batteries is greater, leading to more lithium entering the system.

All four scenarios show a decline at a certain point due to the increasing demand for lithium, which the recycling capacity in the European Union cannot keep up with. In none of the scenarios, according to the Figure, the recycling benchmark to produce at least 25% of the Union's annual consumption after 2030 seems to be met.

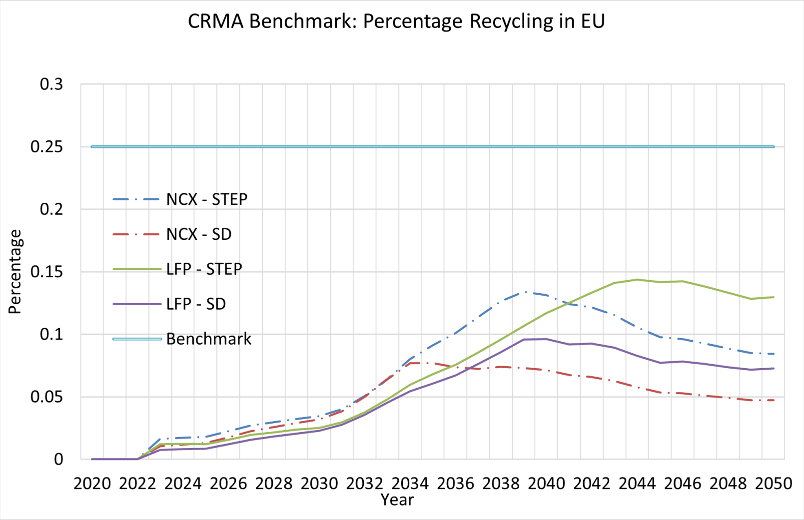


Figure 3.8: CRMA Benchmark: Recycled

3.3.2. Outflows

In Figure 3.9 the outflow of Black Mass Waste is shown. In the initial years, black mass waste is minimal due to the low levels of battery recycling, which is constrained by the lifespan of the batteries. As recycling capacity begins to grow, the amount of black mass waste increases correspondingly. Until 2040, much of the recycling is conducted using pyrometallurgy. At a certain point, however, the growth of black mass waste levels off even as demand continues to rise. This plateau occurs because the recycling process transitions to hydrometallurgy, which is more efficient. Despite this transition, the demand for lithium continues to increase at a faster rate than the capacity of hydrometallurgical recycling can accommodate.

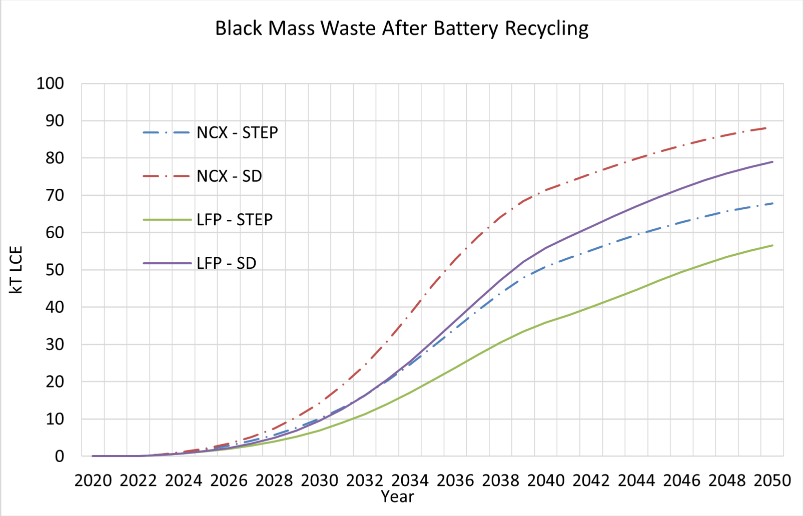


Figure 3.9: Outflow: Black Mass Waste (In kilotonnes LCE)

In Figure 3.10 the amount of Black Mass that leaves Europe is shown. Black mass waste outside Europe remains quite low for a long time, but then grows significantly. This increase occurs of long lifetimes of batteries and because the recycling capacity within Europe is not sufficient to handle the volume of black mass waste generated. As a result, a substantial portion of this waste is exported outside Europe for recycling. The limited capacity within the European Union drives the need to rely on external facilities, leading to a marked rise in black mass waste managed outside the region.

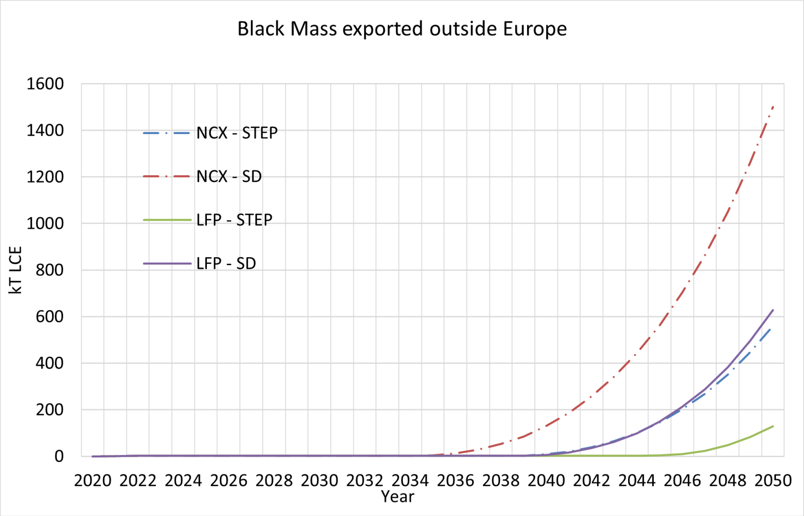


Figure 3.10: Outflow: Black Mass outside Europe (In kilotonnes LCE)

In Figure 3.11 the ouflow for lithium batteries that are shipped outside Europe is shown. As the demand for lithium continues to grow rapidly, the amount of lithium being shipped outside Europe also increases significantly. This trend is not primarily due to recycling capacity limitations but rather the likelihood that end-of-life (EoL) products, such as electric vehicles, are transported to countries outside Europe. Consequently, many batteries are leaving the European Union after their use. This outflow occurs as EoL electric vehicles and other lithium-containing products are sold or shipped to other regions, contributing to a substantial export of lithium resources embedded in these products.

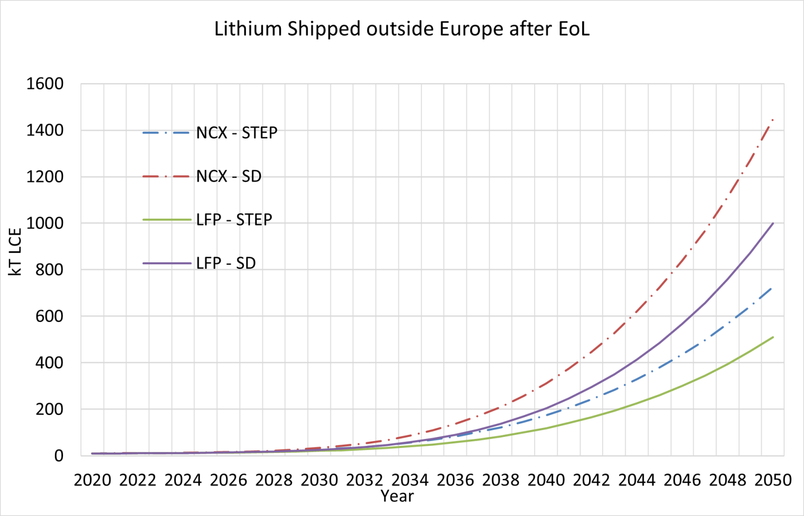


Figure 3.11: Outflow: Lithium batteries outside Europe (In kilotonnes LCE)

In Figure 3.12 the amount of small lithium products that is shipped outside Europe is shown. As the demand for lithium continues to grow rapidly, the amount of lithium being shipped outside Europe also increases significantly, even for small lithium products. These products are smaller than batteries and exist in fewer quantities, but their recycling rates are even lower. Consequently, the total numbers eventually become quite large. Many of these small lithium-containing products are not correct recycled, contributing to a substantial outflow of lithium resources embedded in these items.

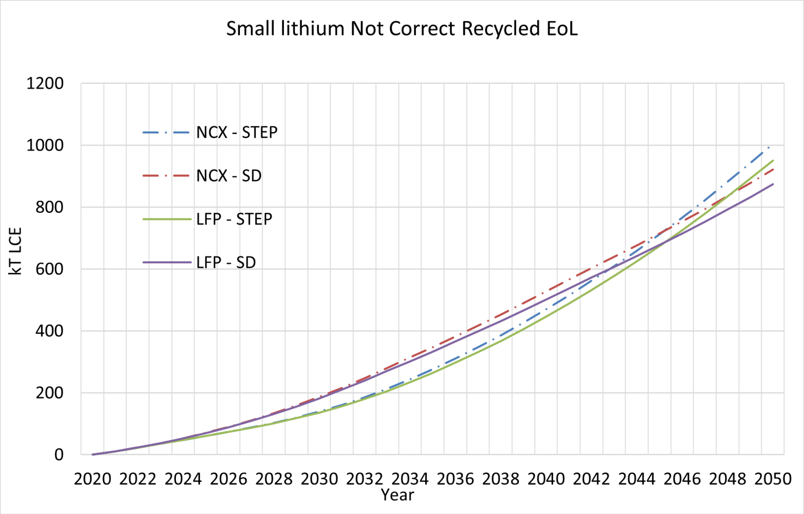


Figure 3.12: Outflow: Small Lithium not correct recycled (In kilotonnes LCE)

3.3.3. Summary of Results

This visual representation of the CRMA benchmark targets is the first of its kind and shows that especially for processing, Figure 3.7, but also for extraction, Figure 3.6, significant new investments in the industry are required to increase the percentage. None of the three benchmarks are met by the 2030 target date according to this research. The recycling benchmark, Figure 3.8, shows the highest percentages, with the LFP - STEP scenario (LFP battery technology and a Stated Policies scenario) having the highest percentage at 14%. The decline in all benchmarks towards 2050 is due to the enormous growth in lithium demand in the future and limited investments after 2030.

In the recycling circuit, it is also evident that NCX battery chemistry leads to a higher recycling percentage faster than LFP batteries. This is due to the shorter average lifespan of NCX batteries (12.5 years) compared to LFP batteries (16 years). However, it is shown that ultimately a higher recycling percentage is achieved for both LFP scenarios (STEP and SD). This is because, although it takes longer, more lithium enters the recycling circuit after 16 years (LFP batteries contain more lithium than NCX batteries).

The outflows of the entire system indicate how lithium exits Europe. The difference per scenario is significant in the export of Black Mass outside Europe, Figure 3.10 (1500 kT LCE in the NCX - SD scenario, 300 kT in the LFP - STEP scenario). There is also a significant difference in the scenario for lithium batteries shipped outside Europe, Figure 3.11. An important graph is Figure 3.12, the outflow of small lithium products because they are not well recycled. These figures are fairly close across all scenarios, but a substantial portion (around 1000 kT LCE) of lithium exits the system this way.

4
Policy Effect

As seen in the results of the MFA, the benchmarks in the base line scenario, are not met. This is due to the increasing demand for lithium and batteries, coupled with the slow growth of the European market for both battery production and recycling. To address the subquestion: ”Which policy effects could significantly influence the material flows of lithium in Europe?” this part of the study explores various potential policies to determine which might have the most effective impact.

As previously described, the benchmark for no third countries accounts for more than 65% of the import of SRMs is not included in the calculations. Given that the scope of this research is focused on Europe, it does not examine which countries supply lithium or its derivatives.

This chapter discusses policies, which all depend on mass movement because the Material Flow Analysis (MFA) relies solely on mass balance. As a result, the policies discussed here focus on the implementation of legislation rather than the legislation itself. This is because the specifics of legislation cannot be determined through the MFA used in this study. Additionally, financial incentives are not considered in this study, as they cannot be modeled with this approach. Only the outcomes of these incentives, such as an increase in lithium battery manufacturers in Europe, are considered.

4.1. Methodology

The methodology describes the rationale behind the various policies used and how they were implemented in the MFA to obtain results.

4.1.1. Data Collection

For this question, several sources are utilized. Firstly, the Actor and Supply Chain analysis established in Chapter 2.3 is used. This analysis has facilitated a MFA of lithium streams in Europe, providing an aggregated view of how these streams move through Europe and highlighting potential bottlenecks. This MFA forms the foundation for implementing the various policies described in the methodology.

Additionally, European legislation concerning lithium is utilized. This legislation is integrated into the MFA and outlines the policies currently in place to, for example, recycle lithium (EU Battery Regulations) or support a European lithium industry (NZIA). By incorporating these policies into the MFA, a clear picture is created of the consequences of these policies in the current landscape.

Furthermore, two interviews are used to gain a better understanding of the CRMA and its implications. The interviewees are both experts in the field of Critical Raw Materials and have provided additional insights into certain aspects of the CRMA. These individuals are listed in Table 4.1. For complete anonymous summaries of these interviews, please refer to Appendix C.

Table 4.1: Interviewees Policies

Interviewee	Specialization
S4	Critical Raw Material Policy Expert
S6	Policy expert from the European Commission

4.1.2. Data Analysis

To provide a clear depiction of potential policies that could influence lithium flows through Europe calculated with this MFA and potentially have a positive impact on the CRMA benchmarks, this study divides the options into different sub models as described in Chapter 3.

European Battery demand

Starting with the European battery demand, this demand is based on the paper by Xu et al. (2020) and acknowledges the growing importance of batteries in both global and European markets. This significance is due to the rapid electrification of the European Union, where energy storage plays a critical role. As the trend toward reducing fossil fuel use continues, it is expected that the demand for key technologies essential for this electrification will not cease.

However, in two distinct scenarios, European battery demand can influence material flows and CRMA benchmarks. First, there could be a reduced focus on electrifying households and industries. Second, new technologies could emerge that decrease the demand for lithium.

Both scenarios are expected to enhance strategic autonomy concerning lithium (less lithium is needed, thus decreasing demand). Additionally, these changes could accelerate the achievement of benchmarks, as they are calculated based on total annual consumption. A reduction in lithium consumption would, therefore, impact the CRMA benchmarks, shifting it to a higher percentage. This method of reasoning is supported by Interviewee S6.

Small lithium products

Although small lithium products accounted for a significant proportion of the total lithium in Europe during the period from 2020 to 2035, they are rarely recycled (J. Liu et al., 2020; Polák & Drápalová, 2012). The total amount of these small lithium products depends on the International Energy Agency's predictions under the STEP or SD scenarios, with estimates around 900 to 1000 kt LCE, as shown in Figure 4.1. This represents a substantial portion of the lithium flows in Europe that are not being recycled. Given that the lifespan of small lithium products is considerably shorter than that of larger batteries, the recycling process can commence much sooner with small lithium products.

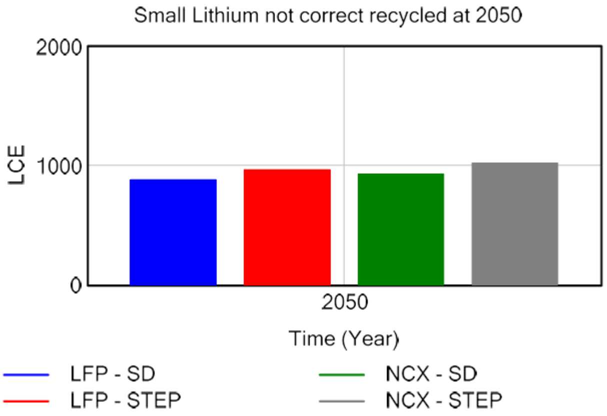


Figure 4.1: Cumulative ammount of small lithium products (in LCE) that is not correct recycled in 2050.

Lithium batteries

One of the most logical steps that can be taken, and towards which the European Union is working with their 'Net Zero Industry Act,' is increasing the European capacity to manufacture batteries. Many of the investments being made now are expected to be realized by 2030. Beyond this date, few plans for new factories are known. This approach is logical: first establish a factory, and then consider expansion. The growth of European battery factories also contributes to becoming autonomous from battery imports outside Europe. An important footnote to this approach is that as long as the lithium chemicals used in European batteries are not sourced from Europe, there is still no strategic autonomy.

Recycling

In this sub-model as well, increasing capacity is the primary and most obvious policies that can be implemented. Although investments are being made in more recycling companies up until 2030, it is still not sufficient according to the model's results. Black mass continues to exit the system, which is also underlined by Interviewee S4, posing a significant obstacle to the lithium recycling process in Europe.

Additionally, many of the recycling facilities in Europe currently utilize pyrometallurgical processes, which achieve a lithium recovery rate of about 40%. By transitioning to hydrometallurgical processes, a significant improvement can be made, potentially increasing recovery rates to between 90-95%.

Mining and refineries

For the mining and refining part of the system, the benchmarks of the European Union are more straightforward. The inflow of materials is primarily dependent on whether there are lithium refineries and if lithium is being mined within Europe. Consequently, the possible policies to improve this are somewhat limited. To meet these benchmarks, an increase in capacity is necessary. The CRMA accounts for this with a reduction in permitting times, as outlined in Chapter 2.2. This reduction in permit times provides greater investment certainty, a point also confirmed by interviewee S6.

However, a realistic view must be taken towards lithium mines. Even though permit durations have been restricted (27 months for a strategic mining project, 15 months for a strategic processing project), building a mine takes longer than the permit time only. On average, the complete process takes between 7 to 10 years (Fuelling, 2021; Lee, 2022). The permitting phase before the CRMA lasts around 36 months. However, the most significant hurdle is not only the time but also that applications could also be rejected, leading to the evaporation of prior investments (Fuelling, 2021). Certainty at this stage of development, which the CRMA creates, is beneficial, as policy expert S6 also mentions.

CRMA policy expert S6 further indicates that there is a significant likelihood that the CRMA benchmarks for recycling and processing might be merged if one of them fails to be met. The interviewee explains that this makes sense as recycling and processing are closely linked; recycled materials ultimately need to be converted back into chemical forms that are used in batteries. According to S6, it is increasingly common to see battery manufacturers also establishing recycling facilities to comply with battery regulations and to immediately reprocess potential scrap back into the system.

4.2. Implementation

To assess the impact of various policies on the material flow and CRMA benchmarks, these policies are implemented in the model. The various policies, their implementation within MFA, and the rationale behind these choices are detailed in Table 4.2.

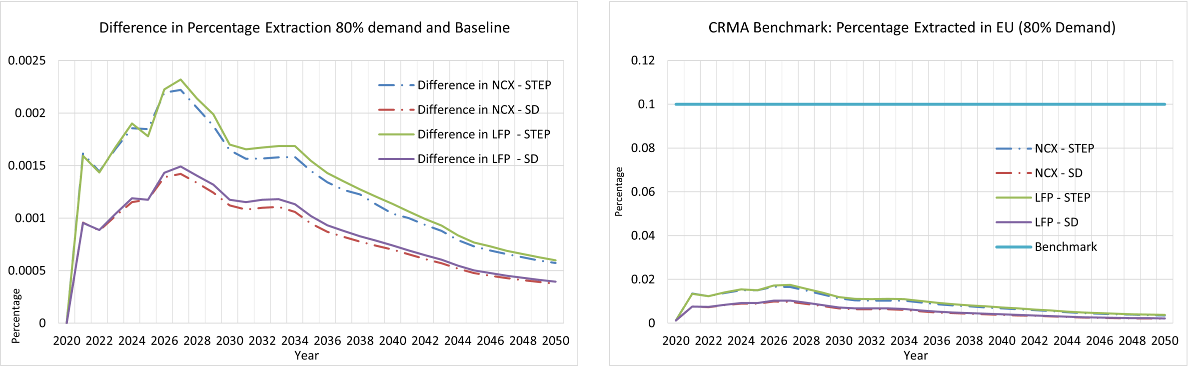
Table 4.2: Policy, Implementations and Reasoning

Policy	**Implementation in the model**	**Reasoning**
Lower battery demand	Two implementations concerning: 1.) 80% demand of the inflow of batteries from outside Europe 2.) 60% demand of the inflow of batteries from outside Europe	This policy is possible if, for instance, there is a restriction on imported lithium, or less lithium is needed in the future because other battery materials are dominant (such as sodium).
Higher capacity of EU battery manufacturing	This implementation assumes: The same linear growth that occurs from 2020-2030 to the timeline of 2030-2050.	The linear growth from 2020 to 2030 is very steep because there are a lot of ongoing investments in the battery industry until 2030. If investments keep up, linear growth seems reasonable.
Higher capacity of EU recycling	This implementation assumes: From 2025: 2 times higher capacity From 2030: 3 times higher capacity From 2040: 4 times higher capacity	Recycling industry growth from 2020 till 2030 is not significant. That is why it is chosen to begin with a smaller growth in the earlier timeline and increase it towards the end.
Higher capacity of EU recycling with faster implementation of small lithium products in the recycling circuit	This implementation assumes: The same recycling capacity as the previous run, but with the implementation of small lithium products in the recycling circuit. 50% Small lithium recycling in 2030 From 2040: 70% From 2050: 80%.	There is no industry that recycles small lithium products to new metals in Europe. However, the possibilities are there (J. Liu et al., 2020), and the amount of waste has potential.
Higher capacity of EU recycling with faster implementation of small lithium products in the recycling circuit and faster, higher recovery rates	This implementation assumes: From 2030, recovery rates of Black Mass Recycling go up from 65% to 95%.	This aligns with the recovery rates of hydro-metallurgical recycling; however, the implementation of hydro-metallurgical recycling is significantly accelerated in the timeline.
Higher capacity of Mining facilities	This implementation assumes: The inflow of European mined lithium is increased by 3 kt of lithium per year, with a delay time of 7 years	This aligns with the opening of new mines, as the Portuguese mine alone could not produce this amount of LCE. However, the average time to establish a mine, which is seven years, has been taken into account.
Higher capacity of Mining and Processing facilities	This implementation assumes: Same mining capacity but with the introduction of processing facilities. 2025: 0 kt LCE 2030: 30 kt LCE 2040: 60 kt LCE 2050: 100 kt LCE	There are a negligible number of processing facilities in Europe. The potential growth of these facilities aligns with the growth of battery production in Europe.

