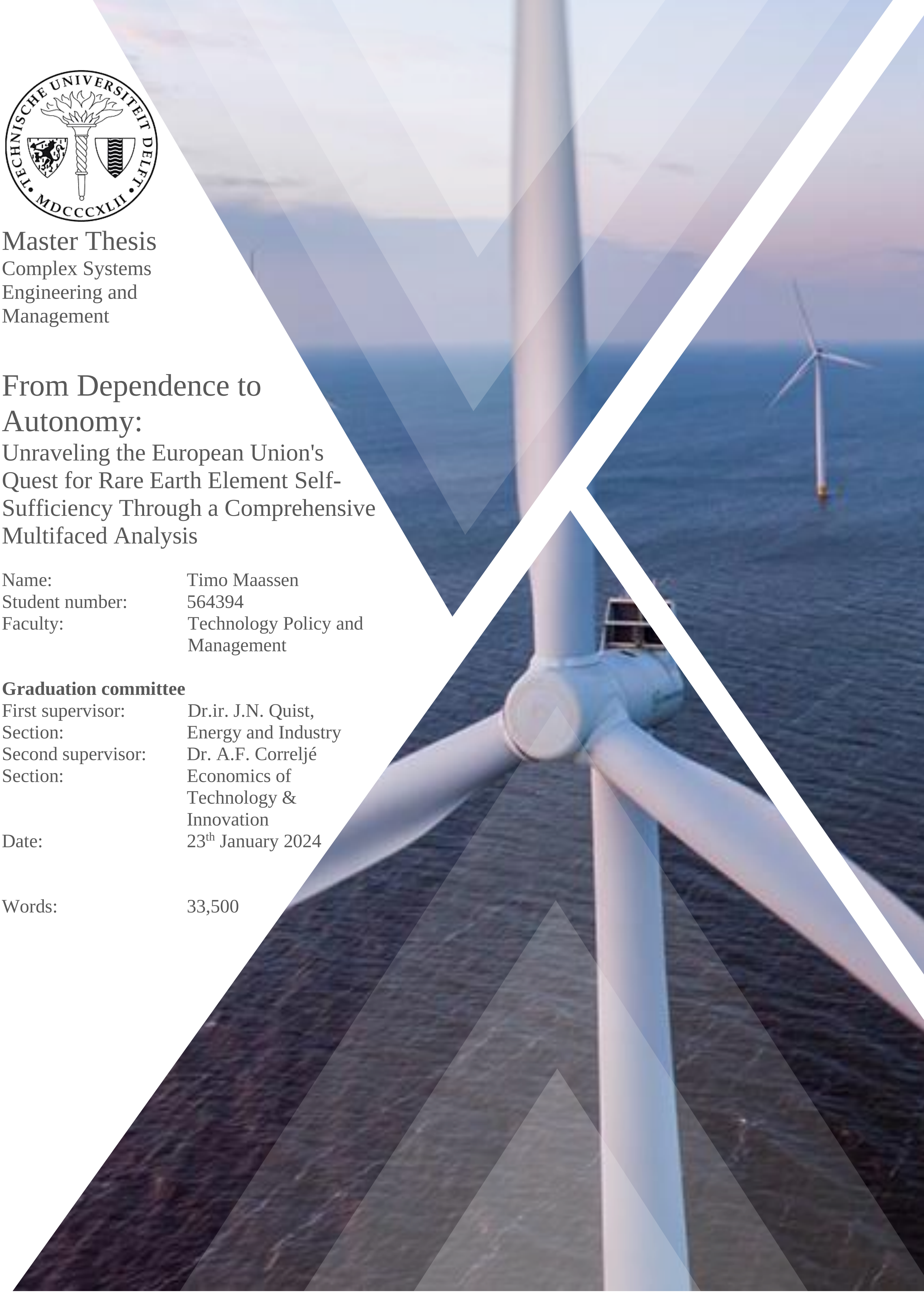

Master Thesis
Complex Systems Engineering and Management

From Dependence to Autonomy:

Unraveling the European Union's Quest for Rare Earth Element Self-Sufficiency Through a Comprehensive Multifaced Analysis

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Dear reader,

As I pen these final words, a wave of gratitude washes over me, recognizing the remarkable individuals who have guided and supported me throughout this transformative academic journey. The completion of this master's thesis represents the culmination of my studies in Complex Systems Engineering and Management at the Delft University of Technology. The past nine months have been a tumultuous period for me, both academically and personally, a journey that would not have been possible without the unwavering support of several individuals. Therefore, I wish to take this moment to express my deepest gratitude to those who have played a pivotal role in making this milestone a reality.

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This milestone marks the end of a remarkable chapter in my life, a chapter filled with challenges, triumphs, and invaluable experiences. I carry the lessons learned with me as I eagerly anticipate the exciting adventures that await me in the future.

Enjoy reading! For questions, feel free to reach out to me

Timo Maassen
Utrecht, January 2024

EXECUTIVE SUMMARY

Research Objective & Methodology

The COVID-19 supply disruptions and the energy crisis triggered by the Russian-Ukrainian conflict emphasize the EU's structural supply dependencies and potential damages during crises. It underscores the critical risk factors, particularly Rare Earth Elements (REEs), which are highly susceptible to supply disturbances due to their increasing demand, limited supply, and reliance on a few suppliers, notably China. REEs are contrary to their name quite abundant, however, their extraction and processing are environmentally intensive, complex, and expensive. These REEs are utilized in numerous applications, including applications used in the energy transition because they exist in the Neodymium-Iron-Boron permanent magnets (Nd-Fe-B PMs). These magnets are used in wind turbine generators and traction motors of EVs. In these technologies, magnets are necessary to convert electricity into kinetic energy in EVs and vice versa for wind turbines.

This thesis focused on understanding how the EU can bolster its autonomy regarding its access to REEs, counterbalance supply risks, examine existing strategies, evaluate their effectiveness, and identify additional institutional interventions to strengthen the EU's position. This led to the following main research question:

How can the European Union improve its autonomy regarding its access to rare earth elements to achieve material security in the context of the European Union's energy transition?

The qualitative approach was chosen as the most suitable design approach to answering this main research question. It enabled a nuanced understanding of the EU's REE dependency issue by considering multiple dimensions and facilitated the development of well-informed and contextually grounded institutional interventions. The findings are triangulated between a literature review, desk research, and semi-structured depth-interviews with seven experts in this field.

This study performed REE value chains, actors, institutions, and PESTEL factor analyses. These four analyses offered a multifaceted insight into the complexities and interactions within this domain. Moreover, the illumination of various perspectives enhanced the overall comprehensiveness and facilitated a more holistic view of the EU's quest for enhanced REE autonomy.

Findings

Regarding the global REE value chain, China's unparalleled dominance, facilitated by generous lines of credits and subsidies, strategic partnerships and initiatives, geopolitical influence, manufacturing capabilities, technology, infrastructure, low labor cost, and lax environmental regulations, presents significant challenges. China's extensive control, especially in REE processing and Nd-Fe-B PM manufacturing, underscores the complex global dependence on China’s REE industry. The critical issues identified include a single third country supply dependency, rising demand for Nd-Fe-B PMs, challenges in recycling and circularity, high cost, stringent environmental regulations, and the need for skilled labor. These concerns, especially during the processing stage, underscore the complex barriers to achieving a resilient REE supply chain.

Globally, the REE landscape is predominantly shaped by China and the US. China maintains its pre-eminence through strategic initiatives, while the US is actively trying to close the gap. Acknowledging the imperative of strategic autonomy, the EU has instituted ambitious regulations, exemplified by the Critical Raw Materials Act (CRMA) and the Net-Zero Industry Act. These regulations established industry benchmarks for domestic extraction, processing, and recycling. However, the effectiveness of the CRMA in ensuring robust REE supply security is questionable.

The legislation lacks clarity on achieving and implementing industry benchmarks, presenting significant challenges in compliance, environmental and societal impacts, navigating shortened lead times for permitting, and addressing hurdles in private investment and fiscal alignment.

Institutional Interventions

This research identified enabling and constraining factors for the EU's autonomy regarding REE. Whereafter institutional interventions were created to cope with these issues. To achieve enhanced autonomy regarding REE access, five main strategies and several interventions are suggested. Conclusively, it is vital to note that the approach here is not a binary choice between strategies; rather, it necessitates the integration of a synergistic blend of the five proposed strategies.

> Firstly, 'Supply Diversification' addresses the introduction of incentives for private demand for diversification, and the enhancement of strategic partnerships with REE-rich, EU-friendly countries.
>
> Secondly, 'Domestic Supply' discusses: regulations incentivizing internal capacity; levelling the playing field; including Nd-Fe-B PM domestic manufacturing benchmarks; raising public acceptance; expanding funding; standardizing long-term contracts; and introducing low-energy zones.
>
> Thirdly, 'Circularity' Encourages Nd-Fe-B PM demand reduction; incentivizes EoL practices; establishes CRMA PM labeling requirements; sets Nd-Fe-B PM collection targets; provides incentive structures; standardizes circularity by design; introduces extended producer responsibility; expands support programs; and impose an export ban on EoL Nd-Fe-B PMs.
>
> Fourthly, 'Substitutes for Nd-Fe-B PMs' proposes: an increase in funding for R&D and innovation; and incentivizes substitutes for EV and wind turbine applications.
>
> Fifthly, 'Strategic Stockpiling': addresses deficiencies in communication, transparency, and clarity by investigating obligation possibilities for Member States to monitor and strategically stock Nd-Fe-B PMs

Furthermore, the European Commission is instructed to consider introducing sub-benchmarks per individual CRM, improving understanding within governmental entities, increasing overall investment, and acknowledging the criticality for the EU to extend its policy horizon beyond 2030, given the long-term impacts of most proposed options. Moreover, EU policy alignment between Member States is critical, especially for creating an EU-level playing field for internal capacity and circularity. Enhancing autonomy in the realm of Rare Earth Elements (REEs) poses significant challenges, yet this thesis equips policymakers with essential findings and tools to navigate and improve access to REEs.

Keywords: Rare earth elements; Neodynium-Iron-Boron permanent magnets; material security; supply chain resilience; energy transition; European Union autonomy

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LIST OF ABBREVIATIONS

BEV:	Battery Electric Vehicle
CAPEX:	Capital Expenditure
CoSEM:	Complex Systems Engineer and Management
CRM:	Critical Raw Material
CRMA:	Critical Raw Materials Act
Dy:	Dysprosium
e.g.:	exempli gratia
EPR:	Extended Producer Responsibility
EU:	European Union
EUR:	Euro
EV:	Electric Vehicle
GW:	Gigawatt
HEV:	Hybrid Electric Vehicle
HREE:	Heavy Rare Earth Elements
IRA:	Inflation Reduction Act
kt:	kilo tonne
LCR:	Local Content Requirements
LREE:	Light Rare Earth Elements
Mt:	Mega tonne
MW:	Megawatt
Nd:	Neodymium
Nd-Fe-B:	Neodymium-Iron-Boron
OPEX:	Operational Expenditure
PEV:	Plug-in Electric Vehicle
PESTEL:	Political, Economic, Social, Technological, Environmental, Legal
PM	Permanent Magnet
PMSG:	Permanent Magnet Synchronous Generator
Pr:	Praseodymium
R&D:	Research and Development
REE:	Rare Earth Elements
REO:	Rare Earth Oxides
SLO:	Social License to Operate
SME:	Small and Medium Enterprises
SQ:	Sub-Question
Tr:	Terbium
UNFCCC:	United Nations Framework Convention on Climate Change
US:	United States
USD:	United States Dollar

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1. INTRODUCTION

The consequences of climate change are becoming increasingly apparent. The European Union (EU) aims to be climate-neutral by 2050 (Fetting, 2020). In order to accomplish this goal, the entire energy and transportation system should be fully sustainable before that time (Fetting, 2020). An enormous amount of raw materials is needed to produce all these wind turbines, solar panels, and electric vehicles (EVs). For most of which, the EU is dependent on imports. Therefore, the European Commission listed the critical raw materials (CRMs), which are essential for digitalization, defense applications, and the energy transition. These CRMs are visualized in terms of supply risks in *Figure 1.1*.

Rare earth elements (REE) are on top of *Figure 1.1* and are this research's primary focus. REEs comprise seventeen elements: scandium, yttrium, and fifteen lanthanides. They are classified between Heavy REEs (HREEs) and the more abundant Light REEs (LREEs). They are defined as critical and strategic raw materials by the European Commission (2023). REEs are, contrary to their name, relatively abundant. However, their extraction and processing are complex, expensive, and environmentally hazardous (Andrew-Speed & Hove, 2023).

REEs are crucial components in various industries, including user electronics, medicine, defense, renewable energy, and transportation (EV); due to their unique magnetic, luminescent, and catalytic properties (EPA, 2012), all the REEs including their applications are listed in *Figure A1*, and *Table A2* in *Appendix A*. This research will be focused on the REEs that are crucial for the energy transition, these elements are Praseodymium (Pr), Neodymium (Nd), Terbium (Tb), and Dysprosium (Dy). These REEs are essential for the energy transition because they exist in the Neodymium-Iron-Boron permanent magnets (Nd-Fe-B PMs). These magnets are used in wind turbine generators and in electric motors of EVs. In these technologies, magnets are necessary to convert electricity into kinetic energy for EVs and vice versa for wind turbines. Nd and Pr create magnetic straight to the PM inside the Nd-Fe-B PM. In addition, Dy and to a lesser extent Tb are added to create demagnetization resistance and high-temperature performances (Li et al., 2020).

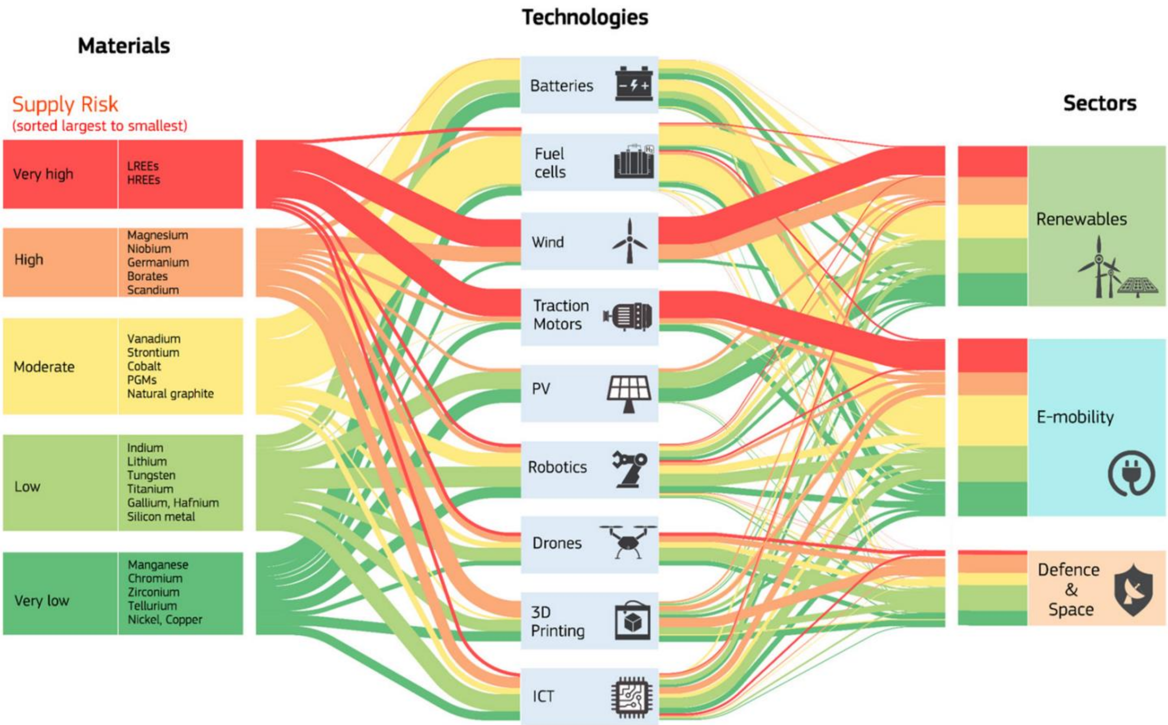

Figure 1.1: *CRMs in terms of supply risk (European Commission, 2020)*

1.1 Challenges in Future REE Demand

The renewable energy industry is expected to grow by 8.6 percent annually till 2030 (PR, 2022). Furthermore, the EV industry will grow by 17 percent annually between 2023 and 2027 (Statista, 2023). Therefore, this will create way more REE demand in the future. In 2022, 300kt of REEs was produced. Roughly 43 percent of the REEs were used for PM production, 14 percent for wind turbines, and 6 percent for the EV industry in 2020(US Department of Energy, 2021). The US Department of Energy (2021) estimated a global Nd-Fe-B PM demand rise from 119.2 kt in 2020 to 387 kt in 2030 and 753.2 kt in 2050, with the combined shares of EV motors and offshore wind turbines rising from 20.3 percent in 2020, to 65.5 percent in 2030, and 71.6 percent in 2050.

1.2 Challenges in Future REE Supply

At the same time, there are supply chain complications. Currently, China has 38 percent of the worldwide reserves in REEs, but they produce 60 percent, process 87 percent of the REE, and manufacture 94 percent of the Nd-Fe-B PMs in 2020 (ERMA, 2021). The EU is 98 percent dependent on Chinese REEs for their industries (Wong, 2023). The dependence on Chinese raw materials, especially REEs, raises questions about the reliability and sustainability of the global supply chain for wind turbine and EV manufacturing. Dy supply is critical since Dy is much less abundant and more geographically concentrated than Nd (Gielen & Lyons, 2022). Moreover, REEs must deal with low investment security and high production costs, creating significant entry barriers (Filho et al., 2023).

1.3 Problem Statement

The COVID-19 supply disruptions of essential goods and the energy crisis ignited by the Russian-Ukrainian war highlighted the EU’s structural supply dependencies and their potential to create damaging effects during times of crisis (European Commission, 2023-I). The CRMs with the highest risk of supply disturbances are REEs (*Figure 1.1).* The ever-increasing demand for REEs, combined with the limited supply and dominant position of a few suppliers, has created a problematic situation that raises concerns about the desirability of the current market for REEs. The EU relies almost wholly on Chinese imports for its REEs and PMs. Furthermore, the EU and the US have grown geopolitical tensions with China over the past decade. The dependency on China for REE and Nd-Fe-B PM supply could have significant implications for the global economy, energy security, and geopolitical relationships. The escalating tensions between China and other countries, such as the US and EU, can potentially undermine the global energy transition as it could jeopardize the establishment of sustainable energy systems. For instance, China could potentially impact EU competitiveness by flooding the market with low-priced Nd-Fe-B PMs. Additionally, there is the risk of China imposing trade restrictions, implementing low production quotas, or even completely banning REE and magnet exports, as discussed by Carrara et al. (2023). These actions would have significant repercussions.

Subsequently, the EU announced the concept of ‘open strategic autonomy,’ which implies an extent of reevaluation and recalibration in the perception of economic interdependence, prioritizing self-reliance, and strategically safeguarding the interests of the EU in a turbulent geopolitical landscape (European Parliament, 2023). However, the term ‘open strategic autonomy’ is inherently ambiguous. On one hand, it reflects the EU's pursuit of strategic autonomy; on the other hand, it acknowledges the continued reliance on external parties, especially considering the EU's fundamental commitment to the free movement of goods. Throughout this study, this terminology will be used when examining EU policy, and the term will be critically discussed in *Section 8.3*.

Adequate and effective policies are needed, to successfully enroll the open strategic autonomy for REEs. This research concentrates on how the EU could increase its autonomy concerning REE supply. Likewise, a literature review in *Chapter 2* has been performed to find the scientific knowledge gaps regarding this topic.

1.4 Research Objective

The aim of this study is to improve the EU's autonomy regarding its access to REE to achieve material security in the context of the EU energy transition. It is essential to investigate the extent to which the current situation is desirable, the possible consequences of the current market for REEs on the global energy transition, and the possible solutions to mitigate the risk of dependence on a monopolistic supplier. Therefore, this study uses a multifaced analysis, as it tries to touch upon the stakeholders, institutions, the value chain, and Political, Economical, Socio-cultural, Technological, Environmental, and Legal factors. This creates the fundament for the institutional interventions presented in *Chapter 7*. A qualitative research approach was chosen to achieve this objective, which is further elaborated in *Section 1.6.*

1.5 Research Questions

The literature review in *Chapter 2* shows that there is already a fair amount of data on energy transition-related REE dependencies. However, the articles and publications do not agree on co-existing solutions and their implementation. Many articles give solutions for supply problems in the future. However, there is no clear consensus about the chosen solutions, let alone from a European perspective. The findings suggest several solutions to address the REE supply chain's challenges, including substitution through the reduction of critical metal use, improving the circular design, and considering a European mining industry. Also, the findings suggest that recycling is a long-term strategy, not a short-term solution, and the dependency on REEs will increase yearly. Although the literature is primarily confirmative about the challenges and solutions, a lack of understanding exists of how the stated solutions can be implemented. The leading knowledge gap is the lack of understanding of what additional measures the EU can take to increase the effectiveness of the adopted policies. This led to the following main research question:

How can the European Union improve its autonomy regarding its access to rare earth elements to achieve material security in the context of the European Union its energy transition?

As discussed, this research will focus on the four critical REEs for the energy transition (Nd, Pr, Tb, and Dy) and their specific application in Nd-Fe-B PMs used in EV motors and wind turbine generators. Four sub-research questions (SQ) will help to answer the main research question. The decomposition of the main research question establishes these SQs:

SQ1: *How is the global REE and Nd-Fe-B PM value chain constructed, and what are the main issues?*

SQ2: *What is the current state of the rare earth element system inside the European Union, and how do existing institutions and stakeholders influence the system?*

- **SQ2.1:** *What are the major stakeholders, and how do they influence the REE system inside the EU?*
- **SQ2.2:** *What are the relevant institutional aspects that affect the EU's REE system?*

SQ3: *What are the main factors and developments, influencing the EU's REE autonomy?*

SQ4: *How can institutional interventions enhance the autonomy in the EU regarding access to REE, and who is responsible?*

1.6 Research Approach

This research aims to investigate the measures implemented by the EU to enhance its autonomy regarding REEs and to identify additional measures that can be taken to strengthen this strategy. A qualitative research approach is considered the best fit as it allows for an in-depth exploration of rich insights, stakeholder perspectives, and institutional aspects related to the EU's REE dependency issue. Qualitative methods, such as interviews and desk research, capture diverse perspectives, gather detailed information, and provide an understanding of the complexities of the EU's REE value chain. These methods provide a nuanced understanding of the issue and allow for exploring multiple dimensions involved. The qualitative research approach enables a contextually grounded analysis that considers the complex characteristics and challenges of the EU's REE autonomy. It facilitates the development of well-informed and relevant institutional interventions that address the specific needs and complexities of the situation. A brief comparison with other research approaches can be found in *Table A1* in *Appendix A*.

1.7 Complex Systems Engineering and Management

This research objective is well related to the aim of a master thesis project from the Complex Systems Engineering and Management (CoSEM) master program to design solutions for complex socio-technical problems, which consider various aspects, e.g., social, institutional, technical, and economic. This research is situated in a socio-technical system, as it focuses on Nd-Fe-B PMs for wind turbines and EVs within the institutional context of the EU. The research contains a comprehensive actor, institutional, value chain, and PESTEL analysis, which requires a deep understanding of the complexities in play. The analyses ensure that the problem and system were well understood by bringing together multiple perspectives. After that, institutional interventions that could increase the EU's autonomy in the REE system will be designed. Therefore, this study clearly has a design component. The establishment of institutional interventions is directed by the Williamson framework, which is used multiple times in the CoSEM curriculum.

1.8 Thesis Outline

This thesis proposal is structured as follows:

This thesis its first chapter, *Chapter 1*, serves as an introduction, by providing background information on REEs and Nd-Fe-B PMs and defining the research problem, objectives, and knowledge gaps. Additionally, the chapter outlines the research questions and the research approach. In *Chapter 2*, a literature review is conducted, leading to the establishment of the academic knowledge gaps, the main research question, and the sub-research questions. Furthermore, *Chapter 2* introduced the background of the Williamson framework. *Chapter 3* describes the methodology, ensuring research reproducibility. Thereafter, *Chapter 4* delves into the REE and Nd-Fe-B PM value chains, and several complex supply issues emerge. *Chapter 5* describes the current state of the REE system by analyzing which stakeholders and institutions are in play. *Chapter 6* functions as an overall system analysis by addressing the enabling and constraining factors for EU autonomy. *Chapter 7* is the confluence of *Chapters 4 -6* and the interview findings, leading to the establishment of institutional interventions. Thereafter, *Chapter 8* discusses the reflections, implications, and limitations. Finally, *Chapter 9* concludes the findings and answers the establishment research questions of *Chapter 1*. The research flow diagram shows the flow of this research in *Figure 1.3*.

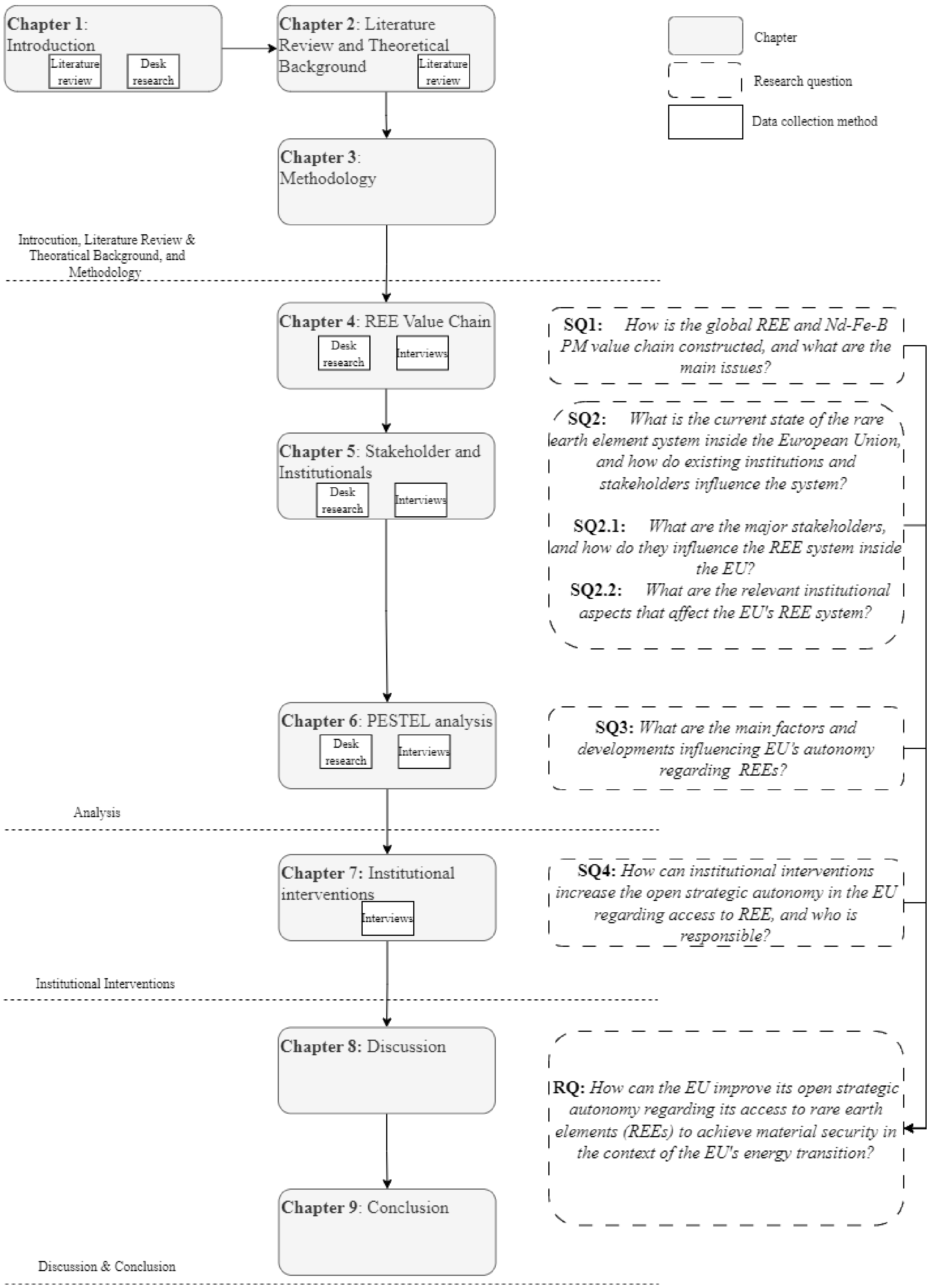

Figure 1.2: *The Research Flow Diagram*

2. LITERATURE REVIEW

This chapter explains the scientific problem in more detail. Reviewing the state-of-the-art scientific literature about the REE market dependencies and their consequences on the energy transition leading to the creation of the research questions. This literature review results in the formation of the academic knowledge gap that needs to be solved in this research project.

2.1 Literature Review Methodology

The primary identification method which was used to find the most relevant articles and reports was literature research, carried out using the following (main) keywords: "Supply," AND "Rare earth elements," AND "Energy Transition." These keywords were used to make an initial selection of relevant articles through Scopus based on the keywords. Both keywords can be phrased in multiple ways. Therefore, different search strings with different keywords were used; see *Table 2.1*. Consequently, the Scopus search string became: "Dependence" OR "Independence" OR "Supply risk" OR "Supply" OR "Autonomy" OR "Value Chain" AND "Rare earth element" OR "rare earth" OR "Rare earth material" OR "Rare earth mineral" OR "Neodymium" OR "Dysprosium" OR "Terbium" OR "Praseodymium" AND "Clean energy" OR "Climate change" OR "Energy transition." This string resulted in 172 hits. Furthermore, the following exclusion criteria are added for further demarcation:

- English,
- Not case-specific (e.g., deep sea mining, end of life, or other circular strategies)
- Focus on Nd-Fe-B PMs
- Published before 2012 (before that time, the REE market was not dependent on PMs, so literature on the topic is deemed to be more speculative and less relevant)

After demarcation, 10 relevant articles were found. Furthermore, five research publications were added to the review. These publications were found using the exact string in Google—furthermore, four articles were found using forward snowballing of the other publications. Finally, the Critical Raw Materials Act (CRMA) is added to the literature review, as it forms the backbone of this study. The CRMA is elaborately discussed in *Section 5.2.1.2* and in the interview findings in *Section 7.1*. So, the total number of publications/articles is twenty (see *Table 2.1*). In *Figure 2.1*, the research methodology is depicted in a visualization.