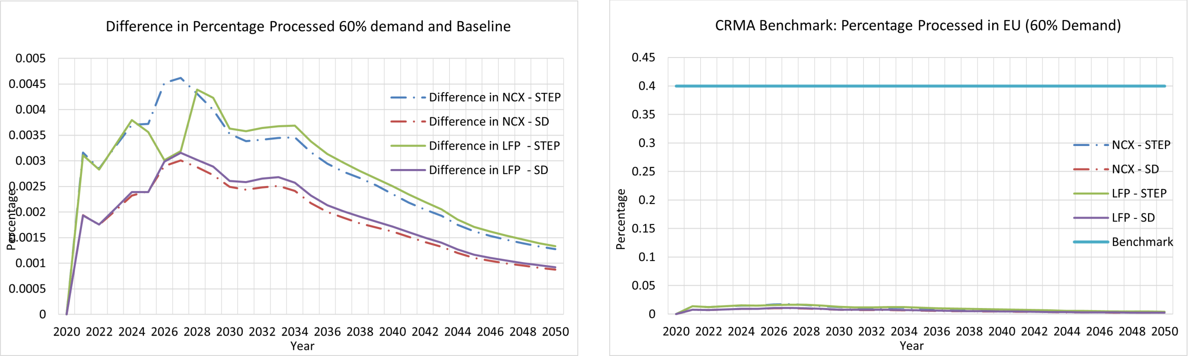
4.3. Results

4.3.1. Lower Demand

The Figures of 4.2 show the examples of CRMA benchmarks Extracted and Processed for respectively 80% battery demand and 60% battery demand. Only these Figures are shown to keep the overview clear, but none of the benchmarks—or outflows—show significant changes in the benchmarks. However, it can be seen in the example that with a lower demand, the percentages of all CRMA benchmarks have a small increase. As described in the methodology, this occurs because the benchmark is divided by the total consumption of the critical material, and the total consumption decreases with lower demand. Even with a 40% reduction in demand for imported batteries, none of the benchmarks are reached. Additionally, it is observed that a reduction of 20% or 40% does not result in an increase of the same percentage, but rather a significantly lower one. This is due to the role of small lithium products on the total consumption.



(a) Difference in Percentage Extracted 80% demand and Baseline **(b)** CRMA Benchmark - Percentage Extracted in EU (80% Demand



(c) Difference in Percentage Processed 60% demand and Baseline) **(d)** CRMA Benchmark - Percentage Processed in EU (60% Demand)

Figure 4.2: Impact of lowering imported battery demand by 60% and 80%.

4.3.2. Higher Battery Manufacturing Capacity

An increase in battery manufacturing has little effect on the benchmarks. The European demand remains the same, only more batteries are imported. However, as seen in Figure 4.3, the proportion of batteries manufactured in Europe increases from 2030, the point at which battery production is increased.

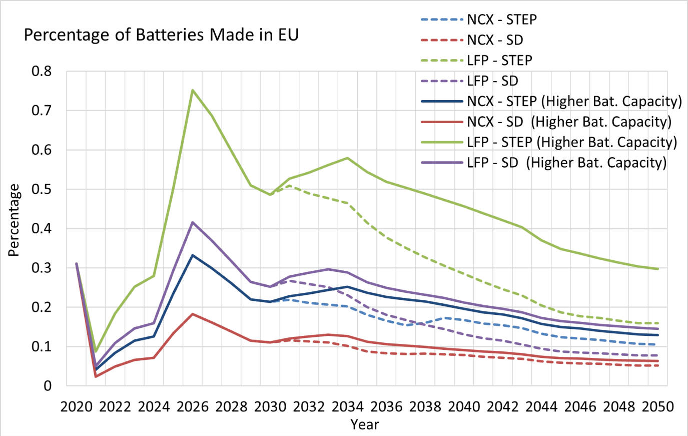
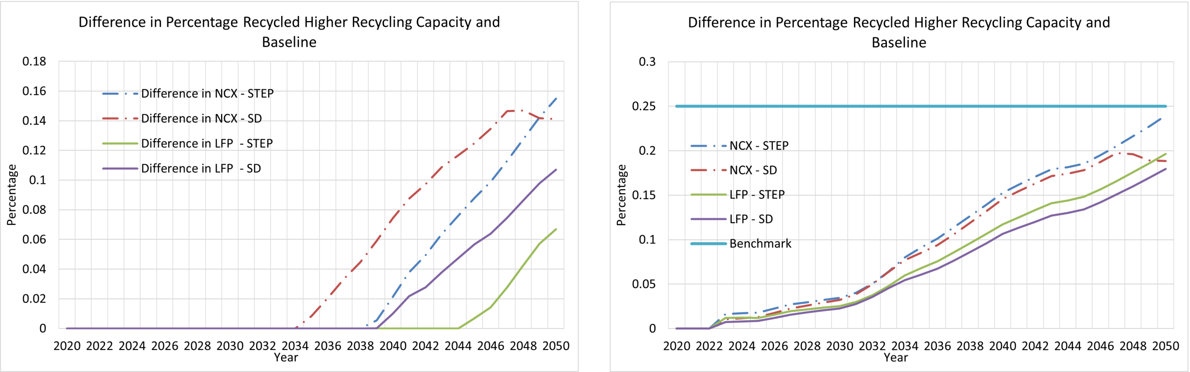


Figure 4.3: Percentage of Batteries made in de EU from Base Line Scenario and with a Higher Battery Capacity.

4.3.3. Higher Capacity Recycling

An increase in recycling capacity only affects the recycling percentage and has no impact on the other benchmarks. As seen in the right Figure of 4.4, significantly less is exported, except in the case of NCX - SD capacity. This is due to the shorter lifespan, resulting in more batteries being recycled faster, combined with the maximum recycling capacity (not everything can be recycled). This is one of the biggest bottlenecks in the supply chain: if there is not enough capacity to recycle, materials disappear from the system. In left Figure of 4.4, the difference between the baseline scenario percentage and the implemented policies is shown. From 2030, the growth in percentages can be seen for NCX - SD, and from 2040 for LFP - STEP. This is due to the lifespan of the batteries.



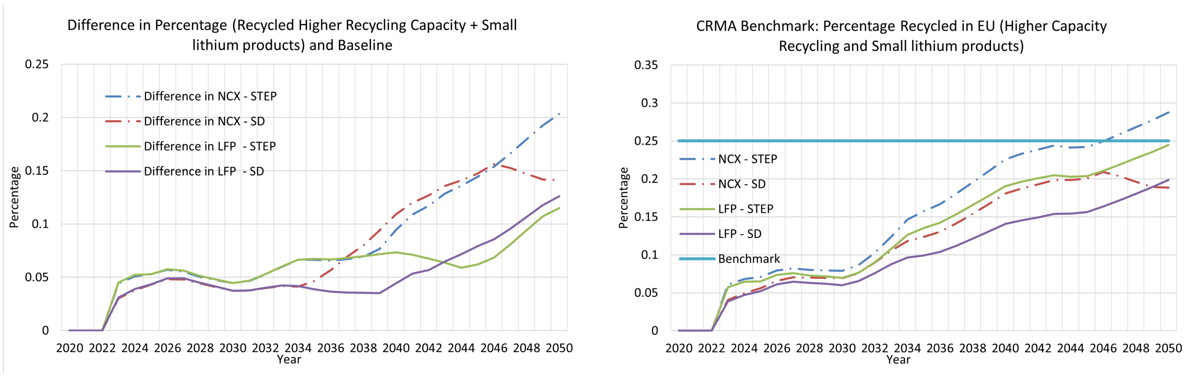
(a) Difference in Percentage between Base Line Scenario and Higher Capacity Recycling (CRMA Benchmark: Recycling)

(b) After Policy implementation: Black Mass Leaving Europe after its shredded.

Figure 4.4: Difference in CRMA benchmark Recycling and Black Mass Leaving Europe after Higher Capacity Recycling Europe. (Higher Capacity Recycling)

4.3.4. Higher Capacity Recycling and Small lithium Products recycled

Implementing small lithium products provides an additional boost in recycling, as this can begin much sooner then that of batteries. Due to this implementation, the difference in the percentage of the recycling benchmark between the baseline scenario and the policy starts growing much earlier, as seen in the left figure of 4.5. Additionally, the right figure of 4.5 shows that the benchmark of recycling can be achieved around 2046 for the NCX - STEP scenario and in 2050 is almost achieved for the LFP - STEP scenario.



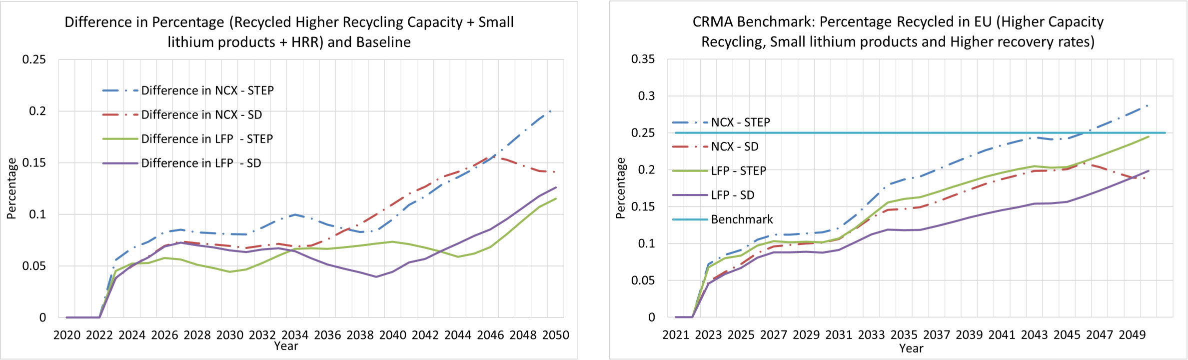
(a) Difference in Percentage (Recycled Higher Recycling Capacity + Small lithium products) and Baseline

(b) CRMA Benchmark: Percentage Recycled in EU (Higher Capacity Recycling and Small lithium products)

Figure 4.5: Difference in CRMA benchmark Recycling and CRMA benchmark recycling (Higher Capacity Recycling and Small lithium Products recycled)

4.3.5. Higher Capacity Recycling, Small Lithium Products Recycled and Higher Recovery Rates

In Figure 4.6, the left side shows the difference in the percentage of the recycling benchmark between the baseline scenario and this policy. On the right side, the recycling benchmark is displayed. These figures show that during the period 2026 - 2030, more is recycled even faster due to the higher recovery rates. As more lithium is recovered, more can be reintroduced into the system. From 2040 onwards, the impact of this policy becomes negligible.



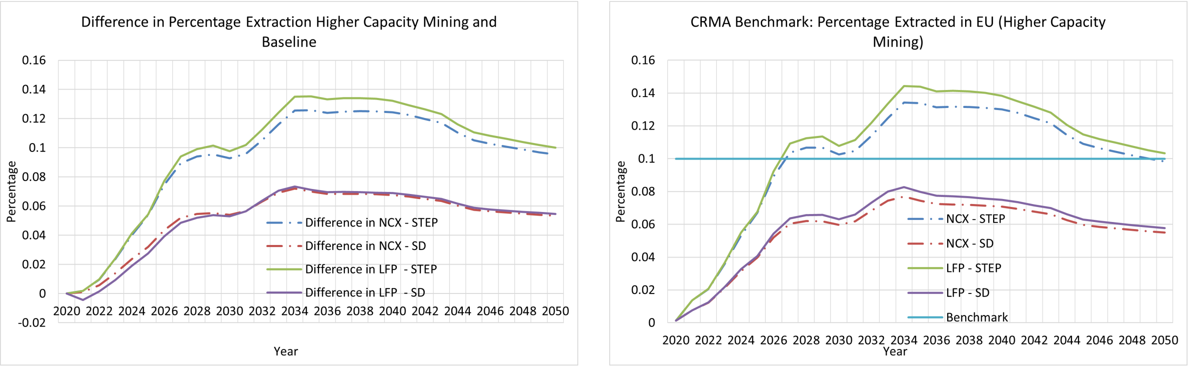
(a) Difference in Percentage (Recycled Higher Recycling Capacity + Small lithium products + Higher Recovery Rates) and Baseline

(b) CRMA Benchmark: Percentage Recycled in EU (Higher Capacity Recycling, Small lithium products and Higher recovery rates)

Figure 4.6: Difference in CRMA benchmark Recycling and CRMA benchmark recycling (Higher Capacity Recycling, Small lithium Products Recycled and Higher Recovery Rates)

4.3.6. Higher Mining Capacity

In Figure 4.7, the left side shows the difference in the percentage of the extraction benchmark between the baseline scenario and this policy. On the right side, the extraction benchmark is displayed. It can be seen that with the implementation of more mines, the STEP scenarios for both battery types are achieved, while the SD scenarios require even more mining activity for reaching the benchmark. The implementation of mining capacity also effect the processing activity, however much more lithium needs to be imported to reach the benchmarks for processing.



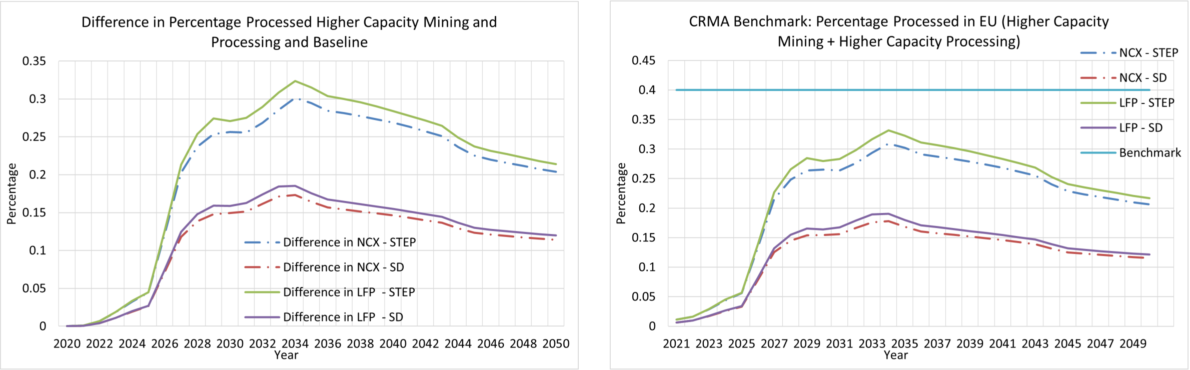
(a) Difference in Percentage Extraction Higher Capacity Mining and Baseline

(b) CRMA Benchmark: Percentage Extracted in EU (Higher Capacity Mining)

Figure 4.7: Difference in CRMA benchmark Extraction and CRMA benchmark Extraction (Higher Mining Capacity)

4.3.7. Higher Mining Capacity and Higher Processing Capacity

In Figure 4.8, the left side shows the difference in the percentage of the processing benchmark between the baseline scenario and this policy. On the right side, the processing benchmark is displayed. The implementation of increased processing capacity results in growth of the CRMA benchmark processing, but it is still insufficient to meet the benchmarks.



(a) Difference in Percentage Processed Higher Capacity Mining and Processing and Baseline

(b) CRMA Benchmark: Percentage Processed in EU (Higher Capacity Mining + Higher Capacity Processing)

Figure 4.8: Difference in CRMA benchmark processing and CRMA benchmark processing (Higher Mining and processing Capacity)

4.3.8. Summary of Results

This research indicates that reducing the demand for batteries coming into Europe by both 20% and 40% has little effect on the CRMA benchmarks. This is because small lithium products also play a role in the total consumption of lithium, and batteries are still produced in Europe in this scenario, which also leads to greater consumption of lithium.

The effect of higher battery production has no impact on the CRMA benchmarks. Since all battery shortages are compensated by the inflow of batteries from outside Europe, total consumption through battery production never increases, as there are never more batteries produced than the total European demand. And because total consumption does not increase, the benchmarks are not adjusted through battery production. However, increasing battery manufacturing capacity does result in more batteries being made in Europe, as shown in Figure 4.3.

The combination of policies around higher recycling capacity, small lithium products, and higher recycling rates significantly increases the recycling benchmark in all cases. Particularly, the combination of higher recycling capacity and small lithium products recycling, shown in Figure 4.5, leads to substantial growth after 2030. Higher recovery rates result in a higher recycling percentage early in the timeline but have less influence later as they are also incorporated into the baseline scenarios. This research indicates that achieving the 25% benchmark for 2030 is nearly impossible, given the rapid increase in lithium consumption over the years and the insufficient lithium available for recycling by 2030.

This research also shows that the mining and processing benchmarks can only be increased by adding more capacity to both parts of the supply chain, as seen in Figures 4.7 and 4.8. It is important to ensure there is enough capacity for processing lithium, otherwise, lithium mined in Europe will be sent directly abroad.

5

Conclusion and Discussion

In this chapter, the research question are answered in the conclusion, the societal and academic relevance is discussed, a critical reflection is given on the methods and assumptions, and recommendations for further research are provided.

5.1. General Conclusion

The European policy landscape surrounding lithium is defined by three pivotal regulations: the Critical Raw Material Act (CRMA), the EU Battery Regulations, and the Net-Zero Industry Act. These policies collectively aim to enhance the autonomy of European industries and create favorable conditions for the growth of Net-Zero technologies.

The European lithium supply chain is complex, involving numerous actors from mining companies and lithium chemistry processors to battery manufacturers, recyclers, and policymakers. Each plays a crucial role in influencing material flows. The supply chain of European Lithium can be segmented into four main parts: the small lithium products industry, the European battery industry, the recycling industry, and the mining and processing industry.

Current lithium flows within Europe are driven by the import of various forms of lithium, including raw materials and products containing lithium, such as batteries. The Material Flow Analysis (MFA) conducted in this research tracks these inflows, internal flows, and outflows, such as the export of electric vehicles (EVs).

This research proves that a MFA with delays can be useful in calculating the CRMA benchmarks and understanding the material flows of Lithium through Europe. The analysis highlights significant challenges in meeting the CRMA benchmarks under the current European lithium landscape. The benchmarks for processing and mining (set at 40% and 10%, respectively) decline over time due to the rapid increase in European lithium demand. The recycling benchmark (set at 25%) shows some growth because of the growth of EoL batteries, but remains insufficient to meet the target.

To answer the main question of this research, “What policies can influence the material flows of Lithium and have a positive impact on the CRMA benchmarks?”, several policy interventions have been identified. These include reducing battery demand, increasing EU battery manufacturing capacity, expanding recycling capacity (especially by incorporating small lithium products), and boosting mining and refining capacity within Europe. Each policy has unique impacts on material flows and CRMA benchmarks.

Following the modelling of the policies, it has become evident that all policies influence material flows across Europe. Additionally, it has been demonstrated that nearly all policies impact the CRMA benchmarks. The exception is the increase in European battery production capacity, which does not affect the CRMA benchmarks due to being offset by the inflow of imported batteries. Nevertheless, investing in this area is advisable to enhance strategic autonomy, a key objective of the CRMA.

All other policies directly impact the CRMA benchmarks. For example, reducing the demand for imported batteries can increase the CRMA benchmarks by decreasing overall lithium consumption. However, this effect is minimal, as total consumption is influenced by both batteries and small lithium products.

Increasing recycling capacity has a significant positive impact on the recycling benchmark, particularly when small lithium products are included in the recycling process. Transitioning to more efficient recycling methods, such as hydrometallurgical processes, initially boosts the recycling benchmark but has a limited long-term impact without substantial increases in capacity.

Expanding mining capacity within Europe is crucial but requires a long lead time, with significant benchmark improvements not seen until after 2032. Similarly, achieving the processing benchmark necessitates increased lithium inflows, potentially through imports from non-European countries.

In conclusion, while the CRMA benchmarks present a challenging target, strategic policy interventions focused on reducing demand, expanding recycling capacities, and increasing mining and processing capabilities can create higher benchmarks. These measures, when effectively implemented, influence material flows in Europe and enhance Europe's autonomy in the lithium supply chain. By achieving higher CRMA benchmarks, these interventions contribute to broader goals of sustainability and strategic resilience.

5.2. Societal Relevance

This thesis is written for academic purposes, but may also be relevant for other stakeholders. These stakeholders include the industry, such as the mining, processing, manufacturing, and recycling industries of lithium in Europe. Governments, the European Union, and all companies involved with Net-Zero technologies. The following chapters discuss the implications for European autonomy, the role of industry, and the policy recommendations derived from this research.

5.2.1. Implications for European Autonomy

This research demonstrates that achieving European autonomy in lithium is not an 'easy fix.' According to several studies (Rossi et al., 2023; Xu et al., 2020) the European lithium market is expected to grow significantly in the coming years. Due to this exploding demand and consequently the exploding consumption of lithium, the CRMA benchmarks can only be met through a substantial increase in extracted, processed, and recycled material. The European Union is attempting to address this issue through legislation. However, the question remains whether this provides a sufficient foundation to turn the tide.

Among the three European policies, the EU Battery Regulations have the most clearly defined legal constraints. This legislation specifies the amount of recycled material that must be included in batteries starting from 2031, which is quite concrete due to the established percentages. In contrast, the Critical Raw Material Act lacks such specificity. The benchmarks were established to allow the European Commission to track whether the targets for 2030 will be met. And apart from the permit time constraints in CRMA, the new amendment of April 2024 of the CRMA includes no additional legal constraints or incentives.

If it appears that the benchmarks for 2030 will not be met, the CRMA mandates 'extra measures.' But are extra measures only after 2030 implemented? And what kind measures? This can only be speculated. Ofcourse, creating policy that ensure businesses establish operations here is challenging, as companies in the European industry decide for themselves whether to set up shop in the EU or not.

At the same time, we may need to reconsider viewing the market for critical materials, including lithium, through the lens of the 'free' market. This market is not as free as it might seem. It is heavily subsidized from various sides, with the United States implementing the 'Inflation Reduction Act' and China supporting state-owned enterprises such as Tianqi Minerals. A potential European industrial policy could be a response to this.

Whether or not a European industrial policy is implemented, investments in a European supply chain for lithium are necessary if it is to be established within Europe. Carrara et al. (2023) highlight that the most significant bottleneck in the supply chain is the processing segment, explaining the 40% benchmark set for this part of the supply chain. The lack of development in this segment poses a significant supply chain risk if it is not scaled up. However, boosting the processing capacity alone is not enough; both Carrara et al. (2023) and this research emphasize that true material autonomy can only be achieved through comprehensive investment across the entire supply chain. Without such investment, downstream stages risk dependency on third countries.

While examining the entire supply chain is crucial, the European Union should not view the resource transition through a 'fossil fuel' lens. Unlike fossil energy sources, which are consumed and cannot be reused, critical materials can be reused through recycling circuits, extending their lifespan significantly. Therefore, focusing on circularity is of utmost importance.

5.2.2. Role of Industry

The industry plays a pivotal role in shaping the future of the European lithium supply chain. There is significant potential for growth in the European market for mining, processing, and recycling lithium. Recognizing this opportunity, investments in these sectors are not only beneficial but necessary to establish a robust and self-sufficient supply chain within Europe.

However, the European Commission cannot achieve this goal on its own. It requires the active participation and collaboration of industry stakeholders. By investing in the European supply chain, companies can help mitigate the risk of a monopoly by foreign entities. This is crucial because while the EU is not aiming to relocate the entire supply chain within its borders, it is focused on preventing a monopolistic dominance by non-European countries.

Moreover, different battery types can significantly impact the recycling process. For instance, Lithium Iron Phosphate (LFP) batteries contain more lithium than other types, leading to a higher potential for recycling at the end of their lifecycle. This increased lithium content in LFP batteries means that, once they reach their end-of-life, more lithium can be reintegrated into the supply chain through recycling efforts.

In conclusion, the industry's involvement is critical to advancing the European lithium supply chain. By leveraging the growth potential in mining, processing, and recycling, and by collaborating with the European Commission, industry stakeholders can help ensure a more balanced and sustainable supply chain, reducing dependence on foreign monopolies and enhancing Europe's strategic autonomy.

5.2.3. Policy Recommendation

To achieve the goals set forth by the CRMA and enhance European autonomy in the lithium supply chain, a comprehensive approach is required. This thesis suggests several key policy recommendations to address these objectives:

1. **Invest in the Entire Supply Chain**: Policies should support the development of all segments of the supply chain, with particular attention to the critical bottlenecks in processing and recycling. Insufficient processing capacity could lead to European-mined Lithium being sent to other countries. Similarly, a lack of recycling capacity would result in black mass being exported out of Europe. Both scenarios negatively impact the CRMA benchmarks and hinder European autonomy. Ensuring adequate capacity in these segments is essential for achieving the desired benchmarks and enhancing strategic independence.
2. **Focus on Recycling Targets for Member States**: Encourage member states to set specific recycling targets, particularly for small lithium products. Integrating these products into the recycling circuit can significantly increase the amount of recycled lithium available, contributing to the CRMA recycling benchmarks in an earlier stage of the timeline.
3. **Establish Clear and Stable Policies**: A clear and stable policy environment is crucial for attracting and securing long-term investments in the European lithium supply chain. Especially in the mining and processing part of the supply chain. Building a mine takes around 7 years, but consistency in policy will provide the necessary confidence for companies to invest in mining and also processing, and recycling facilities within Europe, which is also underlined by Interviewee S6.
4. **Integrate Recycling and Processing Benchmarks**: Given the interconnected nature of recycling and processing, these two CRMA benchmarks should be considered together. Effective recycling processes should naturally lead to an increase in available material for processing, enhancing the overall efficiency and sustainability of the supply chain.

By implementing these policy recommendations, the European Union can better position itself to meet the CRMA benchmarks, foster a more resilient and autonomous lithium supply chain, and support the broader goals of sustainability and strategic independence.

5.3. Academic Relevance

This research has been conducted for the master's program in Engineering and Policy Analysis (EPA). EPA is an interdisciplinary field at the intersection of system understanding, modeling, simulation, policy, and politics. This study aligns well with the EPA research domain as it combines a significant political issue with modeling to analyze the problem effectively.

Moreover, MFA is an analytical approach widely used in the fields of industrial ecology and sustainability. This research contributes to industrial ecology and introduces new insights relevant to multiple academic fields. These include the calculation of CRMA benchmarks, the modularity of MFA, and the incorporation of delays in MFAs. Each of these aspects is explored in the sections below.

5.3.1. Delays in a dynamic MFA

The integration of delays in MFA presents an advancement in the field. Traditionally, MFA studies have primarily used software like STAN, which often operate within a static framework and a fixed timeframe, typically spanning a year. This conventional approach, while effective, lacks the dynamic capabilities needed to fully capture the temporal variations and complexities inherent in material flows.

In this study, the MFA was developed using the Vensim software, which allows for a dynamic analysis over multiple years. This shift in methodology is particularly noteworthy due to the incorporation of delays, which play a crucial role in accurately modelling real-world scenarios. By accounting for delays, the analysis provides a more realistic representation of how materials move through the supply chain over time.

The inclusion of delays in a dynamic MFA framework enhances the analytical depth and possibly the reliability of the results. Delays help to illustrate the time-dependent nature of processes such as mining, processing, recycling, and the eventual reintegration of materials into the supply chain. This methodological innovation offers a more nuanced understanding of material flows and their impacts, thereby contributing valuable insights to the field of industrial ecology and material management.

Overall, the use of Vensim and the focus on delays represent a methodological enhancement that improves the precision and applicability of MFA studies. This advancement underscores the importance of adopting dynamic modelling techniques in future research to better capture the complexities of material flows and their long-term implications.

5.3.2. MFA proven to be helpful in calculating CRMA

The application of MFA has proven effective in calculating CRMA benchmarks. This approach offers several advantages that enhance the depth of the analysis. Firstly, MFA enables precise calculation of the total consumption of lithium, including both small lithium products and batteries, which is crucial for setting and evaluating benchmarks. Additionally, MFA allows for detailed tracking of other flows such as extraction, processing, and recycling. This ensures that all benchmarks can be calculated by dividing the flows by the total consumption.

Moreover, the dynamic nature of this MFA offers valuable insights into the long-term impacts of various factors. For example, the lifespan of batteries can significantly influence material availability and recycling rates over time. By incorporating these elements, MFA can more accurately predict how material flows and CRMA benchmarks will evolve.

Overall, MFA stands out as a useful tool for calculating and understanding CRMA benchmarks. Its ability to provide insights on the long-term about material flows makes it an invaluable resource for policymakers and researchers aiming to enhance strategic planning and sustainability in the critical materials sector.

5.3.3. Modularity for Critical Materials

The modularity of the MFA allows it to be applied to a wide range of critical materials beyond lithium. This approach is particularly beneficial for materials essential in battery production, such as nickel and cobalt, which share similar supply chain characteristics with lithium. This makes this research a tool for analysing multiple critical materials within the same methodological framework.

Additionally, the modular nature of this research extends to the inclusion of 'Small Lithium products,' which can be adapted to other supply chains involving residual streams. This flexibility ensures that MFA can address various types of material flows and supply chain configurations.

The possible use of the subscript tool in Vensim further enhances this modularity. By enabling a layered and detailed investigation, this tool allows for the simultaneous analysis of multiple materials within the same model. This capability supports a better understanding of material interactions and dependencies.

Overall, the modular approach of MFA, combined with tools like Vensim's subscript feature, makes it a powerful and adaptable method for studying a wide array of critical materials, thereby contributing significantly to the fields of industrial ecology and material management.

5.4. Limitations and Future Research

This research focuses on the Lithium flows based on current literature and future projections with reasonable certainty due to the different scenarios that have been modelled. However since the analysis is based solely on mass balances, some real-world dynamics are not modelled. These and other limitations are discussed in this section.

5.4.1. Financial Aspects and the European Market

Firstly, this model was created without considering the economic aspects of material flow. The price of Lithium is not included in the model, which means that this model always prefers European Lithium over other sources. In reality, if a company can obtain Lithium at half the price from outside Europe, it will probably choose the cheaper option. These financial incentives present interesting avenues for future research, such as how financial incentives affect the purchase and sale of European lithium, and the impact of monopolistic structures from foreign sources on European buyers' purchasing behavior. Will European battery manufacturers buy European Lithium to minimize monopoly from third countries, knowing that it will be more expensive?

Another limitation related to financial incentives is that this model revolves around the predicted inflow of Lithium batteries and small Lithium products. It assumes that everything not made in the EU is imported, and if it is made here it remains in Europe after production. Thus, EU-made batteries are not shipped to Asia or America post-production. This model only models Lithium batteries outside Europe after EoL.

Since the inflow of batteries is balanced with European demand, the actual inflow of batteries not made in Europe is the difference between European Demand and European Manufacturing of Lithium batteries. As a result, many sub-models within this model are 'decoupled'. This means that increased capacity in European mines affects the import of EU Lithium chemistry's for battery production but does not impact the inflow of batteries to users, as this is balanced by the inflow of batteries from outside Europe.

Furthermore, this model views the European market as a single internal market. Differences between member states, the existing industrial base, and potential competition between companies and countries are not considered. This could be an interesting area for future research, where this model is developed for individual countries to see how markets interact with each other.

In future research, it could be interesting to explore a System Dynamics model of this case. By utilizing System Dynamics, one can examine not only the material flows present in this MFA but also other variables such as the European lithium price relative to other countries. Additionally, future research could delve deeper into the interactions between (European) countries and investigate the reasons behind their lithium exchanges using Agent-Based Modeling (ABM). This approach could consider not only markets and prices but also factors like distance and alliances between countries.

5.4.2. Batteries

The rise of battery storage is inherently linked to lithium in this model, which may not be entirely accurate. The emergence of other battery technologies could change the future demand for lithium. Upcoming but not yet fully operational battery types, such as Sodium-Ion batteries, are not included but could significantly impact CRMA benchmarks by reducing the total demand for lithium. Future research could investigate the effects of other battery types - that do not contain lithium - on the CRMA benchmarks. Additionally, if lithium were to be replaced by another critical material, the impact of this substitution on both materials should be examined.

Additionally, the calculations for the required lithium in kT LCE are based on the amount of kT LCE per GWh for either NCX and LFP batteries. Therefore, all batteries made in Europe are assumed to be either NCX or LFP. This assumption could provide a skewed perspective if European battery manufacturers switch to other battery types or strategies in the future. Future research could involve considering market share percentages for each battery type, instead of using a single battery type to measure the amount of lithium produced in Europe. By accounting for potential mixtures of battery types, a more accurate total amount of lithium produced in Europe can be calculated.

To accurately estimate the current and future capacity of the battery and recycling industry in Europe, this research relies on various sources (Battery News, 2023; Carrara et al., 2023; Joint Research Centre et al., 2020; Matos et al., 2022; Volta Foundation, 2023). While these projections are based on existing investments, the actual completion and production capacities of these projects remain uncertain. Consequently, this study adopts a conservative approach, adjusting future project capacities to 70% of their projected numbers and production capacities, as suggested by Interviewee S1. Although this estimate may be on the lower side, it underscores the need for future research to assess the actual capacities of existing companies and to provide a more accurate reflection of reality.

Lastly, European Lithium processing in this model is exclusively for battery-graded Lithium implemented, and no European processed Lithium is supplied to small Lithium products. This assumption is based on the European Commission’s emphasis on ’battery-grade’ Lithium as a strategic material, However, it might not fully reflect reality. Future research could look into the possibility that European made lithium is also used in small lithium products.

5.5. Personal Reflections

In this Section, the author summarizes what he has learned during this research.

This research has taught me that planning the critical steps is very important, but that in actual practice, things often go differently than initially expected. The research was structured in advance through the sub-questions, with the first two questions serving as the foundation for the MFA, which could only be constructed afterward. In practice, a lot of valuable information is obtained from the interviewees, but scheduling, preparing for, and conducting these interviews take a lot of time and often were completed only after the first two sub-questions were addressed. As a result, many adjustments had to be made retrospectively. Conducting the interviews earlier could have been beneficial, but at the same time, you often do not know precisely what questions to ask until after the interview is completed.

Creating an accurate MFA is also an extremely time-consuming task; a significant amount of time was spent making and remaking this MFA. When reviewing the model afterward, errors are always found. This is an enjoyable but also very frustrating process. In hindsight, a tip would be to focus on obtaining results more quickly rather than constantly doubting the variables.

Additionally, I found describing the results to be an incredibly enjoyable process. Being in control of your own model made it interesting to discover the reasons behind the behavior of certain stocks and flows. Overall, this project has taught me how to conduct a relatively long research project independently while also emphasizing the importance of asking questions when needed.

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A
Model

A.1. General Simulation settings

The model was executed on the Vensim software (Ventana Systems) with the subsequent settings:

Table A.1: General Simulation Settings

Parameter	Value
Initial time [Year]	2020
Final time [Year]	2050
Time Step [Year]	0.015625
Integration technique	Euler

A.2. Data Inputs

This section presents all data inputs applied to capture exogenous variables in the model. The variables are divided into the different sub models of this model, All data inputs, which are presented in the subsequent tables, are listed in alphabetic order. Each section has two different tables, the first table focuses on data for constant variables, whereas the second one provides data inputs for lookup variables. All variables with LCE are in kT LCE.

European Demand (Look Up variables are located at the last page)

Table A.2: Variable Names, Values, and References European Demand (variables)

Variable name [Unit]	Value	Reference(s)
Converter to kilotonnes [Dmnl]	1000	
Li Metal to LCE converter [Dmnl]	5.323	Volta Battery Report (2023)

Small Lithium products

Table A.3: Variable Names, Values, and References Small Lithium Products (variables)

Variable name [Unit]	Value	Reference(s)
2nd life small lithium products ratio	0.1	Own Assumption based on Interviewee S5
Delay 2nd life small products [Year]	3	Pólak (2012)
Delay 2nd not recycled [Year]	3	Pólak (2012)
Delay lithium not recycled [Year]	4	Pólak (2012)
Delay repurposing small lithium [Year]	4	Pólak (2012)
Delay small lithium manufacturing to sales [Year]	0.0385	Barboza (2016)
Delay small lithium products [Year]	4	Pólak (2012)
Delay small lithium to sales [Year]	0.0577	Barboza (2016)
Delay small lithium to user [Year]	0.0577	Barboza (2016)
Delay transport refined small to manufacturing [Year]	0.0577	Barboza (2016)
EU users small lithium products [LCE]	40	Based on Matos et al. (2020)
Imported small Lithium products EU [LCE]	6	Based on Matos et al. (2020)
Inflow refined lithium for small products EU-Transport to small products manufacturing [LCE]	1	Based on Matos et al. (2020)
Small Lithium not correct recycled [Year]	0	
Small Lithium products 2nd life [LCE]	0.2	Based on Matos et al. (2020)
Small Lithium products sales EU [LCE]	6	Based on Matos et al. (2020)
small Lithium products Manufacturing EU [LCE]	1	Based on Matos et al. (2020)

Variable name [Unit]	Values & reference(s)
STEPsc [Dmnl]	[(0,0)-(10,10)],(2020,0.703),(2030,0.322),(2040,0.26),(2051,0.23) IEA (2020)
SDsc [Dmnl]	[(0,0)-(10,10)],(2020,0.703),(2030,0.169),(2040,0.084),(2051,0.08) IEA (2020)
Not recycled ratio small lithium [Dmnl]	[(0,0)-(10,10)],(2020,1),(2025,1),(2040,0.8),(2051,0.5) Liu et al. (2020)

Table A.4: Variable Names, Values, and References Small Lithium Products (LookUp)

Batteries

Table A.5: Variable Names, Values, and References Batteries (variables)

Variable name [Unit]	Value	Reference(s)
2nd life Lithium batteries [LCE]	2	based on Matos et al. (2020)
2nd life ratio [Dmnl]	0.25	Carrara et al. (2022)
Battery Manufacturing EU [LCE]	3	based on Matos et al. (2020)
Delay Batt to User [Year]	0.25	Interviewee S5
Delay import to sales [Year]	0.25	Interviewee S5
Delay Manufacturing [Year]	0.25	Interviewee S5
Delay manufacturing to sales [Year]	0.167	Interviewee S5
Delay recycled import [Year]	0.167	Interviewee S5
EU users batteries [LCE]	16.5	based on Matos et al. (2020)
Imported Batteries EU [LCE]	10	based on Matos et al. (2020)
Imported refined Battery Lithium [LCE]	3	based on Matos et al. (2020)
Imported Recycled Lithium [LCE]	0	based on Matos et al. (2020)
LFP GWh [LCE/GWh]	0.0693	Quan et al. (2022)
LFP lifetime [Year]	16	Xu et al. (2020)
LFP second [Year]	10	Xu et al. (2020)
Lithium shipped outside Europe [LCE]	10	based on Matos et al. (2020)
NCX GWh [LCE/GWh]	0.0315	Quan et al. (2022)
NCX lifetime [Year]	12.5	Xu et al. (2020)
NCX second [Year]	7.75	Xu et al. (2020)
Not recycled ratio [Dmnl]	0.33	Interviewee S5
Reducing Imports factor [Dmnl]	1	

Variable name [Unit]	Values & reference(s)
GWh EU Manufactured [GWh/Year]	[(0,0)-(10,10)],(2020,1.25), (2021,25.75),(2024,120.295), (2025,389.795), (2026,457.415), (2027,495.635), (2028,581.532),(2029,596.232), (2030,864.492),(2051,1200) Battery-news.de (2023); JRC Report Carrara et al. (2023); Volta Battery Report (2024)
Battery regulations Act [Dmnl]	[(0,0)-(10,10)],(2020,0),(2030,0),(2031,0.06),(2035,0.06),(2036,0.12), (2051,0.12) EU Commission (2023)

Table A.6: Variable Names, Values, and References Batteries (LookUp)

Recycling

Table A.7: Variable Names, Values, and Recycling (variables)

Variable name [Unit]	Value	Reference(s)
Black Mass outside Europe [LCE]	0	
Black Mass recycling EU [LCE]	0	based on Matos et al. (2020)
Black Mass Shredder [LCE]	0.5	based on Matos et al. (2020)
Delay Recycling to manu [Year]	0.167	Own Assumption based on other transportation times
Delay shredder to recycling [Year]	0.167	Own Assumption based on other transportation times
Delay transport BM outside Europe [Year]	0.167	Own Assumption based on other transportation times
Delay waste4 [Year]	0.167	Own Assumption based on other transportation times

Variable name [Unit]	Values & reference(s)
NCX Recycling Capacity EU [LCE]	[(0,0)-(10,10)],(2020,0),(2022,0),(2023,2.35215),(2024,2.93715),(2025,3.34215),(2027,3.97215),(2030,5.07465),(2033,5.64165),(2037,6.77565),(2038,7.34265),(2041,7.90965),(2042,8.47665),(2045,9.04365), (2046,9.61065),(2049,10.1777),(2050,10.7446) Battery-news.de (2023); Volta Battery Report (2024)
LFP Recycling Capacity EU [LCE]	[(0,0)-(10,10)],(2020,0),(2022,0),(2023,3.1362),(2024,3.1362),(2025,3.6762),(2027,4.5162),(2030,5.9862),(2033,6.7422),(2037,7.9742),(2038,9.0872),(2041,10.2002),(2042,11.3132),(2045,12.4262), (2046,13.5392),(2049,14.6522),(2050,15.7652) Battery-news.de (2023); Volta Battery Report (2024)
Waste ratio 4 [Dmnl]	[(0,0)-(10,10)],(2020,0.4),(2030,0.65),(2040,0.95),(2051,0.99) Interviewee S4; Battery-news.de (2023)

Table A.8: Variable Names, Values, and References Recycling (LookUp)

Mining and refineries

Table A.9: Variable Names, Values, and References Mining and Refineries (Variables)

Variable name [Unit]	Value	Reference(s)
Delay EU mine to refinery [Years]	7	Lee (2022)
Delay raw Lithium to Refinery [Year]	0.167	Own Assumption based on other transportation times
Delay Refinery to Manu [Year]	0.167	Own Assumption based on other transportation times
Delay waste3	0.167	Own Assumption based on other transportation times
Imported raw Lithium	0	based on Matos et al. (2020)
Inflow EU Lithium 2019 [LCE]	1.5	RMIS – Lithium (2023)
Lithium Processing EU	0	Carrara et al. (2023)
Processing Waste	0	
Starting date (2019) [Dmnl]	2019	RMIS – Lithium (2023)
Waste ratio 3	0.9	Interviewee S5
Yearly grow rate Lithium [LCE]	0.03	RMIS – Lithium (2023)

Variable name [Unit]	Values & reference(s)
Capacity of EU Processing facilities [LCE/Year]	[(0,0)-(10,10)],(2020,0),(2025,0),(2030,0),(2040,0),(2050,0)

Table A.10: Variable Names, Values, and References Mining and Refineries (LookUp)