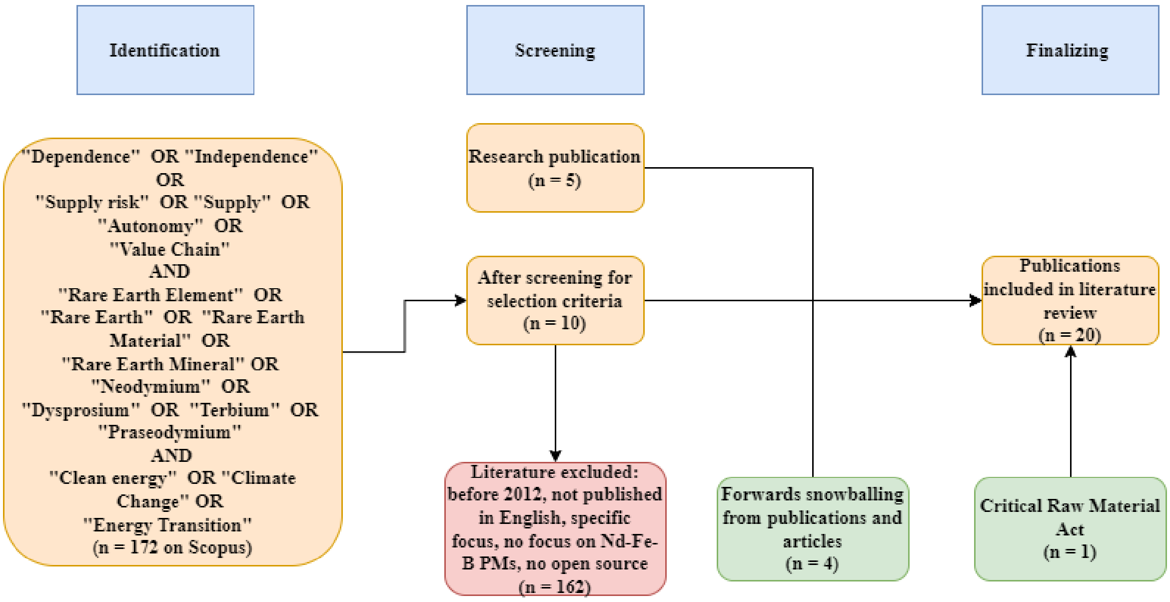

Figure 2.1: *Visualization of the research methodology*

2.2 Literature Overview

Table 2.1: *Literature overview*

NO.	AUTHOR/ PUBLISHER	YEAR OF PUBLICATION	TITLE
1	Alves Dias et al.	2020	The role of rare earth elements and electric mobility in wind energy
2	Andrew-Speed & Hove	2023	China's rare earths dominance and policy responses
3	Baldi, Peri, and Vandone	2014	Clean energy industries and rare earth materials: Economic and financial issues.
4	Ballinger et al.	2020	The vulnerability of electric-vehicle and wind-turbine supply chains to the supply of rare-earth elements in a 2-degree scenario.
5	EMRA	2021	Rare Earth Magnets and Motors: A European Call for Action
6	EPA	2012	Rare Earth Elements: A Review of Production, Processing, Recycling, and Associated Environmental Issues
7	European Commission,	2023	A framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU)
8	Exter et al.	2018	Metal demand for renewable electricity: Navigating a complex supply chain.
9	Gielen	2021	Critical minerals for the energy transition, International Renewable Energy Agency
10	Gielen & Lyons	2021	Critical materials for the energy transition: Rare earth elements
11	Gielen & Papa	2022	Materials for the energy transition, International Renewable Energy Agency and ENEL
12	Habib & Wenzel	2014	Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling.
13	IEA	2022	The Role of Critical Minerals in Clean Energy Transitions
14	Leader, Gaustad, and Babbitt	2019	The effect of critical material prices on the competitiveness of clean energy technologies.
15	Li et al.	2020	Critical Rare-Earth Elements Mismatch Global Wind-Power Ambitions.
16	Pawar & Ewing	2022	Recent advances in the global rare-earth supply chain.
17	Riddle et al.	2021	Agent-based modeling of supply disruptions in the global rare earths market.
18	Vikstrom	2020	Risk or opportunity? The extractive industries' response to critical metals in renewable energy technologies
19	Wang et al.	2020	Metal-energy nexus in the global energy transition calls for cooperative actions.
20	Zhou et al.	2016	Dostawy pierwiastków ziem rzadkich (REE) a czyste technologie energetyczne:

2.3 Results from the Literature Review

The literature makes clear that the REE market is likely to grow intensely over the coming decades, and this will impact the competitiveness of the EV and wind energy market. REEs are essential in EV motors and wind energy generation and play an important role in the energy transition. Furthermore, most of the literature points out that the REE market has serious challenges. The main challenge pointed out in the majority of the sources is the Chinese REE dominance. Across the publications, different solutions and supply risk management strategies are discussed to cope with Chinese dominance. Furthermore, the literature makes clear there will be significant consequences for the speed of the energy transition in the EU with a status quo situation (Van Exter et al., 2018; Gielen, 2021; IEA, 2022; Ballinger et al., 2020; Riddle et al., 2021).

The REE market drivers are the elements used in clean energy technologies because clean energy is the most rapidly growing market (Van Exter et al., 2018; Zhou et al., 2016; Li et al., 2020). REEs in clean energy technologies are mainly used for PMs used in EV motors and wind turbine generators. Ballinger et al. (2020) point out that the growing EV industry will make the wind industry more vulnerable and vice versa because both rely on REEs. PMs use Neodymium (Nd), Dysprosium (Dy), Praseodymium (Pr), and Terbium (Tb); these elements are the driving force for REE mining in the future (Van Exter et al., 2018; Zhou et al., 2016; Li et al., 2020). Nd-Fe-B (Neodymium-Iron-Boron) PMs are used in EV motors and turbine generators. These magnets typically consist of 30 percent of REEs (Gielen, 2021; Riddle et al., 2021). Several articles showed the vulnerability of Dy. Dy is one of the Heavy REEs (HREE), has a lower abundance than many other REEs, and has an even higher dependence on China. Habib & Wenzel (2014) and Riddle et al. (2021) claim that Dy is the most critical REE. EV and wind turbine manufacturers are trying to find alternatives for their Dy usage (IEA, 2022; Van Exter, 2018).

IEA (2022), Wang et al. (2020), and Van Exter et al. (2018) pointed out that different demands for different elements are a severe challenge for the business case of REE mining. REEs are mined together, so there is the risk of price spikes for those elements in high demand (e.g., Nd) and plunges for those in low demand. Furthermore, the articles discuss the environmental challenges related to REE mining and processing. Social and environmental problems will likely create significant resistance forces in Europe (Van Exter et al., 2018). Long lead times for new projects are another significant challenge; lead times are typically between 10 and 20 years. The publications pointed out several solutions to improve European independence in the REE market.

Firstly, the diversification of supply by international collaboration. Baldi, Peri, and Vandone (2014) explicitly mentioned improving cooperation between the EU and China, while more recent publications contrastingly say the EU should try to diversify its supply and try to move away from Chinese dependency, also because of the changed geopolitical context (European Commission, 2023). Vikstrom (2020) suggests international collaboration between 'politically stable countries and regions'— likewise, IRENA (2022) and Van Exter et al. (2018) suggest that the EU collaborate. The literature also points out reasons for the short to medium-term unlikelihood of supply chain diversification are outlined in the findings. Chinese firms hold a monopoly over each step of the REE supply chain, from extraction to PM production, and the government has the willingness to protect its REE interest through geopolitical actions (Pawar & Ewing 2022).

Secondly, promoting the EU mining industry has been described as a solution. REEs are rare but de facto not that scarce, and REEs are also found in European soil (Van Exter, 2018). Currently, several projects are under investigation. However, public resistance will likely play a significant role in the EU. Since mining and processing activities of REEs pose severe environmental risks.

Thirdly, the literature points out how to improve the circularity design, develop the end-of-life of REEs, and construct a collection, reuse, and recycling infrastructure. There is a broad consensus about recycling being a solution for the REE supply in the future. However, circularity alone will not be able to deal with the enormous demand in the upcoming decades. There is not enough REE in cycles yet to cope with the enormous demand (Van Exter, 2018; IEA, 2022). Only in 2100, it could serve 50 percent of the supply. Currently, recycling rates for Nd are meager (<1 percent) (EPA, 2012; Van Exter et al., 2018). The collection will be an essential first step (EPA, 2012).

Fourthly, substituting non-REE technologies is an option for improving EU independence. Moving away from REE usage or PM altogether is one of the solutions. There are, however, some bottlenecks with this solution. Currently, efficiencies favor REE usage in PMs compared with alternatives. Furthermore, alternatives often use other scarce materials so that substitution could shift the problem to something else (e.g., way more copper usage in PM motor alternatives, 30 percent more battery capacity for EVs).

Fifthly, improvements in the material efficiencies are stated as a solution, e.g., by reducing the REE ratio in PMs, with a primary focus on decreasing the Dy quantity, as Dy is most critical.

3. THEORY AND METHODOLOGY

The literature review of the previous chapter led to an understanding of which academic knowledge already exists in the REE market and their dependence on the energy transition. The review points out that there is still a lack of information on what additional measures the EU can take to increase the effectiveness of the adopted policies. This chapter begins by discussing the theoretical framework that has been used. Thereafter, the methodology elaborately discusses which data collection and analysis methods were used for the established research questions.

3.1 Theoretical framework

3.1.1 The Williamson Framework

The Williamson framework is the theoretical backbone of the institutional analysis in *Chapter 4* and the creation of institutional interventions in *Chapter 7*. This thesis uses the institutional framework to classify the existing institutions in *Chapter 5*, and provides guidance and structure for the proposed institutional interventions in *Chapter 7*.

Drawing from Williamson's (2000) work, the outlined framework delineates four distinct institutional levels.

Level 1, or the embeddedness level, deals with informal institutions such as customs, traditions, religion, and norms and undergoes gradual changes from 100 to 1000 years. Williamson emphasizes that these institutions significantly impact societal structure and functioning.

Level 2, the institutional environment, encompasses formal rules, including laws, regulations, constitutions, and property rights, and is dictated by law and government structures. Transformations here are often slow, as institutions primarily stem from the legislative, judicial, and executive branches of government and are influenced by power distribution across different government levels. Implementing progressive changes in L2 proves challenging due to rigid governmental structures. However, defining moments can create opportunities for sharp breaks and drastic transformations. However, it can undergo sharp breaks during historical and societal breakdowns (e.g., wars, financial crises, military coups, and the collapse of the Soviet Union). Nevertheless, such moments are rare, and the usual frequency of change within L2 spans from 10 to 100 years.

Level 3 focuses on governance institutions, predominantly contract governance, and changes occur within shorter spans. Transaction cost economics provides a lens for analyzing this level, with transactions between entities (e.g., individuals or organizations) being structured through contracts. Change frequency within level 3 typically ranges from 1 to 10 years.

The fourth level, L4, delves into neoclassical economics, focusing on resource allocation and employment. Change occurs continuously at this level, as demand and supply continually impact prices and quantities of products and services.

The framework's four levels directly influence one another. The solid arrows in *Figure 3.1* indicate the direct influence of higher levels on lower levels of institutions. Conversely, the dashed arrows connecting lower levels with higher levels indicate a feedback loop between the levels. Thus, lower levels can also influence higher levels. Williamson's framework serves as a theoretical tool for identifying different levels of institutions and explaining their mutual influence. Williamson (2000) states that the second and third levels are essential for numerous public policy matters. This research employed Williamson's framework by identifying the different levels of institutions, elucidating their relationships, and exploring their interactions. This established the basis for the developed institutional interventions to create more independence in the EU REE (Nd-Fe-B PM) market. The institutional interventions' predominant focus was within levels 2 and 3 due to their significant relevance to public policy matters.

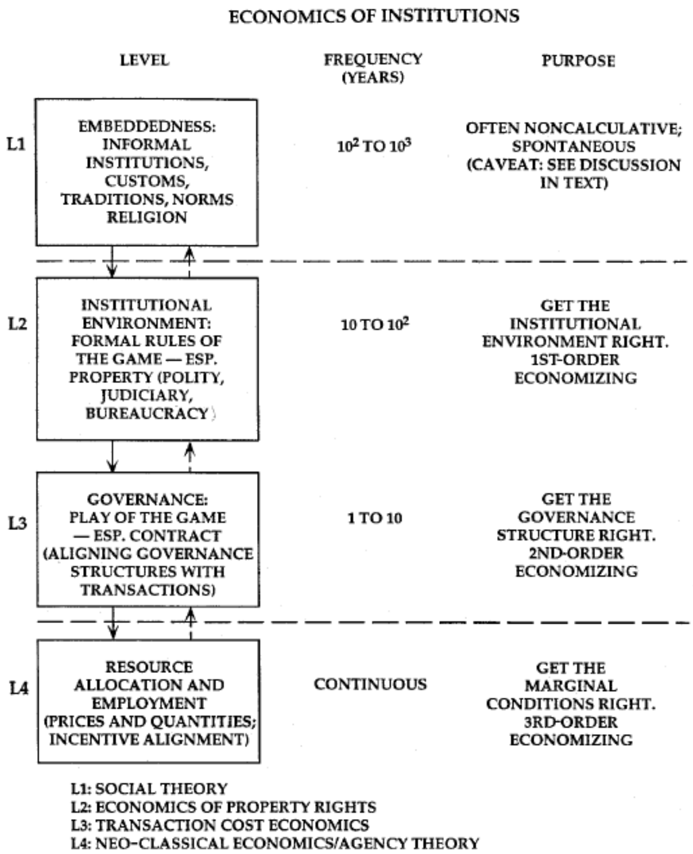

Figure 3.1: *The Williamson framework*

3.2 Applied Research Methods

3.2.1 Research Methods for the Introduction, Literature Review & Theoretical Background, and Methodology

An initial literature review is used to find relevant scientific knowledge gaps. Scopus has been used to find relevant articles related to the research objective. This search methodology is described in *Section 3.1*. Additionally, desk research has been conducted to support the literature review's main findings and obtain more knowledge about PMs, REEs, and existing policies. Search engines such as Google Scholar and Google were used to find grey literature and relevant scientific publications.

3.2.2 Research Methods for the Analysis

Chapters 4 up until *6* are included in this research stage, and this stage will provide an answer to one of the sub-questions and four partial sub-questions.

SQ1: *How is the global REE and Nd-Fe-B PM value chain constructed, and what are the main issues?*

- Data collection:
  - **Desk research:**
    This was the primary form of data collection in this part. The desk research builds upon the initial literature review described in *Chapter 2.* This desk research provides relevant additional information by using grey literature; for this chapter, relevant supply and demand information is needed for each step of the REE supply chain. Search strings such as “Rare earth elements” AND “Value Chain” have been used for this desk research.
  - **Interviews:**
    The semi-structured interviews of *Chapter 7* are used to validate the findings. Furthermore, it gave more insights into unavailable knowledge and data for the global value chain.

- Data analysis:
  This question covers all the relevant steps in the global REE value chain: REE extraction, processing, assembly, distribution, use, and end-of-life. These steps are identified in the literature of *Chapter* 2, notably Gielen & Lyons (2022), Andrew Philips & Hove (2023), ERMA (2021), and Van Exter et al. (2018). The function of this chapter is to provide the reader with an overview of the global REE market, specifically for wind turbine generators and EV motors. Furthermore, this chapter included all the REEs, not only the four critical ones (Nd, Dy, Tb, and Dr), to fully understand the entire market and the fact that REEs are mined together.

SQ2.1: *What are the major stakeholders, and how do they influence the REE system inside the EU?*

- Data collection:
  - **Desk research:** Again, desk research was the primary means of data collection. Grey literature like reports and the stakeholders' websites will be relevant to find information.
  - **Interviews:** The *Chapter 7* interviews can help better understand the stakeholders' relationship.
- Data analysis:
  This SQ has been answered using the actor analysis described in Enserink et al. (2010). A stakeholder analysis aims to identify the interests, objectives, and perspectives of individual actors within a multi-actor system to understand the system better. Furthermore, a stakeholder analysis identifies common ground and shared values among different actors, allowing for the generation of alternative strategies and tactics (Enserink et al., 2010). It also highlights how actors can contribute to these shared values and identifies the need for compensation or mitigating measures to address specific concerns. This helps policymakers develop strategies that satisfy multiple actors while working towards shared goals. The six-step approach of Enserink et al. (2010) was used in this study. In the first step, the process begins with the articulation of a problem and the identification of the decision arena related to that problem. The second step involves identifying the various actors or stakeholders that play a role in the defined decision arena. Step three sees a mapping of the formal institutional landscape, including the depiction of formal institutions and the relationships among the identified actors. Moving on to step four, the focus is on gaining a comprehensive understanding of the actors by determining their interests, objectives, perceptions, and available resources. The fifth step summarized the interdependencies among the identified actors, which this research facilitated through the creation of overview tables and diagrams. In the final step, the analysis extends to evaluate the implications of the gathered information on the initial articulation of the problem. This six-step approach provides a structured method for conducting actor analysis, offering a systematic way to understand and assess the dynamics within a decision-making context (Enserink et al., 2010).

SQ2.2: *What are the relevant current institutional aspects and policies that affect the EU's REE system?*

- Data collection:
  - **Desk research:** The 'European Green Industry Plan,' including the Critical Raw Materials Act, was a vital source. Furthermore, other directives and regulations were searched through Google and the European Commission's website; the main policy documents can be found in *Table 3.2*. Lastly, Chinese and US institutions were also analyzed, as they significantly affect the European REE system.
- Data analysis:
  The idea of this question is to find the relevant institutions and existing EU policies regarding REE independence. The found policies and institutions are placed in the Williamson framework afterward. The scope of this SQ is all the REEs.

SQ3: *What are the main factors and developments, influencing the EU's REE autonomy?*

- Data collection:
  - **Desk research:** The desk research used search strings that combined the PESTEL category with its scope (e.g., "REE" AND "Environmental impact'), "CRMs" were also used depending on the context (e.g., "CRMs" AND "Geopolitics")—scientific articles on specific (technological) solutions where relevant to this question. The primary solution pathways are Exploring REE projects, Reopening mines, Developing recycling and substitution techniques, and Reducing critical REE content in end-use products (e.g., reducing Dy content in PMs). Furthermore, grey literature was used to get to know the latest information.
  - **Interviews:** The semi-structured interviews of *Chapter 7* were used to validate the findings. Respondents will be asked to give their views on the extent of enhancement of independence for each of the factors—furthermore, the findings were validated through their responses.
- Data analysis:
  The PESTEL analysis was used to answer this SQ. PESTEL is a type of analysis that studies the key factors of a system by analyzing the following categories: Political, Economic, Socio-cultural, Technological, Environmental, and Legal. The scope of this analysis was explicitly on the EU. To prevent overlapping with SQ1 and SQ2.2

3.2.3 Research Methods for the Institutional Interventions

SQ4: *How can institutional interventions increase the autonomy in the EU regarding access to REE, and who is responsible?*

- Data collection:
  - **Desk research:** This could be an additional input to this chapter in case earlier chapters fail to provide sufficient data (e.g., using case examples of policy interventions).
  - **Interviews**: Interviews are the main piece of data collection for this SQ. Therefore, the first section of *Chapter* 7 is the interview findings—the interviews were conducted in the way *Section 3.3.3* describes. The interview protocol can be found in *Appendix C*. Furthermore, the findings of these interviews were also used to provide feedback on the previous chapters to make necessary additions or adjustments.
- Data analysis:
  The previous chapters provided this stage's input. Institutional interventions were formulated based on those insights and identified issues. The Williamson framework was used to structure and guide these institutional interventions and established policy options. The institutional interventions' predominant focus was within levels 2 and 3 due to their significant relevance to public policy matters. For establishing possible and, more importantly, politically feasible policy options, context-specific information on the open strategic autonomy in the EU regarding access to REE is needed. The policy documents, reports, and academic literature, e.g., *Chapter 2* and the expert interviews, form this context-specific information.

3.3 Data collection methods

Data collection can occur through multiple means such as observations, documentation (e.g., reports, newspaper articles, or scientific publications), or interviews; this research used a literature review, desk research, and interviews as primary data collection forms.

3.3.1 Literature review

The initial literature review was the academic backbone of this research, as it provided the knowledge and knowledge gaps. The central literature review is performed to find the most relevant literature relevant to the research question. *Chapter 2* shows the conducted literature review and the methods used to obtain the findings.

3.3.2 Desk research

In addition to the literature review, desk research was used to find answers to the sub-research questions. Each sub-question had its own specified desk research. The data was collected from different sources. First and foremost, scientific databases such as Scopus and Google Scholar provide relevant academic publications. Secondly, relevant research publications and newspaper articles on the topic of interest were used and found through Google, interview responses, supervisor suggestions, and snowballing with other publications. Moreover, policy documents, notably the CRMA, were essential for this study. These policy documents were found through Google and sites from relevant institutions (e.g. ec.europe.eu); an overview of the main policy document can be found in *Table 3.1*.

Table 3.1: *Overview of main policy documents*

AUTHORS	YEAR OF PUBLICATION	TITEL
CARARRA ET AL.	2023	Supply chain analysis and material demand forecast in strategic technologies and sectors in the EU
EUROPEAN COMMISSION	2006	Regulation (EU) 1013/2006
EUROPEAN COMMISSION	2021	Regulation (EU) 2021/821
EUROPEAN COMMISSION	2023	A framework for ensuring a secure and sustainable supply of critical raw materials and amending regulations
EUROPEAN COMMISSION	2023	CRMA working document impact assessment report
EUROPEAN COMMISSION	2023	A Green Deal Industrial Plan for the Net-Zero Age
SCHEINERT	2023	EU's response to the US Inflation Reduction Act (IRA).
US DEPARTMENT OF ENERGY	2021	Funding notice: bipartisan infrastructure law: rare earth element demonstration facility

3.3.3 Interviews

Finally, interviews were conducted to support, validate, and add information to the literature review and desk research findings. Interviews are an essential part of this research. According to Bryman (2016), qualitative interviews are very well suited to retrieve information from the interviewee's point of view, see what the interviewee sees as necessary, and be flexible with an in-depth exploration of exciting topics. The interviews were semi-structured and transcribed afterward. In this study, there was only one set of interviews, and the findings are discussed in *Chapter 7*; however, information in the earlier chapters was added or adjusted based on the interview findings. The overview of the expert interviewed can be found in *Table 3.2*, where square brackets "[ ]" were used to refer to an expert. Relevant interview respondents are actors, stakeholders, and policymakers with a high amount of knowledge and are considered experts in the European REE system and its applications for EV or wind energy. The interviews were roughly one hour long to have data saturation. The interview protocol can be found in *Appendix B.*

3.3.3.1 Interview Data Management and Processing

Expert interviews were conducted with human subjects in this research project, and the Human Research Ethics Committee (HREC) from TU Delft needed to approve this research. All the respondents were obliged to sign a consent form for participation in this study. The consent form, containing all relevant information about data protection and processing, was placed in *Appendix C.* Each of the respondents noted beforehand that the participation is voluntary. Furthermore, permission for recording and anonymity was asked beforehand. The interviews were held through Microsoft Team, automatically transcribed, and later checked for errors. Afterward, the participants had the option to receive transcripts of the interviews to check whether there were any misconceptions. There was only one set of interviews, which data was used across multiple chapters. The interview protocol can be found in *Appendix C*.

Table 3.2: *Overview of Expert Interviewees*

INTERVIEWEE	ROLE	FIELD OF EXPERTISE
EXPERT 1 [E1]	Strategic Advisor in the Energy Transition Program of The Hague Centre for Strategic Studies (HCSS)	Geopolitics/ Materials/ International Energy Markets/ Energy Transition/ Climate Change Policies
EXPERT 2 [E2]	Policy Officer in the Director-General Growth of the European Commission (Internal Market, Industry and SMEs)	Materials/ Hydrogen/ Energy Intensive Industries
EXPERT 3 [E3]	Assistant Professor at the Faculty of Industrial Design Engineering at the Delft University of Technology	Materials/ Supply Chain Resilience/ Sustainable Design/ Quantification of Environmental Impacts/ Industrial Ecology
EXPERT 4 [E4]	Policy Officer in the Director-General Trade of the European Commission (Policy and Agreements on Trade Outside the EU)	Geopolitics/ Trade/ International Agreements
EXPERT 5 [E5]	Former Director of Innovation and Technology for the International Renewable Energy Agency (IRENA)/ Senior Energy Economist for The World Bank	Materials/ Climate Change Policies/ Energy Transition/ Geopolitics
EXPERT 6 [E6]	Product Manager of Nd-Fe-B PM distributor Bakker Magnetics	Magnets (Nd-Fe-B PMs)/ Materials/ Nd-Fe-B PM Supply Chain
EXPERT 7 [E7]	Associate Professor in Critical Materials and Product Design at the Delft University of Technology	Critical Materials/ Circular Economy/ Sustainable Design

3.3.3.2 Interview Data Analysis

The findings of the literature review and the interviews were analyzed by applying the coding tool Nvivo. Labeling the segments of the transcripts into categories allows the essential data to be easily identified. At first, all findings have been open-coded; codes will be created and categorized. Thereafter, categories were compared in axial coding. Finally, causal connections were obtained through selective coding, validating the categories' relationships. The interview findings are discussed in *Section 7.1*.

3.3 Data Requirements

Much of the data was collected through a literature review and desk research. Some restrictions on literature selection were necessary to guarantee the data's trustworthiness. For the literature review, no grey data was used; the data used was either published by a prominent research institute or scientific data, peer-reviewed, and published in a journal. Both were considered trustworthy data. Furthermore, EU policy documents related to REEs and Nd-Fe-B PMs were studied. Similarly, some restrictions were necessary to find proper interviewees. A hard constraint was that the respondent was considered an expert. Both professional and scientific experts were considered (e.g., people who work a significant amount of time in the energy and/or material sector or energy scientists). In order to find sufficient information, seven in-depth interviews of at least one hour were conducted, all interviewees with different expertise.

3.4 Reliability & Validity

A critical look at how reliability and validity emerge is essential for the quality of the research (Bryman, 2016). According to Bryman (2016), reliability can be distinguished between internal and external reliability. Internal reliability is about the logic and consistency used in the research. During this study, internal reliability was preserved through peer feedback from supervisors and peers. Further, external reliability refers to the extent of replicability; would the findings be comparable if someone else conducted the research under similar circumstances. This research uses the theoretical framework of Williamson as a guideline for the institutional analysis, the six step stakeholder analysis of Enserink et al (2010), and the six factors PESTEL analysis. Furthermore, questions were asked in an open and non-guiding way to prevent respondents from being influenced by the questioning.

For validity, Bryman (2016) makes a similar distinction between internal and external validity. Internal validity is about the extent of correct causality and whether the observations lead to reasonable conclusions. Internal validity perseveres through interviews and peer-reviewed literature. Both interviews and peer-reviewed literature contain a lot of trustworthy information that can validate each other. Furthermore, interviews were recorded and transcribed to ensure that everything was said. Lastly, external validity refers to the extent of the generalizability of the findings. This study aimed to design a strategy for the EU to become less dependent on a single third-country supply of REEs for energy and material security. Therefore, external validity is low because the study focuses specifically on one region, so it cannot be immediately generalized. Furthermore, due to limited time, only seven interviews were conducted. Therefore, this reduced the external validity since smaller sample sizes are more challenging to generalize.

4. RARE EARTH ELEMENT VALUE CHAIN

This chapter provides a comprehensive overview of the global REE value chain, encompassing the extraction and mining processes, processing and refining, manufacturing and component production, assembly and final product, distribution and logistics, stages, assembly and distribution, consumption and end-use and the ever-growing importance of the recycling and re-use stage. Since REEs are mined together, this chapter will consider all the 17 REEs described in *Table A1* of *Appendix A*. REEs are pretty abundant in the earth's crust. However, mining and extracting the elements is expensive, complex, and environmentally hazardous (Andrew-Speed & Hove, 2023). They are often found in relatively small concentrations and are often mixed together with other radioactive elements, such as uranium. Therefore, extracted REEs are commonly dangerous to handle and hard to purify. For that reason, REE production comes from a small number of sources and geographies. This chapter's distinction between HREEs and LREEs is essential, as HREEs are less abundant and even more geographically concentrated than LREEs. Furthermore, the global market for upstream tradeable REEs is estimated to be between three and five billion dollars. However, the end-market downstream products that use REEs in their final product (e.g., user electronics, magnets, EVs, and wind turbines) are estimated to be worth over a trillion dollars (Diaz et al., 2021). This chapter will describe how constant value is added across the steps of the value chain.

4.1 Extraction and Mining

The first step is the extraction and mining of Rare Earth Oxides (REOs). REOs are primarily found in complex mineral deposits requiring extensive mining operations (Gielen & Lyons, 2022). There are roughly 245 types of known REO deposits. Almost 95 percent of REO production originates from three types, as they have the highest economic viability: bastnaesite, monazite, and xenotime. These deposits contain a mixture of REOs co-produced from a single deposit. Besides these complex mineral deposits, some ion clays contain significant REEs. Most deposits accumulate mainly LREEs and much smaller quantities of HREE, except for China's Zhaibei deposit and Japan's deep seabed muds (Gielen & Lyons, 2022; Andrew-Speed & Hove, 2023). Typically, REO deposits are mined using an open pit. Which means blasting rocks open with explosives to expose the ore. Thereafter, the ore is transported to a concentration plant, where the rock is crust, treated with chemicals, and smelted to be separated into different parts. Important to note is that open-pit mining is commonly known as the most environmentally harmful type of mining. In 2022, 300kt of REOs were globally produced. Over 70 percent was produced in China alone. *Table 4.1* shows all countries with REO reserves and their production levels in 2022. *Figure 4.1* shows the annual REO production by country.

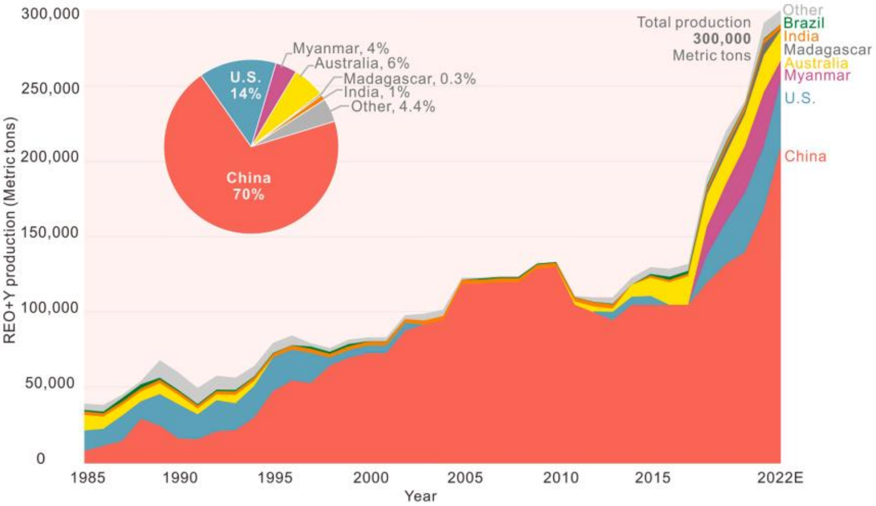

Figure 4.1: *Global REO mine production by country between 1985 and 2022 from (Liu et al, 2023)*

As can be observed in *Table 4.1*, global reserves are equivalent to almost 400 years of current demand. Thereby highlighting that abundance is not a major issue in the REE value chain. Global REO production has risen in the past years, as shown in *Figure 4.1*. *Table 4.2* shows the production outputs of the producing countries in the years 2016 to 2022. As shown in *Table 4.2*, Greenland has a significant REE reserve. However, recently, the Greenland government passed legislation to prohibit prospecting, exploration, and exploitation of uranium, thereby blocking the development of the Kuannersuit mine, which is one of the world's most significant HREE deposits containing Tb and Dy (Gielen & Lyons, 2022). *Figure 4.2* shows all the present active and advanced REE mining projects.