A.3. Policy settings

Variable name [Unit]	Value
Reducing Imports factor [Dmnl]	0.8 and 0.6
GWh EU Manufactured [GWh/Year]	[(0,0)-(10,10)], (2020,1.25), (2021,25.75), (2024,120.295), (2025,389.795), (2026,457.415), (2027,495.635), (2028,581.532), (2029,596.232), (2030,864.492), (2051,2593.49)
NCX Recycling Capacity EU [LCE]	[(0,0)-(10,10)], (2020,0), (2022,0), (2023,2.35215), (2024,2.93715), (2025,6.6843), (2027,7.9443), (2030,15.224), (2033,16.9249), (2037,20.327), (2038,22.028), (2041,23.729), (2042,33.9066), (2045,36.1746), (2046,38.4426), (2049,40.7106), (2050,42.9786)
LFP Recycling Capacity EU [LCE]	[(0,0)-(10,10)], (2020,0), (2022,0), (2023,3.1362), (2024,3.1362), (2025,7.3524), (2027,9.0324), (2030,17.9586), (2033,20.2266), (2037,23.9226), (2038,27.2616), (2041,30.6006), (2042,45.2528), (2045,49.7048), (2046,54.1568), (2049,58.6088), (2050,63.0608)
Not recycled ratio small lithium [Dmnl]	[(0,0)-(10,10)], (2020,1), (2025,0.5), (2040,0.3), (2051,0.2)
Waste ratio 4 [Dmnl]	[(0,0)-(10,10)], (2020,0.4), (2030,0.95), (2040,0.95), (2051,0.99)
Yearly grow rate Lithium [LCE/(Year*Year)]	3
Capacity of EU Processing facilities [LCE/Year]	[(0,0)-(10,10)], (2020,0), (2025,0), (2030,30), (2040,60), (2050,100)

Table A.12: Variable Names and Values Policy settings (variables & LookUp)

Variable name [Unit]	Values & reference(s)
European Share Lithium batteries demand [Dmnl]	[(0,0)-(10,10)], (2020,0.06), (2021,0.07), (2022,0.08), (2023,0.09), (2024,0.1), (2025,0.11), (2026,0.12), (2027,0.13), (2028,0.14), (2029,0.15), (2030,0.16), (2031,0.16), (2032,0.16), (2033,0.16), (2034,0.16), (2035,0.17), (2036,0.17), (2037,0.17), (2038,0.17), (2039,0.17), (2040,0.17), (2041,0.17), (2042,0.17), (2043,0.17), (2044,0.18), (2045,0.18), (2046,0.18), (2047,0.18), (2048,0.18), (2049,0.18), (2050,0.18), (2051,0.18), (2052,0.18), (2053,0.18), (2054,0.18), (2055,0.18), (2056,0.18), (2057,0.18), (2058,0.18), (2059,0.18), (2060,0.18), (2061,0.18), (2062,0.18), (2063,0.18), (2064,0.18), (2065,0.18), (2066,0.18), (2067,0.18), (2068,0.18), (2069,0.18), (2070,0.18), (2071,0.181) Rossi et al. (2023)
”NCX.STEP” [LCE/Year]	[(0,0)-(10,10)], (2020,0.03604), (2021,0.03672), (2022,0.04113), (2023,0.04693), (2024,0.05456), (2025,0.06465), (2026,0.06486), (2027,0.07818), (2028,0.09437), (2029,0.11401), (2030,0.13761), (2031,0.15365), (2032,0.16071), (2033,0.16812), (2034,0.17562), (2035,0.19448), (2036,0.21362), (2037,0.2336), (2038,0.25484), (2039,0.27775), (2040,0.30273), (2041,0.3308), (2042,0.36118), (2043,0.39399), (2044,0.42832), (2045,0.46344), (2046,0.49904), (2047,0.53484), (2048,0.57194), (2049,0.61107), (2050,0.64652), (2051,0.68334) Xu et al. (2020)
”NCX.SD” [LCE/Year]	[(0,0)-(10,10)], (2020,0.0656), (2021,0.0626), (2022,0.0707), (2023,0.0818), (2024,0.0969), (2025,0.1176), (2026,0.1199), (2027,0.147), (2028,0.1805), (2029,0.2218), (2030,0.2727), (2031,0.2908), (2032,0.3056), (2033,0.3218), (2034,0.3628), (2035,0.4065), (2036,0.4512), (2037,0.4973), (2038,0.5455), (2039,0.5965), (2040,0.6509), (2041,0.7109), (2042,0.7743), (2043,0.8412), (2044,0.9096), (2045,0.9781), (2046,1.0463), (2047,1.1138), (2048,1.1828), (2049,1.2541), (2050,1.3216), (2051,1.3904) Xu et al. (2020)
”LFP.STEP” [LCE/Year]	[(0,0)-(10,10)], (2020,0.0361), (2021,0.0364), (2022,0.0403), (2023,0.0454), (2024,0.0523), (2025,0.0614), (2026,0.0614), (2027,0.0737), (2028,0.0887), (2029,0.1069), (2030,0.1287), (2031,0.1437), (2032,0.1503), (2033,0.1572), (2034,0.1644), (2035,0.182), (2036,0.2002), (2037,0.2192), (2038,0.2395), (2039,0.2615), (2040,0.2856), (2041,0.3124), (2042,0.3414), (2043,0.3727), (2044,0.4055), (2045,0.4392), (2046,0.4733), (2047,0.5077), (2048,0.5435), (2049,0.5812), (2050,0.6152), (2051,0.6506) Xu et al. (2020)
”LFP.SD” [LCE/Year]	[(0,0)-(10,10)], (2020,0.0657021), (2021,0.0619821), (2022,0.0692079), (2023,0.0791446), (2024,0.0928209), (2025,0.111642), (2026,0.113435), (2027,0.138631), (2028,0.169663), (2029,0.207914), (2030,0.254942), (2031,0.271851), (2032,0.285737), (2033,0.300936), (2034,0.339487), (2035,0.380446), (2036,0.422712), (2037,0.466571), (2038,0.512589), (2039,0.561566), (2040,0.614149), (2041,0.671282), (2042,0.731795), (2043,0.795713), (2044,0.861178), (2045,0.926847), (2046,0.992367), (2047,1.05737), (2048,1.12387), (2049,1.19263), (2050,1.25754), (2051,1.32384) Xu et al. (2020)

Table A.11: Variable Names, Values, and References European Demand (LookUp)

Table A.13: Battery recycling tech in Europe (2023)

Country	**Manufacturer**	**Headquarters**	**Sources**
Germany	Primobius GmbH Umicore Nickelhütte Aue GmbH LiCycle Roth GmbH Redwood Materials Accurec GmbH Bas-F Mercedes-Benz Green Li-Ion Duesenfeld GmbH	Germany Belgium Germany Canada Germany United States Germany Germany Germany Singapore Germany	Volta Battery report (2023) Volta Foundation, 2023
France	Solvay (in cooperation with Veolia) Veolia (in cooperation with Solvay) SNAM Groupe	Belgium France France	
Sweden	NorthVolt HydroVolt (Norway)	Sweden Sweden	
Finland	Umicore Fortum	Belgium Finland	
Belgium	Umicore	Belgium	
Poland	Umicore	Belgium	
Netherlands	TES	Singapore	
Spain	Sung Eel HiTech	South-Korea	

Table A.14: Gigafactory Plants in Europe (2023)

Country	Manufacturer	Capacity	Sources
France	ACC	40 GWh*	Battery Factory Database; Bench mark Minerals; Battery-news.de as cited in Volta Foundation (2023)
	Envision AESC/Renault	30 GWh*	
	Verkor/Renault	50 GWh*	
	Prologium	48 GWh*	
Germany	ACC	40 GWh*	
	CATL	14 GWh*	
	Leclanche	2.5 GWh	
	NorthVolt	60 GWh*	
	SVOLT	24 GWh	
	SVolt	16 GWh*	
	Tesla	100 GWh*	
	PowerCo	40 GWh*	
Italy	ACC	40 GWh*	
	ITAVOLT	70 GWh*	
Portugal	CALB	45 GWh*	
Netherlands	Eurocell	1 GWh	
Sweden	NorthVolt	60 GWh*	
	Volvo	TBD	
	NOVO	50 GWh*	
Hungary	CATL	100 GWh*	
	Cellforce Group	10 GWh*	
	EVE Energy	28 GWh*	
	Samsung SDI	40 GWh*	
	SK	47.3 GWh*	
Spain	Envision AESC	50 GWh*	
	PowerCo	60 GWh*	
	Baquevolt	10 GWh*	
Slovakia	Inobat	10 GWh*	
Poland	LGES	115 GWh*	
Czech Republic	MES	15 GWh*	

B

Verification and Validation

B.1. Verification

To ensure that the system works smoothly and does not make any errors, parts of the model have been checked for verification. These steps include the time step, checking for any inconsistencies in the units, and conducting a structural behavior test.

B.1.1. Timestep Test

After the model was completed, it is important to test the time step that the model can handle. A crucial tip from researcher to researcher: make sure to actually do this! Due to the numerical integration method, a time step that is too large can produce values that do not stabilize, while too small a time step generally requires much more computational power, which is disadvantageous as it consumes time (and computing resources) and is unnecessary if not required. In this study, Euler numerical integration was used because Look-Up Functions and Max/Min functions were utilized, making Runge-Kutta 4 less appropriate.

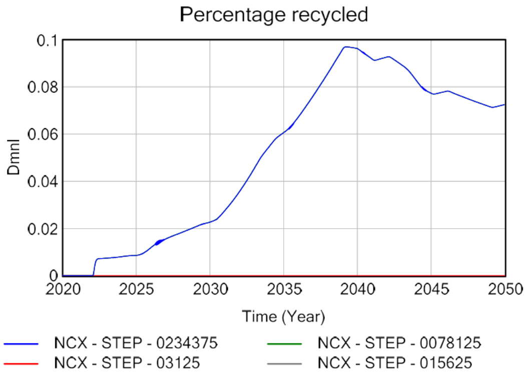


Figure B.1: CRMA Benchmark - Recycled (All time steps)

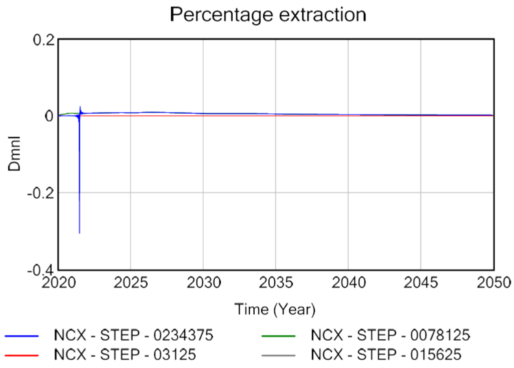


Figure B.2: CRMA Benchmark - Extraction (All time steps)

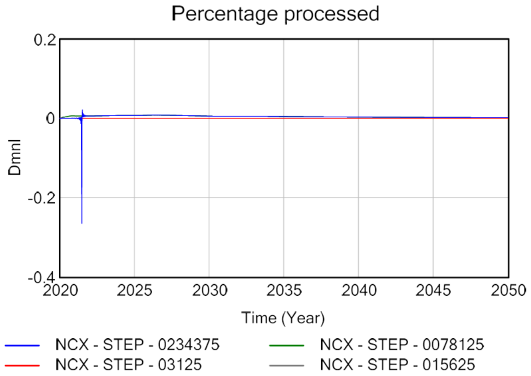


Figure B.3: CRMA Benchmark - Processed (All time steps)

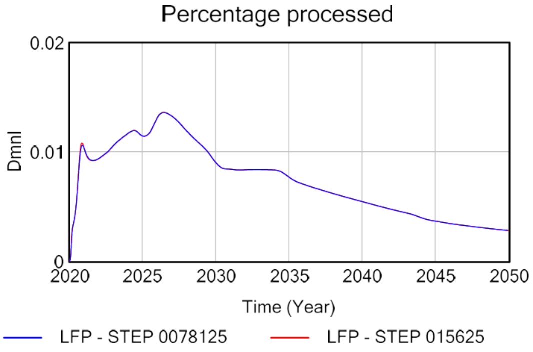


Figure B.4: CRMA Benchmark - Processed (Example with only smallest two time steps)

Figure B.5: Justification of the use of timestep 0.015625

The chosen time step is 0.015625. This was the first time step where all variables did not diverge to infinity, and the time step was small enough to create a stable system. In Figure C1, C2 and C3, you can see that different time steps were selected, and in Figure C.4, the two smallest time steps 0.015625 and 0.0078125 are shown.

B.1.2. Unit Consistency Test

Ensuring unit consistency in MFA is crucial for maintaining accuracy and reliability in tracking material flows. Inconsistent units can lead to calculation errors, misinterpretations, and flawed conclusions. By standardizing units, we ensure that all data is comparable and integrable, facilitating clear communication and informed decision-making. This practice minimizes errors and enhances the overall robustness of the analysis, leading to more reliable and actionable insights.

In this model, there are no unit errors. However, there are 31 warnings in the model created by the Look-Ups, as they are bounded until 2050 or sometimes 2051. Vensim issues these warnings because, should you choose to simulate a longer timeline, the Look-Ups would not be suitable beyond these bounds.

B.1.3. Structure Behaviour Test

Some of the stocks in this model transition into various flows, which are divided by different built-in ratios. To ensure that no material ”disappears” from the system—meaning too much material leaves the stock or too much accumulates in the stock—it is important to verify that all ratios eventually add up to 1. This has been done for all components, but to illustrate it visually, an example is provided in Figure B.6.

For instance, from EU Users Small Lithium, there are three flows to other stocks. The values $0.8 + 0.1 \times (1 - 0.8) + (1 - 0.1) \times (1 - 0.8)$ add up to 1. The same applies for $(1 - 0.8) + 0.8$. This calculation has been done for all stocks with more than one flow, and they always add up to 1, meaning that no material is leaving the system improperly.

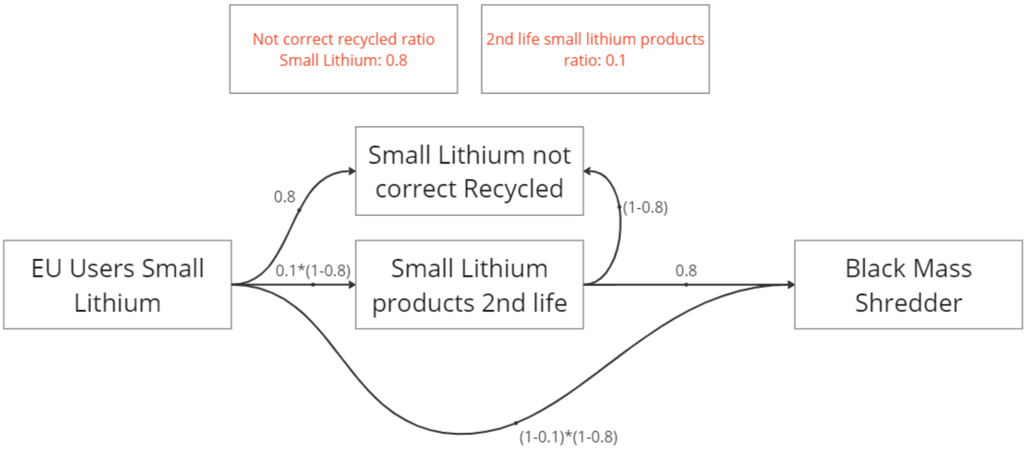


Figure B.6: Structure behaviour overview Small Lithium Products

B.2. Validation

Next, the validation section examined whether the model fulfills the objectives of this research. In other words, it assessed whether the model is fit for purpose. The research aims to conduct a Material Flow Analysis aggregated across all of Europe. Various companies are combined into single sectors, such as mining, battery manufacturing, and recycling industries. This approach ensures that the model does not attempt to replicate the complete reality, as it does not model every individual country within Europe or every company within those countries. Instead, it provides an overview of the amount of lithium entering, remaining in, and leaving Europe. This is the goal of the research, and therefore, the level of aggregation makes the model fit for purpose. Additional tests have been conducted to ensure that the model performs as required.

B.2.1. Structure-Verification test

The model described is based on Actor and Supply Chain Analysis, as detailed in Chapter 2. It is primarily grounded in the supply chain framework outlined by Sun et al. (2012), with extensions from various sources such as Matos et al. (2023) and Bruno and Fiore (2023). Due to variations in quantity and lifespan, distinctions have been made between different lithium products, which can be seen as an expansion of the original model. Furthermore, this model has been discussed with various experts who have reviewed the supply chain and concurred with the model's design. Keeping in mind the same fundamentals as other Material Flow Analyses, and considering the scope of this research, it can be concluded that the structure of the model is comparable to the real-world in the purpose of answering the main question, as it provides a comprehensive representation of reality.

B.2.2. Boundary Adequacy test

The Boundary Adequacy Structure Test (Schwaninger & Groesser, 2011), which builds on ideas from Forrester (1980), Lane (1995), and Sterman (2002), evaluates whether a model encapsulates all necessary and sufficient structural relationships to fulfill its intended purpose. This test checks if the level of aggregation chosen for the model is suitable and ensures that it encompasses all crucial structural elements. It's important for the model to incorporate key concepts that are essential for addressing the core problem from within the system itself. For example, variables that might vary over time need to be integrated into the model as endogenous factors. The critical validation question to consider is whether a parameter should be endogenized, based on the specific objectives of the model.

This model represents all lithium flows through Europe. This means that all lithium used within the European Union, including small lithium products and batteries, is included. Activities occurring outside the European Union are considered exogenous in this model. The values from which the key outcomes, the CRMA benchmarks, are derived are calculated by the system. As a result, a clear picture of how the benchmarks behave over time can be depicted. The European capacity for manufacturing and recycling batteries is also included in the system. This is not calculated endogenously within the system but is tied to the actual capacity that companies within the European Union have over time.In addition to the inflows, everything is described endogenously within the system. This approach allows for a clear depiction of how batteries move from production to the user and eventually enter the recycling circuit, incorporating all relevant timelines.

To conclude, this model operates at the European level and does not account for individual countries. This approach is suitable for the purpose of this research. However, if future research focuses on the interactions between individual countries, this model would no longer be fit for purpose.

B.2.3. Extreme values test

Extreme conditions are rare in real-world scenarios and typically stand as outliers Schwaninger and Groesser, 2011. The validity of a model under such conditions is determined by comparing the outcomes produced by the model's equations with the expected real-world outcomes under similar circumstances. Testing for extreme conditions is an intellectual exercise that does not rely on computer simulations. This method should ideally be applied individually to each equation, involving the assignment of extreme values to the input variables. The resulting outputs are then analyzed to understand what would occur in the actual system under these conditions. For instance, if a population is considered to be zero, there would logically be no births, deaths, or resource consumption. If this model receives no inflow into the system, all values will drop to zero, except if the inflow from European mines continues. This scenario is unlikely to occur unless all countries outside Europe impose a complete export ban on lithium products. The variables in the model do not generate lithium themselves, so the flow of lithium would cease entirely in such a situation.

After the mental exercise, the lithium inflow from outside Europe is set to zero, except for the inflow of batteries produced within Europe. As can be seen, there is hardly any lithium being transported, which is evident from the outflows of the system. However, the CRMA benchmarks are high because the total consumption of lithium has also decreased. This reduction in the denominator of the ratio increases the percentages. Overall, both the mental extreme values test and the modeled extreme values test accurately reflect reality, making the model fit for purpose in this area.

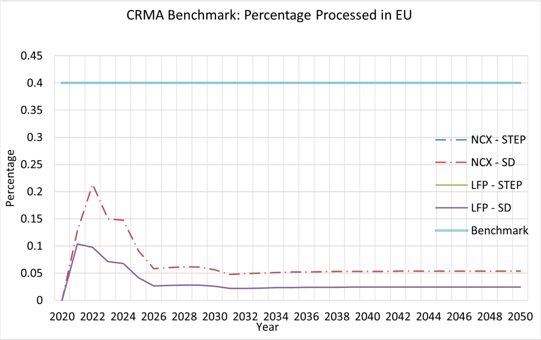


Figure B.7: CRMA - Processed

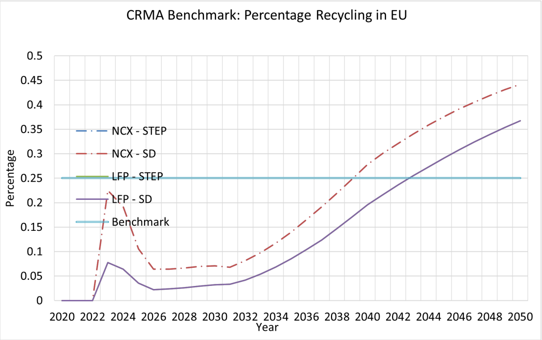


Figure B.8: CRMA - Recycled

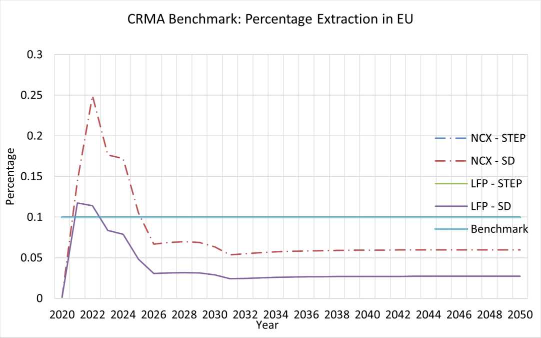


Figure B.9: CRMA - Extracted

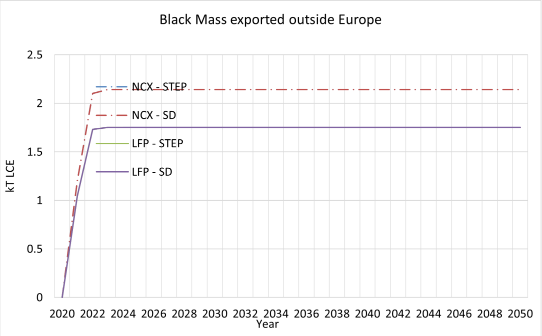


Figure B.10: Outflow - Black Mass exported outside Europe

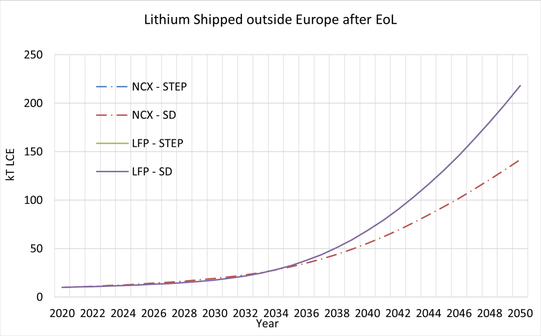


Figure B.11: Outflow - Lithium batteries outside Europe

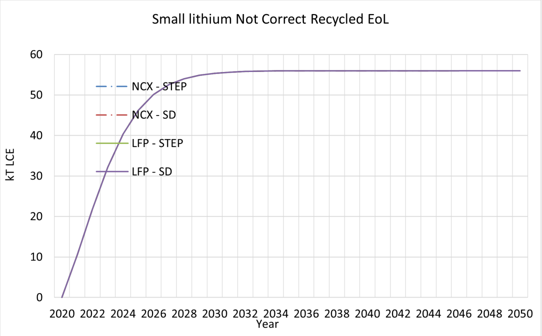


Figure B.12: Outflow - Small lithium Not Correct Recycled EoL

Figure B.13: Extreme values test, where all the inflow of lithium is set to 0 except for the lithium factories in the EU

B.2.4. Sensitivity Analysis

The extreme values test investigates the effects of uncertain inputs or approximations within a system to determine if the model performs as expected under non-standard conditions. This test forms an integral part of the wider sensitivity analysis framework that explores the relationship between minor input fluctuations and their impact on outputs. A model is considered highly sensitive when small modifications (+/- 10%) result in behavioral rather than merely numerical changes. This indicates that in this model slight shifts in parameter values can significantly influence the behavior of the CRMA benchmarks, deviating from the model's typical responses.

A Material Flow Analysis should not manifest behavioral sensitivity, as the system is predicated on maintaining mass balance and should not develop feedback loops. Nevertheless, even though it is not standard practice, conducting a sensitivity analysis can be advantageous. This analysis serves to verify the operational integrity of the system by identifying any potential issues.

The sensitivity analysis comprises a univariate sensitivity analysis that involves evaluating various variables. These variables can be found in Table B.1.

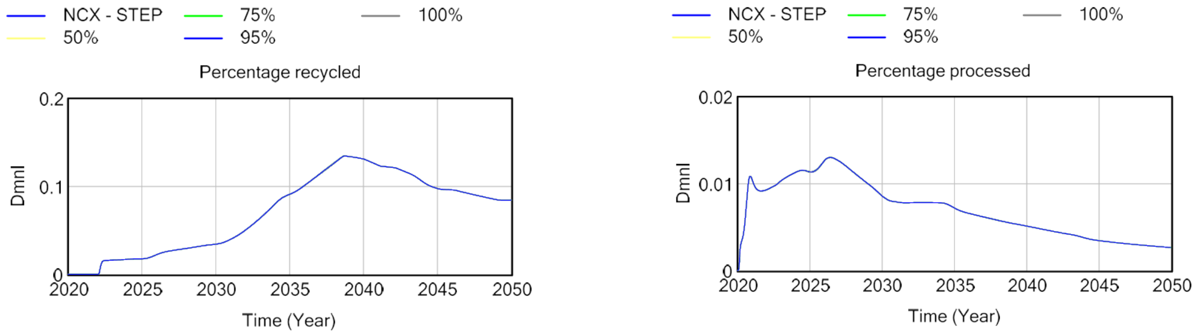
Name Variable	Lower bound (-10%)	Current Value	Upper bound (+10%)
NCX GWh (in Kt LCE)	0.02835	0.0315	0.03465
LFP GWh (in Kt LCE)	0.06237	0.0693	0.07623
Lifetime NCX (In years)	11.25	12.5	13.75
Lifetime LFP (In years)	14.4	16	17.6
Amount of imported batteries	0.9	1	1.1

Table B.1: Values used for sensitivity analysis

Results for NCX and LFP GWh (the total GWh produced within the European Union) are displayed in Figures B.14, B.15, B.16, and B.17. The model exhibits no behavioral sensitivity across its entirety. For both battery chemistries—NCX and LFP—in both scenarios, SD and STEP, there is negligible sensitivity in the CRMA benchmarks. This stability arises because, in the Material Flow Analysis, any decrease in batteries produced within the EU is offset by an increase in imported batteries.

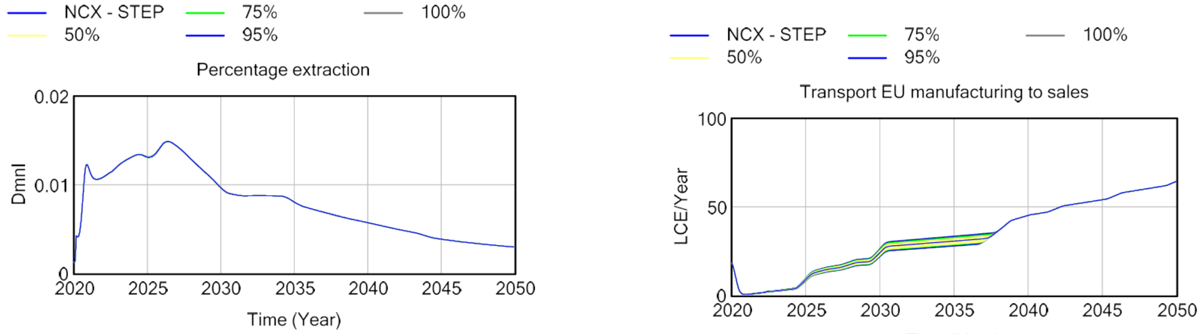
Results regarding the lifetime of NCX and LFP batteries are presented in Figures B.18, B.19, B.20, and B.21. No behavioral sensitivity is observed in the complete model. However, within the CRMA Benchmarks, there is a slight numerical sensitivity noted in the CRMA Benchmark for recycling. This observation is reasonable, as longer or shorter battery lifetimes result in smaller or larger flows of end-of-life (EoL) products, respectively, affecting the volume of materials available for recycling.

The amount of lithium imported to the EU, as depicted in Figures B.22, B.23, B.24, and B.25, does introduce some changes to the system, although these are primarily of numerical sensitivity within the model. It is important to highlight that the greatest sensitivity occurs post-2035 to 2040. This heightened sensitivity is likely due to the fact that new investments in EU battery manufacturing beyond this period have not yet been announced—and consequently are not integrated into the model. As a result, the demand for imported batteries increases.



(a) CRMA Benchmark: Recycling in EU. Sensitivity Analysis for NCX GWh

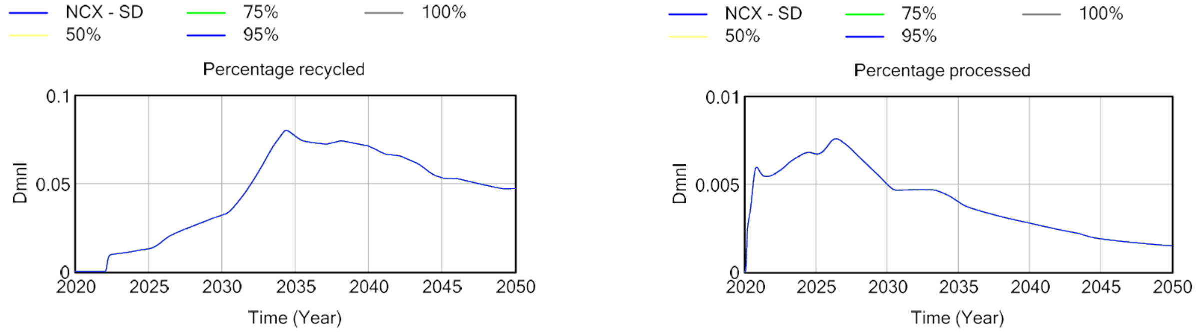
(b) CRMA Benchmark: Processed in EU. Sensitivity Analysis for NCX GWh



(c) CRMA Benchmark: Extraction in EU. Sensitivity Analysis for NCX GWh

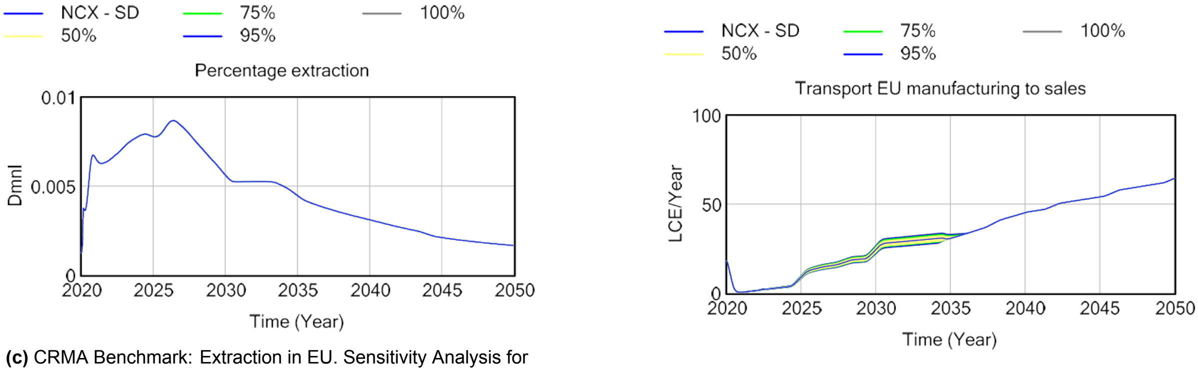
(d) EU Battery Manufacturing. Sensitivity Analysis for NCX GWh

Figure B.14: Sensitivity Analysis for NCX GWh for scenario NCX - STEP.



(a) CRMA Benchmark: Recycling in EU. Sensitivity Analysis for NCX GWh

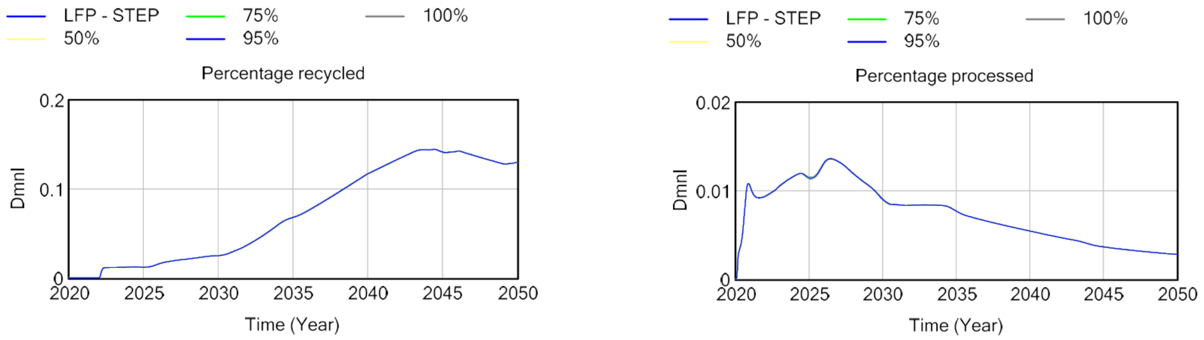
(b) CRMA Benchmark: Processed in EU. Sensitivity Analysis for NCX GWh



(c) CRMA Benchmark: Extraction in EU. Sensitivity Analysis for NCX GWh

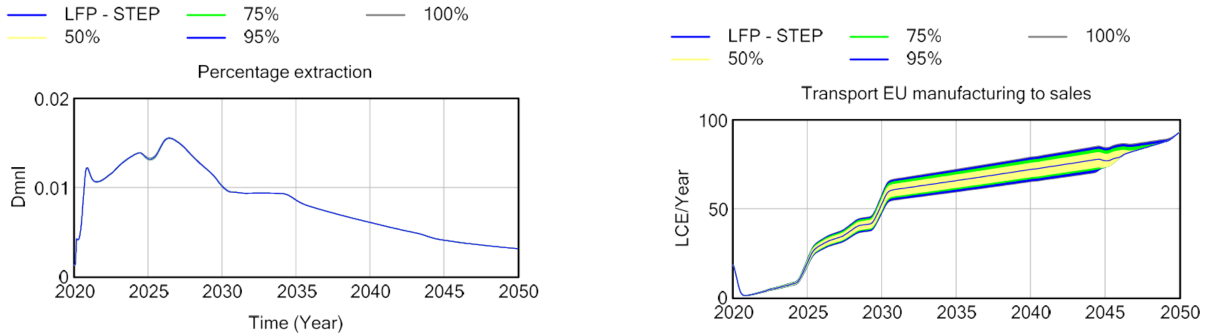
(d) EU Battery Manufacturing. Sensitivity Analysis for NCX GWh

Figure B.15: Sensitivity Analysis for NCX GWh for scenario NCX - SD.



(a) CRMA Benchmark: Recycling in EU. Sensitivity Analysis for LFP GWh

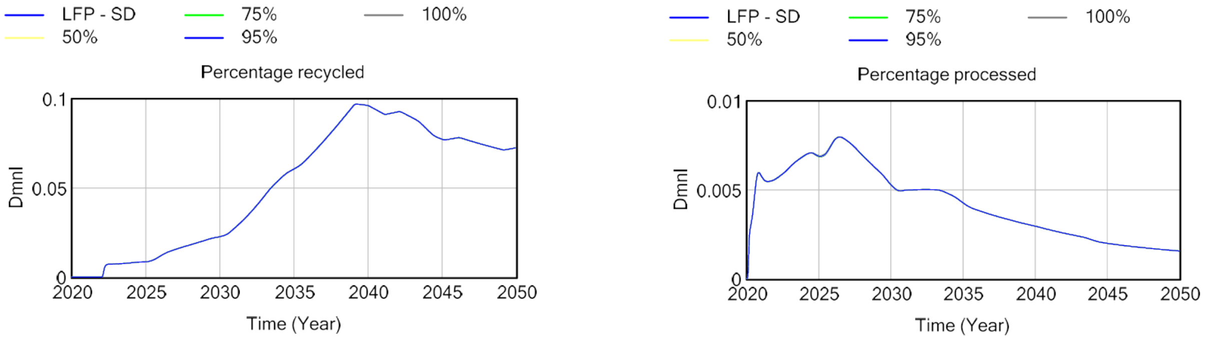
(b) CRMA Benchmark: Processed in EU. Sensitivity Analysis for LFP GWh



(c) CRMA Benchmark: Extraction in EU. Sensitivity Analysis for LFP GWh

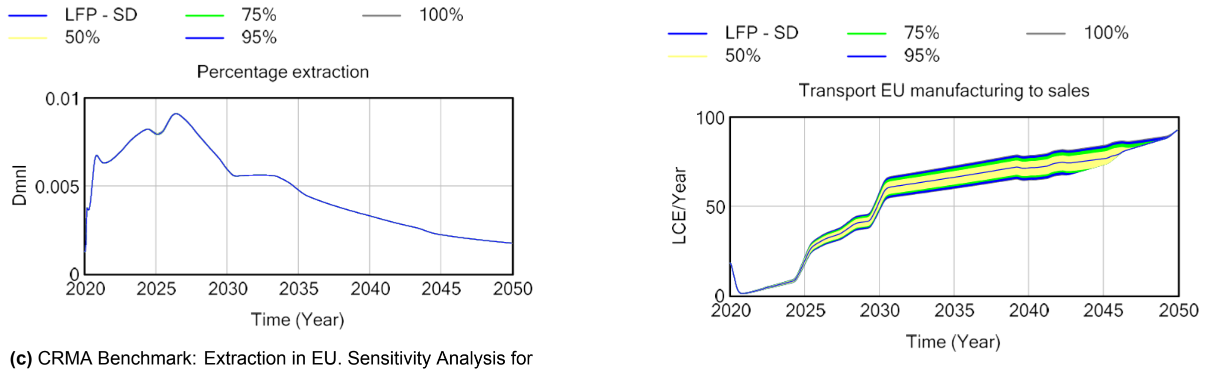
(d) EU Battery Manufacturing. Sensitivity Analysis for LFP GWh

Figure B.16: Sensitivity Analysis for LFP GWh for scenario LFP - STEP.



(a) CRMA Benchmark: Recycling in EU. Sensitivity Analysis for LFP GWh

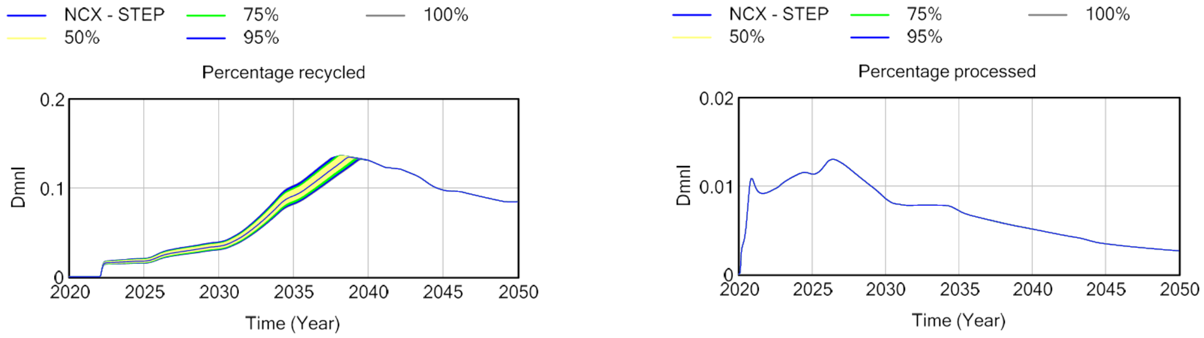
(b) CRMA Benchmark: Processed in EU. Sensitivity Analysis for LFP GWh



(c) CRMA Benchmark: Extraction in EU. Sensitivity Analysis for LFP GWh

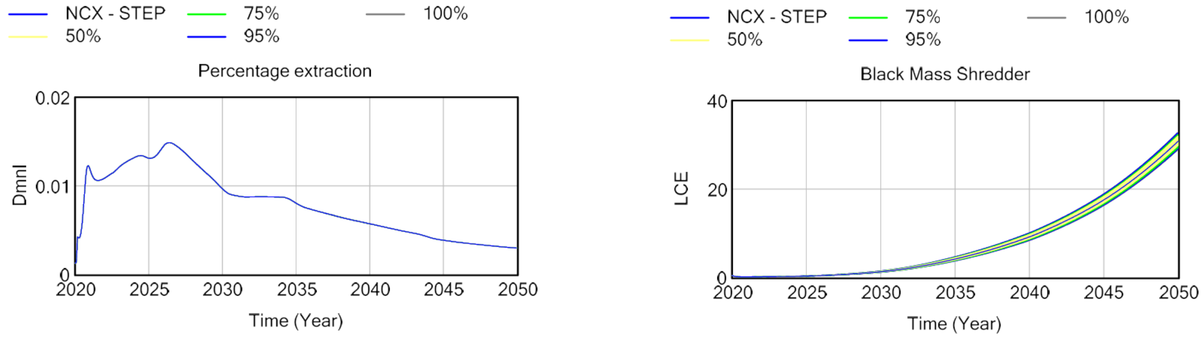
(d) EU Battery Manufacturing. Sensitivity Analysis for LFP GWh

Figure B.17: Sensitivity Analysis for LFP GWh for scenario LFP - SD.



(a) CRMA Benchmark: Recycling in EU. Sensitivity Analysis for NCX Lifetime

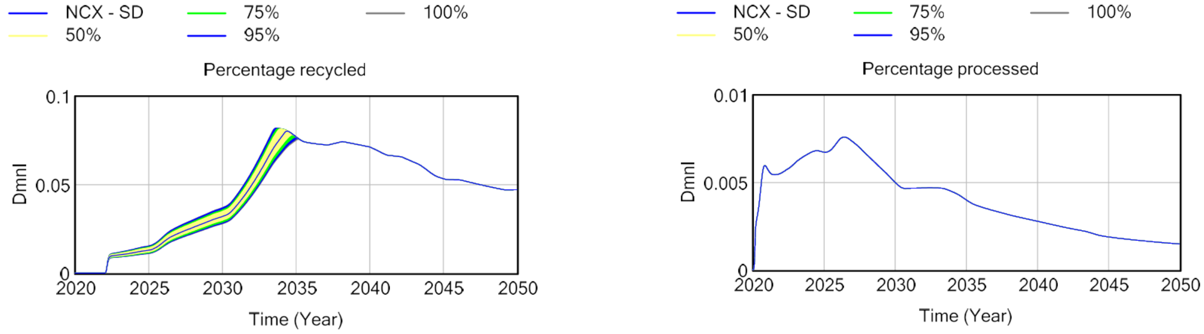
(b) CRMA Benchmark: Processed in EU. Sensitivity Analysis for NCX Lifetime



(c) CRMA Benchmark: Extraction in EU. Sensitivity Analysis for NCX Lifetime

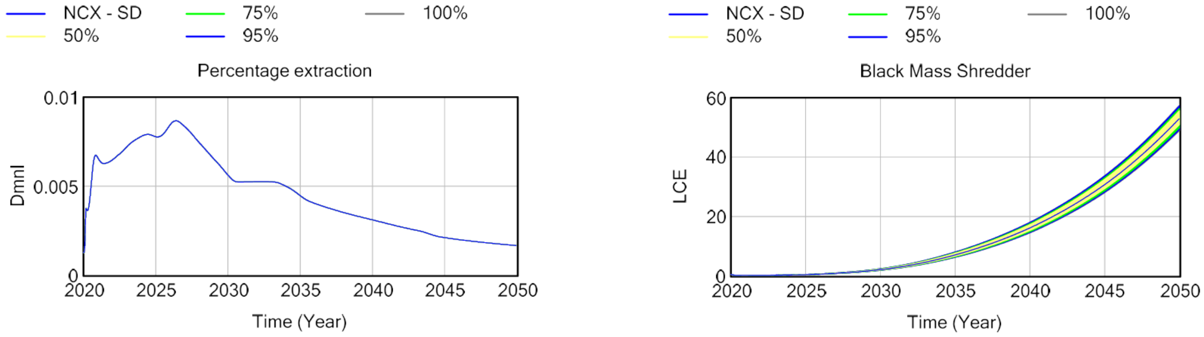
(d) EU Battery Manufacturing. Sensitivity Analysis for NCX Lifetime

Figure B.18: Sensitivity Analysis for NCX Lifetime for scenario NCX - STEP.