Table 4.1: *REE production and reserves by country, in tons of REOs in 2022 (Gielen & Lyons, 2022)*

COUNTRY	MINE PRODUCTION	PROVEN RESERVES	% OF GLOBAL RESERVES
CHINA	210,000	44,000,000	38.00%
VIETNAM	4,300	22,000,000	19.00%
BRAZIL	80	21,000,000	18.10%
RUSSIA	2,700	12,000,000	10.40%
INDIA	3,000	6,900,000	6.00%
AUSTRALIA	18,000	4,100,000	3.50%
UNITED STATES	43,000	1,500,000	1.30%
GREENLAND	0	1,500,000	1.30%
TANZANIA	0	890,000	0.80%
CANADA	0	830,000	0.70%
SOUTH AFRICA	0	790,000	0.70%
OTHER COUNTRIES	100	310,000	0.30%
BURMA	12,000	N/A	N/A
MADAGASCAR	1,000	N/A	N/A
THAILAND	7,100	N/A	N/A
BURUNDI	500	N/A	N/A
WORLD TOTAL	**301,780**	**115,820,000**	**100%**

** does not include the Swedish Kiruna deposit and the Japanize Minamitori deposit, as they are only potential reserves*

Table 4.2: *Production levels of producing countries in tons of REEs between 2016 and 2022 (USGS, 2023)*

COUNTRIES	2016	2017	2018	2019	2020	2021	2022
AUSTRALIA	15,000	19,000	21,000	20,000	17,000	24,000	18,000
BRAZIL	2,700	1,700	1,200	710	1,000	500	80
BURUNDI	-	40	620	200	500	35,000	12,000
CHINA	105,000	105,000	120,000	132,000	140,000	168,000	210,000
INDIA	1,500	1,800	2,900	2,900	3,000	2,900	2,900
MADAGASCAR	-	-	2,000	4,000	8,000	6,800	960
MALAYSIA	1,100	180	990	-	-	-	-
MYANMAR	3,500	15,000	23,000	-	-	500	12,000
RUSSIA	2,700	2,700	2,700	2,700	2,700	2,600	2,600
THAILAND	1,600	1,300	1,000	1,900	2,000	8,200	7,100
UNITED STATES	-	-	14,000	28,000	38,000	42,000	43,000
VIET NAM	240	220	920	1,300	1,000	-	-
WORLD TOTAL	**133,340**	**146,940**	**190,330**	**193,710**	**213,200**	**290,500**	**308,640**

**different sources are used for Tables 5.1 and 5.2, causing a slight difference in total output for 2022*

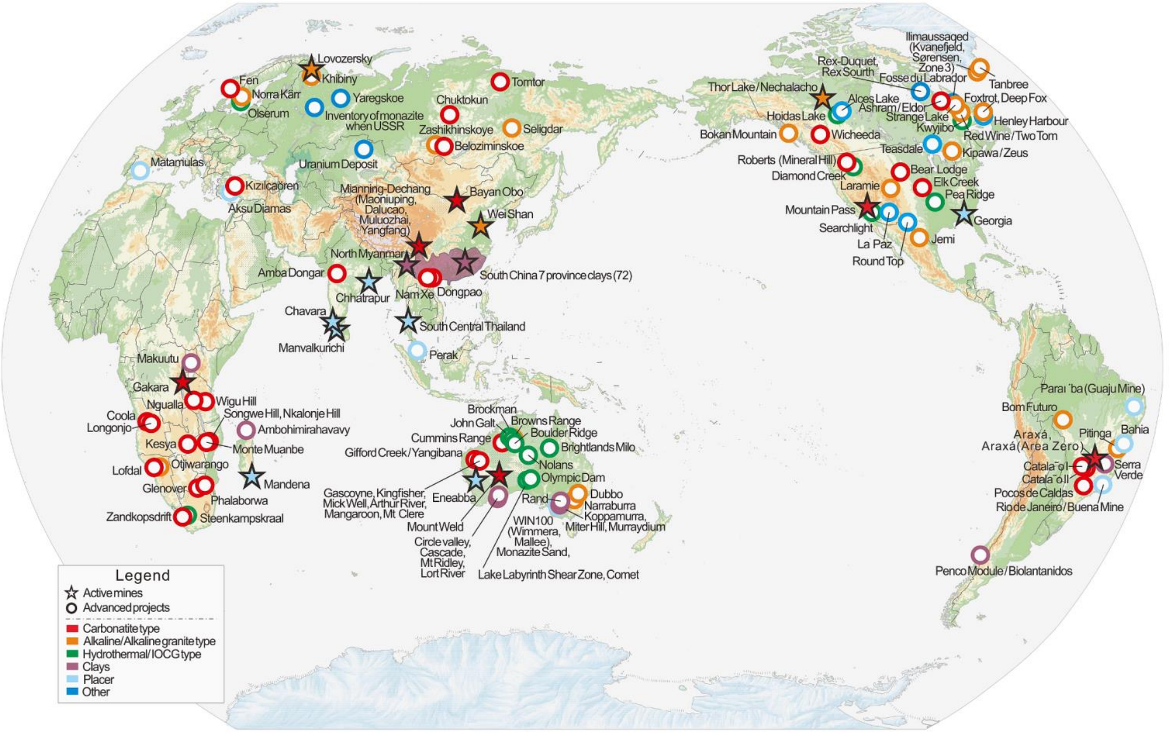

Figure 4.2: *Current global active mines (stars), and advanced projects (circles), visualization and data from Liu et al. (2023)*

Developments of REE mining projects are advancing; e.g., Canada's REE resources are estimated to exceed 14Mt while current reserves are 830kt. Moreover, the country is expected to produce 5kt of REEs by 2025 onward (Gielen & Lyons, 2022). Furthermore, Africa's multiple projects will open in the coming years. Japan could also become a critical REE player; a deposit near Minamitori contains roughly 16Mt valuable metals. Moreover, more investigation and research are increasingly going into exploring deep-sea REE mining. Balaram (2019) estimates that the Pacific mud deposit alone contains 100-1000 times more REE than all the global land reserves combined. However, seabed mining has environmental consequences and is difficult and expensive (Gielen & Lyons, 2022).

Dy and Nd are the drivers of the REE extraction as their demand is highest. Dy is critical in REE supply since it is more scarce then Nd, Tb, and Pr (Gielen & Lyons, 2022). Until 2021, the HREE was almost exclusively mined in China, giving China a monopoly in the HREE markets (European Commission, 2023-I; Liu et al., 2023). Furthermore, in terms of relative abundance, Dy accounts for less then one percent of all REEs, therefore Dy is unlikely to keep up with the growing Nd-Fe-B PM demand (Gielen, 2021).

4.2 Processing and Refining

After the extraction and mining, the raw REO undergoes processing and refining to separate into the individual REEs. REE processing is even more geographically concentrated than REE mining. REE processing is critical as it determines the purity and quality of the REEs obtained. Various steps are needed to extract individual REEs. *Table 4.3* describes the primary separation and refinement steps. *Figure 4.4* visualizes the processing scheme of Nd. Note that the five processing and refining steps do not have to occur at the same facility; conspicuously, step 5 is refining REOs to REEs (ERMA, 2021).

Only two countries are significant in processing REOs, with China processing 87 percent of REOs in 2021 (IEA, 2022; ERMA, 2021). Apart from China, Malaysia processes roughly 11 percent (of Australian-produced ore) of the global REOs. The remainder is processed in Estonia and India (IEA, 2022; ERMA, 2021). Refining REOs into REEs is done for 91 percent in China, 7 percent in Japan, and 1 percent in Estonia (ERMA, 2021).

The complete REE refining and processing practices account for 80 percent of the mine-to-metal supply chain's capital cost and 50 – 75 percent of the operating cost. Labor, energy, and chemical costs make the operating costs volatile. Processing sites need access to transportation infrastructure, cheap electricity, natural gas supply, and reagent producers. Furthermore, the environmental regulations further increase processing costs (Andrew-Speed & Hove, 2023). There are three main reasons separation and refinement are even more geographically concentrated. Firstly, a skilled workforce with specific knowledge of the chemical and separation processes is required because of the complexity of the processes. Secondly, economies of scale are significant, as higher quantities reduce the cost per unit processed. Finally, environmental regulations are essential, as processing facilities are known for their environmental footprint (Sykes, 2013; Andrew-Speed & Hove, 2023).

The processing and refining stage determines the individual REE's purity and quality, making it a critical step in the value chain. Over the past decades, China has been the dominant player in this value chain stage, accounting for a significant share of global REE processing and refining capacity. However, in recent years, other countries have recognized the strategic importance of securing their own rare earth supply chains and have taken steps to facilitate REE processing and refining facilities.

REE separation is a challenging process, which requires 'special knowledge,' and plants have high capital and variable costs (Gielen & Lyons, 2022). This is one of the reasons that processing is centered mainly in China, as they have all this 'special knowledge.'

As mentioned, China has a well-established REE extraction, processing, refining, and manufacturing infrastructure. Pawar & Ewing (2022) explain eight reasons why China obtained this dominant position: Generous lines of credit and subsidies, strategic partnerships and initiatives, geopolitical influence, manufacturing capabilities, technology, infrastructure, low labor cost, and lax environmental regulations. *Section 5.2.1.4.* dives deeper into how China established its pre-eminence. China's dominant position has raised global concerns about the supply security of REEs since many countries rely heavily on China's exports. Therefore, other countries have recently been developing new processing projects (Gielen & Lyons, 2022).

The country that is reacting most strongly to this supply trait is the US. As of 2021, most US-mined REOs were shipped to China for resource endowment (Gielen & Lyons, 2022). Multiple new projects are being developed, the most important being the Mountain Pass Mine in California. This mine was once the largest REE mine in the world. The mine was closed in the early 2000s because of environmental pollution. However, recent developments in the global supply chain caused it to resume operations, and efforts have been made to develop downstream processing facilities (Gielen & Lyons, 2022).

Table 4.3: *Description of the five main steps in REE processing and refining (Andrew-Speed & Hove, 2023)*

RARE EARTH ELEMENT PROCESSING AND REFINING STEPS
In the first step, REOs will be separated from other minerals through magnetic separation, flotation, gravity separation, or a combination.
The second step involves REO 'cracking,' Common chemical treatments are baking and acid digestion.
The third step concerns REO dewatering through precipitation
The fourth step is (99%) purification through biosorption, electro-winning, solvent extraction, ion exchange, or supercritical fluid.
The fifth and final step is REO refining to rare earth metals through electrowinning or electrochemical methods. Zone refining and electro-transport can achieve further purification (99.9%).

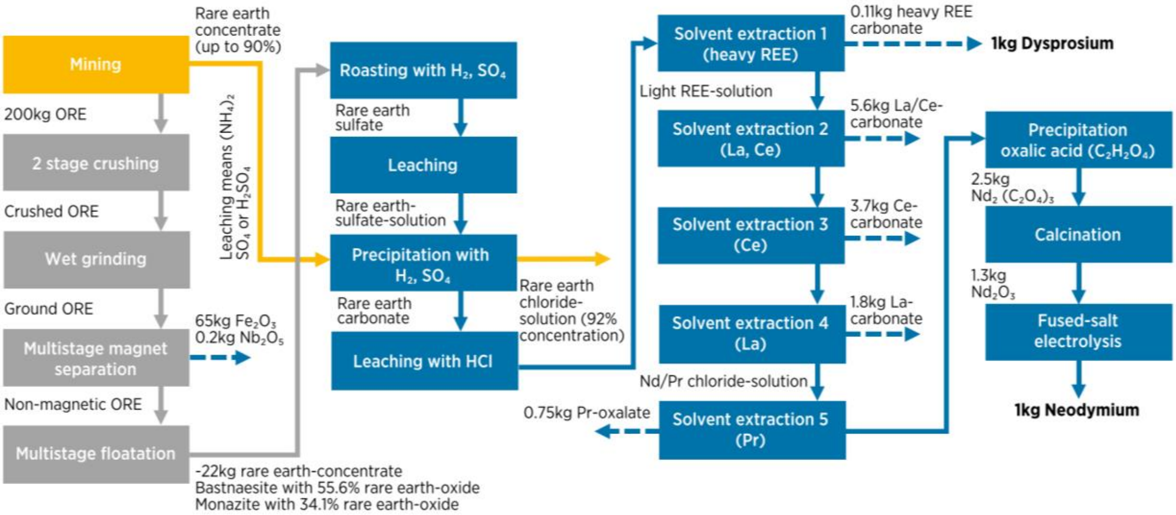

Figure 4.3: *Nd processing scheme (Gielen & Lyons, 2022)*

Although Australia is already a significant producer of REEs, it has never had domestic processing facilities. Therefore, they have been looking to increase their role in the value chain and aim to develop processing and refining facilities, with multiple projects in development (Gielen & Lyons, 2022). Likewise, Canada also possesses substantial rare earth resources and has been exploring the possibility of establishing its own processing and refining facilities (Gielen & Lyons, 2022). Several projects and partnerships have been initiated to develop a domestic supply chain for REEs. Similarly, India has substantial rare earth reserves and is eager to develop its processing and refining facilities. The country has plans to invest in new facilities and strengthen its position in the global REE market (Gielen & Lyons, 2022). Several other countries are also exploring entering the REE processing and refining market. These include countries in Europe, such as Germany and the United Kingdom, among others. Other countries, such as Germany and the United Kingdom, are also exploring the possibility of REE processing and refining market entrance. However, they are in an earlier stage than the countries' projects above (Gielen & Lyons, 2022). *Figure 4.4* shows (upcoming) global supply outside China.

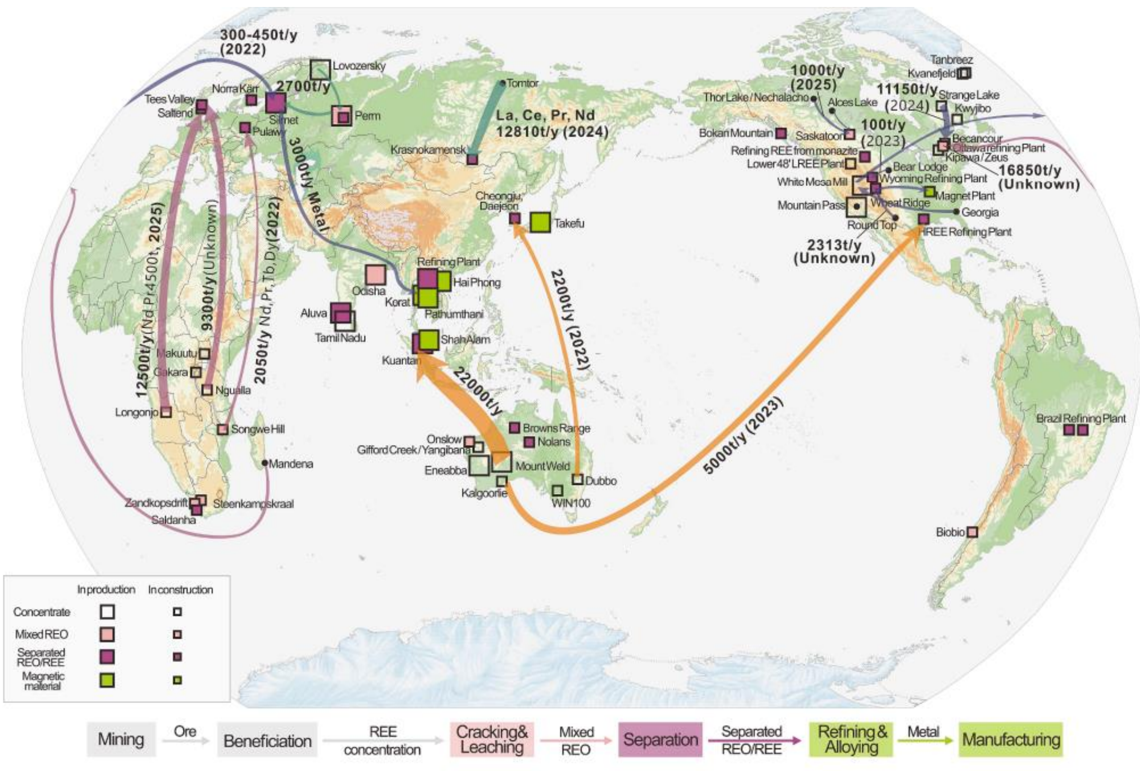

Figure 4.4: *Global REE supply chains outside China, data and visualization from Liu et al. (2023)*
* Note that the five processing steps in this study's *Table 4.3* are similar to the five steps in this figure.

The processing and refining supply chain stage forecast is likely to further diversify in the upcoming years. Already, numerous countries have taken steps toward domestic processing. This trend will persist as more countries recognize the importance of securing independent supply chains for REEs. However, it is essential to note that developing new processing facilities is time-consuming and expensive. Furthermore, facilitating independent REE processing is accompanied by complex challenges. This diversification trend will likely enhance supply security and reduce the dependency on a single country for critical materials, ensuring a more sustainable and resilient future for global REE industries.

4.3 Manufacturing and Components Production

Once the REEs are separated into individual elements and sent to manufacturers and component producers worldwide. These firms use REEs to manufacture various products, e.g., magnets, catalysts, and polishing powders. *Table 1.1* shows all the REEs with their applications. *Figure 4.6* shows the most common global REE uses in 2021. Furthermore, *Figure 4.7* summarizes the global supply chain. This section will mainly focus on Nd-Fe-B PMs, as that is the scope of this research.

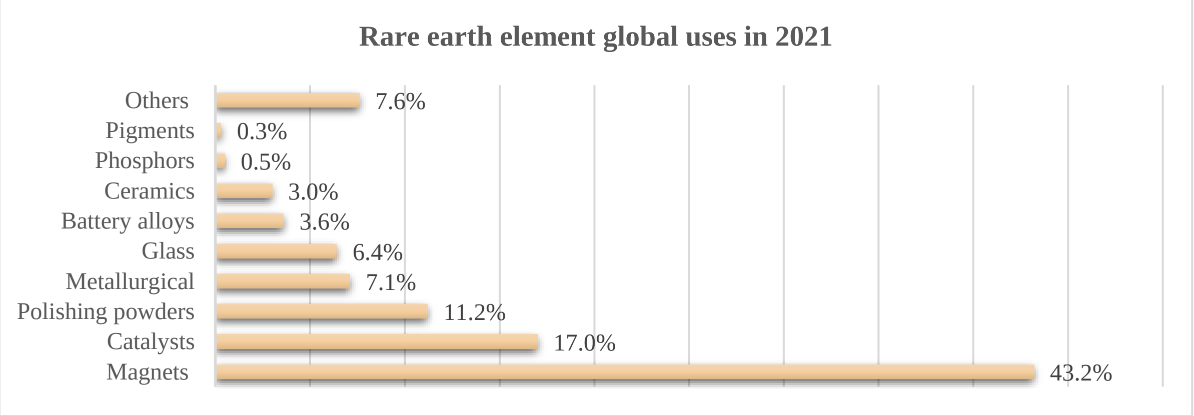

Figure 4.5: *Rare earth element global uses in 2021 (IEA, 2022).*

4.3.1 Magnet Manufacturing

REEs are known for their magnetic solid capabilities. As mentioned before, permanent magnets play an essential role in the energy transition as they are used in wind turbine generators and EV motors. PM production is rapidly increasing because of the increasing demand for both wind energy and EVs. Currently, over 40 percent of produced REEs are used for magnet applications. The two most common REE magnet types are the neodymium-iron-boron (Nd-Fe-B) permanent magnets and the samarium cobalt (SmCo) magnets. Besides their applications in the wind and EV industry, these magnets are found in speakers, hard-drive disks, and various other uses where strong magnetism is necessary (Cavallo, 2023). *Table 4.4* shows the demand per application for Nd-Fe-B PMs in 2020 and its projections in 2030 and 2050. By 2030, the EV motors and offshore wind turbine generators will require 65.5 percent of the entire Nd-Fe-B PM production, compared to 20.3 percent in 2020 (US Department of Energy, 2021).

The composition of Nd-Fe-B PMs utilized in EV motors and wind turbine generators generally includes approximately 25 – 32 weight percent neodymium/praseodymium (Nd/Pr), 60 – 70 weight percent iron (Fe), and 1 – 1.2 weight percent boron (B). Additionally, small quantities of terbium (Tb) and dysprosium (Dy) are incorporated, typically ranging from 1 – 5 weight percent, to create demagnetization resistance and high-temperature performance properties (Li et al., 2020; Gielen, 2021; Maani., 2021; Riddle, 2021). Nd-Fe-B PMs have various chemical compositions, that vary between applications and even products (Burkhardt et al., 2020).

Table 4.4: *Nd-Fe-B magnet applications global (high growth) demand forecast, per thousand tonnes of magnet (US Department of Energy, 2021)*

APPLICATION	**PART OF ENERGY SECTOR**	**DEMAND IN 2020**		**DEMAND IN 2030**		**DEMAND IN 2050**	
		Amount (kt)	Share	Amount (kt)	Share	Amount (kt)	Share
OFFSHORE WIND TURBINES	Yes	16.9	14.2%	139.2	36.0%	273.7	36.3%
ELECTRIC VEHICLES	Yes	7.3	6.1%	114.1	29.5%	266	35.3%
CONSUMER ELECTRONICS	No	35.1	29.4%	41	10.6%	65.4	8.7%
INDUSTRIAL MOTORS	No	36	30.2%	53.7	13.9%	85.7	11.4%
NON-DRIVETRAIN MOTORS IN VEHICLES	No	9.4	7.9%	18.3	4.7%	29.3	3.9%
OTHER SINTERED MAGNETS	No	6.5	5.5%	9.6	2.5%	15.3	2.0%
BONDED MAGNETS	No	8	6.7%	11.1	2.9%	17.7	2.3%
TOTAL	**-**	**119.2**	**100%**	**387**	**100%**	**753.2**	**100%**

China has progressively increased its PM production capacity. Roughly 80 percent of the PM manufacturing supply chain was located in China in 2014. In 2021, that percentage was 94 percent (Alves et al., 2021). According to Alves et al. (2021), this expansion results from low labor costs and closer access to REE suppliers. Japan and Germany are making up for the remainder of the high-performance Nd-Fe-B PMs (IEA, 2022). EU-manufactured Nd-Fe-B magnets are 20 – 30 percent more expensive than equivalent magnets produced in China (ERMA, 2021).

4.3.2 Catalyst Manufacturing

REEs are also commonly used as catalysts in the chemical industry. REE chemical catalysts are typically made from the more abundant REEs, such as cerium and lanthanum. These catalysts are used in various products, e.g., fuel cells, plastics, exhaust applications, hydrocarbon refinement, and capture for fuel (Cavallo, 2023).

4.3.3 Polishing Powders Manufacturing

REE polishing powders are typically a mixture of light REOs such as cerium oxide. It is used to improve the surface of finished products or parts. It is widely adopted because of its excellent physical and chemical properties (Cavallo, 2023)

4.3.4 Metal Alloys (metallurgical) Manufacturing

REEs are famous for their unique properties, e.g., flame resistance, high-temperature strength, corrosion resistance, and castability improvement. Therefore, they are widely used in metal alloys to achieve the necessary material characteristics for a given application (Cavallo, 2023). For effectiveness, Lanthanum anodes are required in nickel-metal-hydride batteries of EVs. Furthermore, dysprosium, erbium, ytterbium, and gadolinium are used as superalloys in high-performance cars and helicopters (Cavallo, 2023).

4.4 Assembly and Final Production

After the manufacturing and component stage, the components are assembled into final products. The Nd-Fe-B PMs are integrated into electric motors and wind turbine generators at this stage. These final products are applied in numerous industries, e.g., automotive, user-electronics, renewable energy, defense, and healthcare (IEA, 2022). Technological alternatives for REE PM usage in EV motors and wind turbine generators are described in *Section 6.4.*

4.4.1 EV Production

There are three main types of EVs: Hybrid EV (HEV), Plug-in Hybrid EV (PHEV), and Battery EV (BEV). BEVs rely solely on electric power stored in an on-board battery. HEVs incorporate internal combustion engines alongside an electric propulsion system. PHEVs share similarities with HEVs but feature larger batteries that can be charged. They have the capability to operate on electric power alone for a certain range. Globally, 92 percent of the newly sold EVs (HEVs, PHEVs, BEVs) will use Nd-Fe-B PM synchronous motors (PMSM) in 2021 (Adamas Intellectual, 2021). This number has even risen over the last couple of years despite the increased cost of REEs. PMSMs are, therefore, considered the dominant design for EV motors. Roughly two to five kg of Nd is used for an average EV motor, with approximately 0.6 kg per 100kW of peak power (Andrew-Speed & Hove, 2023). PMSMs are both in-house and outsourced produced. A company like Tesla produces their motors, whereas others like to outsource (e.g., Bosch Mobility Solutions, ABB Co. Ltd., Nidec Corporation, Brose Fahrzeugteile SE & Co. KG and Johnson Electric Group (Mordor Intelligence, 2023). Global Nd demand for EV motors is projected to increase from 2,000 tonnes in 2020 to 25,000 in 2040 (Andrew-Speed & Hove, 2023).

4.4.2 Wind Turbine Production

Four main types of wind turbines exist, as described in *Section 6.4*. Two of them use Nd-Fe-B PMs in their generator. These are typically used for offshore wind turbines. Unlike EV companies, wind turbine manufacturers typically produce the generators themselves or at least have substantial control over the design performance and reliability (Andrew-Speed & Hove, 2023). According to Andrew-Speed & Hove (2023), wind turbine generator-related Nd demand will rise from 4,000 tonnes in 2020 to 12,000 tonnes in 2040.

4.5 Distribution and Logistics

Products will need to be distributed after the manufacturing and final product assembly. Finished REE products often operate in complex supply chains in a global market.

4.5.1 EV Distribution

The central EV-producing countries are China, Japan, Germany, the US, France, and South Korea. China is the most dominant player in this stage as well. In 2022, 35 percent of the EVs came from China, which was 25 percent in 2021 (IEA, 2023). Norway, China, the Netherlands, Germany, and France are among the leading importing countries of EVs worldwide. Despite China, Germany, and France producing EVs, they also account for the top importing countries. China and Europe have the most robust logistic relationship, with the highest volume of EVs exchanged between these regions. Furthermore, Japan – Europe and the US– Europe relations are also very significant (IEA, 2023).

4.5.2 Wind Turbine Distribution

The EU is the global leading manufacturer of wind turbines, accounting for 58 percent of the production in 2021. Major manufacturing companies, e.g., Vestas (Denmark), Siemens Gamesa (Spain/Germany), and Nordex (Germany), are located in the EU. The solid European market makes Europe a significant export of wind turbines through other parts of the world (ERMA, 2021). Furthermore, unsurprisingly, China is also a significant producer, accounting for 23 percent of production in 2021.

4.6 Consumption and End-Use

This section discusses the consumption and end-use stage.

4.6.1 EV Consumption

Table 4.5 depicts the top EV-consuming regions or countries in 2022. Forecasts are that EV sales will exponentially rise (IEA, 2023). Striking to this table is the high amount of adoption in China, Sweden, and especially Norway, where almost 90 percent of the sold cars where EVs in 2022. All three countries have generous incentive structures for EV usage (IEA, 2023).

Table 4.5: *Light-duty plug-in EV (PEV) sales and market share per region in 2022 by IEA (2023)*

	COUNTRY OR REGION	**PEV STOCK/ CUMULATIVE SALES 2022**	**ANNUAL SALES 2022**	**MARKET SHARE 2022**	**% OF CARS IN USE 2022**
1	*China*	14,100,000	5,924,421	30.00%	4.90%
2	*Europe*	7,800,000	2,602,431	23.00%	2.40%
3	*United States*	2,960,000	990,000	7.70%	1.30%
4	*Germany*	1,877,721	832,652	31.40%	3.85%
5	*California*	1,385,383	343,244	18.70%	3.85%
6	*France*	990,000	346,849	21.60%	2.70%
7	*United Kingdom*	950,000	368,617	22.90%	2.80%
8	*Norway*	817,471	153,144	87.80%	27.73%
9	*Netherlands*	515,838	106,854	34.90%	5.80%
10	*Sweden*	440,000	161,649	56.10%	8.80%
11	*Japan*	410,000	102,000	3.00%	0.60%
12	*Canada*	380,000	114,000	9.40%	1.60%
TOTAL	*Global*	25,900,000	10,200,000	14.00%	2.10%

* The second column accounts for the cumulative manufactured end products till 2022.
* Plug-in EVs take into account BEVs and PHEVs, but no HEVs (as they cannot be charged)

4.6.2 Wind Turbine Consumption

A growing number of wind turbines use Nd-Fe-B PMs. The IEA (2022) expects an even bigger market for wind turbines with PMs, which could dramatically increase REE demand, thereby increasing the pressure on the already unstable supply chain over the coming decades, especially off-shore projects (IEA, 2022). ERMA (2021) estimated an annual European need of 7,000 tonnes of magnets till 2030 to cover the offshore wind projects. The EU's offshore wind capacity will increase from 12 GW to 73 GW by 2030, with an average of 650 kg of Nd-Fe-B PM per MW.

4.7 End-of-Life

The last step in the REE value chain is the end-of-life stage. An increasing number of REE end-of-life projects intend to reuse the REEs. REEs are especially suitable for end-of-life (EoL) projects because of their extraction and processing complexity and environmental impact.

Below one percent of the REE PMs are recycled from their end-products (ERMA, 2021). However, some recycling projects are starting up and are in development (ERMA, 2021). REE extraction is a complicated process, e.g., Nd-Fe-B PMs often contain different amounts of magnet grades. Not all REE PMs are directly re-useable in new magnets (Burkhardt et al., 2020). The highest success was found with a classification system requiring the magnet grade, coating type, and chemical composition (Burkhardt et al., 2020). Besides magnet recycling, projects are also including e-waste recycling (e.g., smartphones and computers, which contain small amounts of REE), fluorescent lamp and CRT recycling (REE phosphors can be reclaimed and re-used), and urban mining (recovering valuable materials from industrial and urban waste stream, including REEs) (Burkhardt et al., 2020). Furthermore, the literature in *Chapter 2* and the experts in *Chapter 7* pointed out that this step is one of the solutions for obtaining material and energy security. However, the literature also pointed out that recycling will not close the gap between supply and demand in the short to medium term. In 2100, recycling is expected to make up only 50 percent of the demand (Habib & Wenzel, 2014). Recycling will trail energy-transition-generated demand for materials for decades to come because more will be needed in the future than is currently in use (Gielen, 2021).

The shortage in REE PM recovery and recycling mainly originated from a lack of collection infrastructure to get the REE-containing products back after the use phase. Moreover, even if the collection infrastructure exists, recoveries often do not bother to extract the REE from the final product because of the small and variable quantities in these products (Burkhardt et al., 2020).

According to E1, to prevent future strategic problems, the EU must try to keep the materials used today. An established European collection and recycling infrastructure is therefore required. *Section 6.4* delves deep into the constraining factors of REE recycling, and *Section 7.3.3* shows various policy options to improve the EoL of REE-containing products.

4.7.1 EV motors EoL

Currently, PM EV motors' dismantling and extraction process is only done on a small scale, which is still very expensive (Burkhardt et al., 2020). Furthermore, the motors are not designed for circularity (with the end-of-life stage in mind), which makes REE extraction more complicated than necessary (Burkhardt et al., 2020).

4.7.2 Wind Turbine Generators EoL

The dismantling and extraction process in generators is relatively easy compared to that of EV motors. One of the reasons is that circularity plays a more critical role in the design of wind turbines, so more wind turbines are designed with the end-of-life in mind (Burkhardt et al., 2020). Generally, the EoL for wind turbine generators should be easily recyclable as they often contain tonnes of PM, and EV motors are typically more complicated as they only contain a couple of kilograms of PM [E3].

4.8 Concluding remarks

This section provides an answer to **SQ1:** *How is the global REE and Nd-Fe-B PM value chain constructed, and what are the main issues?*

This study made the distinction between seven main stages in the REE value chain: 1) REO mining, 2) REO processing and REE refining, 3) Component manufacturing, 4) Assembly, 5) Distribution, 6) Use-phase, 7) End-of-Life.

Over the past decades, China has been the dominant power across most of these stages of the REE value chain. *Figure 4.7* clearly demonstrates this dominance, as it shows the market shares across the value chain. China is particularly dominant in the HREE market, as they almost exclusively mine and process these, making Dy the most critical REE. Moreover, China has recently been moving further downstream in the value chain, making successful efforts in final product manufacturing by producing 94 percent of the Nd-Fe-B PMs and an increasing share of the global wind turbines and EVs. Their dominance is unlikely to change in the upcoming decade, given the scale of its existing industry ([E1], Andrew-Speed & Hove, 2023). This single-country dependency raises concerns about supply security and is the first and foremost identified issue in the REE value chain [E1 – E7]. Secondly, the growing demand for Nd-Fe-B PMs in EVs and wind turbines will likely exacerbate these supply chain vulnerabilities even further [E1 – E7].

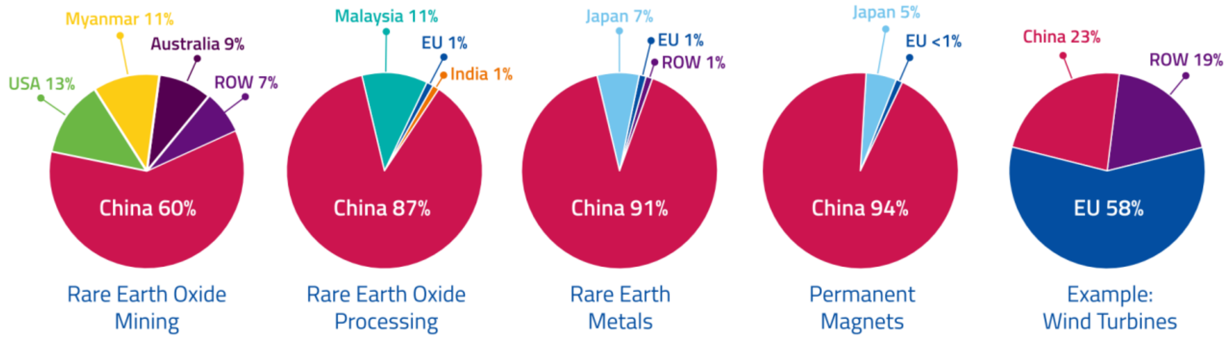

Figure 4.6: *REE mining to wind turbine manufacturing, with market share estimations for 2021, data and visualization obtained from ERMA (2021).*

Thirdly, establishing new mining, processing, and magnet manufacturing projects has to deal with a lot of hurdles, e.g., high costs (CAPEX and OPEX are more extensively discussed in *Section 6.2*), long lead times, infrastructure needs, environmental regulations, and a skilled workforce (*Chapter 6* delves deeper into constraining factors) [E1 – E7]. Thereby creating investment uncertainty [E1, E2, and E5]. Lastly, recycling challenges (e.g., lack of collection infrastructure, complexities in the REE extraction process) and a lack of circular design pose significant challenges for mitigating supply chain risk strategies [E1, E3, E5, and E7]. *Figure 4.8* is a visual representation of the global REE value chain and summarizes the main issues identified by triangulating data with expert findings.

In essence, the most pivotal challenge emerges during the processing stage of the value chain, characterized by its heightened concentration and formidable establishment barriers [E5]. Through the analysis, it has become evident that there are ample economically viable REE mining opportunities, with global reserves exceeding current annual production by a factor of 400. Despite ongoing endeavors to diversify the current supply, it is crucial to observe that time emerges as the most scarce resource in mitigating dependencies, especially as China's production share continues to rise [E1 – E7]. New extraction and processing projects often have lead times between 10 and 20 years (Van Exter et al., 2018).

Chapter 5 delves into the current state of the REE system inside the European Union, and how existing institutions and stakeholders influence the system. This will clarify and help to understand why the EU performs poorly in the upstream REE value chain. Furthermore, *Chapter 6* goes into the relevant factors for the EU, thereby going deeper into the identified issues of this chapter.

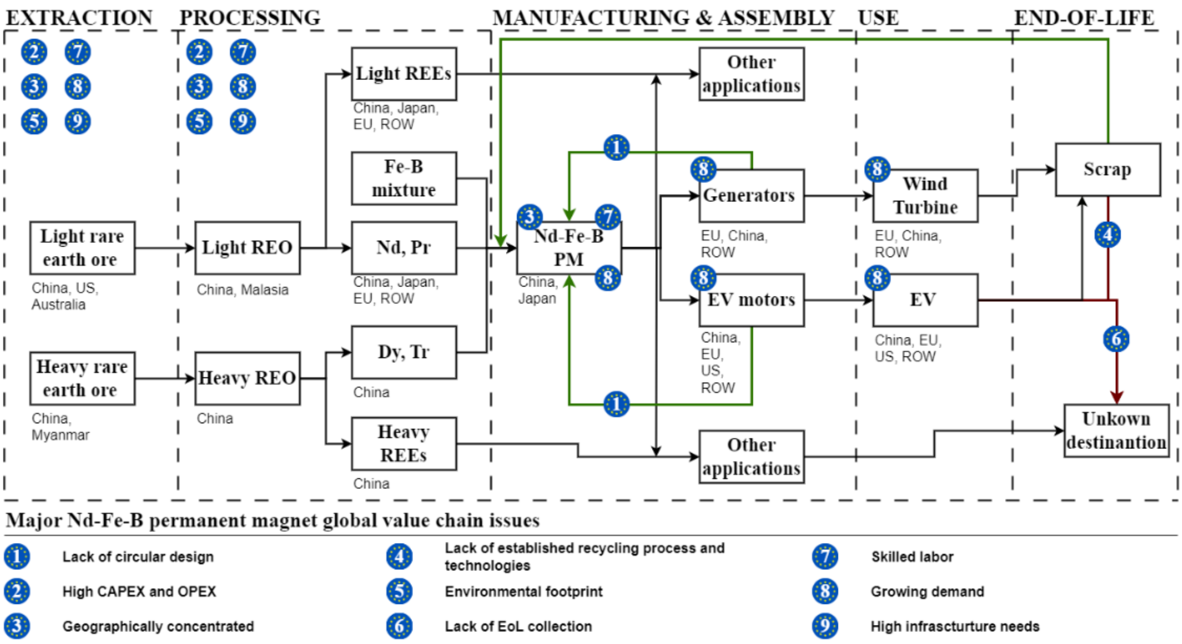

Figure 4.7: *REE supply chain including identified main issues*

5. STAKEHOLDERS AND INSTITUTIONS

This chapter is discussing the Stakeholder and Institutional analysis, going into the following research questions:

SQ2: *What is the current state of the rare earth element system inside the European Union, and how do existing institutions and stakeholders influence the system?*

- **SQ2.1:** *What are the major stakeholders, and how do they influence the REE system inside the EU?*
- **SQ2.2:** *What are the relevant institutional aspects that affect the EU's REE system?*

SQ2.1 is discussed in *Section 5.1*, SQ2.2 in *Section 5.2*, and SQ2 in *Section 5.3.* These sub-questions aim to understand better the relevant stakeholders and institutions in the REE system in the EU, which was required to establish institutional interventions in *Chapter 7.*

5.1 Stakeholder Analysis

This analysis aimed to understand how stakeholders involved and operating in the field of Nd-Fe-B PM with applications in wind turbine generators and EV motors influence the REE system in the EU. Government and regulatory bodies of non-EU countries, such as the Chinese and the US governments, are critical stakeholders that could significantly affect this system. However, this analysis did not consider them as they are only indirectly involved. Furthermore, their contribution is comprehensively discussed in the remainder of this rapport. This document uses Enserink's (2010, p79) definition of an actor: *"An actor is a social entity, a person or an organization, able to act on or exert influence on a decision."* The analysis begins with a stakeholder-type overview. Fifteen stakeholder types are distinguished and are described below in *Section 5.1.1*. *Section 5.1.2* analyses the objectives, dynamics, and structures between the actors.

5.1.1 Overview Stakeholder Types

Table 5.1 shows the stakeholder types per stakeholder. It is important to note that some of the stakeholders differ between EU Member States, mainly the stakeholder types: regulatory bodies and governmental bodies. National policies greatly influence the power dynamics between the stakeholders and are, therefore, different in each EU country. The categorization of stakeholder types stems from an amalgamation of insights derived from the REE value chain outlined in *Chapter 4*; the actors examined in the literature discussed in *Chapter 2*, and notably, insights gleaned from Hool et al.'s (2023) article on the impact of the CRMA on stakeholders. This synthesis identifies fifteen relevant stakeholder types, which are discussed below.

1. **REO Suppliers:**

The first relevant stakeholders are the raw material suppliers, the companies that mine for REOs. In 2021, industry consolidation resulted in four major REO mining and refining state-owned companies in China, together forming the China Rare Earth Group (Anderw-Philips & Hove, 2023). Lynas Corporation (Australia), MP Materials (US), and Neo Performance Materials (Canada) are the world's leading rare earth mining companies by market cap outside China in 2023 (Linn, 2023). The Swedish state-owned LKAB will likely become a significant European REO supplier, as they own the Kiruna mine in southern Sweden (Frost, 2023), where LKAB discovered one million metric tons of REO earlier this year. Nevertheless, up to this day no European enterprise mines for REOs.

2. **REE Processing and Refining companies:**

The second step in the REE value chain is processing and refining the elements, as *Section 4.2* describes. Refining companies are responsible for separating and extracting the REOs into single elements. The China Rare Earth Group described above is responsible for both mining and processing of REE, and is considered the most significant REE producer, as they control 70 percent of the country's production, which itself produces roughly 90 percent of the REEs. The Australian company Lynas processes roughly 10 percent of the world's REEs. Furthermore, Estonia has a small facility (Andrews-Speed & Hove, 2023).

3. **Nd-Fe-B PM Manufacturers:**

The third step in the supply chain is component manufacturing, so Nd-Fe-B PM manufacturing in the case of EV motors and wind turbine generators. These companies combine the different elements and materials into usable components. The biggest Nd-Fe-B PM producers for both EV motors and wind turbine generators are Ningo Zhaobao Magnet Co., Ltd, Hengdian Group DMEGC Magnetic Limited, and Zhong Ke San Huan (Zhaobao Magnet, 2023). In total China produces 94 percent of the global PMs. Hitachi Metals and Shin-Etsu Chemical Co., Ltd are Japan's biggest Nd-Fe-B PM manufacturers outside China. The German Vacuumschmelze GmbH & Co. KG (VAC) and the Finish Neorem are the most prominent European producers of Nd-Fe-B PMs (Zhaobao Magnet, 2023; Cararra et al., 2023).

4. **(EV) Component Suppliers:**

Next in the value chain is the assembly and final product phase. In this phase, manufacturers assemble all the components into the final product. In this case, that will be EV motors and wind turbine generators. As already became apparent in *Chapter 4*, some EV companies, such as Tesla Inc., produce their own motors. However, the majority of the EV companies are outsourcing their EV-motor production, e.g., ABB Co. Ltd. (Switzerland), Nidec Corporation (Japan), Bosch Mobility Solutions (Germany), Brose Fahrzeugteile SE & Co. KG (Germany), and Johnson Electric Group (Hong Kong) (Mordor Intelligence, 2023). Wind turbine manufacturers typically produce their own generators (See: 5. Wind Turbine Manufacturers).

5. **Wind Turbine Manufacturers:**

Next in the value chain is the assembly and final product phase; in this case, the wind turbine manufacturers. These include Vestas (Denmark), Siemens Gamesa (Germany/Spain), GE Renewable Energy (US), Nordex SE (US), Goldwind (China), and Dongfang Electric (China) (Blackrid Research, 2022).

6. **Electric Vehicle Manufacturers:**

Similarly to wind turbine manufacturers, EV manufacturers assemble all the components into the final product. The leading global BEV manufacturers are BYD (China), Tesla Inc. (US), VW Group (Germany), GM (US), and Stellantis (US/France) (Mordor Intelligence, 2023). Leading PHEV manufactures are Mitsubishi (Japan), Toyota (Japan), Chevrolet (US), and BMW (Germany).

7. **End Users:**

The consumer and end user in this system are permanent magnet synchronous motor (PMSM) EV owners and wind turbine owners (which can be, e.g., utility companies, cooperatives, government entities, and independent power producers (IPPs)). The whole value chain is in service of the end user's needs.

8. **Recycling and Waste Management Companies:**

The final step in the value chain is the End-of-Life. This step aims to recycle or re-use the REE in the used REE products, including the PMs. Collection and waste management companies play a critical role in this process. Some of the already established REE recycling companies are Umicore (Belgium), SOLVAY (Belgium), MP Materials (US), Retriev Technologies (US), and Blue Oak Resources (US). Noteworthy is the France start-up MagREEsource, as they have developed an environmentally friendly process for Nd-Fe-B PM recycling (Randall, 2023)

9. Government Bodies:

There are more relevant stakeholders besides the relevant players in the REE value chain. Government bodies play an essential role, as they are responsible for the policy decision-making process in the REE system. In the EU's REE system, the relevant legislative bodies are Member States (e.g., Germany, Spain, France, the Netherlands, Denmark), the European Parliament, the Council of the European Union (National Ministries of: Energy, Natural Resources, Environment, Trade, and Industry), and the European Raw Material Alliance.

10. Regulatory Bodies:

Next to the government bodies, regulatory bodies play a crucial role as well, as they are responsible for the policy-designing, standards setting, setting up guidelines, implementation, and enforcement of the adopted policies to ensure safety, performance, and environmental compliance. The most significant regulatory body in this system is the European Commission. Other regulatory organizations are the European Chemicals Agency (ECHA), the European Environment Agency (EEA), and the International Electrotechnical Commission (IEC).

11. Research and Development Institutions:

R&D institutions are also essential stakeholders, as they drive technological innovations, inform policy decisions, and enhance sustainable practices. Indeed, in this system, technological innovation is necessary. Examples of relevant R&D institutions are the European Commission's Joint Research Centre (JRC), the Fraunhofer Institute for Manufacturing Technology and Advanced Materials (Fraunhofer IFAM), the Institute for Energy Technology (IFE), European universities, and the European Institute of Innovation and Technology, notably EIT Raw Materials.

12. Environmental and Sustainability Organizations:

Environmental and sustainability organizations influence policy and regulation, promote sustainable practices, and create awareness—for instance, Greenpeace, Extinction Rebellion, EcoWaste Coalition, Circular Economy Stakeholder Platform, and the World Business Council for Sustainable Development (WBCSD).

13. Trade Associations and Industry Groups:

Trade associations and industry groups are essential as they advocate for interests and share knowledge for companies, organizations, and individuals operating in the European PM system. WindEurope and the European Association for Electromobility are examples of such associations.

14. Investors and Funding Organizations:

Investors and funding organizations determine where the money will go, influencing innovation and technological trajectories. They are essential as capital infusion will be necessary for the establishment of European REE capacity. Examples include the European Investment Bank, Private Equity Firms, the Clean Energy Fund, Horizon Europe, the European Sovereignty Fund, and Venture Capital Firms.

15. Local communities/ residents

The last relevant type of stakeholders on this list is local communities/ residents. They are essential in establishing European REE projects as they deal with externalities.

Table 5.1: *Main stakeholders per stakeholder type*

NO.	STAKEHOLDER TYPE	STAKEHOLDERS
1	*REO Suppliers*	Rare-Earth Hi-Tech Company, China Minmetals, Lynas Corporation, MP Materials, Neo Performance Materials
2	*REE Processing and Refining companies*	Shenghe Resources, China Northern Rare Earth Group, Lynas Corporation
3	*Nd-Fe-B PM Manufacturers*	Ningo Zhaobao Magnet Co., Ltd, Hengdian Group DMEGC Magnetic Limited, Zhong Ke San Huan, Hitachi Metals, Energetic Materials & Products Inc. (EMP), Shin-Etsu Chemical Co., Ltd, Vacuumschmelze GmbH & Co. KG (VAC)
4	*(EV) Component Suppliers*	Bosch Mobility Solutions, ABB Co. Ltd., Nidec Corporation, Brose Fahrzeugteile SE & Co. KG, Johnson Electric Group
5	*Wind Turbine Manufacturers*	Vestas, Siemens Gamesa, GE Renewable Energy, Nordex SE, Goldwind, Dongfang Electric
6	*Electric Vehicle Manufacturers*	BYD, Tesla Inc., VW Group, GM, Stellantis, Mitsubishi, Toyota, Chevrolet, BMW
7	*End Users*	(PMSM) EV owners, (PM) wind turbine owners
8	*Recycling and Waste Management Cos.*	Umicore, SOLVAY, MP Materials, Retriev Technologies, Blue Oak Resources
9	*Government Bodies*	Member States, European Parliament, National Ministries of Energy, Natural Resources, Environment, Trade, and Industry, European Raw Material Alliance
10	*Regulatory Bodies*	European Commission, European Chemicals Agency (ECHA), European Environment Agency (EEA), International Electrotechnical Commission (IEC)
11	*Research and Development Institutions*	European Commission's Joint Research Centre (JRC), National Renewable Energy Laboratory (NREL), Fraunhofer Institute for Manufacturing Technology and Advanced Materials (Fraunhofer IFAM), Institute for Energy Technology (IFE), European universities, European Institute of Innovation and Technology
12	*Environmental and Sustainability Orgs*	Greenpeace, Extinction Rebellion, EcoWaste Coalition
13	*Trade Associations and Industry Groups*	WindEurope, European Association for Electromobility
14	*Investors and Funding Organizations*	European Investment Bank, Private Equity Firms, Clean Energy Fund, Venture Capital Firm
15	*Local communities/residents*	Neighboring communities, and civilians of REE (novel) projects inside the EU

5.1.2 Stakeholder Relations and Dynamics

Figure 5.1 The Formal Chart visualizes the stakeholders' formal positions and hierarchic relations. The hierarchy flows from top to bottom. In this case, the European Commission proposed the CRMA to the European Parliament and the Council of the European Union. After adopting the new policy, it became law for all the EU Member States. This power relation is complex since Member States are also represented in the EU institutions (see *Section 5.2.1*). The goal of the formal chart is to enhance the clarity and accessibility of this analysis by offering a visual guide that aids in understanding the formal relationships, hierarchies, and decision flows within the EU. On the next page, *Table 5.2* shows the fourth step in the Ensirink et al. (2010) actor analysis to identify actor characteristics. In this step, the interest, desired objectives, gaps, perceived causes, and possible stakeholder types solutions per stakeholder type are identified in the table. These insights helped to understand how the stakeholders influence and interact with each other.

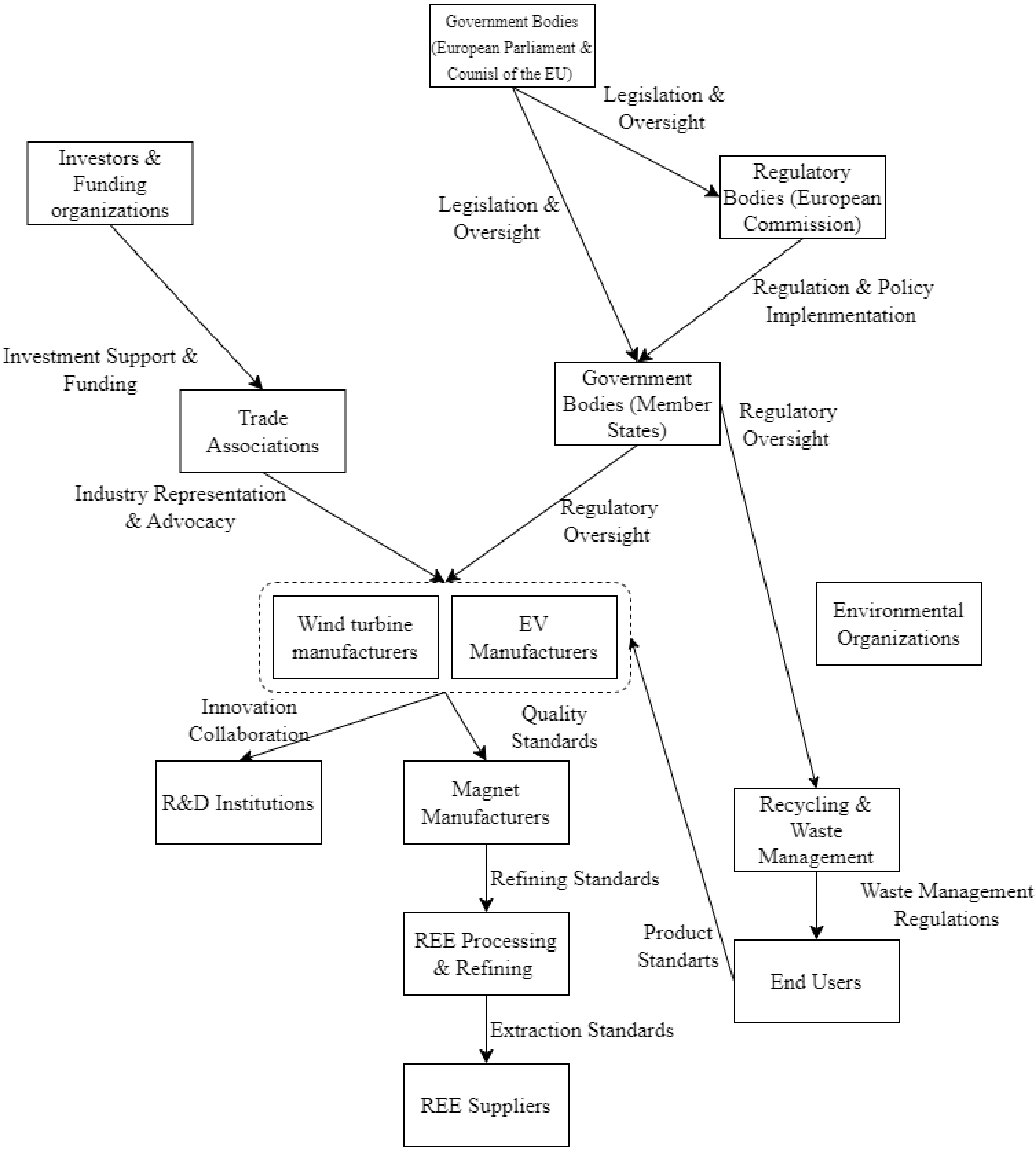

Figure 5.1: *Formal Chart*

Table 5.2: *Systematic comparison of interest desired objectives, gaps, perceived causes, and possible solutions per stakeholder type*

NO.	STAKEHOLDER TYPE	INTERESTS	DESIRED OBJECTIVES	EXISTING/EXPECTED SITUATION & GAP	CAUSES	POSSIBLE SOLUTIONS
1	REO Suppliers	Economic profit, Continuity	Increase profits, Business continuity	Growing REO demand	Energy transition, electrification	Streamlined mining processes, Secure access to REO deposits, Diversification of REO sources, opening new mines
2	REE Processing and Refining	Efficiency, Compliances	Optimize refining processes, Compliance	Cost-efficient and sustainable separation and extraction of REOs	Processing facilities, Infrastructure, Environmental compliance	Technological advancements in refining, Enhanced compliance measures, Recycling of refining byproducts
3	Nd-Fe-B PM Manufacturers	REE quality and stable supply	Continuously produce reliable PMs	Resource availability to cope with the demand growth	Access to REEs, Energy transition, electrification	Research for novel magnet materials, Automation in manufacturing, Sustainable sourcing of materials
4	(EV) Component Suppliers	Cost-efficiency, supply security	Secure supply of high-quality, cost-effective components	PM availability, supply security, demand growth	Geopolitical instability	Innovations in dematerialization, product longevity, and REE substitution, Material recycling and reuse.
5	Wind Turbine Manufacturers	Supply security, Sustainability	Produce reliable and efficient wind turbines, continuity	Demand growth and resource availability	Geopolitical instability, Energy transition, electrification	Innovations in turbine generator design, Nd-Fe-B PM substitution
6	Electric Vehicle Manufacturers	Supply security, Sustainability	Produce competitive EVs, Promote sustainability, continuity	Demand growth and resource availability	Geopolitical instability, Energy transition, electrification	Innovations in EV motor designs, Nd-Fe-B PM substitution
7	End Users	Cost-effectiveness, sustainability	Acquire cost-effective, energy-efficient solutions	Functional and efficient products, cost-effectiveness, sustainability	Financial capacity, Demand for REE-based products	Incentives for efficient usage, Consumer education on product benefits, Affordable REE alternatives
8	Recycling and Waste Management Companies	Sustainability, Compliance	Efficient and compliant recycling and waste management	Optimal recycling processes, adherence to standards	Recycling facilities, Access to recycling technologies	Advanced sorting technologies, Public awareness campaigns, Collaboration for efficient recycling processes
9	Government Bodies	Economic stability,	Formulate and enforce policies for objectives	Address environmental concerns, promote economic growth	Legislative and regulatory authority, Budgetary allocations, Legal frameworks	Policy frameworks supporting sustainable practices, Incentives for REE research and development, achieve strategic autonomy
10	Regulatory Bodies	Legal compliance, Sustainability	Develop and enforce industry regulations	Ensure compliance with regulations, maintain standards	Regulatory authority, Legal frameworks, Expertise in policy and regulation	Stringent regulations for safe practices, Technology-driven compliance measures, Continuous monitoring
11	Research and Development Institutions	Technological advancement, Innovation	Drive technological innovation, foster R&D	Lack of performance in Ne-Fe-B PM alternatives	Research facilities, Funding, Skilled researchers, unique properties	Collaboration for research, Funding support for innovation, Encourage interdisciplinary R&D projects
12	Environmental and Sustainability Organizations	Environmental protection, Sustainable practices	Advocate for sustainable policies and practices	Raise awareness on environmental impact	Advocacy platforms, Public support, Expertise in environmental issues	Collaboration for policy influence, Public engagement on sustainability, Awareness campaigns
13	Trade Associations and Industry Groups	Industry representation, Knowledge sharing	Advocate for industry interests, share knowledge	Promote industry-friendly policies, facilitate information exchange	Representation platforms, Networking opportunities, Industry expertise	Collective advocacy for industry growth, Knowledge sharing platforms, Engage in policy dialogues
14	Investors and Funding Organizations	ROI, Sustainable investments	Attain profitable returns, promote sustainability	Lack of profitability, and investment security	Lack of level playing field, high cost, geopolitical tensions	Appropriate regulatory or financial incentives
15	Local residents/ communities	Well-being, environmental impact	Esurance of safe and sustainable practices	Balancing economic development with environmental preservation	Local development projects, access to information, negative externalities	Community engagement, involvement in local planning, environmental education

5.1.3 Main Takeaways

This section answered **SQ2.1:** *What are the major stakeholders, and how do they influence the REE system inside the EU?*

Fifteen main stakeholder types were identified with the help of the value chain analysis in *Chapter 4*, the literature review in *Chapter 2*, and the findings of Hool et al. (2023). The analysis highlights the balancing act between REE supply security, affordability, and environmental responsibility, with a notable emphasis on Chinese dominance, particularly in the upstream REE industry. Downstream, major European players, including EV component suppliers, wind turbine manufacturers, and EV manufacturers, heavily depend on Chinese imports of Nd-Fe-B PMs, rendering the supply chain susceptible to disruptions.

Moreover, governmental and regulatory bodies significantly influence the EU REE system; their current role is elaborately discussed in *Section 5.2.* Notably, the intertwining of US and Chinese REE companies with their respective governments, given the geopolitical importance of REEs, presents challenges for EU firms, hindering their competitiveness. Additionally, the EU's non-federal state structure complicates policy alignment and regulation, impacting the business landscape for investors.

Currently, REO suppliers and processors wield substantial power due to their concentration, as outlined in *Sections 4.1* and *4.2*. Disruptions within this concentrated segment reverberate throughout the value chain. Anticipating the forecasted demand growth could enhance future supply security. Moreover, it is crucial to acknowledge the paramount role of local communities and residents in shaping the dynamics of the REE system. Engaging and accommodating the concerns of these stakeholders is imperative for establishing an ethical, social, resilient, and sustainable internal REE capacity within the EU. This will prevent public backlash, social opposition, project delays, and long-term inviability.

The absence of European REO suppliers poses a challenge in establishing internal capacity but is desirable given the strategic relevance of REEs. State ownership, exemplified by China's dominance in mining and refining, contributes to concentrated control over the global REE supply, presenting geopolitical challenges and vulnerabilities. Likewise, the geographical concentration of the PM manufactures, poses significant risks for the overall stability. Additionally, strategy adjustments of the major wind turbine or EV manufactures, such as Telsa’s move away from REEs (*Section 6.4*) have direct cascading effects on the entire REE value chain. Government and regulatory bodies are tasked with balancing trade-offs in REE supply security, affordability, and environmental responsibility, emphasizing the need to level the playing field to attract REE investors.