(a) CRMA Benchmark: Recycling in EU. Sensitivity Analysis for NCX Lifetime

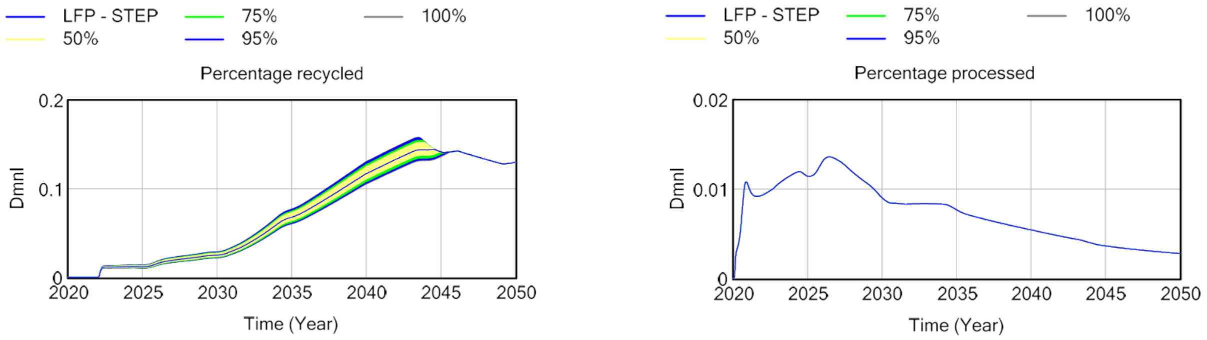
(b) CRMA Benchmark: Processed in EU. Sensitivity Analysis for NCX Lifetime



(c) CRMA Benchmark: Extraction in EU. Sensitivity Analysis for NCX Lifetime

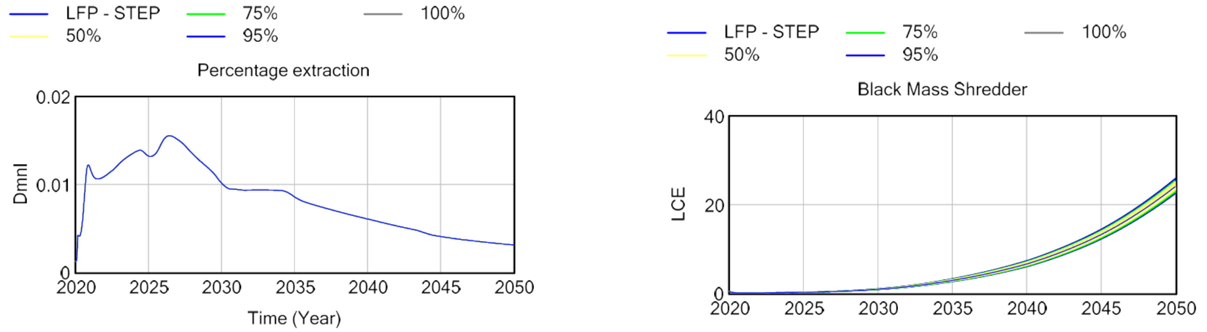
(d) EU Battery Manufacturing. Sensitivity Analysis for NCX Lifetime

Figure B.19: Sensitivity Analysis for NCX Lifetime for scenario NCX - SD.



(a) CRMA Benchmark: Recycling in EU. Sensitivity Analysis for LFP Lifetime

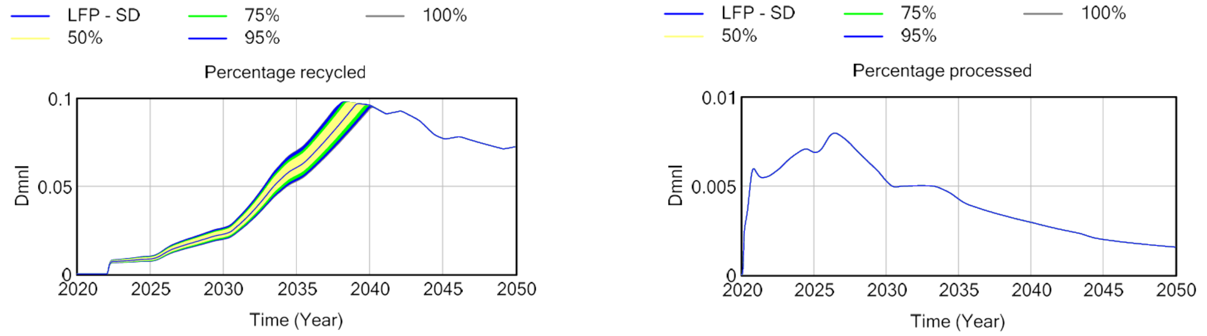
(b) CRMA Benchmark: Processed in EU. Sensitivity Analysis for LFP Lifetime



(c) CRMA Benchmark: Extraction in EU. Sensitivity Analysis for LFP Lifetime

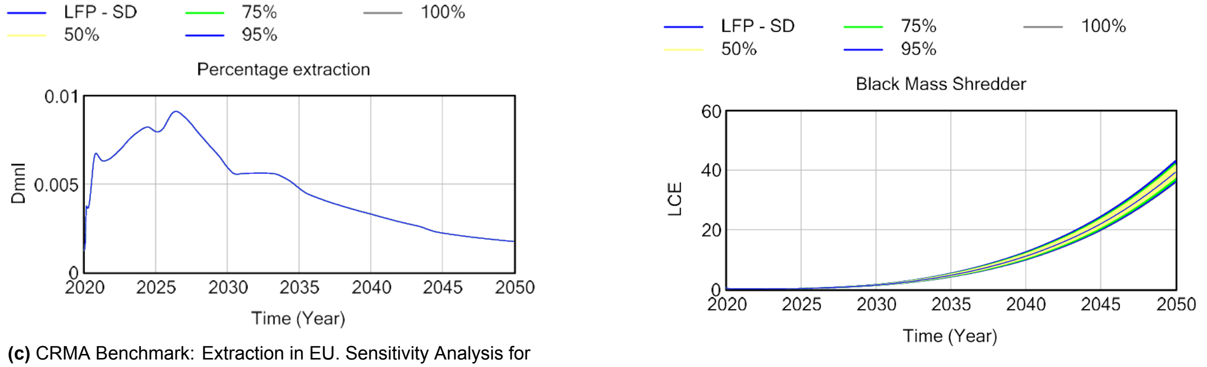
(d) EU Black Mass Shredder. Sensitivity Analysis for LFP Lifetime

Figure B.20: Sensitivity Analysis for LFP Lifetime for scenario LFP - STEP.



(a) CRMA Benchmark: Recycling in EU. Sensitivity Analysis for LFP Lifetime

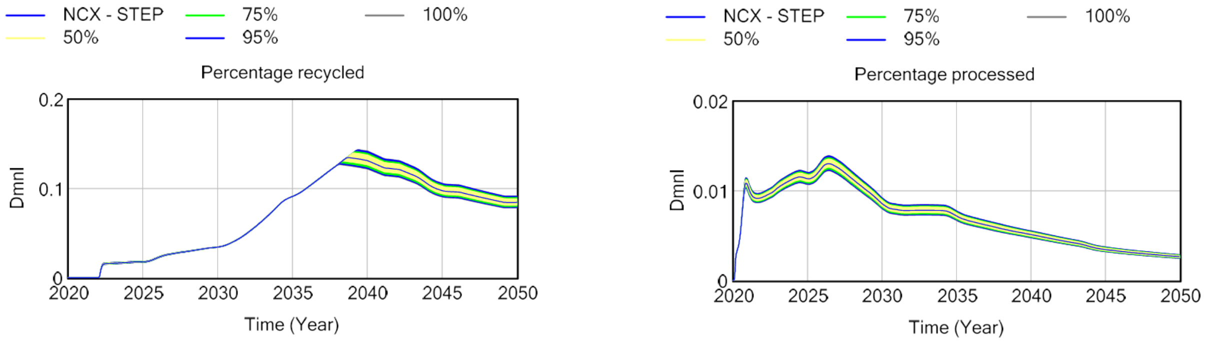
(b) CRMA Benchmark: Processed in EU. Sensitivity Analysis for LFP Lifetime



(c) CRMA Benchmark: Extraction in EU. Sensitivity Analysis for LFP Lifetime

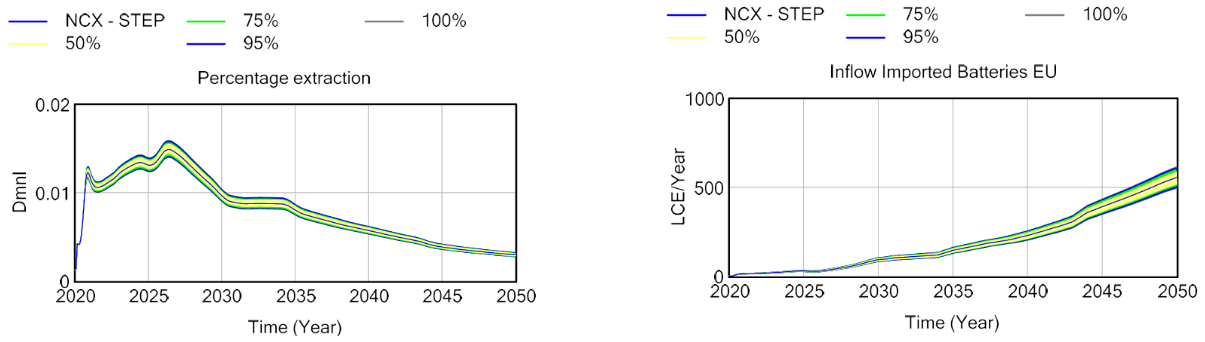
(d) EU Black Mass Shredder. Sensitivity Analysis for LFP Lifetime

Figure B.21: Sensitivity Analysis for LFP Lifetime for scenario LFP - SD.



(a) CRMA Benchmark: Recycled. Sensitivity on amount of imported batteries EU

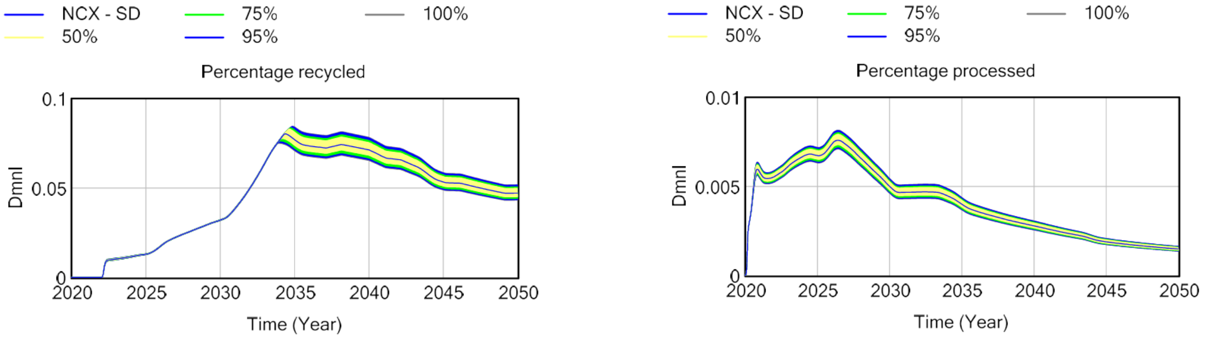
(b) CRMA Benchmark: Processed. Sensitivity on amount of imported batteries EU



(c) CRMA Benchmark: Extraction. Sensitivity on amount of imported batteries EU

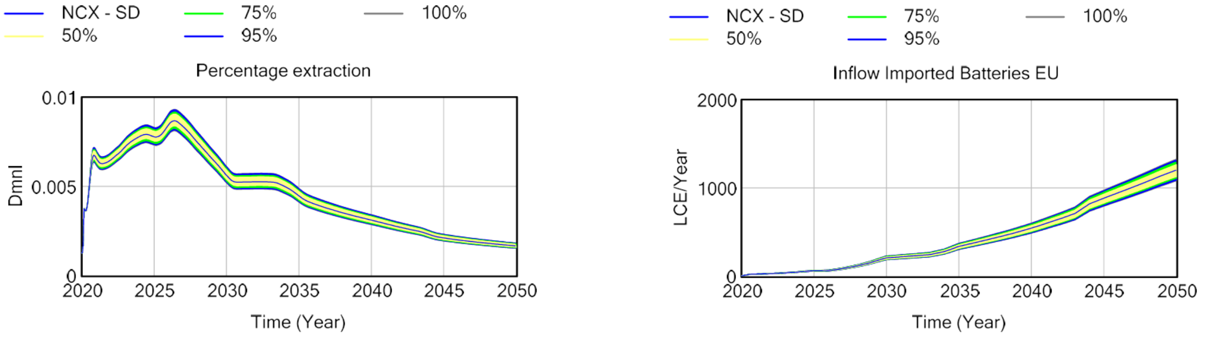
(d) Imported Batteries in the EU. Sensitivity on amount of imported batteries EU

Figure B.22: Sensitivity Analysis for amount of imported lithium batteries for scenario NCX - STEP.



(a) CRMA Benchmark: Recycled. Sensitivity on amount of imported batteries EU

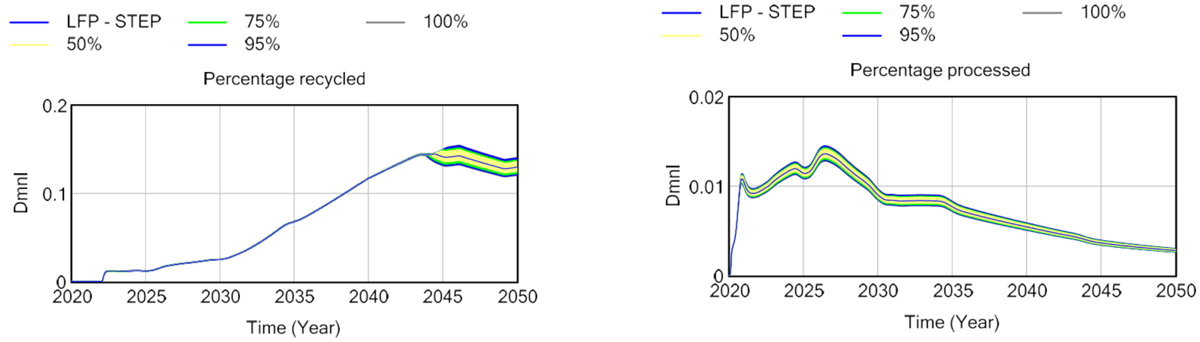
(b) CRMA Benchmark: Processed. Sensitivity on amount of imported batteries EU



(c) CRMA Benchmark: Extraction. Sensitivity on amount of imported batteries EU

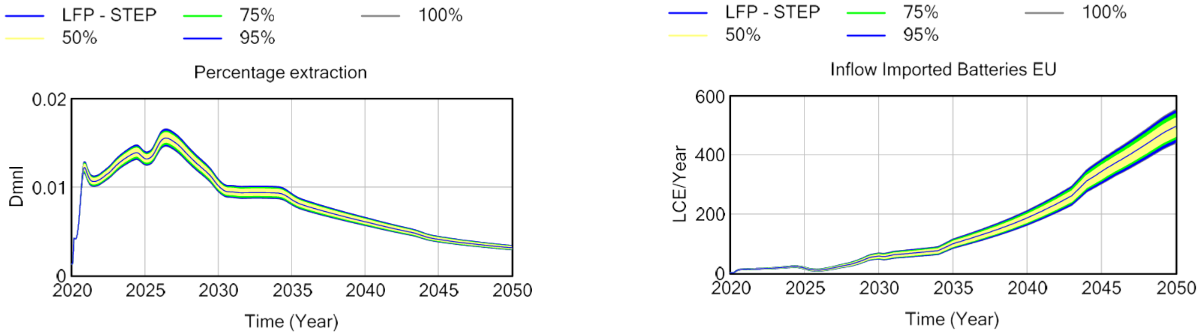
(d) Imported Batteries in the EU. Sensitivity on amount of imported batteries EU

Figure B.23: Sensitivity Analysis for amount of imported lithium batteries for scenario NCX - SD.



(a) CRMA Benchmark: Recycled. Sensitivity on amount of imported batteries EU

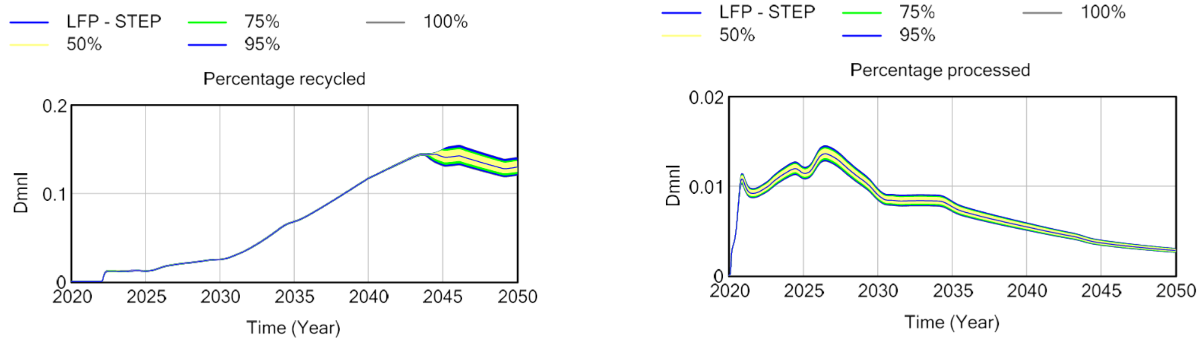
(b) CRMA Benchmark: Processed. Sensitivity on amount of imported batteries EU



(c) CRMA Benchmark: Extraction. Sensitivity on amount of imported batteries EU

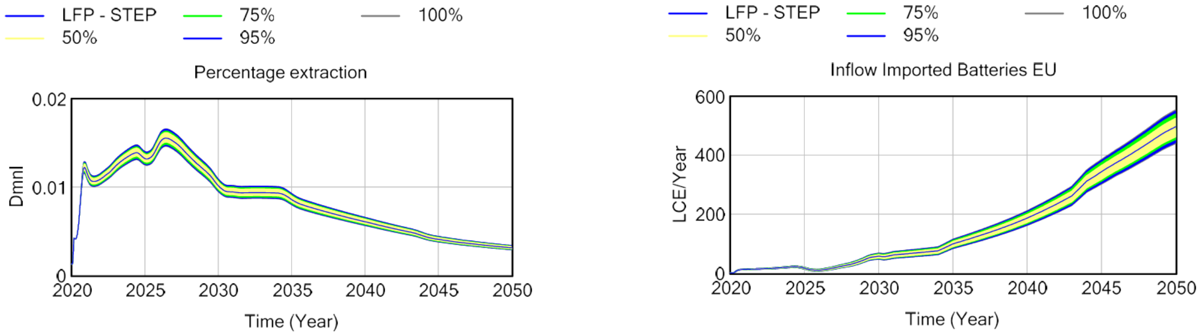
(d) Imported Batteries in the EU. Sensitivity on amount of imported batteries EU

Figure B.24: Sensitivity Analysis for amount of imported lithium batteries for scenario LFP - STEP.



(a) CRMA Benchmark: Recycled. Sensitivity on amount of imported batteries EU

(b) CRMA Benchmark: Processed. Sensitivity on amount of imported batteries EU



(c) CRMA Benchmark: Extraction. Sensitivity on amount of imported batteries EU

(d) Imported Batteries in the EU. Sensitivity on amount of imported batteries EU

Figure B.25: Sensitivity Analysis for amount of imported lithium batteries for scenario LFP - SD.

C
Summaries

The interviews were conducted in a semi-structured format. This approach involved preparing and sending a set of predefined questions to the interviewees beforehand, while also allowing for additional questions or comments to arise during the conversation. One interview was conducted on-site, while the rest were conducted via Microsoft Teams. All interviews were recorded. The on-site interview was recorded using a dictaphone, and the other interviews were recorded using the transcription function of Microsoft Teams.

All interviews were conducted in accordance with the HREC guidelines of TU Delft. Each interviewee completed an informed consent form, which stated that the interviews would be recorded. Subsequently, anonymous summaries of the interviews were created and sent to the interviewees for approval. Once the anonymous summaries were written, all recordings were deleted. Only after receiving their approval were the anonymous summaries included in this research as reference material.

The anonymous summaries were structured around the main points discussed, but all questions that received responses were included in the summaries. These summaries can be reviewed per interviewee. Table C.1 lists the interviewees who participated.

Table C.1: Interviewees

Interviewee	Specialization
S1	Professor in Critical Materials
S2 and S3	Industry experts in Minerals Mining
S4	Policy Expert CRMA
S5	European Battery Expert
S6	Policy Expert CRMA - specialized in Lithium

Because not every interviewee could answer all questions, for instance, due to some being experts in the European supply chain of lithium but not in the CRMA, the questions were divided between lithium experts and CRMA experts. The questions are described in Chapter C.1.

C.1. Questions

Supply Chain Questions (S1, S2, S3 and S5):

- Do you agree with this (simplified) supply chain of lithium flows in the EU?
- Are there any steps missing in the supply chain?
- Do you think European mines will play a larger role in the future?
- Does processing, in your opinion, also mean that more lithium will be refined in Europe?
- How will the European Union ensure these measures are upheld, so that materials do not end up leaving the EU (for cheaper)?
- Where do you think the most potential lies, when it comes to the critical raw material act?
- What do you think is the most logical implementation of the four (separate) points as European policy?
- There is mention of a 'CRM-club' with like-minded countries. Does this also mean that within the European Union, parties will be directed towards joint procurement?

CRMA Questions (S4 and S6):

General:

1. Do you anticipate the creation of individual targets for each Strategic Raw Material (SRM), or will there be an average-based system?
2. Will there be a unified benchmark for the entire European Union, or will individual member states have distinct benchmarks that consider factors like reserves or mining facilities?
3. The CRMA speculates on the possibility of joint procurement. Do you think this is feasible, and if so, how would it be implemented?
4. Currently, it appears that there is no direct funding from the EU to its member states to support the implementation of the CRMA. Do you foresee this changing in the future, and what impact might such a change have on the CRMA?
5. Are companies that are not 'European' but with factories in Europe part of the benchmarks?

Extraction:

1. Is there sufficient demand from companies in opening new mines?
2. Is the primary incentive for establishing new mines the reduction in permit processing times? Will this be adequate to achieve the 10% benchmark?
3. What does EU involvement in the initiation of new mines entail except for permit processing?

Processing:

1. If 40% of the Strategic Raw Materials (SRMs) need to be processed in Europe, but only 10% is currently mined within the EU, will the EU need to import unprocessed lithium from other regions?
2. If this is the case, how does the European Union plan to create business opportunities for companies to invest in processing lithium, particularly if European lithium is more expensive than lithium sourced from elsewhere?
3. If unprocessed lithium is not imported, how will the EU achieve the 40% processing benchmark?
4. Will lithium processed from strategic partner sources be considered as 'processed in the EU' for the purposes of meeting EU benchmarks?

Recycling:

1. Do you consider a 25% recycling rate to be overly ambitious?
2. Could setting overly ambitious recycling rate targets potentially deter investment from recycling firms?
3. In your opinion, should recycled lithium be classified as domestically mined within Europe?
4. Will recycled lithium be exclusively sourced from strategic partners?

In your opinion, where does the greatest potential and pitfall lie within the Critical Raw Materials Act?

C.2. Anonymous Summary Interviewee S1

This summary is the only summary with bullitpoints as answers.

Answers on the general questions about the CRMA:

- It's also interesting to see how the Net Zero Industries Act and CRMA align with each other.
- The idea of the EU is more like we have a goal: if we don't meet it, then we'll put extra pressure on it.
- The biggest tension factor at the moment is not autonomy, but the political game. As soon as the populist parties come to power in the EU, just like in the Netherlands, all industry policies and also the Green Deal will off the table.
- The discomfort in the European way of industry: privatizing profits but socializing risks.
- Personal note: instead of subsidies, invest billions in buying shares in the company. Over-national state-owned companies.
- Be aware that we talk a lot about the free market, etc., but the raw materials market/mining market is not a free market at all. Tianqi Minerals and SQM are simply state-owned companies. And if the free market really worked so well, they would have been played out much earlier, but that's not the case in the real world.
- Also have a conversation with the someone within the Ministry of Economic Affairs, under raw materials strategy.
- Solving problems in times of crisis is always more expensive than otherwise.

Answers on the questions concerning EU Mines:

- European mines are likely to be established.
- Lithium is secretly not very rare; it is also found in groundwater here (not geographically limited).
- Money needs to be invested in it.
- But it's not just about economics: France has a better chance than Portugal, as it can use old mining systems/facilities. Portugal would need to be set up from scratch. However, Portugal, being a traditionally poorer country, might be more open to mining.
- The vision of European countries is very different.
- In China and Japan, you have state companies that play a much broader social role (or are state-owned).
- Here, companies focus only on shareholder value, and all other things are handled by the government.
- Industrial policy at the European level is difficult to discuss and almost impossible since there is no central fund (as is the case in America with federal vs. state taxes).
- Interestingly, it is possible with agricultural subsidies, so in theory, there could be a way to prod companies.
- It must be a total package, so not just manufacturing the battery and then transporting it to China. Otherwise, you are subsidizing China.

Answers on the questions concerning EU Processing:

- 'Processing' is somewhat a flexible concept. But in this case, I believe that processing begins after mining (and the possible initial 'cleaning session') and extends to the conversion of lithium into specific chemical elements like chloride and hydroxide.
- Also, look at the Net Zero Industries Act. This is a very important addition, or actually an extension, of the CRMA and Battery Regulations.
- Also look into the Eco Design Directive.
- For more information, send an email to the European faction of GroenLinks (the Dutch Green Party).
- Also, make sure to thoroughly read the complementary texts of all three. Recycling:
- Recycling is important, but the unfortunate part of this narrative is that there is no consideration for material reduction.

Answers on the questions concerning EU Recycling:

- Be careful with treating speculations about the future (>2045) as truth. Everything planned for 2045 is purely to attract investors, with all the grand talk that involves. Look at the plans up to 2030 for reliable figures, and even then, it's still the 70%/70% rule: so 70% of the announced plans are executed, and of those, you often have 70% capacity filled.
- For example, NorthVolt also had all sorts of grand statements but is now already moving towards America.
- Also, look at the hydrogen stories from 5 years ago and how they are now completely collapsing.

C.3. Anonymous Summary Interviewees S2 and S3

CRMA questions

Are mines going to play a bigger role in Europe in the Future?
The future role of mining in Europe is closely tied to the implementation of the Critical Raw Materials Act (CRMA). This legislation is filled with positive intentions and aims to increase the number of new mining operations. The success of the CRMA will largely depend on its execution by member states and the European Commission, particularly how it influences permitting processes and the granting of social licenses for mines.

There is a significant emphasis on strategic autonomy and linking the supply of raw materials to the defense industry and broader material self-sufficiency. Achieving social license to operate is critical; shifting public perception in Europe to support mining is essential for the industry's expansion. This shift is crucial for Europe to reach, or at least approach, the goal of deriving 10% of its annual raw material consumption from domestic extraction.

However, there is scepticism regarding the timeline set for these targets, particularly by 2030, due to the traditionally slow pace of mining permitting. Yet, there is hope that initiatives like the Raw Materials Act will significantly impact this year, accelerating progress towards these goals.

Do you think the CRMA focusses to much on extracting instead of for instance recycling?
The discussion around the Critical Raw Materials Act (CRMA) suggests that there is a significant focus on extraction rather than recycling. However, this is also quite logical, because the growth in electric vehicle (EV) sales, dramatically increases the demand for lithium. Currently, the volume of end-of-life EV batteries isn't substantial enough to meet recycling needs. It's anticipated that post-2030, there will be sufficient volumes of these batteries to make recycling a viable option on a larger scale.

Additionally, there are technical challenges in recycling lithium compared to metals like nickel and cobalt, which are easier to recover. Advancements in technology will be crucial to improving the efficiency of lithium recycling. The economics of mining and recycling also play a role; the cost-effectiveness of opening new mines is fixed on metal prices. If metal prices remain low, it might discourage the development of new mines unless there are incentives to make such ventures more profitable. These dynamics highlight the need for a balanced approach in the CRMA that supports both sustainable extraction and the development of recycling capacities.

How do you think the European Union is going to stimulate manufacturers to buy (more expensive) European Lithium? The European Union should think about considering implementing local content requirements as a strategy to encourage manufacturers to use more expensive, locally sourced lithium. This approach would mandate that a certain percentage of lithium used in products like electric vehicle batteries—For instance around 10%—must originate from within Europe, whether extracted or recycled. This policy could significantly boost both the extraction and recycling industries in Europe.

However, this proposal has not yet been formally introduced; it remains a topic of advocacy and discussion among stakeholders. Manufacturers are generally resistant to this idea because it could lead to increased costs for raw materials such as lithium and nickel. The anticipated rise in costs is a concern for manufacturers as it could impact their sourcing strategies.

Implementing such a requirement by 2030 is seen as ambitious, given the current lack of sufficient operational lithium mining facilities in Europe. Therefore, while this policy could potentially be beneficial in the long run, its realization and practical impact might not be felt until closer to 2035 or 2040. This timeline considers the need to develop local mining operations and the infrastructure necessary to support such an industry.

Two different mines to look into: The focus in Europe is on two significant mining operations that have high chances of succeeding:

1. Portugal: The Barroso Lithium mine Project in Portugal is indicative of the region's potential for mining operations. However, like many mining projects, it faces challenges in securing a social

license to operate, which involves gaining approval and maintaining ongoing support from local communities and stakeholders.

2. Serbia (Operated by Rio Tinto): This mine is noted for its size and high potential. Rio Tinto's involvement suggests a significant investment and a strategic interest in the region's mineral resources. However, the operation has encountered issues related to obtaining and sustaining a social license to operate. This is often due to environmental concerns, community relations, and the impact of the mining activities on the local area.

Processing Lithium
The discussion about the specifics of lithium processing for battery-grade material and other uses reveals some uncertainty within the CRMA. The process could extend to the production of cathode active material or perhaps stop at a earlier stage, but the exact details are unclear. Furthermore, there is doubt regarding how the Critical Raw Materials Act will address and calculate the requirements for lithium processing, particularly whether the Commission will allow flexibility in meeting these targets.

Key points of concern include the processing of lithium hydroxide and lithium carbonate, with questions about whether these processes are included in the Act's scope or if it extends to the production of catalytic materials. The Act emphasizes the need for lithium to be battery-grade, suitable for EV batteries.

Overall, the uncertainty and lack of detailed disclosure in the legislation highlight the complexities of regulating and supporting the lithium industry, from mining through to the advanced processing stages required for high-quality end products.

What is the 'so-called' Critical Material Club?
The concept of the "Raw Materials Club" appears to focus primarily on fostering partnerships with like-minded countries outside Europe. This initiative is aimed at decentralizing raw material imports to ensure that Europe is not overly reliant on or vulnerable to disruptions from any single country. The strategic approach here is not so much about elevating individual European countries to become major raw material providers ("creating rock stars within Europe") but rather about securing a diverse and stable supply of raw materials through international collaborations.

These partnerships are likely focused on joint procurement and strategic alliances, which can provide more security in raw material supplies. By decentralizing imports, Europe aims to mitigate risks associated with geopolitical tensions or supply chain disruptions that can affect critical raw materials needed for various industries, including technology and manufacturing.

However, the specifics of these partnerships or the exact role of the Raw Materials Club in these processes seem to be under-examined or not currently highlighted in the latest discussions or readings available to the public. Thus, while the initial concept focuses on securing and diversifying Europe's raw material supply chain through external partnerships, further details on ongoing or future initiatives may not be fully delineated yet.

What are the biggest pitfalls for the CRMA?
One of the major pitfalls for the Critical Raw Materials Act (CRMA) is the lack of direct funding linked to the regulation. This presents a significant challenge as the CRMA sets benchmark targets that member states are expected to meet, but without associated financial support, enforcement becomes problematic. This issue is compounded by the regulatory requirement for implementation at the member state level, which varies significantly in effectiveness across the EU.

Additionally, there are concerns about the enforcement mechanisms of the CRMA. When member states fail to meet the requirements, such as those for permitting timelines, the proposed sanctions appear to be minimal. The European Commission has mentioned the possibility of placing non-compliant member states on a blacklist, but this has historically had little impact. Many states are already on various blacklists and show little concern about their status, which could undermine the overall effectiveness of the CRMA.

This situation is particularly challenging because the willingness to comply varies widely among member states. For example, the Nordic countries typically strives to be a role model in implementing EU regulations swiftly and effectively, contrasting sharply with other member states that may be less concerned with EU requirements or any reputational consequences of non-compliance. Therefore, the effectiveness of the CRMA in bringing about significant changes in the critical raw materials sector remains uncertain, largely due to these enforcement and funding challenges.

Other sidenotes about the CRMA
The Critical Raw Materials Act (CRMA) benchmark specifically strategic raw materials, not merely all critical materials. This distinction means that only certain materials that are vital for specific sectors, such as the battery industry, are prioritized under this act. For instance, only the nickel used in battery production is considered under the CRMA, while nickel used in other industries like stainless steel manufacturing is not included. This selective focus aims to bolster the supply chain for essential technologies while not overextending resources on less critical applications.

Furthermore, there is a notable concern regarding the overall demand projections for lithium, as reported by the Joint Research Centre (Carrara, 2023), which appears to be on the lower side. This underestimation could impact planning and policy development, particularly in sectors reliant on lithium, such as electric vehicle manufacturing.

A critical issue also highlighted is the potential inefficiency in the current raw material supply chain, e.g. where materials are mined and processed in Europe but then exported outside the continent for battery production. This process might result in finished products, such as cars, needing to be imported back into Europe, creating an unnecessary and costly loop in the supply chain (and missed GDP opportunity for EU) that undermines the goal of enhancing local industry and reducing logistic dependencies.

Supply Chain Questions Lithium

Will the scenarios LFP, NCX and Li-Air still be possible dominant?
Recent analyses on battery chemistries reveal that while lithium-air technology has not been significantly encountered, especially in the context of electric vehicles (EVs), the dominant chemistries expected to lead production are lithium iron phosphate (LFP) and nickel-rich chemistries. These include NMC 622 and NMC 811, which are anticipated to make up the majority of battery production. The shift towards these high-nickel chemistries is driven by their higher energy density, which enhances battery performance.

Moreover, there's ongoing development in alternative battery technologies, such as sodium-ion batteries. However, projections indicate that their market volumes won't significantly impact overall demand until around 2030. The focus remains on LFP and nickel-rich chemistries due to their established production processes and performance benefits.

Geographical constraints on raw materials like cobalt, which is primarily sourced from the Democratic Republic of Congo (DRC), pose challenges due to ethical concerns and supply chain risks. Efforts are ongoing to reduce reliance on cobalt to mitigate these issues, further steering developments towards alternative chemistries that lessen environmental and humanitarian impacts. These trends underscore the dynamic nature of the battery industry, which is continually evolving to balance performance needs with sustainability and supply chain reliability.

Percentages of Lithium not correct recycled:
While the interviewee doesn't have precise numbers, it's evident that the volume of lithium recycling in Europe is substantial but not yet fully developed compared to regions like China, where the recycling industry is well-established and functioning efficiently. Europe is gradually realizing the importance of enhancing its recycling capabilities to retain valuable materials within its own borders, rather than exporting them primarily to Asia for processing.

Regarding the costs associated with recycling versus primary lithium processing, recycling is generally less energy-intensive, which should theoretically reduce costs. However, the financial viability of recycling also heavily depends on the market price of lithium. If the price of lithium is low, recycling might not be as cost-effective unless there are premiums or other financial incentives to make recycling more appealing than sourcing virgin materials.

These dynamics highlight the ongoing need for Europe to develop a more robust recycling infrastructure to improve resource sustainability and reduce dependency on imported materials.

Black Mass waste

The transportation of black mass, which is classified as hazardous waste, has historically been challenging within the European Union. This complexity might lead to outsourcing activities such as shredding to regions like Asia, where regulations may differ or facilities are better equipped to handle such materials. According to recent developments, it has become more difficult for Europe to import black mass from Asia. Asian suppliers are keep the materials locally, which affects the volumes available for Europe. This shift might be due to changes in regulatory landscapes or strategic decisions by Asian firms to enhance their own recycling capacities. Link to a interesting and reliable website: https://battery-news.de/batterierecyling/

C.4. Anonymous Summary Interviewee S4

The Interviewee highlights at the beginning of the meeting that the CRMA benchmark for recycling is changed from 15% to 25% in the newest version of the Act.

General questions:

Do you anticipate the creation of individual benchmarks for each Strategic Raw Material (SRM), or will there be an average-based system as outlined in your paper?
The interviewee discusses the possibility of setting individual targets for each Strategic Raw Material (SRM) versus adopting an average-based system. They mention that while ideally, individual assessments would be made, which is easier for the fourth point the CRMA (Not more than 65% of the Union's annual consumption for each strategic raw material at any relevant stage of processing from a single third country.), but for the other three points practical constraints might necessitate using an average-based approach. The interviewee speculates that it may be necessary to compensate for the limited potential or capacity of some materials by enhancing the rates of other strategic materials within a short timeframe.

On whether an average-based approach is effective for reaching benchmarks or just a policy tool, the interviewee reflects on similarities with the battery regulation, which sets very ambitious recycling rates. They express scepticism about the realism of achieving such inflows of end-of-life products quickly, especially if manufacturing scrap is not considered as part of recycled raw material. The interviewee suggests that these regulations might also serve a signaling function, indicating a preference by the Commission to meet targets for each material, though it is acknowledged that this may not be feasible for all. They conclude that the policy may allow for deviations due to circumstances, which would explain why not all targets can be met, thereby maintaining a focus on reducing dependencies on specific raw materials while striving to meet critical material benchmarks as effectively as possible.

Will there be a unified benchmark for the entire European Union, or will individual member states have distinct benchmarks that consider factors like reserves or mining facilities?
The interviewee discusses the overall approach to benchmarks within the European Union, noting that while the benchmarks apply to the EU as a whole, individual Member States will likely have tailored strategies based on their unique capabilities and circumstances. Although not a member of the Commission, the interviewee speculates that the approach will involve assessing the specific potential of each Member State. For example, the Netherlands is noted for its strengths in circular economy practices but has limited mining capabilities. The likely strategy will involve collaborating with Member States to identify their preconditions, areas for improvement, and contributions towards meeting the benchmarks. This would result in each Member State developing individual plans to achieve the benchmarks, with some focusing on areas for processing and manufacturing SRM or technologies — and others, possibly Scandinavian countries or nations like Portugal or Serbia, might focus more on mining activities such as lithium extraction.

The CRMA speculates on the possibility of joint procurement. Do you think this is feasible, and if so, how would it be implemented?
The interviewee discusses the concept of joint procurement within the EU, particularly in response to crises, like the energy crisis, where the EU has coordinated efforts through government agencies to secure supplies for the economic region. However, they note that the system for joint procurement of critical raw materials is still under development and lacks maturity.

The interviewee questions how a supranational entity responsible for procurement would function, and whether Member States and their industries would simply approach this entity with their needs. They express skepticism about the readiness of such a system and its integration into the current political and economic frameworks. Furthermore, the interviewee draws some parallels to a state capitalist approach in the Critical Raw Materials Act, suggesting it represents a shift towards more centralized purchasing by the state. They speculate on the future of this institution, considering whether it might serve as an emergency response mechanism or develop into a more permanent fixture. However, they doubt the feasibility of centrally purchasing all strategic raw materials given current political realities and market dynamics, where industries might still prefer to procure materials from cheaper market sources.

In conclusion, the interviewee believes that the development of this procurement system is still in its early stages and that its future shape will largely depend on forthcoming political and economic developments.

Currently, it appears that there is no direct funding from the EU to its member states to support the implementation of the CRMA. Do you foresee this changing in the future, and what impact might such a change have on the CRMA?
The interviewee discusses the current lack of direct EU funding to support the implementation of the Critical Raw Materials Act (CRMA) and speculates on possible future changes. Drawing parallels with the EU's tradition of subsidizing farmers to ensure food security and cultural preservation, the interviewee suggests that there isn't a similar tradition for subsidizing metals or critical materials. They describe the CRMA as balancing regulation with ambiguity, particularly regarding who will finance what.

Comparing this situation to the U.S. Inflation Reduction Act, which provides subsidies labeled as tax credits, the interviewee notes that such measures are essentially protectionist policies designed to support the local economy without explicit financial commitments from the state. They express that in the face of tightening geopolitical situations, it's possible that funding might become available, but the specifics regarding the amount and mechanism of such funding remain uncertain. The interviewee concludes that the future of financing for the CRMA will likely be clarified in the coming years as the political and economic landscape evolves.

Extraction:

Do you believe that European mines will assume a more significant role in the future?
The interviewee expresses a strong belief that European mines will play a more significant role in the future, influenced by both geopolitical instability and increasing consumer awareness regarding the origins of raw materials. They mention potential developments in the Critical Materials Act, such as mandatory environmental footprint declarations for specific raw materials, which could drive greater transparency and sustainability in mining practices.

The discussion also highlights that the European Commission is serious about implementing extraction benchmarks, suggesting that there will be substantial efforts to establish and maintain mining operations within Europe or with partners that adhere to similar standards. The interviewee sees the mandatory environmental footprint as a tool to create a level playing field, ensuring materials are mined sustainably, which could lead to new regulations setting minimum sustainability standards.

Social aspects, such as the impact on local communities and indigenous rights, are acknowledged as challenging but are seen as less potentially damaging in Europe compared to places like China. The interviewee notes a cultural shift towards greater community engagement and consensus-building in mining projects, which can also bring economic opportunities to local regions. They suggest that the acceptance of mining projects may vary across Europe, influenced by regional economic conditions and the potential for economic development through more advanced stages of the value chain and associated educational opportunities.