5.2 Institutional Analysis

This institutional analysis aims to provide information on what institutions related to REE material security exist within the EU and give insight into what institutions the US and China have implemented related to REEs. This study uses Hodgson's (2006, p. 13) definition of an institution: *"Institutions are systems of established and embedded social rules that structure social interactions,"* and starts by describing the institutions inside the EU.

5.2.1 Institutional differences between the EU, US and China

5.2.1.1 Institutions of the European Union

The EU is an economic and political union of 27 Member States with a population of roughly 450 million people. The EU aims to protect Member States' peace, stability, and cooperation through shared governance and economic integration. The EU is a complex political entity with seven prominent seven institutions (and more lower-level bodies). By design, the EU was organized to create checks and balances to ensure no one country, institution, or person has all the power (Hodson et al., 2022). Policymaking starts at the European Council, which is the institution that decides the general direction and priorities of the EU. The European Council consists of all the Member States' political leaders and the European Council's leader. After that, the European Commission established new policies. Whenever all the 27 (one per member-state) commissioners and the president of the European Commission agree on a new policy, they will propose it. The proposal is then sent to the European Parliament and the Council of the EU (NOT European Council), the two EU institutions adopting new policies. The EU citizen directly (democratically) chooses the European Parliament, and all Member States are represented in proportion to their population. The Council of the EU comprises all the Ministers of the Member States, thereby representing the national governments (Hodson et al., 2022). A new policy or law is only passed if both institutions agree on adopting it. *Table 5.5* summarizes these seven institutions. The bureaucratic complexity and the different interests between Member States and the EU are more elaborately discussed in *Section 6.1.*

Table 5.3: *The seven prominent EU institutions with description (Hodson et al., 2022)*

INSTITUTION	DESCRIPTION
EUROPEAN COMMISSION	The executive body is responsible for proposing legislation, implementing policies, and managing the EU's budget.
EUROPEAN PARLIAMENT	The directly elected legislative body representing EU citizens, participating in law-making and oversight.
COUNCIL OF THE EU	Comprising representatives from Member States' governments, it adopts legislation and coordinates policies.
EUROPEAN COUNCIL	Composed of EU leaders, it sets overall strategic direction and provides political guidance for the EU.
EUROPEAN COURT OF JUSTICE	Make sure Member States and EU institutions abide by EU law.
EUROPEAN CENTRAL BANK	Responsible for monetary policy and the euro currency, aiming for price stability and economic growth.
EUROPEAN COURT OF AUDITORS	Monitors EU financial management, ensuring accountability and transparency in using EU funds.

5.2.1.2 Green Deal Industrial Plan

The Green Deal Industrial Plan is the European Commission's proposal to enhance the competitiveness of the EU's net-zero industry while supporting the transition to climate neutrality. The proposal is based on four pillars: resilient supply chains, enhancing skills, speeding up access to finance, and the proper regulatory environment (Scheinert, 2023).

> *"We have a once-in-a-generation opportunity to show the way with speed, ambition, and a sense of purpose to secure the EU's industrial lead in the fast-growing net-zero technology sector. Europe is determined to lead the clean tech revolution. For our companies and people, it means turning skills into quality jobs and innovation into mass production, thanks to a simpler and faster framework. Better access to finance will allow our key clean tech industries to scale up quickly."* - President Ursula von der Leyen (European Commission, 2023-II p. 1)

As a part of the Green Deal Industrial Plan, the European Commission constructed the 'Net-Zero Industry Act' (NZIA) to establish a regulatory structure that enables the rapid establishment of net-zero industrial capabilities. This involves streamlining and expediting permitting processes and encouraging strategic projects within Europe (European Commission, 2023; Scheinert, 2023). Furthermore, the NZIA emphasizes circular economy principles by promoting resource efficiency, waste minimalization, and value creation from EoL products. The NZIA also encourages R&D activities that support a net-zero industry. Furthermore, in March 2023, the European Commission proposed 'The Critical Raw Material Act' (CRMA). CRMs are raw materials that are economically and strategically important for the European economy but have high risks associated with their supply (European Commission, 2023-I). The EU established 2011 the initial list of CRMs; after that, the list was updated several times. The list accounts for over 30 elements, including all the REEs [E1 & E2]. The CRMA has the objective of strengthening the different stages of the European critical raw materials value chain, diversifying the EU's imports of CRMs to reduce strategic dependencies, improving the EU's capacity to monitor and mitigate current and future risks of disruptions to the supply of critical raw materials; and finally, ensuring the free movement of critical raw materials on the single market while ensuring a high level of environmental protection, by improving their circularity and sustainability (European Commission, 2023-I; [E2]). The regulations and benchmarks are specified in *Section 5.2.5*.

Figure 5.2 shows the regulation overview of the CRMA. At the moment of writing, the European Council proposed increasing the benchmarks to 40 to 50 percent for processing and 15 to 20 percent for recycling (Leikin et al., 2023). Another part of the plan is to reform the electricity market design to incentivize clean energy while delivering energy security and affordability (Scheinert, 2023). Lastly, the European Commission announced the 'European Sovereignty Fund' for industry "made in Europe" to help de-risk and secure the bankability of projects that help Europe's strategic autonomy (Scheinert, 2023).

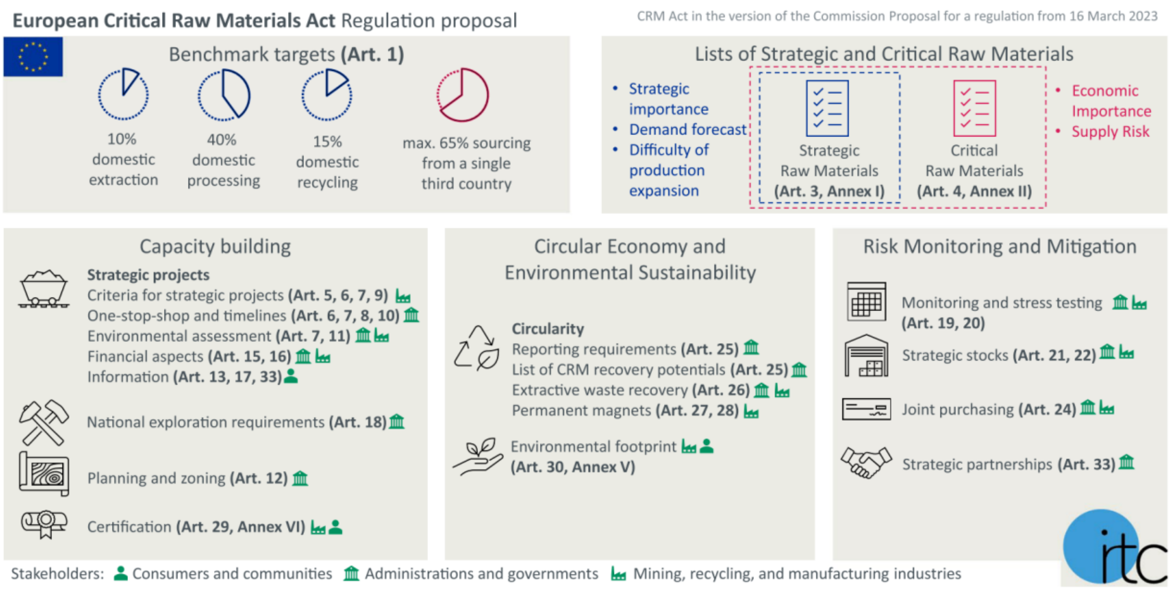

Figure 5.2: *An overview of the CRMA regulation proposal from Hool et al. (2023).*

5.2.1.3 The Inflation Reduction Act

The US equivalent to the Green Deal Industrial Plan is the Inflation Reduction Act (IRA). As the name suggests, the main goal of the IRA was to reduce domestic inflation; nonetheless, the IRA also addresses domestic energy security and climate change mitigation (Scheinert, 2023). The IRA includes the New Advanced Manufacturing Production Credit, which incentivizes domestic production of numerous components applicable in clean energy-related technologies, including critical minerals, the US equivalent to CRMs, used in clean energy technologies. This regulation awards tax credits of 10 percent of the production cost to the producers and manufacturers of the critical minerals. The constraint is that the minerals must be produced in the US, which is called local content requirements (LCRs). LCRs discriminate against foreign producers; therefore, it could pose a danger for European companies, as they are not entitled to the tax benefit (Scheinert, 2023).

The Green Deal Industrial Plan, *Section 5.2.1.2*, is the EU response to the IRA and its LCRs. The main difference with the EU legislation is that the IRA does not create funds, while the EU mainly relies on funds (Scheinert, 2023). The IRA is using tax breakers as a mechanism. This is impossible for the EU, as Member States are responsible for fiscal policies. Relying on tax breakers could turn out to be a significant pitfall as they are not capped. A Jansen et al. (2022) study even calculated that 1.200 billion USD of tax relief could be reached instead of the initially communicated 370 billion USD. Moreover, the IRA poses a severe political risk, as the next administration might not be interested in climate action (Jansen et al., 2022). Besides favorable policies toward the REE industry, the US has also formed strategic alliances with befriended nations such as Canada, Australia, Chili, and Japan to ensure future CRM imports.

5.2.1.4 China’s REE Establishment

The EU and the US REE-related policies are in response to the Chinese pre-eminence. China’s dominance is the result of early engagement in the REE industry, generous lines of credit and subsidies across the entire value chain, cost-effective labor, export controls, lax environmental regulations, and their technological and manufacturing capabilities (Andrew-Speed & Hove, 2023; Pawar & Ewing, 2022).

Bayan Obo in Inner Mongolia is currently the world's largest REE mine and China’s first encounter with REEs after its discovery in 1927. In 1975, the Chinese administration recognized the significance of REEs and established the National Rare Earth Development and Application Leading Group 1975, subsequently boosting R&D funding. China emerged as a significant REE producer by the late 1980s. Investments in the 1990s improved the quality and reduced processing and refining costs. By that time, China began exporting REE metals at low prices, leading to the shutting down or downsizing of other producers (Aguiar de Medeiros & Trebat, 2017; Kalantzakos, 2018; Shen et al., 2020; Andrew-Speed & Hove, 2023).

The Chinese administration classified REEs as 'protected and strategic minerals' in 1990. Consequently, foreign mining became restricted, and processing would only be possible through joint ventures with Chinese businesses (Kalantzakos, 2018; Andrew-Speed & Hove, 2023). In the early and mid-2000s, export and production quotas were implemented. Moreover, loose regulations and outdated techniques caused severe environmental and health impacts at the Bayan Obo mine. Therefore, in 2010, the government consolidated plans to significantly reduce the number of mines and processing plants (Shen et al., 2020). The government responded by announcing industry consolidation plans in 2010, aiming to reduce the number of mines and processing plants significantly (Zhang Qi, 2010; Andrew-Speed & Hove, 2023). Afterward, strategies focused on enhancing resource management, environmental standards, and coordination within the industry. Furthermore, the government reformed resource taxes to extract fiscal revenues and combat illegal practices. In 2016, a Rare Earth Industry Development Plan outlined profitability, recovery rate, and expenditure on R&D targets, emphasizing increasing their market share of high-end downstream REE products and reducing exported REE (Andrew-Speed & Hove, 2023). In 2022, China's REE mine production rose to 210,000 tonnes, 70 percent of the global total. Furthermore, they processed and manufactured 94 percent of the world's REEs and Nd-Fe-B PMs (see *Chapter 5*). The Chinese government is expected to improve enterprise management, meet domestic REE demand, and potentially consider export restrictions on certain REE technologies (Oki, 2023; Andrew-Speed & Hove, 2023).

5.2.2 The Applied Williamson Framework

In this section, the institutional EU REE system is discussed and structured through the four levels of Williamson, explained in *Section 3.1*.

5.2.2.1 Level 1: Embeddedness (informal institutions, customs, norms):

An embedded European belief is our fundamental trust in the liberal, open, and globalized market. In the last centuries, definitely after the collapse of the Soviet Union, the world became interconnected at an unprecedented scale. Globalization fostered economic growth, technological advancement, and enhanced consumer choice. Global competitiveness and high population density led to the outsourcing of many upstream practices in Europe. At the same time, Europe held much downstream industry, causing global interdependence. Interdependencies could be seen as essential peacekeepers. However, currently, a paradigm shift is taking place. For the first time in decades, the world is deglobalizing due to the Russian aggression in Ukraine and the rising tensions between the US and EU with China [E1, E2, E5, and E7]. Protectionism is rising, causing the world to enter a second cold war [E1]. Deglobalization exposes supply chain vulnerabilities, raises costs, reduces consumer choice, and influences sociocultural experiences [E1]. Nevertheless, there is still much trust in open markets. One of the EU officials also emphasized that the EU will not advocate deglobalization; they are trying to de-risk, not decouple [E4].

Furthermore, a fundamental EU norm related to the REE system is the belief in one single market, with free movement of goods between EU countries. The single market principle enhances competition, efficiency, the economics of scale, innovation, consumer choice, economic growth, and crisis resilience [E2]. The EU single market mitigates some of the challenges associated with deglobalization, as it provides a diversified and secure trading environment within the EU.

Furthermore, the EU has a competition policy, promoting fair competition to prevent monopolistic market behavior and thereby ensuring a level playing field. This policy and common belief will help to prevent anti-competitive practices. The LCRs in the IRA violate this policy; therefore, the EU was required to complain to the WTO and develop a counter policy, as described in *Sections 5.2.3* and *5.2.4*.

Additionally, human rights are firmly embedded as EU beliefs. This results in supply chain responsibilities such as stringent labor and community engagement compliances.

Sustainability and environmental protection are also embedded beliefs in the EU. Beliefs on climate change and air pollution mitigation have strongly influenced the sharp demand for REEs in recent years. Furthermore, this belief also created a wish for circularity. Likewise, ecological, environmental, and health standards are essential norms in the EU. These norms will likely influence the EU's REE extraction, processing, and refining possibilities.

Economic prosperity and the highly developed nature of the EU led to high energy and material needs. Which strongly influences the demand for REE. Demand-side policies are unpopular but could play a significant role in mitigating European dependencies.

Finally, innovation, research, and an overall belief in the scientific method are embedded in European culture. Therefore, this influences technological developments and the development of alternative technologies.

5.2.2.2 Level 2: Institutional Environment (rules of the game):

This section addresses the existing institutions in the institutional environment, which account for level 2 in the Williamson framework. This level will include the formal rules of the game, such as laws and regulations.

The first formal rules of the game that will be discussed are the international agreements. One of the most significant agreements is the Paris Agreement, adopted under the United Nations Framework Convention on Climate Change (UNFCCC). By being part of this agreement, the EU is committed to aiming to limit global warming well below 2 degrees Celsius. As a result, the EU is obligated to mitigate its greenhouse gas emissions.

Furthermore, the EU has trade (bilateral and multilateral) agreements with non-EU countries to ensure access to raw materials such as REEs and reduce geopolitical risks. The Global Gateway is the EU program that focuses on supply security by international collaboration. The program already established strategic alliances for REEs with Namibia, Kazakstan, Ukraine, and Canada [E4]. The EU is furthermore negotiating with Argentina, Chile, Greenland, Norway, DRC, Rwanda, and Australia [E4].

Moreover, the EU is strengthening ties with the World Trade Organization and is pushing harder on enforcement to combat unfair trade practices in the supply chain. In 2021, the EU seized all import rates for REEs (CRM alliance, 2021).

As discussed in *Section 5.2.3*, the European Commission established the 'European Critical Raw Material Act' in the spring of 2023 because The act sets clear priorities for action by setting benchmarks on domestic capabilities along the REE supply chain. The following regulations are drafted and will need to be met before 2030:

- At least 10 percent of consumption will need to be domestically extracted
- At least 40 or 50 percent of consumption needs to be domestically processed
- At least 15 or 20 percent of consumption needs to be recycled
- Not more than 65 percent of consumption from a single third country
- Products containing PMs will need to meet circularity requirements and need to provide information on the recyclability

Moreover, the NZIA streamlined and expedited permitting processes concerning strategic projects such as REE mining and processing practices, and highlights the importance of circular economy principles (*Section 5.2.1.2*).

These directives can potentially be a mismatch with the EU's environmental and ecology standards. Both REE extraction and production are known to be heavily reliant on violent chemical processes that are known to have the possibility to bring damage to the surrounding environment (Gielen & Lyons, 2022). Furthermore, domestic extraction will lead to laws and regulations for governance to ensure responsible practices abiding by environmental and safety standards. Moreover, mining companies must obtain licenses and permits to operate, which includes requirements for the local community and environmental impact assessments. Finally, the econ-design directive and the circular economy action plan both could steer the development of a circular REE economy in the EU.

5.2.2.3 Level 3: Governance (play of the game):

The third level of the Williamson framework is about governance, which includes contracts and transaction costs.

Relevant for this level are contracts; e.g. the CRMA aims to recycle at least 15 percent of consumption by 2030 – this would require a massive switch in waste management. REEs need to be collected before being able to get recycled. Contracts between recyclers, local governments, and waste management companies will need to be established to define responsibilities for collecting, recycling, and disposing of end-of-life REE-containing products.

Moreover, opening new European mining and processing sites probably requires compensation schemes or buy-out measures for residents and companies. Currently, 14 European REE investment proposals have been submitted to the European Raw Material Alliance (ERMA), visualized in *Figure 5.3*. These projects include REE mining, processing, magnet manufacturing, and recycling. The overall investment cost of these projects is 1.7 billion EUR and will ramp up annual REE magnet production from 500 tonnes to 7,000 tonnes by 2030, which accounts for 20 percent of the expected needs (ERMA, 2021). These projects qualify for the announced 'European Sovereignty Fund,' which will help de-risk and secure bankability when in place.

Figure 5.3: *ERMA investment cases for European REE projects (ERMA, 2021).*

Furthermore, the EU established the Horizon Europe funding program, and the European sovereignty fund, which are the most significant EU funding programs for REE projects and R&D-related businesses (ERMA, 2021; Scheinert, 2023).

The European Institute of Innovation and Technology (EIT) also initiated EIT Raw Materials, the world's most significant raw materials consortium, by connecting over 300 industry, research, investment, and scientific partners (ERMA, 2021). Furthermore, ERMA is notably part of the EIT Raw Materials as the foremost research institute. Intellectual property rights can help secure European innovative power, e.g., extraction, processing, substituting, and recycling technologies. Moreover, research institutions will likely undertake collaborative agreements with other stakeholders in the REE system. Transaction costs can be decreased by sharing knowledge.

5.2.2.4 Level 4: Resource Allocation

This section discusses the fourth and final level of the Williamson framework, which relates to resource allocations, market dynamics, and employment.

The incentives for sustainable technologies are the first resource allocation type that impacts the REE system. Numerous incentives exist in the EU and its Member States, e.g., most countries in the EU have incentive structures for either or both EVs and wind energy. Moreover, the EU uses the EU emissions trading system as a financial instrument to limit greenhouse gas emissions for specific pollutants. These incentives increase demand for alternative technologies such as EVs and wind turbines, indirectly increasing the EU material dependency.

5.2.3 Main Takeaways

This section goes into **SQ2.2:** *What are the current institutional aspects that affect the EU's REE system?*

The institutional analysis comprehensively described the relevant institutions and policies regarding REEs in the EU. The most pivotal piece of legislation is the CRMA, as part of the Green Deal Industrial Plan. The EU's focus on diversification, circular economy, and establishing internal capacity demonstrates a commitment to addressing material security challenges in the global REE system. Furthermore, the US and Chinese REE policies are discussed as well. Both countries have a competitive fiscal advantage regarding REE production and Nd-Fe-B PM manufacturing. This is insufficiently addressed in the CRMA and could harm EU businesses. The levels of Williamson's findings in *Section 5.2.2* are summarized in *Table 5.6.* Notably, the embedded EU beliefs in open and liberal global markets are being questioned as geopolitical tensions are rising. Moreover, the EU strongly believes in environmental protection, sustainability, and safety and health standards. Multiple REE-related policies and projects have been developed. The general direction of the EU is moving toward a more autonomous EU regarding REEs, even though unclarity exists in implementing the CRMA on the lower levels of Williamson. *Chapter 7* touches upon some of these institutional flaws by suggesting institutional interventions.

Table 5.4: *Existing relevant institutions for the EU REE system per Williamson level*

LEVEL OF INSTITUTION	EXISTING INSTITUTIONS RELEVANT TO THE EU REE SYSTEM
LEVEL 1 EMBEDDEDNESS (CUSTOMS, TRADITIONS, NORMS)	• Fundamental trust in liberal markets and globalized trade is shifting • EU single market (acting as one entity in the global playing field) • Competition policy (belief in fair competition) • Strong belief in human rights • Strong belief in sustainability and environmental preservation • High energy and material needs and wants • Strong belief in the scientific method fosters innovation and research

LEVEL 2 INSTITUTIONAL ENVIRONMENT (POLICY, JUDICIARY, BUREAUCRACY)	• International agreements
	    o Climate agreements (UNFCCC Paris Climate Agreement)
	    o Trade agreements (WTO, Global Gateway)
	    o No import tariffs for REEs
	• Critical Raw Material Act
	    o At least 10% of the consumption needs to be domestically extracted
	    o At least 40% of consumption needs to be domestically processed
	    o At least 15% of consumption needs to be recycled
	    o Not more than 65% of consumption from a single third country
	    o Products containing PMs will need to meet circularity requirements and need to provide information on the recyclability
	• Net-Zero Industry Act
	    o Streamlined and shortening of the permitting for strategic projects
	    o Promotion of circular economy principles
	• Eco-design directive
	• Circular economy action plan

LEVEL 3 GOVERNANCE (ALIGNMENT STRUCTURES WITH TRANSACTIONS)	• Contracting (between various actors in the REE value chain)
	• Funding
	    o European sovereignty fund
	    o Horizon Europe
	• Projects (14 European REE investment proposals)
	• Policies
	    o Buy-out measures and compensation schemes
	    o Community engagement
	• Public-private partnerships (sharing resources)
	    o EIT Raw Materials (ERMA)

LEVEL 4 RESOURCE ALLOCATIONS (PRICES AND ALIGNMENT)	• Renewable energy and EV incentives • EU carbon permits • Government support for R&D

5.3 Influence of Stakeholders and Institutions

SQ2: *What is the current state of the rare earth element system inside the European Union, and how do existing institutions and stakeholders influence the system?*

The REE system within the European Union is a complex network influenced by various stakeholders and regulatory frameworks, offering both enabling and constraining effects. The CRMA is the main piece of relevant EU legislation regarding this topic and has the most significant impact on the stakeholders. This section digests these institutional and stakeholder impacts on the system. Furthermore, this section is partially based on the findings of Hool et al. (2023), which analyzed the challenges and opportunities of the CRMA.

The global REE landscape exists primarily out of three geopolitical blocks; the EU, China, and the US. China's government has strongly focused on strengthening its REE value chain for decades and successfully obtained pre-eminence through generous lines of credits and subsidies, strategic partnerships and initiatives, geopolitical influence, manufacturing capabilities, technology, infrastructure, low labor cost, and lax environmental regulations. In the last couple of years, the US has been trying its best to catch, as it recognizes the strategic importance of the REEs. Finally, the EU also acknowledges the need for strategic autonomy and launched several new initiatives, including the CRMA and the NZIA. However, in order to obtain European strategic autonomy regarding REEs, more will be needed, desirably REE-specific institutions. Moreover, the CRMA does not explicitly set benchmarks for Nd-Fe-B PM imports, which will be critical in the quest for strategic autonomy. To avoid reliance on third nations, the EU must ensure the development of a comprehensive REE industry that includes robust Nd-Fe-B PM manufacturing capabilities. Simply establishing a REE industry without concurrent advancements in Nd-Fe-B PM production could perpetuate dependence on external parties.

The CRMA, notably the implementation of industry benchmarks, exerts pressure on the REE industry to establish domestic capacities for extraction, processing, and recycling to meet the escalating demand within the region. Benchmarks are proportionate to consumption levels, which are likely to rise vastly. Therefore, this puts much pressure on the industry, as they should start and ramp up production levels. Concurrently, Nd-Fe-B PM manufacturers face additional responsibilities driven by requirements for enhanced recyclability through labeling and compliance with monitoring and reporting mandates under the CRMA. As the CRMA focusses on sustainability and internal capacity, it has the potential to stimulate job creation, especially within local communities, the regulatory landscape raises valid concerns about environmental and societal impacts. Shortened lead times for permitting and the overall intricacies of meeting these new regulations present tangible challenges. As the main driver of the REE system's trajectory, the multifaceted CRMA requires a delicate balance between regulatory demands, industry capabilities, and their environmental and social repercussions. Effectively navigating this complex landscape will be crucial for the sustainable advancement of the REE sector within the European Union. The CRMA emphasized the need for monitoring and reporting to understand better the complex supply chains and quantities of CRMs in the system. Moreover, Nd-Fe-B PM manufacturing firms must comply with labeling requirements to increase recyclability.

6. RARE EARTH ELEMENT FACTOR ANALYSIS

This chapter delves into **SQ3:** *What are the main factors and developments, influencing the EU's REE autonomy?* The scope is narrowed to the EU, specifically focusing on wind turbines and EVs. This chapter considers various factors by analyzing relevant Political, Economical, Social, Technological, Environmental, and Legal factors in the REE system.

6.1 (Geo)Political

The first category of the PESTEL analysis is political. In this section, the main political and geopolitical factors are discussed. Geopolitics is central to this research, as *Chapter 5* shows increasing protectionist policies, and *Chapter 4* shows the supply dependency of a single third country.

Raising global tensions and resource nationalism [E1 – E7]
During the last couple of years, geopolitical tensions have risen between the US, the EU, and China. Firstly, China lays territorial claims in the South China Sea by constructing military installations and artificial islands. Moreover, China considers Taiwan a part of its territory, and experts do not rule out the use of force to achieve reunification. Teer & Bertolini (2022) even estimated a higher than 50 percent probability of a Chinese blockade and/or invasion of Taiwan within the next 10 years. With the US ensuring Taiwan's security, it will be implausible for EU – China trade relations to go unharmed in such an event.

Furthermore, tensions arose because of China's Belt and Road Initiative (BRI), a vast infrastructure and investment project aiming to enhance connectivity and economic development by revitalizing ancient trade routes to connect Asia with Europe and Africa. The BRI has been subject to criticism and concerns about potential debt dependency on China and the geopolitical implications of the project (Sielker & Kaufmann, 2020; [E4]). In addition, the Russian-Ukrainian war and the improving military and economic ties between China and Russia. Moreover, BRICS, an acronym for five major emerging economies: Brazil, Russia, India, China, and South Africa, which aim to increase, deepen, and broaden cooperation among its members, is increasing its influence, and more countries have recently joined them. BRICS offers an alternative to 'the West' for emerging economies, gradually decreasing Western power and threatening its hegemony (Ostrowski, 2023).

Additionally, technological competition and trade restrictions significantly divided both parties. Lastly, ideological differences and human rights violations further strained Western relations with China. Consequently, resource nationalism is emerging- what can be defined as anticompetitive behavior by individual nations is designed to control and limit the export of a natural resource (Sielker & Kaufmann, 2020). Local governments often want to profit from their resources by, e.g., imposing taxes and export restrictions (Vikstrom, 2020). The LCRs in the IRA are an excellent example of recourse nationalism. Besides the fact that it is jeopardizing European resource autonomy, it is also detrimental to local mining and processing companies because higher taxes come at the expense of business profitability (Vikstrom, 2020).

Geopolitics has several essential factors in the scope of this research. The global value chain of *Chapter 4* elaborately explains the EU's reliance on Chinese exports; as mentioned before, this dependence constrains the EU's resilience in terms of material security. This problem became apparent when China briefly reduced its REE exports by 40 percent in 2010. It temporarily banned exports to Japan after a maritime collision in the South Chinese Sea in 2011. The reduced REE circulation immediately led to soaring REE prices, especially Dy (as this is one of the HREEs) (Baldi et al., 2014; [E6]). Concerns arose during the aftermath of this incident for the significant importing countries, e.g., the US and Japan.

However, European dependencies even grew further after this incident. E6 expressed concerns when mentioning that current export relations also benefit China.

Nevertheless, the 2010-2011 incident showed China can use REEs as a geopolitical pressure agent. Potential disruption of supply due to natural and environmental events, such as epidemics and damaged facilities; trade distortions, such as the ban on Germanium and Gallium; and geopolitical events eliminated in the Russian–Ukrainian war, would be catastrophic in the short to medium term for the European EV and wind turbine industry (Carrara et al., 2023). Shifting to other materials or supply chains will likely take many years [E1 – E7].

Supply diversification

After the incident, mitigation measures were taken by Japan by initiating diversification of supply by shifting more to Australia and Malaysia for its REEs. Japan successfully decreased its dependence on Chinese REE from 82 percent in 2010 to 58 percent in 2018 (Velez, 2023). Likewise, supply diversification is one of the significant factors in improving the EU material autonomy, and international cooperation with ‘friendly’ REE-producing nations exists with Namibia, Kazakstan, Ukraine, and Canada [E4]. The EU is furthermore negotiating with Argentina, Chile, Greenland, Norway, DRC, Rwanda, and Australia [E4]. However, the impact of free trade agreements alone could be limited, as the EU already applies low tariffs on CRMs. Moreover, strategic raw material alliances are often handled with long-term contracts, making short-term diversification efforts more difficult. Furthermore, countries such as Japan and the US are also taking diversification measures, creating competition for non-Chinese REEs.

EU bureaucratic complexity

The EU policy system is often criticized for being slow and bureaucratic [E1, E3, E5, E6]. The EU institutions are explained in *Section 6.2.1*. The complicated policy establishment and veto power of each member-state make it challenging for the EU to respond quickly and efficiently. The extent of Chinese reliance is a hot topic within the EU and its Member States. Over recent decades, the EU and China have become interdependent. Last May (2023), president of the EU Commission Ursula von der Leyen and France President Emanual Macron visited Chinese President Xi Jinping to discuss trade relations after the increased tensions through the Russian-Ukrainian war. While the US uses “de-coupling” with China, Von der Leyen and Macron kept it with “de-risking” (EC, 2023). The current EU stands to keep diplomatic and trade ties with China while simultaneously trying to de-risk its reliance on China (EC, 2023). The opinion of EU Member States regarding China can vary significantly based on factors such as economic interest, historical ties, security concerns, and political ideologies (e.g., policy alignment with the US, human rights and values, and the BRI). All these factors, including electoral shifts within the Member States over time, make unitary policy incredibly complex. EU Member States in the BRI are Greece, Italy, Poland, Hungary, Czechoslovakia, Croatia, Bulgaria, Latvia, Portugal, Romania, and Slovakia, considered some of the weaker economies in the Union (Sielker & Kaufmann, 2020). Furthermore, EU Member States with strong economic ties with China, such as Germany and the Netherlands, strive to maintain good relations while managing ideological and human rights concerns (E1; Sielker & Kaufmann, 2020). France typically takes a more balanced approach by balancing economic interests with geopolitical concerns. Sweden, Lithuania, and Estonia exposed concerns about human rights issues in China and looked in general for more geopolitical alignment with the US (Sielker & Kaufmann, 2020).

Political reluctance, and incapability

The European Green Industry Plan, including the CRMA, shows the EU’s vast energy transition and CRM ambitions. However, experts still acknowledge a lack of clarity in implementing the ambitions [E1, E3, E5, E6]. E3 even states that political reluctance is the prime constraint, as the problem is straightforward and well-understood. An explanation that could play a significant role in this status quo is political lobbying and corporate interest [E3, E4].

Furthermore, the NZIA and the CRMA fail to tackle significant challenges e.g. high energy prices, high labor costs, unskilled labor, and the lack of a level playing field [E1, E3, E5]. Moreover, a lack of understanding at the governmental level hampers communication and, ultimately, adequate policy-making [E1].

6.2 Economical

The second category of the PESTEL analysis is the economic category. This category builds upon the value chain analysis of *Chapter 4* and will further discuss economic dynamics, trends, and prices. Furthermore, it covers the economic factors of establishing the EU's internal REE capacity.

Market dynamics [E1 – E7]

The speed of growth

As discussed in *Chapter 4*, demand for REEs is expected to grow enormously. According to the European Commission (2023-I), the EU's demand for REEs is expected to increase six to seven-fold by 2050. Naturally, higher demand and scarcity in supply will lead to higher prices in the future. The demand forecasts led to apprehensions about a gap between supply and demand. In regular markets, supply follows demand relatively quickly. However, for raw materials, even if the market signals higher prices through increased demand, the supply tends to follow much slower, as it takes a long time to increase capacity and start new operations (Carrara et al., 2023). The global supply of REE will likely struggle to keep up with the increasing demand if no new production projects are implemented (Carrara et al., 2023). Lastly, according to Vikstrom (2020), high prices caused by the portrayed demand surge are an enabler for mining and processing companies.

REEs are mined together

Another crucial economic factor regarding REEs is the fact that REEs are mined together. If a company aims to increase Nd production to address growing demand, it will consequently encounter an excess of cerium, which is expected to sustain its limited price (IEA, 2022). This surplus might negatively impact the overall profits derived from REE production, resulting in higher prices for Nd, which might not necessarily trigger new investment (IEA, 2022).

Long project lead times [E1 – E7]

Even with the shortening of the permitting process, it can take up to many years for extraction, recycling, and processing projects to get up and running due to, e.g., exploration and feasibility studies, land acquisition, financing, infrastructure development, stakeholder collaboration, and community engagement. Opening new mines takes approximately 10 to 20 years (Van Exter et al., 2018).

Price volatility

Table 6.1 shows the price history of the four critical REEs. The volatility of the prices immediately becomes apparent when looking at the differences between the current (19-11-2023) price and the average annual price. The main factors determining the volatile nature of REE prices are geopolitical events, supply and demand dynamics, technological advancements, global market conditions, and speculations [E6]. *Figure 6.1* depicts the Nd-oxide price history over the past 10 years. The price soared during and after the pandemic and is currently stabilizing. The same trend can be seen for the three other REEs. After a peak in 2022, prices dropped after China ramped up production. Furthermore, E6 mentioned that panic and uncertainty contributed to the price spike. As of November'23, Chinese-manufactured Nd-Fe-B PMs cost between 15 and 32 EUR/kg (ISE, 2023). The European price for an equivalent PM is about 20 to 30 percent more expensive, as illustrated in *Section 4.1*. The costs of a magnet strip alloy are 90 percent determined by the costs of the raw materials and 40 to 45 percent of the final sintered magnet, depending on the price fluctuation of the raw materials (ERMA, 2021). Price volatility makes it challenging to plan and make informed decisions regarding production levels and creates uncertainty in profitability [E6]. Thereby causing business and investment uncertainty.

Table 6.1: *Rare earth oxide prices ISE (2023).*

RARE EARTH OXIDE	**USD/KG**				
	2017	2018	2021	2023 (19-11-2023)	Average price
PRASEODYMIUM	65	63	140	103	59
NEODYMIUM	50	50	143	83	60
TERBIUM	501	455	1720	1325	932
DYSPROSIUM	187	179	452	420	285

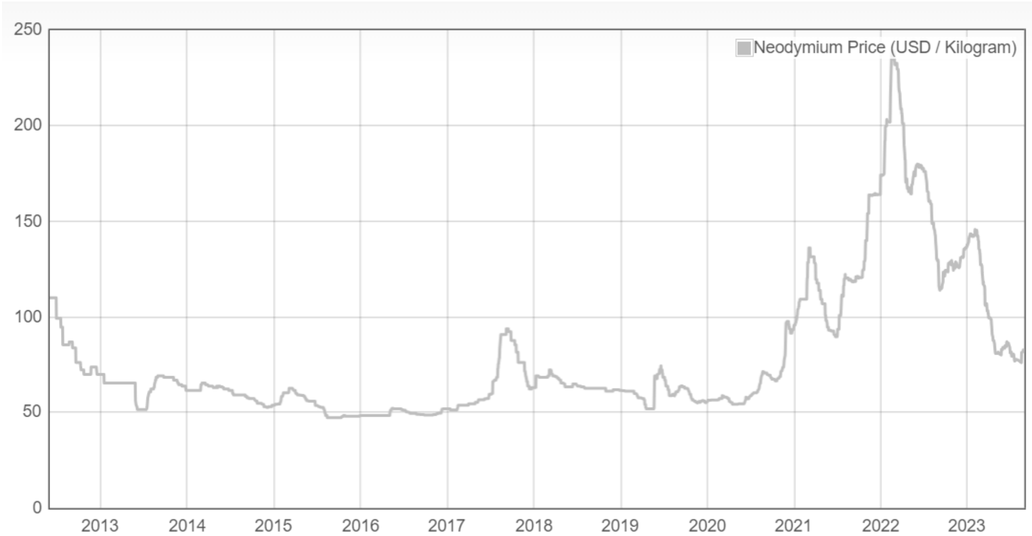

Figure 6.1: Daily metal price (2023)

Project feasibility and profitability

Relatively high CAPEX and OPEX [E1, E3, E5]

Capital cost (CAPEX) and operating cost (OPEX) are essential factors for considering novel REE projects. REE projects can differ in both their CAPEX and OPEX. Inputs for the CAPEX are exploration: site preparation and infrastructure, mining equipment, and processing plants. REE processing accounts for 80 percent of the capital cost (Andre-Speed & Hove, 2023). Inputs in the OPEX are labor, energy, raw chemicals, maintenance and repair, transportation, rehabilitation, and waste management. Labor, energy, and chemical costs make the operating costs volatile. Furthermore, processing cities must access transportation infrastructure, cheap electricity, natural gas supply, and reagent producers (Andre-Speed & Hove, 2023). Typically, European labor is more expensive than in most other regions [E1, E5]. Furthermore, 30 percent of the OPEX usually accounts for energy costs (Vikstom, 2020). Generally, natural gas and electricity prices in the EU are higher than in India, China, and the US. They will make the European energy-intensive industry (internal REE capacity; recycling, extraction, processing) less competitive. Conversely, according to Vikström (2020), newly found deposits are typically found in remote areas without access to those specific requirements. Furthermore, the environmental regulations further increase mining and processing costs (Andrew-Speed & Hove, 2023).

Lack of European funding [E3, E5]

A combination of factors makes accessing funding for the European REE projects challenging, e.g., stringent environmental regulations, relatively high energy prices, high labor costs, and lack of fiscal certainty.

European REE resources and degrading and lower ore grades

Figure 6.2 demonstrates that Europe has a wide range of REE deposits, and multiple of them are currently under development, e.g., Norra Karr, Kwanefield, Kringlerne, and Kiirunavaara (Geus & D’Appolonia., 2017). Most promising European REE extraction projects can be found in Scandinavian countries; *Figure 6.3* illustrates the Scandinavian REE deposits. REE projects' profitability and economic feasibility greatly depend on the ore's REO grade. Typically, future REE projects, have to deal with lower REO grades, driving up the total cost (Vikström, 2020). *Figure 6.2* shows the grade tonnage plot of European REE deposits compared to current producers. European deposits typically have lower ore grade and/or lower ore tonnage than current producers.
The following formulas are used for REE cost calculations:

$$Ore\ throughput * REO\ grade * recovery = REO\ production$$

$$\frac{(Ore\ throughput * Cost\ per\ tonne\ of\ ore)}{REO\ production} = Cost\ per\ kg\ REO$$

The formulas show the importance of REO grades, as lower grades will automatically lead to higher costs. *Table 6.2* shows the critical parameters for REE-exploration feasibility.

Table 6.2: *Commonly used parameters for REE-exploration project feasibility (Geus & D'Appolonia., 2017)*

PARAMETERS	DEFINITIONS
ORE GRADE (%)	Total REE content of one ore unit (does not reflect individual REE distribution). Typically relatively low (See *Figure 6.2*)
ORE TONNAGE	The ore volume (economic part of the rock hosting REEs). Some EU projects with significant ore tonnage (e.g., Kringleme, *Figure 6.2*)
INDIVIDUAL REE-GRADE (%)	Individual REE as a fraction of the total REE. Most promising resources have significant shares of HREE Nd/Pr and lower REE-grades for HREEs Tb/Dy.
ORE VALUE	Total REO-value per unit mass of the mineral resource (EUR/ton)
BASKET PRICE (EUR/KG)	Cost per kg of REO

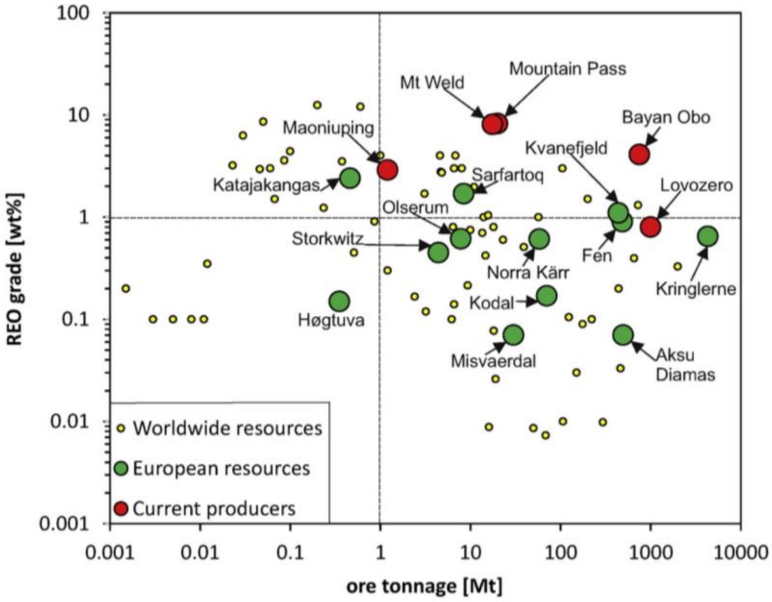

Figure 6.2: *Grade and tonnage plot comparing European REE deposits with current producers (Goodenough, 2016).*

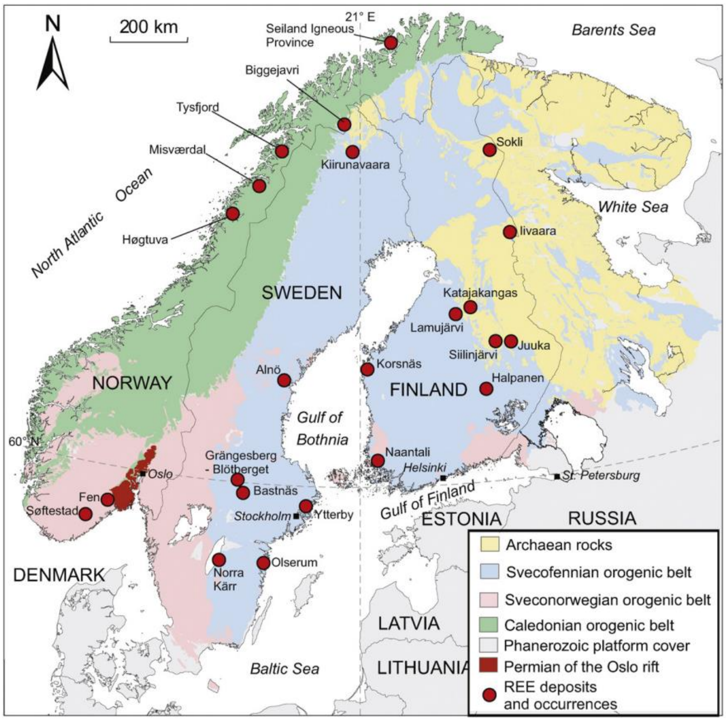

Figure 6.3: *Known REE deposits in Scandinavian countries by (Goodenough, 2016).*

6.3 Socio-cultural

Public acceptance [E1 – E7]
An important socio-cultural factor is the public perception of opening new mining, processing, and recycling facilities in Europe. Mining and processing activities are often associated with resistance from local communities because of pollution and possible safety and health risks. This type of resistance is commonly known as the, not in my backyard (NIMBY) principle.

NIMBY could potentially disrupt and slow down REE projects in EU Member States. *Sections 4.1* and *4.2* describe fair reasons for not wanting an REE mine or processing plant in your backyard. Developments and remedies for environmental and health issues will be necessary for public acceptance. Therefore, the needs and wants of residents, sustainability, health, and safety standards must be respected – this can furthermore prevent project delays or conflicts.

<u>Social license to operate</u>
During the last decades, globalization has resourced a lot of harmful industries from developed countries to developing countries. Developed countries more often have to deal with environmental justice practices, which has resulted in growing difficulty in obtaining mining and processing permits. The Mountain Pass REE mine in the US closed temporarily because of environmental regulations. Furthermore, Australia's REE mining and processing company Lynas got much resistance after relocating their processing plant to Malaysia instead of Australia. People questioned whether this move was driven solely by economic factors or by anticipated social resistance (Ali, 2014).

<u>Increased public awareness [E1 – E7]</u>
Creating awareness of the EU's critical raw material security problem is essential for public acceptance of domestic REE projects. Public perception made a radical change after the Russian invasion of Ukraine. People are more aware of dependencies and the importance of European autonomy. Increasing public awareness further could be an essential solution for the NIMBY phenomenon.

High energy and material needs/wants [E3 and E5]
A more embedded constraining factor is our high energy and material needs in the EU. Consequently, this leads to high REE demand as well. Circular strategies such as Refuse, Rethink, and Reduce could significantly reduce demand and increase autonomy.

6.4 Technological

Alternative technologies
Several high-performance alternative technologies are available for EV motors and wind turbine generators. However, predictions suggest that Nd-Fe-B PM technologies will continue to dominate the market despite their reliance on REEs, as no competitive alternative exists, especially in cases where magnet size and energy efficiency are relevant (Geus & D'Appolonia., 2017). Permanent magnet synchronous motor (PMSM) EVs, in particular, exhibit superior efficiency and power density compared to current alternatives. In their base case, IEA (2022) anticipates a growing preference for permanent magnet synchronous generator (PMSG) wind turbine technologies, forecasting a 95 percent market adoption in offshore wind and a 40 percent adoption in onshore wind by 2040. This trend is attributed to their superior efficiency, reduced weight, and lower maintenance costs (IEA, 2022). Nd-Fe-B PMs are renowned for their exceptional magnetic strength, high-temperature performance, and demagnetization resistance, giving them a significant advantage (EPA, 2012). In contrast, non-PM technologies, such as induction technologies, experience energy losses since they need to generate an electromagnetic field, making PM technologies more efficient [E6]. *Tables 6.2* and *6.3* compare the main EV motors and wind turbine generators with each other.

<u>*Component substitution for EV motors*</u>
The surge in REE prices caused by the COVID-19 pandemic (*Section 6.2*) prompted major automotive manufacturers, including Renault, Mercedes, BMW, and Audi, to intensify their efforts in minimizing

REE consumption. These leading companies have committed to redesigning their vehicles, making notable advancements to enhance performance and circumvent the limitations associated with non-permanent magnet motors (Andrew-Speed & Hove, 2023; Edmondson, 2023). Additionally, Tesla has announced a groundbreaking move by incorporating induction motors in its next-generation EVs. This strategic shift alone is anticipated to result in a significant reduction of 3-4 percent in REE demand when fully implemented, as highlighted in the study of Andrew-Speed & Hove (2023).

However, this announcement is against the grain, as the market generally prefers the more efficient PMSM motors. Furthermore, induction motors shift the problem to other materials that will become scarce over time as well. As it uses significantly more copper, non-PM motors will need 30 percent more battery capacity (Gielen & Lyons, 2022). Therefore, the IEA (2022) expects that PMSM motors will remain dominant in the future. Currently, a third type of EV motor, the switched reluctance motor, is in its early stages of development and does not require any copper or REEs. Car manufacturers must navigate a delicate balance considering factors such as price, performance, and supply security when making these kinds of strategic design decisions.

Table 6.3: *Comparison of current PMSMs with some REE-free alternatives (Zheng et al., 2022)*

ELECTRIC VEHICLE MOTOR TYPES	REE CONTENT	TECHNOLOGY READINESS	STRENGTHS	WEAKNESSES
PERMANENT MAGNET SYNCHRONOUS MOTOR (PMSM)	High	Matured, Dominant Design, ~90% market adoption, e.g. Nissan Leaf, BMW i3	• Very high efficiency • Compact design • High power-density • Low maintenance • Instant torque	• High production cost • REE dependency
INDUCTION MOTOR (IM)	None	Matured, ~ 10% market adoption, e.g. Tesla Model S, Mercedes B class	• Reliability • Cost-effectiveness • Durable	• Lower efficiency • Bulkier design • Reduced torque at low speeds • Lower power-density • High copper content
SWITCHED RELUCTANCE MOTOR (SRM)	None	First prototype	• Robust design • High power-density • Enhanced efficiency under certain conditions	• Complexity of control • Limited commercial adoption • Vibration and noise
SYNCHRONOUS RELUCTANCE MOTOR (SYNRM)	None	Development stage	• High torque • High power-density	• Lower energy efficiency at high speeds
EXTERNALLY EXCITED SYNCHRONOUS MOTOR (EESM)	None	Used in several EVs e.g. Renault Zoe	• High efficiency	• Lower power-density • High cost • More package space needed

Component substitution for wind turbine generators

Today, four main types of wind turbine generators exist. The most adopted model is the gearbox double-fed induction generator (GB-DFIG), with a 70 percent market share in 2022, and does not contain any REEs (IEA, 2022). An alternative is the gearbox permanent magnet synchronous generator (GB-PMSG). Furthermore, the direct-drive permanent magnet synchronous generator (DD-PMSG), which has a 20 percent market share, has doubled since 2010. The DD-PMSG is the leading choice for off-shore wind turbine applications, with a 60 percent market share in the offshore market. This is mainly because of their weight, efficiency, and maintenance requirements (as it does not contain a gearbox or moving parts) (IEA, 2022). The amount of REE per DD-PMSG wind turbine is generally between 100 kg and one metric ton. However, the REE amount strongly depends on its size, the generator's power rating, and the rotor diameter (IEA, 2022). Finally, the non-permanent magnet direct-drive electrically excited synchronous generator (DD-EESG) is one of the models. Wind turbines based on PMSGs require Nd and Dy. DD- PMSGs contain more significant quantities of REEs compared to GB- PMSGs for smaller overall size and higher efficiency, lower weight, and less maintenance, 80-100 kg of Nd-Fe-B PM per MW for gearbox systems compared to 700-1200 kg of Nd-Fe-B PM per MW for direct drive wind turbines (IEA, 2022; Binnemans, 2015).

Table 6.3 compares the four main types of wind turbine generators with each other. Some promising innovative designs are the high-efficiency, ultra-light, low-temperature superconducting generator from General Electric and the ferrite-based direct drive permanent magnet generator from Greenspur (Carrara, 2023).

Table 6.4: *Comparison between four main wind turbine generator types (IEA, 2022)*

WIND TURBINE GENERATOR TYPE	REE CONTENT	TECHNOLOGY READINESS	STRENGTHS	WEAKNESSES
GEARBOX DOUBLE-FED INDUCTION GENERATOR (GB-DFIG)	None	Matured, widely used, 70% market adoption, dominant design for the onshore market	• Grid compatibility • Cost-effective	• Maintenance requirements
GEARBOX PERMANENT MAGNET SYNCHRONOUS GENERATOR (GB-PMSG)	Medium	Matured	• Highly efficient • Reliable	• High capital cost • REE dependence
DIRECT-DRIVE PERMANENT MAGNET SYNCHRONOUS GENERATOR (DD-PMSG)	High	Matured, widely used, 20% market adoption, dominant design for off-shore market	• Excelled efficiency • Lower weight • Reduced maintenance	• High capital cost • REE dependence
DIRECT-DRIVE ELECTRICALLY EXCITED SYNCHRONOUS GENERATOR (DD-EESG)	None	Evolving technology	• Low maintenance	• Low efficiency • More R&D needed

Material substitution
Alternative magnets for the Nd-Fe-B PM have been developed, e.g., Al-Ni-Co, Ce-Co, SmCo, plastic ferrites, and ceramic ferrites magnets. So far, all of them are considered uncompetitive alternatives for EV and wind turbine applications, as Nd-Fe-B PMs have the highest theoretical maximum energy capacity of any other PM to date, so more R&D is needed for viable alternatives (Carrara et al., 2023; Geus & D'Appolonia., 2017).

Dematerialization
Reduction of REE content in Nd-Fe-B PMs is happening, e.g., with hybrid drive generators, which use a smaller PM. Potentially, this could lead to savings of up to two-thirds of the amount REE per turbine (Carrara, 2023). Furthermore, according to Pavel et al. (2017), further design optimization could lead to much less use for Nd-Fe-B PMs per generator/motors, and would it be feasible for the share Nd/Pr to decrease from 30 percent to 26.5 percent of the magnet composition, and for the Dy content to decrease from 7.5 percent to 5 percent. Lastly, developments are ongoing to reduce or discard HREE Dy altogether. However, performance reduction is generally the result of innovative product design (Gielen & Lyons, 2022).

Lack of skilled workforce and limited REE R&D capacity compared to Asia, North America, and Australia [E3 and E5]
There is a lack of scientific workforce, research infrastructure, and funding in the European REE and PM systems compared to other regions (ERMA, 2021). Consequently, limited R&D capacity could make the EU even more vulnerable, as the EU is less likely to develop innovations in this field. Investments are needed to establish a significant European internal capacity and attract and educate a skilled workforce [E3, E5].

Complex recyclability [E1, E2, E3, E5, and E6]
As discussed in *Section 4.7*, REEs currently have a recycling rate below one percent. This is due to several constraining factors (Burkhardt et al., 2020; Carrara et al., 2023; Geus & D'Appolonia., 2017).

Lack of collection infrastructure [E1]
Most of the EoL Nd-Fe-B PMs are getting lost because efficient collection schemes are not yet available. Additionally, scrap Nd-Fe-B PMs are the majority getting shipped to third countries [E1].

Lack of economically viable industry-scale REE recycling technologies
Magnet extraction technologies have already been developed. However, technological improvements will be necessary to implement industrial-scale REE recycling.

Limited availability as a secondary source [E1, E3, E5, E6]
The deployment of Nd-Fe-B PM in our technologies is a relatively recent development; therefore, most of the produced Nd-Fe-B PMs are still in use today, e.g., wind turbines have average lifetimes of 30 years.

Wide variety in Nd-Fe-B PM composition
Nd-Fe-B PMs are used in numerous applications and designs that complicate the set-up for standardized recycling processes, such as the PM size differences between EVs (2-5 kg Nd-Fe-B PM) and wind turbines (> 100 kg of Nd-Fe-B PM).

Recycling is a long-term strategy and not a short-term solution (Van Exter et al., 2018). Nevertheless, it requires immediate action to cover the 20 percent recycling rate benchmark in 2030. Establishing industry-scale REE recycling infrastructure will require standardized collection and decommissioning, specific know-how, investments, and a demand for secondary Nd-Fe-B PMs (Carrara et al., 2023; [E3]).

6.5 Environmental

REEs and Nd-Fe-B PM play a crucial role in enhancing the efficiency of clean energy and transportation technologies, contributing to reduced pollution in these sectors. From an environmental standpoint, REEs prove to be a boon for the technologies they support. However, it is essential to acknowledge that their extraction, processing, and recycling are known to be very environmentally intensive processes.

Environmental impact of setting up an internal capacity
The historic REE value chain was far from environmentally friendly. Primarily, the extraction and processing are environmentally intensive activities. Mining generally uses a lot of water and energy and creates a lot of land, water, and air pollution. All of which can affect biodiversity, human health, and ecosystem health. It is even estimated that one tonne of REEs produced produces 2,000 tonnes of solid waste (Andrew-Speed & Hove, 2023; McNulty et al., 2022).

Furthermore, some REE ores are found in the same rock with radioactive materials such as Uranium and Thorium. Proper waste stream management is essential for environmental and health impact mitigation. Years of unregulated mining and processing have led China to the creation of 70.000 tons of radioactive Thorium lake next to the Bayan Obo mine and processing facilities, leading to environmental catastrophe. Moreover, much of that region's soil is contaminated with toxic arsenic and chlorite. Additionally, mining operations, especially open-pit mining, lead to permanent land degradation. Open pits, where ore is excavated, are left open after extraction and are generally filled with leftover rock, which alters biochemistry and groundwater. Lastly, Nd-Fe-B PM production requires much energy (mainly natural gas and electricity), particularly REE extraction and processing. Energy requirements are strongly dependent on the individual REE and the ore type. Moreover, Jin et al. (2018) performed a Life Cycle Assessment to produce Nd-Fe-B PMs from virgin and recycled material. The results are depicted in *Table 6.3*, including the total amount of Nd-Fe-B PMs used for wind turbine generators and EV motors in 2020, 2030, and 2050 (*Table 4.6*). In the fourth column (B/A), the table clearly shows that magnet-to-magnet recycling significantly reduces the environmental impact in all categories. Furthermore, the last three columns show the production of 3.2 Mt of CO_2eq in 2020, 33 Mt of CO_2eq in 2030, and 70 Mt of CO_2eq in 2050, which is respectively comparable with the total annual greenhouse gas emissions of Guyana in 2020, New Zealand in 2030, and Austria in 2050 (Worldometers, 2023). Lastly, the average water consumption, depending on ore type and individual REE, is 11,200 kg/kg of REE produced (Browning et al., 2016).

Table 6.5: *Jin et al. (2018) Nd-Fe-B PM Life Cycle Assessment results for Virgin and Recycled material*

IMPACT CATEGORY	UNIT	VIRGIN (A)	RECYCL-ED (B)	B/A DIST-IN-CTIVE	TOTAL (VIRGIN) PRODUCTION 2020	TOTAL (VIRGIN) PRODUCTION 2030	TOTAL (VIRGIN) PRODUCTION 2050
OZONE DEPLETION	kg CFC-11 eq	0.000018	8.1E-07	5%	435.6	4559.4	9714.6
GLOBAL WARMING	kg CO2 eq	130	25	19%	3.15E+09	3.29E+10	7.016E+10
SMOG	kg O3 eq	12	1.1	9%	2.9E+08	3.04E+09	6.476E+09
ACIDIFICATION	kg SO2 eq	1	0.38	38%	24200000	2.53E+08	539700000
EUTROPHICATION	kg N eq	1400	0.11	0%	3.39E+10	3.55E+11	7.556E+11
CARCINOGENICS	CTUh	6.8E-06	0.0000013	19%	164.56	1722.44	3669.96
NON-ARCINOGENICS	CTUh	0.000036	0.000009	25%	871.2	9118.8	19429.2
RESPIRATORY EFFECTS	kg PM2.5 eq	0.21	0.025	12%	5082000	53193000	113337000
ECOTOXICITY	CTUe	900	230	26%	2.18E+10	2.28E+11	4.857E+11
FOSSIL FUEL DEPLETION	MJ surplus	160	25	16%	3.87E+09	4.05E+10	8.635E+10

Development of efficient and environmentally friendly REE extraction technologies

Currently, research is looking to remedy the current issues involved in the REE mining and processing practices, e.g., bacteria and filters with lower acidity are being used; electrokinetic mining, which relies on electric currents, realizing the REEs, sharply reducing the need for toxic chemicals (Opare et al., 2021). Innovation in REE extraction, separation, and processing technologies could benefit public acceptance by making the processes cleaner and more efficient. Further developments are REE extraction from manufacturing by-products, such as extracting REEs from coal fly ash, which is a waste product from coal production, it uses supercritical fluid to recover REEs from products that otherwise would end up in a landfill (Opare et al., 2021).

6.6 Legal

While *Chapter 4* already described which relevant institutional aspects influence the EU REE system. This section delved explicitly into the legal factors and developments that enable or constrain REE autonomy regarding REEs.

The Green Deal Industry Plan

The CRMA and the NZIA, discussed in *Section 5.2.1.2*, is an essential steps in mitigating REE supply risks as it created benchmarks, shortened and simplified permitting procedures, discussed supply diversification, focused on sustainability and circularity, and the risk monitoring and mitigation efforts. Benchmarks will obligate countries to make the necessary legal efforts. Shortened and simplified permitting procedures, making it more appealing for companies to invest in European CRM projects. Diversification of supply makes the EU less dependent on a single third party. The focus on sustainability and circularity increased recyclability and stimulated secondary supply. Lastly, monitoring and mitigating efforts, e.g., monitoring and building strategic Nd-Fe-B PM stocks, mitigate short-term supply risks (European Commission, 2023-I; [E2]).

Experts criticized the CRMA for being vague and failing to address several critical aspects [E1, E3, E5, E6, E7]. Predominantly the challenge of attracting private investment, as there is a lack of and difficulty of creating a level playing field. Although the CRMA is an enabling piece of legislation, the EU does not have fiscal jurisdiction, thereby making appropriate and aligned implementation of the CRMA more difficult. As discussed, there is a lack of playing field, even within the EU. This creates unfair competition and hampers European REE autonomy. China wants to protect higher value creation steps from competition by imposing an import tax on processed REE materials, including Nd-Fe-B PMs. At the same time, REO is imported duty-free (ERMA, 2021). Moreover, Chinese policy does not VAT refund the export of processed REOs, metals, and alloys (ERMA, 2021). In contrast, there is a VAT refund for REE magnet exports. This creates a cost disadvantage of 13 percent of the full price for non–Chinese magnet customers (ERMA, 2021). Fiscal discrimination against global competitors is also happening in the US, with their LCRs in the IRA (*Section 4.2.4*). Creating a level playing field is more difficult for the EU, as Member States have their fiscal policies; moreover, imposing tax exemptions contradicts solid European beliefs in free markets; it could even further increase resource nationalism, which is undesirable in European access to REE.