What measures will the European Union implement to ensure that lithium mined within the EU remains in the region, and to prevent the export of raw materials to countries like China where processing costs are lower? And if not in the mining part of the supply chain, can this also be the case somewhere else up or down the chain?
The interviewee reflects on the potential for mining and processing raw materials in Europe, suggesting that while there isn't currently a provision for it, industries might favor labels such as "mined in Europe" or "processed in Europe" if feasible. They acknowledge potential skill gaps in the industry but are optimistic that skills for advanced processing could be developed or imported. The interviewee believes that if stakeholders are willing to bear the higher costs of mining in Europe, they are likely also willing to invest in local processing to ensure the entire supply chain is managed within Europe.

Regarding export restrictions, the interviewee notes that while such measures are becoming more common globally (US is doing It more regularly), often justified under national security exceptions which cannot conflict with WTO law, the EU has not yet adopted this approach. They speculate that, given global trends, the EU might consider such measures in the future to secure supply chains, especially in scenarios where securing later stages of the supply chain becomes critical. The discussion indicates that while the EU currently does not employ export restrictions, the evolving international context could potentially change this stance in the long term.

Processing:

What does processing means? Which parts of the supply chain is part of 'processing'?
The interviewee discusses their uncertainty about the specific stages of raw material processing, particularly in the context of mining. They mention that while concentration and initial chemical processing typically occur near mining sites, the subsequent steps like producing carbonate and hydroxide might take place either locally or elsewhere. However, they admit to not being sure about the usual forms in which these materials are imported and suggest that a colleague who served as an expert on Lithium would be better equipped to provide detailed answers.

The interviewee also expresses uncertainty about where the term ”processing” officially begins in the sequence of raw material handling, hypothesizing that it likely starts post-purification but acknowledging that this can vary significantly between different raw materials due to their distinct processing requirements. They reflect on the challenge of defining the transition from extraction to processing, suggesting that while some may consider initial chemical treatments as part of mining, the exact demarcation is unclear and could vary.

Recycling:

Could overly ambitious recycling rate targets deter recycling firms from investing?
The interviewee discusses the potential impact of ambitious recycling rate targets on investment within the recycling industry. They express doubt that these targets would immediately make industries liable for failing to deliver sufficient product quantities, suggesting it is not an immediate concern for deterring investment. The interviewee draws a comparison with EU Battery Regulations (2023), where there is an emphasis on recycling efficiency. Companies might choose less efficient processes if those are more feasible in other locations. But this is not the case with the CRMA's benchmarks.

Regarding the clarity of recycling input rates, the interviewee notes that current guidelines are somewhat vague, implying that while the European Union might set expectations for recyclers to deliver specific quantities (e.g., X tonnes per year), possible enforcement mechanisms like withholding tax credits serve more as incentives rather than strict penalties. They describe these as ”positive nudges” to encourage compliance but acknowledge that such incentives could, in theory, become coercive over time, leading to a situation where companies feel pressured to comply to avoid losing benefits. For now, the interviewee views these measures as incentivizing rather than punitive, suggesting a cautious approach to regulation that encourages compliance without imposing severe penalties.

In your opinion, should recycled lithium be considered as domestically mined lithium within Europe?
The interviewee discusses the concept of equating recycled lithium with domestically mined lithium within Europe, in the context of recycling targets and the broader goals of the circular economy. They express a view that recycled materials, such as lithium, should potentially be regarded on the same footing as domestically extracted resources. This perspective is based on the assumption that recycled metals possess equivalent properties and quality to those sourced directly from mines.

The interviewee acknowledges the current high recycling targets, suggesting that while ambitious, they may not suffice to compensate for any shortfalls in mining benchmarks. However, looking toward the future, they advocate for a shift in perspective where recycled raw materials are valued equally to mined ones, emphasizing that both are sourced domestically—whether from ’urban mines’ (recycled materials) or geological mines.

The dialogue also touches on the logistical and regulatory nuances of categorizing materials as either ’domestically sourced’ or ’recycled.’ The interviewee hints at potential complications in this classification, such as the possibility of not being able to double-count materials for both categories. They mention specific materials like tungsten, where high recycling rates are achievable and beneficial, suggesting that in some cases, boosting recycling might be more advantageous than increasing extraction.

Overall, the interviewee reflects on the importance of integrating recycled materials more seamlessly into the supply chain, potentially treating them as equivalent to domestically mined resources.

Do you think that recycled lithium is exclusively sourced from strategic partners?
The interviewee discusses the sourcing of recycled lithium and its potential classification as being from strategic partners within the context of the Critical Raw Materials (CRM) Act. They note that, unlike the U.S. Inflation Reduction Act, which specifies that certain raw materials must be sourced domestically or from strategic partners, the EU's CRM Act does not currently have specific provisions defining how strategic partners are involved in the sourcing of recycled materials. The concept of a "CRM club", which appears to be a part of the broader CRM Act framework, although its exact role and definition are not fully clear. The interviewee speculates that future geopolitical developments might influence provisions regarding strategic partners, suggesting that raw materials sourced from these partners might eventually be considered nearly equivalent to domestically sourced materials in meeting benchmarks for domestic extraction or recycling.

Furthermore, the interviewee hints at the possibility of adjusting the benchmarks if it becomes clear that domestic extraction or recycling targets are unachievable, by potentially counting materials sourced from strategic partners as domestic. They reflect on the changing dynamics with traditional strategic partners like the U.S., indicating that the relationships and strategies might be evolving. The discussion also ties the CRM Act to broader legislative responses like the Net Zero Industry Act, which itself is seen as a reaction to international initiatives such as the U.S. Inflation Reduction Act, highlighting the interconnectedness of these regulations in addressing strategic and critical material supply chains.

In your opinion, where does the greatest potential and pitfall lie within the Critical Raw Materials Act?
The interviewee evaluates the European Union's approach to managing critical raw materials, reflecting on the progress and challenges since the first criticality screening published in 2011. They acknowledge various initiatives aimed at securing raw material supplies but note that despite these efforts, significant improvements have been elusive over the past decade. They express optimism about the latest steps, viewing them as a concrete advancement likely to impact positively due to their incentivizing nature.

However, the interviewee points out potential pitfalls associated with setting overly ambitious targets. They differentiate between targets and benchmarks, suggesting that some goals may not be realistically achievable, which could undermine the credibility of the regulations. The blend of visionary planning and regulatory measures is appreciated, yet it also appears somewhat incongruent to them, especially when benchmarks are set very high without a clear path to achievement. This approach might send mixed signals to industries, implying that while efforts are expected, failing to meet targets might not have severe repercussions.

Additionally, the interviewee expresses personal concerns about increasing protectionism, viewing it as a worrying trend that could escalate. They fear that such protectionist policies might become more common, potentially complicating international trade and economic relations in the future, but also the achievement of global goals such as decarbonization.

C.5. Anonymous Summary Interviewee S5

Small Lithium Products:
Interviewee S5 highlighted that the production of small lithium products within Europe is limited, with a maximum estimate of around 20% being created in the EU. Recycling these small lithium products in Europe poses significant challenges. Although the battery regulations set target collection rates for small devices at 50%, these targets are often not met. Even when collected, these devices are frequently not integrated into the lithium recycling circuit. The majority of small lithium products are portable devices, such as iPhones. Interviewee S5 mentioned that there is minimal data available on how many of these small lithium products receive a second life. Even if they do get a second life, it typically involves a new battery, meaning it is not truly a second life for the lithium component of the small product itself.

Batteries:
According to Interviewee S5, the vast majority of lithium batteries are used in electric vehicles (EVs). Currently, LFP (Lithium Iron Phosphate) and various NCM (Nickel Cobalt Manganese) chemistries, such as NCM811 and NCM622, are the leading types. LFP batteries are gaining popularity, especially in China, due to their longer lifespan, making them suitable for both cars and stationary storage. The interviewee mentioned that he does not have specific data on the manufacturing time for electric vehicles. However, he noted that the manufacturing time for cars varies significantly depending on the manufacturer and the type of car ordered. When the researcher suggested that custom-made cars typically take 3 to 6 months to produce, the interviewee acknowledged that this timeframe seemed reasonable.

Recycling:
Interviewee S5 noted that black mass, which constitutes a significant portion of an EV battery, is expected to play a crucial role in future lithium recycling efforts. Currently, nearly 50% of an EV's weight is the battery, emphasizing the importance of black mass in the recycling process. However, Europe lacks sufficient recycling capacity to handle all generated black mass, leading to its export outside Europe. The switch from pyro-metallurgical to hydro-metallurgical recycling methods is underway, as noted in the Volta Foundation report. However, the timeline for this transition remains uncertain due to the higher capital costs associated with hydro-metallurgical processes, despite their lower operational costs compared to pyro-metallurgical methods.

Mining and Refinery:
Interviewee S5 pointed out that there are almost no lithium processing facilities in Europe, except for some recycling facilities. However, VARTA is reportedly establishing a significant processing facility in Germany. This development is crucial for increasing Europe's domestic lithium processing capabilities and supporting the strategic goals outlined in the CRMA.

C.6. Anonymous Summary Interviewee S6

General questions about the CRMA:

Do you anticipate individual targets for each Strategic Raw Material or an average-based system, and will there be a unified benchmark for the entire European Union or distinct benchmarks for individual member states considering factors like reserves or mining facilities?

The response begins by clarifying the distinction between targets and benchmarks for Strategic Raw Materials (SRMs), where targets are legally enforceable, and benchmarks serve as guidelines to monitor and evaluate and track progress within the EU's raw material system. The approach to benchmarks is not about achieving desired outcomes through "wonderful arithmetic" but rather to accurately track developments and adapt strategies accordingly for each SRM, considering its unique ecosystem.

The speaker discusses recycling strategies, emphasizing the impracticality of assigning specific recycling targets to individual Member States, given the variance in available waste streams. A more unified approach within the EU single market is suggested, where centralized recycling facilities might handle larger volumes more efficiently than a fragmented system would.

In terms of legislation, the discussion highlights existing EU targets on waste collection, reuse, and specific recycling streams. The feasibility of enforcing these targets is critically examined, with the speaker noting the complexities involved in legislation that needs to be both practical and enforceable. For example, the discussion around permanent magnets illustrates targeted measures where Member States might focus on collection and sorting rather than direct recycling mandates, facilitating the recycling process without overly stringent requirements.

The economic considerations surrounding SRM strategies are also addressed, recognizing that market forces often dictate the movement of waste outside the EU due to higher bids from international buyers. This economic reality underscores the delicate balance between maximizing profits within the current market system and achieving strategic environmental goals. The speaker suggests that while legislative measures can guide and incentivize proper waste management and recycling practices, the inherent economic incentives present a constant challenge to the effective enforcement of such policies within the EU.

The CRMA speculates on the possibility of joint procurement. Do you think this is feasible, and if so, how would it be implemented?

The concept of joint purchasing is discussed as feasible and articulated in CRMA legislation, indicating confidence in its practicality. Drawing parallels with successful joint purchasing initiatives for gas, COVID vaccines, and medical supplies, the speaker emphasizes that while not all industries need the same raw materials, consolidating the demands of multiple companies could enhance market conditions. This aggregation could offer better transparency and purchase terms.

The EU's role in joint purchasing is described not as a direct buyer or owner of the materials but as a facilitator of transactions between industries. For example, in strategic projects like the hypothetical involvement with the Cinovec lithium project, the EU could coordinate with relevant sectors—such as battery manufacturers and chemical companies—to understand their needs and assist in establishing offtake agreements. This doesn't always need to be strategic partnerships, because for instance the market for copper is already a steady market in the European Union (and listed as a SRM).

Currently, it appears that there is no direct funding from the EU to its member states to support the implementation of the CRMA. Do you foresee this changing in the future, and what impact might such a change have on the CRMA?

While it's somewhat accurate that there is no direct funding from the EU specifically earmarked for the implementation of the CRMA, the EU does offer avenues for member states – and industry to request financial support for activities related to strategic raw materials. There is a strategic support instrument mentioned in the regulatory framework that allows member states to apply for funding to aid their exploration programs or to establish and train personnel at one-stop administrative shops.

In addition to this, the EU provides funding through broader platforms and programs such as the Strategic Technologies for Europe Platform (STEP), which consolidates various EU funding sources like the Innovation Fund, the Resilience Fund, and portions of Horizon and climate funds. These funds have been made accessible for raw materials projects, which was not the case previously.

Furthermore, the European Investment Bank (EIB) and the European Bank for Reconstruction and Development (EBRD) support raw materials projects that meet their funding criteria, using funds from the EU's Regional Development Fund. Internationally, EU development aid can also support raw materials projects outside of the EU if they align with development goals, such as increasing value-added in the host country.

Thus, while there is no direct, dedicated fund within the CRMA for raw materials projects, multiple funding mechanisms are in place that member states can leverage to support their initiatives under the CRMA. The availability of these funds allows for a flexible, project-based approach to financing that can adapt to specific needs and objectives of raw materials management within the EU.

Are companies that are not 'European' but with factories in Europe part of the benchmarks?
The speaker clarifies that in the context of EU benchmarks, the focus is not on the nationality of the companies but rather on the production activities within Europe and their contributions to the European economy. Non-European companies with manufacturing facilities in Europe are included in the benchmarks because what matters is the output—such as batteries produced by CATL in European factories—which is considered beneficial for Europe.

The rationale for this can be seen in twofold. Firstly, it aligns with the broader goal of enhancing Europe's self-sufficiency and reducing dependency on external sources, especially in strategic sectors like raw materials and battery production. Secondly, the presence of these companies in Europe is seen as advantageous amidst global geopolitical uncertainties that can affect supply chains, such as unexpected disruptions in international transport routes (e.g., a hypothetical scenario where the Panama Canal becomes impassable).

By including the production of non-European companies in European benchmarks, the EU aims to fortify its economic resilience, ensuring that despite the global nature of many corporations, their contributions within Europe are recognized and factored into strategic planning and policy-making. This inclusion also addresses potential vulnerabilities by maintaining a level of production capacity within the continent, which is critical in times of global crises or logistical challenges.

Questions about benchmark extraction:
Is there sufficient demand from companies in opening new mines, and is the primary incentive for establishing new mines the reduction in permit processing times? Will this be adequate to achieve the 10% benchmark?
The discussion acknowledges that there is indeed a significant demand for new mining ventures in Europe, particularly for lithium, reflecting a broader interest in securing domestic sources of strategic raw materials. However, the primary hurdles hindering the expansion of mining activities are not merely due to a lack of demand but also involve other complex factors, including the lengthy permit processing times that have historically slowed down the initiation of new mining projects.

Addressing the permit processing times, it is highlighted that introducing more streamlined and predictable processes could substantially enhance the investment appeal of mining projects. The certainty provided by having a clear timeline for permits — as mandated by CRMA regulation — would not only reduce the risk of capital being indefinitely tied up but also improve overall investment security. This regulatory assurance is seen as a critical incentive for investors who might otherwise be hesitant due to the uncertain duration of capital commitment in mining projects.

What does EU involvement in the initiation of new mines entail except for permit processing?
EU involvement in the initiation of new mines extends beyond simply streamlining permit processing times. One critical aspect is the consideration of geological availability, which fundamentally limits where mining can occur. Unlike processing, which can be established in various suitable locations, mining activities are confined to areas where the raw materials naturally occur. This geographical constraint shapes much of the strategic planning and regulatory oversight in the mining sector.

Furthermore, Member States plays a significant role in spatial planning through the Critical Materials Act, which prioritizes the occurrence of strategic raw materials in land-use decisions. This means that if a valuable raw material like tungsten is discovered underground, that area is more likely to be designated for mining rather than for other uses such as agriculture or forestry. This prioritization helps the mining industry by ensuring that areas known to contain valuable raw materials are considered more critically for mining rather than other long-term land uses.

Additionally, the EU supports the mining sector through consultations on financing options or can increase access to finance. However, financial support or a financing mechanism in and by itself is not in the package. I.e. projects will not receive money when recognised as strategic, but the possibility of receiving funding through EU programmes or the European banks, or private investors may increase with this recognition.

Questions about benchmark Processing:
If 40% of the Strategic Raw Materials (SRMs) need to be processed in Europe, but only 10% is currently mined within the EU, will the EU need to import unprocessed lithium from other regions? If this is the case, how does the European Union plan to create business opportunities for companies to invest in processing lithium, particularly if European lithium is more expensive than lithium sourced from elsewhere?
Given the current mining capacity within the EU, which meets only 10% of its needs, it is indeed likely that the EU will need to import unprocessed lithium to meet the 40% processing benchmark. The majority of lithium processing occurs outside Europe, notably in China, which indicates that the EU will have to significantly increase its imports of lithium concentrates and other unprocessed forms of the mineral. The strategic intent behind importing is to secure a stable supply chain for industries reliant on lithium, such as battery and component manufacturers.

The emphasis is on balancing cost with security, encouraging companies to not only seek the cheapest sources of raw materials but also to invest in more secure, but potentially more expensive, local sources. This strategy aims to make European companies less vulnerable to external supply shocks and monopolistic pricing by diversifying their sources and enhancing their processing capabilities within Europe.

Furthermore, the EU plans to support the entire value chain from raw material extraction to final product manufacturing, ensuring that strategic raw materials like lithium are not just imported and processed, but also contribute to the broader economic and industrial policies aimed at strengthening Europe's technological and industrial base.

If unprocessed lithium is not imported, how will the EU achieve the 40% processing benchmark?
Achieving the 40% processing benchmark for lithium within the EU could involve using secondary raw materials alongside the processing of primary raw materials. This approach reflects a broader strategy that incorporates recycling and the use of recycled materials, such as black mass from spent batteries, into the production process. For instance, in industries like copper or aluminium, a significant portion of the material processed includes scrap.

The EU's strategy emphasizes the integration of primary and secondary processing to meet benchmarks. By accounting for both types of materials in the benchmarks, the EU aims to reduce the pressure on primary resource demand. Companies that process these materials often report the proportions of scrap and primary materials used, which facilitates this accounting. If this data is available and reliable, it can substantiate the contribution of recycled materials to meeting processing targets.

Furthermore, the legislative framework, including the Net Zero Industry Act (NZIA), is designed to complement the Critical Raw Materials Act (CRMA) by ensuring a seamless transition between end-of-life product recycling and the reuse of these materials in new production cycles. This integrated approach helps close the loop within the value chain, enhancing resource efficiency and supporting the EU's broader sustainability and industrial goals.

Will lithium processed from strategic partner sources be considered as 'processed in the EU' for the purposes of meeting EU benchmarks?
Not, but it will count for the 65% diversification benchmark.

Questions about benchmark Recycling:
Do you consider a 25% recycling rate to be overly ambitious?
The 25% recycling rate, while ambitious, is not considered overly so across all contexts but may be challenging for certain materials, like lithium. This rate is seen as a deliberate target that sends a strong political signal about the EU's commitment to sustainable materials management and the circular economy. The biggest challenges to achieving this rate are not inherently in the recycling process itself but in the preceding steps of collection and sorting. Improving these processes is crucial as they are often where most material loss occurs, indicating that significant gains in recycling rates could be achieved by focusing on these areas.

For lithium, specifically, reaching a 25% recycling rate by 2030 is acknowledged as almost impossible under current conditions. However, this target is tied to the proportion of European demand—highlighting that if demand decreases significantly, the needed recycling target, in absolute terms, becomes lower as well . This underscores the dynamic nature of such targets, which are inherently linked to market demand and consumer behaviour. Hence, while the 25% goal is a stretch, it serves as an important motivator for improving recycling infrastructure and technology, as well as enhancing the efficiency of collection and sorting systems to ultimately obtain more strategic secondary raw materials.

In your opinion, should recycled lithium be classified as domestically mined within Europe?
Recycled lithium, according to the perspective shared, should more accurately be classified as domestically processed rather than domestically mined. This classification is based on the nature of recycling operations, which typically involve significant processing steps. Recycling and processing are closely interlinked activities; often, the entities that recycle materials also engage in their processing, or at least the initial stages such as producing black mass from spent lithium batteries. The most critical role within recycling is the selection, sorting, and directing of correct waste streams to appropriate recycling processes.

Will recycled lithium be exclusively sourced from strategic partners?
In the field of strategic raw materials (SRMs), opting for exclusivity in sourcing or processing is not a luxury we have. The nature of the industry and the essential need for these materials mean that there is little to no flexibility for such restrictions.

In your opinion, where does the greatest potential and pitfall lie within the Critical Raw Materials Act?
The greatest potential within the Critical Raw Materials Act (CRMA) lies in enhancing supply security and sustainability in sourcing practices. By promoting diversification in sourcing, the CRMA encourages actors within the raw materials ecosystem to consider more sustainable options. This can lead to a shift away from the singular focus on cost minimization, which often results in monopolistic supply chains, towards a more balanced approach that includes sustainability as a key criterion. This is particularly significant in industries like electric vehicle manufacturing, where companies benefit from ensuring their supply chains are not only secure but also responsibly managed.

The primary pitfall of the CRMA, however, is the risk of failing to implement these changes swiftly enough to maintain stakeholder engagement and see tangible results within a reasonable timeframe. The slow pace of change inherent in the raw materials sector, combined with the typically short political cycles, could result in a lack of visible progress that is necessary to sustain momentum and commitment to the act's objectives. If these initiatives take too long to bear fruit, there is a danger that stakeholders will become disillusioned and revert to less secure and sustainable practices, leaving the field open to actors who do not prioritize the security and sustainability of Europe's raw materials supply.

Understanding the demand for lithium is crucial, especially considering its finite availability. It's important to not only focus on securing as much lithium as possible but also to explore alternatives like sodium, which the Chinese are investigating as a substitute. This strategy highlights the importance of diversifying technological inputs. Diversification can be as strategic as outbidding competitors for resources and helps mitigate supply risks while adapting to resource limitations, ensuring a more sustainable approach for long-term technological development.