Furthermore, Findeisen & Wernert (2023) warn that oversimplification of the permitting process could lead to unintended consequences, potentially causing more harm than benefit, especially as the permitting procedure has only limited contribution to the overall lead times. Moreover, the CRMA lacks an incentive structure for EU companies to diversify their own supply and does not touch upon the associated cost of achieving REE supply resilience and the necessary infrastructure (Findeisen & Wernert, 2023). Lastly, Findeisen & Wernert (2023) argue that establishing internal REE capacity in the EU is a European public good; therefore, the EU, and not the Member States, should be responsible for the investments in mining, processing, and recycling projects.

Lastly, the EoL EV directive should help with REEs' collection and recyclability, promoting circularity by design is a central theme in several EU acts [E2].

Environmental regulations

The EU has stringent environmental regulations compared to China. Although necessary for limiting environmental impact, it also creates an uncompetitive situation for European CRM and REE projects. At least if not compensated for external benefits, as sustainability comes with a higher price.

6.7 Concluding Remarks

This section goes into answering **SQ3:** *What are the main factors and developments, influencing the EU's REE autonomy?*

First of all, the current geopolitical situation, rising tensions, and resource nationalism are impacting trade relations between the US, EU, and China, thereby constraining the EU's REE autonomy. Consequently, creating a growing awareness of the need for an open strategic autonomic EU is enabling solid development as it creates a political and public will for installing EU internal capacity. Moreover, the EU legislation, mainly the CRMA, is a step in the right direction by creating benchmarks, shortening and simplifying permitting procedures, diversifying supply, focusing on sustainability and circularity, and the risk monitoring and mitigation efforts. Another enabler is scarcity and price spikes, as they could give the EU market autonomy projects the right incentive, e.g., circularity by design, recycling, mining, and processing companies. Lastly, the fact that multiple, already matured, and widely adopted Nd-Fe-B PM alternatives exist for both wind energy generators and EV motors lowers the criticality of the REEs in these industries. Nevertheless, it is essential to note that the unique properties of Nd-Fe-B PMs are yet to be met by these alternatives, and the prospects are that the market will stay in favor of Nd-Fe-B PM options.

The implementation of the CRMA is expected to be complex, e.g., bureaucracy, lack of fiscal alignment, REE EU internal capacity investment uncertainty, NIMBY, low recycling rates, and the limited academic attention and human capital make the designed CRMA benchmarks challenging to meet before 2030 for REE specific.

While the EU funds REE projects, businesses' viability hinges on actual demand for EU-mined, processed, and recycled REEs. Without consumer demand for EU internal capacity, businesses may face challenges, as consumers are inclined to opt for less expensive options elsewhere. An important constraint to the lack of demand for European REEs is the lack of a level playing field in price incentives between the EU and, e.g., China and the US. Creating a level playing field while managing increasing resource nationalism is difficult for policymakers. However, it is considered essential for establishing a thriving European CRM industry. The return on investment on EU REE projects is uncertain due to degrading ore, stringent safety and environmental regulations, lack of human resources, high energy and labor costs, price volatility, long project load times, and the lack of demand for EU capacity. These problems are insufficiently addressed in current policies, making investing in European REE projects unattractive. An embedded constraint is the high European energy and material needs and wants. Focusing on refuse, rethinking, reducing, reusing, and repairing could reduce REE demand, thereby mitigating supply risks.

Table 6.6 summarizes this chapter's enabling and constraining factors. *Chapter 7* delves deeper into potential solutions to the constraining factors as it establishes institutional interventions.

Table 6.6: *Summary of Enabling and Constraining Factors for EU's Autonomy on REEs*

PESTEL CATEGORY	FACTORS/ DEVELOPMENTS	TYPE (ENABLING/ CONSTRAINING)	DESCRIPTION
POLITICAL	Geopolitical tensions	Constraining	Geopolitical tensions impacting trade relations and potential resource nationalism. EU's reliance on Chinese exports and the use of REEs as geopolitical leverage.
	Supply diversification	Enabling	Mitigation measures through diversification of supply, international cooperation with other REE-producing nations.
	EU bureaucratic complexity	Constraining	Slow and bureaucratic EU policy system, and different perspectives among Member States makes quick, efficient and unified policy response challenging.
	Political reluctance and incapability	Constraining	Political reluctance, and a lack of know-how and understanding at the governmental level challenges the implementation of the ambitious plans.
ECONOMICAL	Market dynamics	Enabling/ Constraining	Anticipated growth in REE demand, potentially leading to higher prices and market opportunities. However, a significant time delay between demand increase and supply exists in the mining industry. Furthermore, price volatility influenced by geopolitical events, supply-demand dynamics, and technological advancements, and the mining nature of REEs increases uncertainty.
	Project feasibility and profitability	Constraining	Lower ore grades, higher capital and operating costs (including relatively high energy and labor cost), long project leas times, and a lack of funding and incentive structure in European REE projects affecting profitability.
SOCIO-CULTURAL	Public perception	Enabling/ Constraining	Growing awareness of critical raw material security issues, potentially facilitating public acceptance.. Local resistance (NIMBY principle) to mining, processing, and recycling facilities, and growing difficulty in obtaining mining and processing permits due to environmental justice practices.
	High energy and material needs/wants	Constraining	High European energy and material demands contributing to high REE demand.
TECHNOLOGICAL	Alternative technologies	Enabling/ Constraining	High-performance REE-free alternatives exist for both EV motors and wind turbine generators. However, the market tend to favor Nd-Fe-B PMs. More dematerialization, product longevity, component, and material substitution developments will be necessary.
	Lack of skilled workforce and limited REE R&D capacity	Constraining	Lack of scientific workforce, research infrastructure, and funding in the European REE system.
	Complex recyclability	Constraining	REEs have a recycling rate below one percent, due to a lack of collection infrastructure, limited economically viable industry-scale recycling technologies, limited availability of secondary sources, and a wide variety of Nd-Fe-B PM compositions
ENVIRONMENTAL	Environmental impact of setting up an internal capacity	Constraining	Historically environmentally intensive REE value chain, issues with pollution, land degradation, and energy consumption.
	Environmentally friendly REE extraction technologies	Enabling	Research and innovation in cleaner and more efficient REE extraction, separation, and processing technologies.
LEGAL	The Green Deal Industry Plan	Enabling	CRMA and NZIA creating benchmarks, simplifying permitting procedures, focusing on sustainability, circularity, and risk mitigation. Criticized for vagueness and challenges in private investment, fiscal alignment, and level playing field.
	Environmental regulations	Constraining	Stringent EU environmental regulations creating competitiveness challenges for European CRM and REE projects.

7. INSTITUTIONAL INTERVENTIONS

This chapter goes into **SQ4:** *How can institutional interventions enhance the autonomy in the EU regarding access to REE, and who is responsible?*

This chapter starts with the interview findings. The conducted expert interviews not only offered triangulation but also yielded fresh critical insights and valuable suggestions for potential policy interventions. Subsequently, the addressed issues and challenges are examined, providing essential input for the formulation of institutional interventions. This synthesis harmonizes the findings from earlier chapters with the perspectives shared by the experts, creating a comprehensive and informed approach to addressing the complexities at hand.

7.1 Interview findings

In this section, the results from the interviews are presented. An interview protocol was developed and can be found in *Appendix B. Table 3.2 (p. 15)* shows the overview of the respondents. Furthermore, the sectors follow the structure of the interview protocol. Several types of stakeholders were interviewed: policy advisors, policymakers, and researchers. All are considered experts in the field of PMs and REEs.

7.1.1 Consensus

Generally, there was consensus about the current view on the global REE value chain and its implications on the EU. All the interviewees [E1-E7] recognized the REE supply chain vulnerabilities for the EU. E3 and E5 highlight the vulnerability in the processing step of the value chain, as 94 percent of the global REEs are processed in China alone. Furthermore, all the experts [E1-E7] acknowledged that the current situation is undesirable for the EU and that strategic measures are needed to mitigate this supply chain vulnerability [E1-E7]. According to the experts, the EU should strive to gain more autonomy because complete self-sufficiency is not feasible or even possible [E1, E3, E5, E6, E7]. To gain more autonomy, a pan-European approach and policy alignment between Member States is strongly desirable [E1, E2, E3, E5].

Strategic differences and geopolitical tensions between China, the US, and the EU were also discussed. China's dominant position in the global REE supply chain is recognized as a significant risk factor for other countries. Export restrictions imposed by China can disrupt the energy transition, impact chip manufacturers, and affect military electronics [E1-E5]. The geopolitical context further compounds these risks. E1, E2, and E5 touched on the establishment of China's dominant position in the REE value chain, emphasizing that the loose environmental regulations are the primary contributor to China's dominance, as REE mining and processing are chemically complex and environmentally intensive practices [E1, E2, E5].

All the experts [E1-E7] agreed that COVID-19 supply chain disturbances and the energy crisis after the Russian invasion of Ukraine were catalysts for the growing need for European open strategic autonomy. Most interviewees recognized a lack of urgency before those events [E1, E2, E3, E5, E6]. The current global geopolitical constellation reminds E1 of the Cold War, where we are thinking about geopolitical blocks. Thereby increasing the risk of material and energy supply insecurity. The most considerable risk of China's dominance is that they could use it as a geopolitical leverage, e.g., as they are currently doing with the export restrictions for Gallium and Germanium [E1].

During the last decades, the US and the EU have firmly believed in liberal markets and globalization [E1 – E7]. E1 states that only after COVID-19 and the Russian invasion of Ukraine did we realize the supply chain risks, which marked the reversal of our belief in globalization.

7.1.2 Policy Differences

The US's expeditious response was discussed with several experts [E1, E2, E3, E5]. E1 and E3 made clear that there is a fundamental difference between the EU and the US. As the EU is no federal state, it is not responsible for what is happening in specific Member States; it only sets the targets. The US can use far-reaching policies and fiscal policies. Furthermore, the nature of the EU is more sluggish and bureaucratic.

The US responded rapidly and adequately with the IRA, whereas the EU responded with the CRMA and the NZIA. According to E1, E3, and E5, the EU’s reluctance to intervene in critical materials policy is not due to a lack of awareness but rather stems from bureaucratic processes, regulations, and the complexities of democratic decision-making. The slow pace of decision-making and the need for coordination at the European level pose challenges [E1, E3]. Hence, the E1 and E3 interviews underscore the European over-organization as a significant challenge and make it less resilient. Furthermore, the EU's environmental, safety, health standards, and climate mitigation measures could obstruct domestic CRM recycling, mining, and processing initiatives. In addition, the densely populated nature of Europe further constrains domestic industry [E1]. E1 further mentions the high European energy prices, the lack of green energy infrastructure (and its intermittency), long lead times, and legal factors such as licensing and permitting as constraining factors as well.

Furthermore, according to E3, the little investment in the EU’s internal capacity is a significant problem. The CRMA is vague, as it does not explain how targets should be met. According to E3, the EU must first create demand for EU-produced REEs before producing the actual REEs. Otherwise, no customers will buy or invest in the EU-produced REEs [E3]. This is something that the US is doing and what makes the IRA effective [E3].

Moreover, E1 suggests that regulations should be enacted nationally and emphasizes the risk of industries relocating to countries with more lenient regulations, such as the US and Canada. As for now, EU Member States are doing too little themselves [E1, E3]. There is a need for policy, and fiscal alignment between all the Member States to create a level playing field within the EU. Additionally, E3 suggests that the EU should incentivize its own REEs. However, E2 and E4 state that that will be against the EU’s belief in a liberal market and with WTO agreements.

7.1.3 The Four Pillars of Strategic Autonomy

Interviewees were asked what, according to them, would be factors that could improve the EU’s REE autonomy. The main success factors are best summarized by E2's explanation of the CRMA's four pillars of success:

The first pillar is the development of <u>internal capacity</u>, which is about how the EU and its Member States can ensure that REE extraction, processing, and magnet manufacturing projects get ground. E2 states that acceleration and simplification of the permitting procedure is the essential first step, with permitting taking no longer than two years for extraction and no longer than one year for processing and recycling [E2]. Currently, permitting procedures can take up to eight years [E1, E2, E5].

The EU's internal capacity targets in the CRMA are seen as unfeasible for most respondents [E1, E3, E5, E6, E7]. As much unclarity exists in how those targets will be accomplished before 2030, even with decreased permitting times, REE projects will likely take long before they get ground in the EU [E1 and E6].

E1 emphasizes that it is vital that European-mined materials are also processed and assembled in Europe or befriended states in order not to create other dependencies.

E2's optimism provided swift implementation; however, he also noted that legislative changes might pose challenges. Furthermore, he indicated the possibility of a review process if targets were not met. Additionally, E2 pointed out differences in feasibility among the different CRMs in terms of readability and clarity; they decided to install the same benchmark for all the CRMs. E5 emphasizes that challenges such as energy and labor costs and environmental regulations remain.

Secondly, E2 discussed circularity as a critical success factor. He stated that specific requirements and information on recyclability and recycled content must be provided for products containing permanent magnets [E2]. Furthermore, the End-of-Life EV directive should help with REEs' collection and recyclability [E2]. Lastly, promoting circularity by design is a central theme in several EU acts [E2].

E1, E3, E5, and E7 state that the recycling target of at least twenty percent of consumption by 2030 is unfeasible, and E7 even claims that it is impossible, as there will not be enough permanent magnets ready to be recycled. Most offshore wind turbines and EVs will still be in use by 2030. Recycling is predominantly a medium to long-term solution [E1, E3, E5, E6, E7]. Nevertheless, the development of a recycling infrastructure is necessary.

The third pillar E2 brought up was substitution and R&D. E5 expressed much trust in substitutions despite concerns about critical materials posing obstacles. According to E5, the energy transition would still be possible without REEs. Technological innovation and substitution using alternative materials are viable solutions for both EV motors and wind turbine generators to reduce dependency on REEs. Furthermore, he refuted the argument that substitution always means shifting the problem from one material to another. As for induction motors for EVs, more copper will be needed, and copper is more accessible than REEs. Nevertheless, E1 and E3 expressed general concerns about substitutes, as they will create other dependencies. Furthermore, E1 and E3 highlighted that substitutes are currently not able to replace Nd-Fe-B magnets, as they are less efficient and require more development and innovation.

The fourth and last pillar to increase the EU's autonomy in REEs is supply chain diversification [E2]. The EU is currently developing several strategic alliances concerning REEs. The EU has trade agreements with third countries to ensure access to raw materials such as REEs and reduce geopolitical risks. Strategic alliances are existing with Namibia, Kazakstan, Ukraine, and Canada [E4]. The EU is furthermore negotiating with Argentina, Chile, Greenland, Norway, the Democratic Republic of Congo (DRC), Rwanda, and Australia [E4]. Furthermore, E4 illuminated the EU’s Global Gateway initiative, which is a fund of 300 billion EUR to support CRM projects, education, health, and infrastructure in third countries.

Supply diversification will come with a price. Western countries are likely to compete for more expensive non-Chinese REEs. E1, E2, E3, E4, E5, and E7 all agreed that the EU should diversify no matter the higher prices, as supply security should have priority. According to E3, high REE prices are desirable, resulting in better material usage.

E6 expresses concerns as there is a lack of concrete plans and strategies to achieve the goal of not more than 65 percent of annual consumption at any relevant processing stage from a single third country by 2030. As of today, 100 percent of his magnets come from China.

7.1.4 Strategic Stockpiling

Another policy option to create supply insurance is stockpiling. According to most experts, one form or another is obvious [E1, E2, E3, E5, and E6]. E2 and E4 say that the EU does not support stockpiling or export restrictions, as the EU should advocate free-flowing trade. Furthermore, E2 clarified that stockpiling should be considered cautiously, as it will disrupt the market. For instance, E6 experienced this during the COVID-19 supply disruptions and the energy crisis. As panic grew, magnet customers increased their demand, increasing the price. Currently, price levels of REEs and magnets are back where they were before those disrupting events. E6 concluded that the demand decrease should result from his customers having stocks.

Furthermore, strategic stockpiling is complex to implement as a policy. It is yet unclear who is responsible for paying for it, and information about stock quantities is very confidential [E1, E2, E5]. Moreover, simply stocking REEs does not help with the autonomy problem because REEs still need to be processed, and magnets still need to be manufactured [E1]. Strategic stockpiling still needs to be elaborated, as it is unclear which and how much materials and products need to be stored and who should be responsible for it [E1]. As for the EU, any recommendations for ideal stock levels would not be mandatory, respecting the sensitivities of Member States [E2]. Therefore, the EU mainly says that the private sector should take responsibility for stockpiling as supply disturbance is part of their business risk. In contrast, E3 states that one cannot take SMEs responsible for geopolitics. Likewise, E6 will not stockpile himself as it will negatively influence his profitability; however, he offers customer-specific inventory upon client request.

7.1.5 Flaws in Current Policy, and Recommendations

The four pillars, as stated in the CRMA for improving the EU's autonomy, are all supply-side focused, by utter animosity from E3. E3 highlighted the importance of tackling demand-side issues. The EU can be self-sufficient by supply-side focus alone [E3, E7]. The emphasis should be on less material need, product longevity, and efficient repairability [E3]. E3 and E7 would prefer to focus more on the basic principles of circularity. Refuse, reduce, rethink, and reduce instead of focusing on recycling alone. In term this would mean a simplification of our society [E7].

"We should think more about what we need instead of what we want." – E7.

Current policies make it difficult to choose sustainable options [E3]. E3 recommends that incentives for increased materials use should be stopped, and selling unsustainable products should be prohibited. Effective policy should distinguish between EVs and wind turbines, as EVs are replaceable with other means of transportation (e.g., shared mobility), and wind turbines are critical for the energy transition [E3].

Another institutional issue that is a constraining factor, according to E1, is that appropriate legislation and communication are complicated because of the lack of understanding and know-how at the governmental level. As a solution, E1 advocates for a focus on education regarding this topic and the introduction of new CRM-related curriculums. E4 pointed out that mining and processing have a terrible reputation among young people, potentially limiting the new inflow of people into the sector.

Political reluctance is a recurring theme in the interviews. The problem is clear and well understood, but this has not returned in explicit governance [E1, E3, E5, E6, E7]. E3 expresses his frustration with the current system, prioritizing short-term economic gains over long-term environmental sustainability. He believes that policy decisions, political lobbying, and corporate interests play a significant role in maintaining this status quo. This is backed by E4 underscoring the strong industry lobby of, e.g., the automotive industry, which hampers things like shared mobility. E1 and E3 both advocate for a long-term industrial policy focusing on the domestic desirability for industries to start or continue their businesses. Creating a demand for European-produced REE products is thereby essential, according to E3. The EU has great ambitions but no clear policy with regard to REEs. Policy instruments such as subsidies, import taxes, and strategic reserves will be necessary to address material dependencies [E1, E5]. Furthermore, E5 highlights that an energy transition without REEs is possible. He suggests that policies should focus on the R&D of substitutes for Nd-Fe-B PMs.

7.2 Challenges for an Open Strategic Autonomy Regarding REEs

The existing EU policy concerning REE is The Green Industrial Plan *Section 5.2.1.2*, particularly the CRMA. Which mitigates dependencies by 1) Supply diversification, 2) Establishing internal capacity, 3) Enhancing reusing and recycling, 4) Substitution and alternative solutions, and 5) Monitoring and stockpiling. Throughout *Chapters 4, 5, and 6* and the conducted interviews, it became evident that there are significant challenges regarding the implementation of the NZIA and CRMA for all five strategies;

Firstly, to achieve effective supply diversification, it is crucial to stimulate private demand for diversified supply. Presently, there is a lack of regulations incentivizing companies to embrace supply diversification. Additionally, recognizing the expansion potential of the Global Gateway is essential. As a result of successful supply diversification efforts and the formation of strategic alliances, the market may experience heightened competition for non-Chinese REEs, likely leading to increased prices and augmenting resource nationalism.

Secondly, for the establishment of adequate internal capacity, it is crucial to acknowledge the existing absence of European REE extraction and limited internal capacity in recycling, processing, and manufacturing. Furthermore, significant challenges include high intellectual barriers, particularly regarding a skilled workforce, and substantial financial barriers encompassing both capital (e.g. infrastructure) and operational (e.g. energy) expenditures. Moreover, similarly to the encouragement of diversification of supply, there is a lack of regulations incentivizing companies to embrace internal capacity. Demand for domestic extraction, processing, recycling, and manufacturing is crucial. Especially since discriminatory policies in the US and China contribute to an uneven playing field. Additional impediments involve suboptimal ore composition, the absence of specific benchmarks for Nd-Fe-B PM manufacturing, public resistance, environmentally intensive processes, and prolonged project lead times. Consequently, this array of challenges has led to a notable deficiency in investments, characterized by heightened uncertainty in the investment landscape.

Thirdly, improving circularity, and meeting the CRMA recycling benchmarks for REEs is likely to be very challenging. A critical underlying impediment is the substantial energy and material demand in Europe, leading to heightened REE demand. Presently, the EUs approach is predominantly supply-oriented, with insufficient emphasis on demand reduction. An alternative strategy involves mitigating dependencies through a focus on the most circular practices such as Refuse, Rethink, Reduce, Reuse, and Repair. Compounding the issue is the absence of regulatory incentives to promote circularity, including the implementation of modular designs and disassembly-friendly product designs.

Furthermore, even seemingly straightforward circular strategies such as recycling face significant hurdles. The current recycling rate is alarmingly below 1 percent, primarily due to the absence of robust collection infrastructure, a dearth of economically viable industry-scale recycling technologies, limited availability of secondary sources, and the diverse compositions of Nd-Fe-B PMs. Adding to the complexity is the fact that existing secondary sources are often relegated as scrap to third countries, perpetuating a situation where valuable REEs are not retained domestically. This practice not only hinders circularity goals but also perpetuates dependencies on external sources. Addressing these multifaceted challenges requires a comprehensive reevaluation of policies and incentives to promote circular practices, as well as strategic initiatives to bolster recycling infrastructure and technology development within the EU.

Fourthly, Nd-Fe-B PM substitutes in EV motors and wind turbine generators are already widely adopted. Nevertheless, manufacturers in the EV and wind turbine sectors (especially in offshore applications) exhibit a preference for Nd-Fe-B PM applications owing to their distinctive properties. These properties, such as higher efficiency, increased durability, and lower operating costs, tend to outweigh the initial associated expenses (as discussed in *Section 6.4*). Consequently, technological alternatives often fall short in terms of performance and desirability. Furthermore, opting for substitutes to Nd-Fe-B PMs tends to shift the challenge to other CRMs. This dynamic underscores the intricate trade-offs involved in seeking alternative materials, as the pursuit of sustainability and reduced dependence on specific elements can inadvertently lead to reliance on other materials with their own set of challenges.

Fifthly, enhancing short-term supply resilience can be achieved through refined monitoring mechanisms and strategic stockpiling. Presently, there exists a notable deficiency in communication, transparency, and clarity among industry stakeholders, Member States, and the EU regarding strategic stockpiling. The responsibility for this crucial task remains ambiguous, and there is a lack of precision regarding the specific quantities and types of materials deemed necessary for effective strategic stockpiling. Addressing these gaps is paramount for establishing a well-coordinated and effective framework that ensures a robust response to potential supply disruptions.

Several overarching issues hinder the progress of achieving strategic autonomy. These include a lack of comprehension within governmental entities, insufficient overall investment, and uncertainty regarding the financial implications of achieving strategic autonomy. Current policies also lack clarity in their implementation strategies, especially concerning the time horizon post-2030.

7.3 Formation of the Institutional Interventions

This section addresses the identified issues and constraints of *Section 7.2* and incorporates them into institutional interventions. Important to note is that open strategic autonomy in the EU can only be achieved with the collaboration and policy implementations of its Member States and industry players. Therefore, this section provides additional policy options for EU decision-makers to consider and more concrete suggestions at the Member State level. In particular, fiscal interventions, as the EU does not function as a fiscal jurisdiction similar to individual Member States. The institutional interventions are predominantly within levels 2 and 3 due to their significant relevance to public policy matters. This section delves into what the EU should do to improve its current strategy of supply diversification, domestic capabilities, circularity, substitution, and stockpiling. Prior to discussing the interventions within those five main strategies, two general interventions are proposed.

First of all, a comprehensive understanding is essential for proficient policy-making, effective communication, and skilled labor activities, and is currently lacking [E1]. Therefore, E1 suggested that the EU should enhance understanding and expertise concerning CRMs and REEs within governance and industry. Implementing interventions at the EU level, involving research and education institutes, can augment understanding and potentially reshape prevailing beliefs and norms (level 1). However, the detailed exploration of various suggestions is primarily situated within the third level of Williamson, where formal rules and regulations, such as those pertaining to research and education, play a crucial role. Numerous possibilities exist, including consultation of a REE-expert group, and improving education in the field of CRMs and REEs, both of which are on Member State level (ERMA, 2021; [E1]). The EU could advocate for ERMA Cluster Rare Earth Magnets and Motors, EIT Raw Materials, and other REE-related organizations to increase their collaboration with research and (national) government institutions.

Secondly, the CRMA currently lacks explicit benchmarks for the import of Nd-Fe-B PMs (*Section 5.2.1.2*). In order to mitigate dependence on third nations and bolster self-reliance, it is imperative for the EU to foster the development of a comprehensive REE industry, encompassing robust Nd-Fe-B PM manufacturing capabilities. The mere establishment of REO extraction and processing, without concurrent advancements in Nd-Fe-B PM production, may inadvertently prolong reliance on external entities (*Section 5.3*). Consequently, a strategic step for the EU, suggested by E1 and E3 would involve updating the CRMA to incorporate specific benchmarks for Nd-Fe-B PMs in the context of domestic manufacturing, thereby aligning policy objectives with the overarching goal of achieving greater autonomy in the REE sector.

7.3.1 Maintaining and Improving External Relations

The CRMA has a benchmark of a maximum of 65 percent sourcing from one single third country by 2030. External supply diversification will need to happen in order to accomplish this benchmark, as the EU is currently almost wholly dependent on Chinese exports. Therefore, the EU is already establishing strategic alliances, and it is considered one of the most important steps for both short and long-term REE supply security, as complete REE autonomy is not feasible or even possible for the EU [E1-E7]. Therefore, it is in the EU's interest to slow down resource nationalism and maintain a solid international dialogue by maintaining international collaboration and dialogue with critical REE-producing countries, including China. According to Gielen & Lyons (2022), this would mitigate resource nationalism and prevent geopolitical tensions from rising further. The EU should initially try to level the playing field by preventing discriminatory policies (e.g., LCRs) in other countries before adopting them among themselves, as discussed with E1. Moreover, attaining open strategic autonomy is a delicate balancing act for decision-makers. They need to be cognizant that specific proposed policy options, while effectively promoting EU autonomy, may adversely affect third-party relations.

Additionally, the EU could diversify supply by forming strategic alliances with more REE resource-rich countries by expanding the Global Gateway program. Potential countries include Brazil, India, Vietnam, and Tanzania, as shown in *Section 4.1*, and *Table 4.1*. Moreover, no REE–related strategic alliance currently exists with the US despite the US' significant resources and processing capacity.

Therefore, the EU should consider an EU–US REE alliance [E1, E5]. Furthermore, the EU could pressure Greenland to extract REEs. Given Greenland's extensive REE reserves, including some of the wealthiest HREE deposits globally, the EU and its Member States might encourage or advocate for Greenland's administration to consider legalizing REE exploration and exploitation [E1]. Policymakers should consider that it is vital that European-mined materials are also processed and assembled in Europe or befriended states in order not to create other dependencies [E1].

Lastly, Findeisen & Wernert (2023) rightly pointed out that the CRMA lacks incentives for EU companies to diversify their supply; effective policies could be introducing diversification requirements, discriminated import tariffs, or financial incentives by member state fiscal policies.

7.3.2 Improving Domestic Supply

Policies within the EU and its Member States must be strategically crafted to stimulate internal capacity effectively. According to E3, a significant issue lies in the inadequate investment in the EU's internal supply capabilities, a significant hurdle that needs immediate attention. E3 emphasizes the EU's need to generate demand for domestically produced REEs before actual production, mirroring the successful approach employed by the US, as noted in the IRA (*Section 5.2.1.3*) [E3]. The critical consideration is that without a pre-established demand, potential customers may refrain from purchasing or investing in EU-produced REEs [E3]. Drawing a parallel with the IRA's success, the EU must implement policy options that foster a level playing field, countering the unfair cost advantages held by Chinese and US REE producers and magnet manufacturers. Notably, non-Chinese magnet customers currently face a fiscal cost disparity of 13 percent of the total price (ERMA, 2021). Additionally, LCRs within the IRA confer a fiscal cost advantage to non-EU entities, constituting a tax benefit of 10 percent of their production cost. Therefore, leveling the playing field demands compensation in the range of 10-13 percent for EU production, processing, manufacturing, and recycling. Given that Nd-Fe-B PMs are 20 to 30 percent more expensive in the EU than in China, governments might even contemplate additional compensation to enhance international competitiveness. It is crucial to navigate these policy considerations mindful of the EU's commitment to a liberal market and adherence to WTO agreements [E2, E4]. Achieving a delicate balance is of utmost importance, wherein policies designed to equalize opportunities should not unintentionally undermine international dialogue or intensify resource nationalism. Crafting such policies necessitates a nuanced approach that harmonizes economic interests with global trade principles and collaborative frameworks. Instruments such as tariffs, quotas, and financial incentives serve as avenues to enhance internal capacity, yet the determination of their efficacy relies on the specific context and circumstances. Ultimately, EU and Member States' policymakers must carefully assess and decide on the most suitable measures, recognizing the contextual nuances that shape the effectiveness of these tools rather than making rigid assertions.

First of all, raising public awareness regarding the importance of European autonomy and its implications on society is essential for public support and strategic project acceptance [E1-E7]. For its majority, the EU is a densely populated area with stringent environmental, health, and safety compliances. Furthermore, public perception hinges on awareness. Various avenues for enhancing public awareness were found in desk research and interviews. The EU could enhance awareness through targeted campaigns in countries with potential REE projects, such as Sweden and Finland, involving industry experts, researchers, and politicians; concurrently, the appointment of a REE ambassador could foster transparency, community engagement, and education, primarily overseen at the Member State level, while the enforcement of social licensing could elevate public acceptance, albeit potentially causing project delays due to resource-intensive community engagement ([E1, E3]; ERMA, 2021).

<u>Tariffs</u>

One way of stimulating EU internal capacity is to reintroduce import tariffs on REEs and Nd-Fe-B PMs produced in third countries by adjusting the Common Customs Tariff (Regulation Regulation (EU) 2018/1602) [E3]. The goal of import tariffs is, first and foremost, to level the playing field; import tariffs will lead to higher (external) REE and Nd-Fe-B PM prices, thereby effectively stimulating; the internal REE market, substitutes for Nd-Fe-B PMs, product innovation, and recycling initiatives. However, the EU generally advocates for an open and liberal market, and the imposition of tariffs carries the risk of fueling resource nationalism in other nations; additionally, elevated REE prices may hinder the widespread adoption of electric vehicles and wind turbines, thereby posing a potential disruption to the European energy transition.

Quotas

An other policy option that would be more intervening in the market would be obligating wind turbine and EV manufacturers to source a certain percentage of their Nd-Fe-B PMs locally (quotas), as is opted in ERMA (2021). Similarly, Nd-Fe-B PM manufacturers should have a certain percentage of their REEs to be sourced domestically. The downstream industry benefits from this type of supply diversification as it reduces supply risk, reduces (environmental) transportation costs, ensures quick response times, and stimulates local innovation by creating knowledge clusters (ERMA, 2021). Although effectively stimulating the internal market, this option is shifting the responsibility of supply security to the industry itself, which could be considered ineffective, as it could net increase climate mitigation costs.

Financial incentives

Finally, Member States have various possible fiscal options. Firstly, Member States could install tax credits by tax crediting companies with X amount of the production cost such as in the IRA (*Section 5.2.1.3*). This measure will lower the investment uncertainty for EU internal capacity and recycling projects, thereby creating more demand for EU-produced REEs and increasing access to finance. The measure will level or increase competitiveness for the entire REE value chain in the Member States, which could lead to increased resource nationalism both internally and externally. Furthermore, the measure will be against the embedded belief of an open and unrestricted market, and it is challenging to align with other Member States. Secondly, ERMA (2021) consults Member States to introduce tax shielding, which tolerates companies not having to pay revenue tax before they recover their investment. Thirdly, Member States could provide low-interest loans to REE mining, processing, recycling companies, and magnet manufacturers to reduce the financial burden and boost investment (ERMA, 2021). Fourthly, Member States could introduce CAPEX subsidies for internal projects to lower investment uncertainty. In contrast with the first three options, this option will not influence the demand for EU-made material, as it does not affect the cost of production (variable cost).

Generally, interview and analysis findings suggest that the EU should also look into expanding the funding of R&D programs along the entire value chain, including REE mining, processing, magnet manufacturing, and recycling – furthermore, the expansion of public-private partnerships to foster collaboration between the industry, research institutes, and governments by communicating technical and financial burdens.

Vikstrom (2020) discusses risk sharing across the value chain through long-term contracts, as another option to reduce investment uncertainty. Stakeholders should agree upon mutually beneficial terms and conditions, including quantity, quality, price, and duration. This approach could significantly reduce investment uncertainty. Mining, processing, and recycling companies would benefit from a stable, fixed-price market - and manufacture from a guaranteed supply (Vikstrom, 2020). Therefore, industry and policy decision-makers should actively advocate for long-term contracts, e.g., by regulating a minimum contract duration.

Lastly, ERMA (2021) and E1 suggested the establishment of low-cost energy zones to support energy-intensive industries, including REE and Nd-Fe-B PM projects in the EU. This would effectively tackle the issue of high energy costs in the EU and improve the competitiveness of EU manufacturers.

7.3.3 Improving Circularity in the REE Value Chain

This intervention aims to increase EU material security by improving the circularity in the REE value chain, which is widely considered to help REE supply security in the medium to long term. The intervention focuses on diminishing newly extracted REE demand by promoting alternative transportation, product longevity, repairability, and recyclability. Additionally, it endeavors to augment the circulation of secondary Nd-Fe-B PMs in the system.

Current policies make it often difficult to choose sustainable options [E3]. E3 advocates that incentives for increased material-use should be stopped, and selling unsustainable products should be prohibited. Furthermore, he states that effective policy should distinguish between EVs and wind turbines, as EVs are replaceable with other means of transportation (e.g., shared mobility), and wind turbines are critical for the energy transition [E3]. Currently, a mere focus on supply-side policy interventions exists within the EU. This intervention aims to increase autonomy by reducing the demand for Nd-Fe-B PMs and, ultimately, REEs. This is, however, highly controversial and has little political support [E3, E4]. Decreasing material and energy demand through policies would predominately fit best in level 2; however, the ultimate goal would be to change public perception and alter customs and beliefs in the first level. Reducing EV demand could significantly influence Nd-Fe-B PM demand, as it makes up for approximately one-third of the total EU Nd-Fe-B PM demand in 2030 (ERMA, 2021). Promoting automobile alternatives could reduce this number significantly, although it would require a significant shift in the EU political landscape, with solid lobbying forces from, e.g., the automotive industry [E3, E4]. A policy option suggested by E3 is the promotion of shared mobility and public transportation to reduce EV and Nd-Fe-B PM demand. Improving shared mobility and public transportation in terms of affordability and accessibility will be the shared responsibility of Member States and municipality governance.

Additionally, numerous policies exist for the promotion of the secondary flow of Nd-Fe-B PMs. Currently, scrap generators and predominantly EV motors are currently being shipped to third countries [E1]. Implementing an export ban would effectively prevent the loss of critical REEs (Kumar, 2022; ERMA, 2021; [E1]). This ban would be exceptionally advantageous as it ensures REEs stay in the EU. An EU-wide ban would require an update on the Waste Shipment Regulation (EC) No 1013/2006 by introducing a ban on the export of the EoL Nd-Fe-B PM generators and motors is desirable as it is highly effective and prevents policy misalignment between Member States as individual Member States perhaps consider other options (Kumar, 2022). Implementing a ban should be done with care, as it could have some repercussions for external relations.

In addition, the CRMA obligates PM products to bear a label indicating the type of PM, weight, chemical composition, coating type, and a sequence of steps to remove the PM from the product. However, the magnet grade is not explicitly mentioned in the CRMA (European Commission, 2023-I). In order to improve recyclability, the magnet grade should be added to the label, such as *Figure 7.1*. As it significantly influences the recycling process.

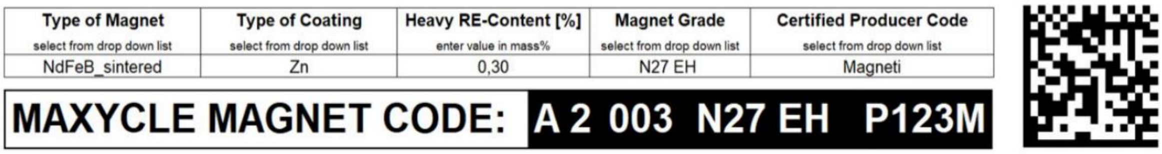

Figure 7.1: *Example of Nd-Fe-B PM labeling Burkhardt et al. (2020)*

Moreover, one of the contributing factors to the low recycling rate of REE is the lack of collection infrastructure. Therefore, Kumar (2022) suggested that Member States could consider, establishing collection targets. They should be based on the net amount of Nd-Fe-B PM generators and motors installed yearly in a given country. Policymakers can gradually increase the target. Proper labeling and monitoring are required for this option.

In addition, integrated components and a lack of standardization make disassembling Nd-Fe-B PMs out of generators and motors challenging (*Section 4.7*). Primarily, EV motors are known to have disassembling issues. Modular designs and designs for disassembly should, therefore, become standardized to increase repair, replacement, and recyclability. This is considered a rigorous approach as it would require manufacturing adaptations, potentially reduce efficiency, and initially increase costs. However, according to E3, in the long term, this approach can kick-start innovation, reduce waste, improve recyclability, and become cost-effective as it reduces disassembly and magnet extraction costs. Enforcement of such standards is done on the EU level. It would require an amendment or expansion of, e.g., the Eco-design Directive No 2009/125/EC, by including requirements for modular designs and designs for disassembly for Nd-Fe-B PMs, motors, and generators. Alternative solutions could be implemented e.g. repairability requirements or extended product warranties [E3].

Furthermore, Kumar (2022) suggests the introduction of Extended Producer Responsibility (EPR) in the EU, a policy approach that assigns the EoL product responsibility to producers and manufacturers. In this case, EV and wind turbine manufacturers. EPRs effectively could make them responsible for the collection, decommissioning/disassembly, magnet extraction, and recycling. Through this responsibility, EV and wind turbine manufacturers will be intrinsically motivated to design for disassembly and organize the appropriate collection and recycling infrastructure. This reduces a significant burden on waste management and recycling companies (Kumar, 2022). EPR should be adopted as an EU-wide policy to prevent Member State policy misalignment. This would require an update of the EoL Vehicle Directive (2000/53/EC). Furthermore, there is currently no specific EU policy regarding the EoL of wind turbines; therefore, the European Commission should introduce a new 'EoL Wind Turbine Directive.' Challenges may arise in ensuring compliance and enforcement, and manufacturers face additional costs for meeting EPR requirements. However, these challenges can be seen as necessary for fostering a more environmentally conscious and responsible industry.

Quota

The European Commission could also effectively support recycling by introducing an obligated percentage to be sourced from secondary materials from wind turbine and EV manufacturers. Similarly as in *Section 7.3.2*. E.g., include it in the Circular Economy Action Plan (European Commission, 2020-II).

Financial incentives

The secondary flow of Nd-Fe-B PMs can also be promoted through price incentives at the Member State level. Incentives for collection, decommissioning/disassembly, magnet extraction, and recycling to foster the secondary flow of REEs. This option aims to create a demand for recycled Nd-Fe-B PMs by regulation or by making the secondary flow cost-competitive with the primary flow. The implementation of price incentives happens on the level of Member States (*Section 7.3.2*), e.g., tax shielding tolerates companies not having to pay revenue tax before they recover their investment (ERMA, 2021); governments could provide low-interest loans to EoL companies to reduce the financial burden and boost investment; provide financial support by subsidizing recycling activities; crediting EoL companies by X-amount of their production cost.

Lastly, the EU could augment its support programs. By e.g., funding R&D Nd-Fe-B PM EoL projects, including decommissioning/disassembly of motors and generators, magnet extraction, and recycling, product longevity R&D and public-private partnership to foster collaboration between the recycling industry, research institutes, and governments by communicating technical and financial burdens. Particularly in the development of large-scale Nd-Fe-B PM recycling technologies.

7.3.4 Supporting Substitution, and REE Content Reduction

Encouraging and promoting the development of dematerialization, and substitution of Nd-Fe-B PMs could significantly reduce supply risk. Dematerialization implies REE content reduction in Nd-Fe-B PMs and substitution shifts to technologies that do not need REEs altogether. More R&D is needed for substitutes to compete with the unique properties of Nd-Fe-B PMs (*Section 6.4*). Policies can be divided between financial incentives, regulatory incentives, and support programs. Several possibilities exist for providing financial incentives for Nd-Fe-B PM alternatives. Price incentives can more aggressively push alternative technologies. Important to consider are efficiency losses compared to Nd-Fe-B PMs, potential problem shifting to other CRMs, and policy alignment with all Member States. Several suggestions are presented and can co-exist with each other.

Incentives could include installing dematerialization requirements by, e.g., setting targets to reduce REE content [E5]. Which possibly decreases the efficiencies of wind turbines and EVs. Furthermore, the EU could direct Member States into the use of fiscal policies, similarly as in *Sections 7.3.2* and *7.3.3*. Firstly, the suggested REE content taxation. Secondly, subsidizing companies that use alternative technologies, e.g., gearbox double-fed induction generator wind turbines and induction motor EVs. Thirdly, tax credit alternative technologies by X amount of the production cost. Fourthly, introducing tax shielding, which tolerates companies not having to pay revenue tax before they recover their investment (ERMA, 2021). Fifthly, governments could provide low-interest loans to companies developing alternative technologies to reduce the financial burden and boost investment.

Lastly, the EU could expand its support programs by, e.g., EU grants awarded to REE dematerialization and substitution projects. Horizon Europe, the European Innovation Council fund[1], and EIT Raw Materials are all already funding these projects. The EU and its Member States should allocate more budget to encourage these R&D projects. Moreover, public-private partnerships should foster collaboration between the industry, research institutes, and governments by communicating technical and financial needs and burdens [E1, E2, E3, E5].

7.3.5 Improving Monitoring and Stockpiling

Secondly, according to most experts, the need for strategic stockpiling is evident [E1, E3, E5, E6]. Strategic stockpiling increases supply chain resilience by reducing the impact of short-term supply disruptions. EU has encouraged its Member States to improve their monitoring capacity. Only Germany and France monitor their industries' CRM supply (European Commission, 2023-III). Furthermore, the EU has established no stringent stockpiling benchmarks because it is confidential data, and the EU advocates the free movement of materials [E2, E4]. Although stockpiling will disrupt the market, it could function as a short-term supply disruption insurance [E2]. E1 and E3 highlighted that the public sector should be responsible for organizing strategic stockpiles, as one could not take SMEs responsible for geopolitics. These stockpiles should exist out of Nd-Fe-B PMs, and public-private partnerships should discuss the quantities, types of magnet, and the timeframe of the stocks (e.g., three months of Nd-Fe-B PM supply per country).

[1] The European Innovation Council fund is a specific fund for high-potential innovative scale-ups that drive EU economic growth.

7.4 Concluding remarks

This chapter covered **SQ4:** *How can institutional interventions enhance the autonomy in the EU regarding access to REE, and who is responsible?*

Achieving greater autonomy for the EU in the realm of REEs demands a comprehensive approach, and is likely to be incredibly challenging. Therefore, a synergistic blend of the five strategies, along with the suggested institutional interventions, becomes imperative. Furthermore, it is crucial to traverse policy concerns considering the EU's commitment to a liberal market and adherence to WTO agreements [E2, E4]. Striking a delicate balance is paramount, as policies should not inadvertently jeopardize international dialogue or escalate resource nationalism. The formulation of such policies requires a nuanced approach to align economic interests with global trade principles and collaborative frameworks.

First of all, the European Commission should contemplate enhancing the CRMA by introducing sub-benchmarks per individual CRM and domestic manufacturing benchmarks for Nd-Fe-B PMs. Additionally, it is crucial for the EU to extend its policy horizon beyond 2030, given the long-term impacts of most proposed options. Essential is establishing adequate incentives for Member States, industry, and companies to diversify their supply and foster the development of domestic supply and recycling capacity, circular practices, and technological substitutes for Nd-Fe-B PMs. A key consideration is that without a pre-established demand, potential customers may refrain from purchasing or investing in EU, or strategic allied produced REEs. Regulations such as; implementing product longevity standards, dematerialization requirements, requirements for modular designs and designs for disassembly (for EV motors, wind turbine generators, and Nd-Fe-B PMs), implementing import tariffs, and local sourcing requirements are effectively incentivizing the market. However, such regulatory measures increase production costs and potentially reduce efficiencies without compensating the manufacturers. Financial incentive structures, especially OPEX subsidies effectively reduce production costs and stimulate the competitiveness of EU-made materials. The downside is that they could foster resource nationalism, and fiscal policies vary among EU Member States. Therefore, policymakers should carefully strike a balance between financial and regulatory incentives, carefully weighing their effectiveness, and implications, and ensuring alignment across the EU.

Expanding funding programs and public-private partnerships for internal capacity, circularity, and substitution will be needed. Fostering collaboration between the industry, research institutes, and governments by communicating technical and financial burdens and expanding funding programs accordingly is crucial for advancing innovation, accelerating research initiatives, and driving sustainable development in the targeted domains.

Implementing the CRMA, and the institutional interventions requires significant financial backing and the implementation of robust incentive structures to encourage investment and consumption. While a substantial part of this responsibility lies with individual Member States, it is crucial for the European Commission to clearly define incentive frameworks. Effective communication at the EU level is imperative to establish policy alignment and mitigate the risk of creating an uneven playing field internally. A strategic approach should ensure that incentives are coordinated, transparent, and collectively contribute to the overarching goal of strategic autonomy, preventing disparities and fostering a harmonized policy landscape across the EU.

In summary, the majority of institutional interventions are strongly recommended. Some interventions require more careful consideration. Policymakers must carefully assess the desirability of regulatory measures and financial incentives. Regulatory measures tend to introduce more market interference, potentially negatively impacting EU competitiveness. However, they offer the advantage of being implementable across the entire EU and are effective in creating a level playing field. Meanwhile, financial incentives are tailored to specific Member States but prove highly effective in fostering a competitive EU REE market. It is vital to note that the approach here is not a binary choice between strategies; rather, it necessitates the integration of a synergistic blend of the five proposed strategies. Numerous possibilities exist, extending beyond the specific institutional interventions outlined in *Figure 7.2*.

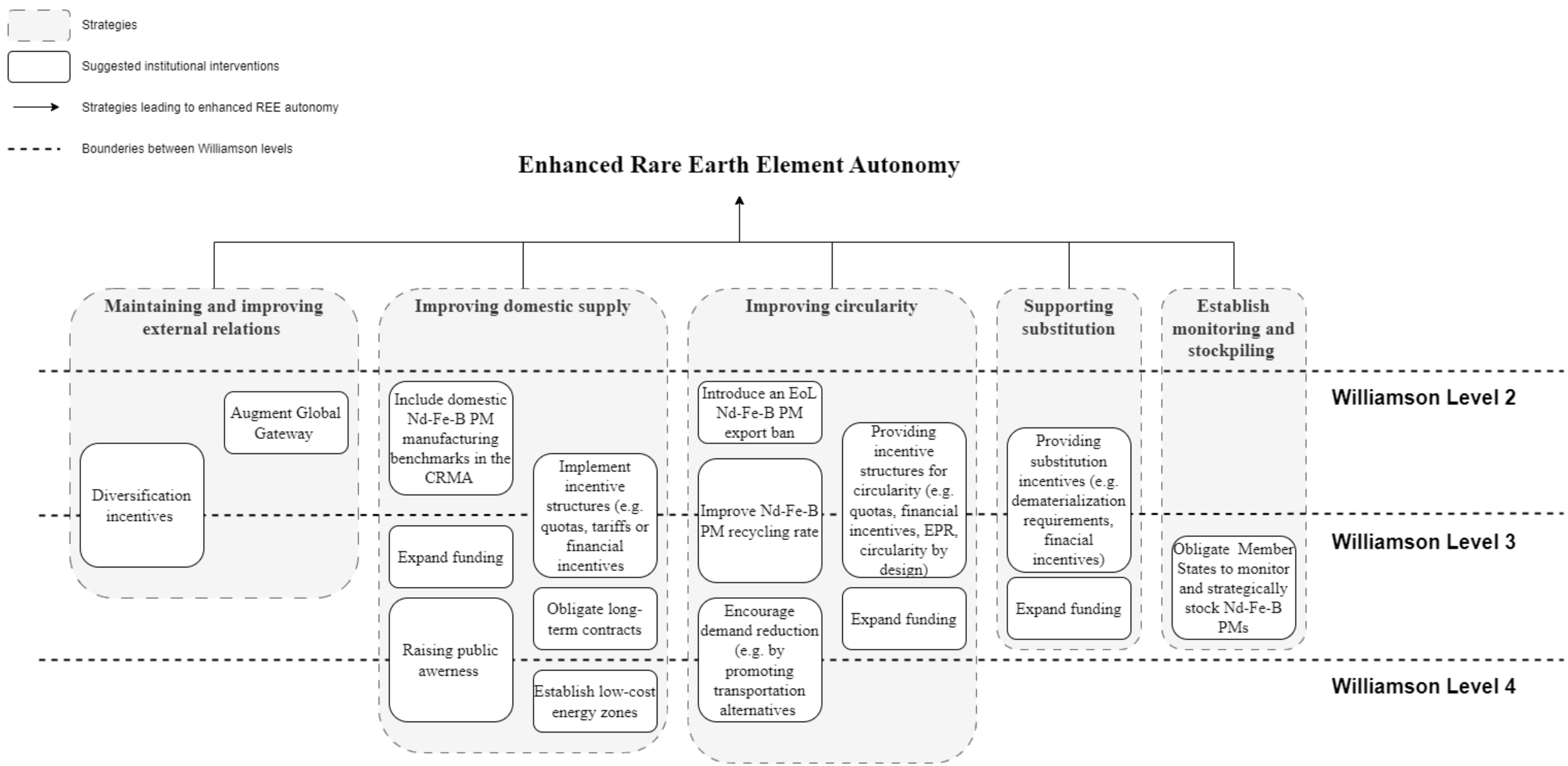

Figure 7.2: *Proposed institutional interventions*
* The means of the incentives structure determines the level of Williamson

8. DISCUSSION

This chapter critically reflects and discusses the implications of this research. This includes societal and scientific implications and a reflection on the potential limitations of this research. Finally, some recommendations are given for both further research and policy.

8.1 Reflection

8.1.1 Reflection on the Theory

Presently, institutional interventions are proposed based on the analyses conducted in *Chapters 4* through *6* and insights gathered from expert interviews. However, a critical shortcoming lies in the absence of theoretical tools for both formulating and assessing the desirability of these institutional interventions. While the Williamson framework effectively structures and elucidates existing institutions, it falls short in furnishing the necessary tools for the establishment and design of interventions. Nevertheless, there is potential utility in other aspects of Williamson's (1998) work, particularly in make or buy decisions, vertical integration, contracting, and transaction coordination, as some identified interventions align with Williamson's insights. Importantly, it should be emphasized that Williamson's focus primarily centers on enterprise dynamics, creating a gap in understanding government operations. Nonetheless, leveraging Williamson's broader insights offers a valuable opportunity for the European Commission to make informed strategic decisions.

For instance with the implementation of strategic stockpiling. Where a shift from market dynamics emphasizing efficiency and just-in-time practices to a contemporary call for heightened supply resilience. Nd-Fe-B PMs, being critical components with unique properties across various industries, exhibit high asset specificity. Furthermore, SMEs, in particular, cannot bear sole responsibility for strategic stockpiling due to its geopolitical implications. Consequently, a public responsibility emerges if Williamson’s ‘simple contracting schema extended’ is followed. The determination of whether strategic stockpiling should be regulated or administered through a public bureau—an organizational entity within the public sector handling specific government functions—hinges on a comprehensive evaluation of various factors (Williamson, 1998). This includes considerations of efficiency, accountability, and the ability to navigate geopolitical intricacies effectively. Ultimately, drawing on Williamson's insights provides a valuable lens for the European Commission to weigh the merits of regulatory measures versus the establishment of a dedicated public bureau in the context of strategic stockpiling.

In addition, retroactively Jaag & Trinkner’s (2011) work could have been an invaluable resource, presenting a comprehensive framework for regulation tailored for network industries. Despite sharing some characteristics with network industries, the REE and Nd-Fe-B PM value chain does not exhibit the robust network effects and high interconnectedness akin to power systems or telecommunication networks, the framework can still be useful, as it provides a toolkit for assessing the desirability and nature of regulation. The framework provides systematic guidelines on when and how to regulate, offering a nuanced understanding of different types of market failures and their appropriate regulatory remedies.

Observant readers may have noticed the absence of level 1 interventions in *Chapter 7*, despite their crucial significance. As discussed in *Section 3.1* the embeddedness level of the Williamson framework includes informal institutions such as the customs, traditions, and norms around the EU's REE system. Beliefs, norms, and customs are deeply embedded in a society’s culture. These shared behaviors and beliefs shape the values and preferences of the community. As a result, this creates social pressure and expectations. Biber et al. (2017) emphasized that transitions in social norms would be more effective for changing the community's behaviors and beliefs, and these transitions can even influence the political feasibility of other legal changes for the REE system. At the same time, Williamson (2000) argues that formal rules can influence informal ones.

Likewise, Biber and Ruhl (2014) suggest that formal rules (in the form of laws) can shape social norms. Williamson (2000) visualized this by creating a direct top-down and indirect bottom-up relationship, visualized by the dotted arrow in *Figure 3.1*.

"Belief systems must change for successful reform since it is the mental models of [political] actors that will shape choices" – (North, 1994p. 366).

So, there is a complex relationship between formal and informal institutions. However, it seems clear that transformations in the embeddedness level will help the transformations in lower levels of the Williamson framework, and some even argue that changes in the embeddedness level are necessary.

In the context at hand, noteworthy shifts in the embeddedness level involve the EU's structural supply dependencies and their vulnerability to adverse effects during crises, vividly illustrated by the disruptions caused by the COVID-19 pandemic and the energy crisis stemming from the Russian-Ukrainian war. These events challenge entrenched EU beliefs in open markets, promotion of globalization, and the "Wandel durch Handel" ideal—German for "change through trade." The Russian aggression demonstrated that interdependencies do not inherently act as guarantors of peace. This fundamental change in the EU's belief system shapes the presented institutional interventions.

Amidst a shift from a unipolar to a multipolar world order, uncertainties loom over which strategic blocks will dominate, encompassing e.g. the US, China, Russia, India, and the EU. The EU's role remains ambiguous as it is primarily designed as an economic union rather than a geopolitical force. Marking a historical first, the EU is formulating industrial policies such as the NZIA and the CRMA, raising questions about its effectiveness as a geopolitical entity. The evolving global landscape prompts contemplation on how the EU will navigate this transition and assert its (‘open strategic’) autonomy in an increasingly complex geopolitical arena.

8.1.2 Reflection on the Methodology

The combination of a comprehensive literature review, meticulous desk research, and insightful interviews culminated in triangulation and robust data validation. This multifaceted approach provided nuanced insights into the intricacies of the subject, shedding light on the REE value chain, stakeholders, institutions, and PESTEL factors. The decision to incorporate expert interviews has proven to be exceptionally beneficial, providing irreplaceable fresh perspectives, reinforcing triangulation efforts, and offering invaluable policy suggestions.

This comprehensive methodology employed a multifaceted approach, encompassing a value chain, stakeholder, institutional, and PESTEL analyses to provide a holistic understanding of the REE system in the EU. *Chapter 4* delved into the value chain, *Chapter 5* analyzed stakeholder and institutional factors, and *Chapter 6* explored PESTEL influences. By analyzing the political, economic, socio-cultural, technological, environmental, and legal factors in *Chapter 6*, this study gains a nuanced understanding of the external influences that shape the REE system in the EU. Without the incorporation of these external dynamics, it would be challenging to grasp the intricacies of the geopolitical situation and assess the current landscape of technological substitutes. The PESTEL analysis added valuable insights to the overall examination, shedding light on potential geopolitical shifts, regulatory changes, and emerging technologies that could significantly impact REE autonomy. This broader perspective enhanced the analysis's robustness, ensuring that policy interventions are not only well-informed regarding current challenges but also adaptable to the evolving external environment.

As discussed in *Section 8.1.1* external reliability of *Chapter 7* could be improved if a theoretical framework for regulation was used (e.g. Jaag & Trinkner, or Williamson’s insights on coordinating contracting and transactions). Moreover, enhancing this study with a clear cost-benefit analysis and scenario analysis for policy implementation would contribute to its overall quality.

8.1.3 Reflection on the Results

This study adopted a thoroughly explorative approach, employing diverse methods and analyses that yielded a comprehensive array of results. The primary focus was on outlining recommendations for the European Union and exploring potential governance instruments. It is important to note, however, that the results do not offer exhaustive insights into the actions the industry itself should undertake.

As discussed, the term 'open strategic autonomy' is inherently ambiguous, encapsulating both the EU's aspiration for strategic autonomy and its simultaneous recognition of the ongoing dependence on external parties. This becomes particularly evident given the EU's foundational philosophy centered around the free movement of goods. It's crucial to note that the EU originated as a trade association and, to a considerable extent, remains more focused on trade dynamics than on geopolitical considerations. This duality poses challenges in implementing policies that balance autonomy with economic interdependence, and it necessitates a careful examination of the potential implications for the EU's overarching goals and strategies. Furthermore, increasing nationalism and protectionism in the EU internally could hamper the EU's attempts to perform as a geopolitical entity.

The suggested design interventions attempted to account for this ambiguity. The five strategies are independently implementable from each other. Nevertheless, it should be imperative that a synergistic blend of them would result in the most favorable result – meaning, the most significant increase in autonomy, supply resilience, and material security regarding the access of REEs and Nd-Fe-B PMs.

Within the strategies, numerous policy mixes, and priorities exist. This study does not provide the methodology for establishing policy priorities or a comprehensive action plan. However, with the insights from the results, it became clear that the EU will still rely on third-party REE supplies for the foreseeable future. Establishing significant domestic mining, processing, manufacturing, and recycling capabilities takes considerable amounts of resources and time (e.g. mining lead times of 10 – 20 years). Furthermore, it became clear that supply diversification can be achieved in the short term, as Japan has shown (*Section 6.1*). However, in the EU, supply diversification alone is likely to insignificantly improve autonomy, as China basically holds monopolies on REE processing and Nd-Fe-B PM manufacturing, so the EU is unlikely to import less than 65 percent from China by 2030 (CRMA benchmark, *Section 5.2.1.2*). Moreover, increasing supply resilience through strategic stockpiling is strongly suggested, as it prevents short-term supply disruptions from happening. However, this strategy does not account for the medium and long-term supply disruptions. Contrastingly, improving circularity in the Nd-Fe-B PM value chain will increase medium to long-term autonomy by simply lowering material demand, and improving the secondary flow of materials. However, the strategy that arguably holds the potential for the most significant impact on REE autonomy, albeit independently, is the substitution of Nd-Fe-B PMs. Despite the unique properties of REE applications, especially their preference for EV motors and offshore wind turbine generators, economically viable alternatives exist for both of these crucial applications. Actively advocating for and promoting alternative REE options such as IMs for EVs and GB-DFIGs for wind turbines has the potential to present a comprehensive solution to the challenge at hand (*Section 6.4*).

"An energy transition without REEs is perfectly possible" – E5

However, it should be noted that an energy transition without REEs is probably not desirable as substitutes experience a loss in performance, as efficiency drops, and potentially create new CRM dependencies. Design choices are an interplay between costs, performance, and supply security. The majority of the market currently still prefers Nd-Fe-B PMs for both applications. Moreover, the question of whether and to what extent the government should intervene in the free choice of technologies remains open for debate.

Furthermore, the feasibility of the proposed interventions within each strategy could raise some doubts, both in terms of economic and political viability. Potential issues may arise during policy implementation, particularly concerning internal fiscal policy alignment. It is crucial not to overestimate the power of the EU as an institution, as its role primarily involves providing guidelines and support structures to Member States and companies.

As highlighted in *Section 8.1.1*, the EU's design is not inherently geared toward geopolitical endeavors, potentially posing challenges to the pursuit of open strategic autonomy and the successful implementation of interventions. Fiscal misalignment could detrimentally impact the single market. While bridging the level playing field with global players like the US and China is a formidable task, achieving internal alignment within the EU is perhaps an even more challenging endeavor. Furthermore, the implementation of incentive structures and the prohibition of End-of-Life Nd-Fe-B PM exports may inadvertently heighten resource nationalism in third countries.

To summarize, for the best result immediate action is required for all the five strategies. Nevertheless, supply diversification, substitution, and stockpiling offer effective short to medium-term solutions, whereas the establishment of domestic supply and the implementation of significant recycling present sustainable yet long-term resolutions.

8.2 Implications

8.2.1 Scientific Contribution and Theoretical Implications

As mentioned in *Section 1.4*, there was a lack of comprehensive research regarding EU REE autonomy and the implementation of the CRMA. This study provided a new understanding of this domain by holistically performing REE actors, institutions, value chains, and PESTEL factor analysis. The combination of these four analyses together with expert interviews offered a multifaceted insight into the complexities and interactions within this domain. Moreover, the illumination of various perspectives enhanced the overall comprehensiveness and facilitated a more holistic view of the EU's quest for open strategic autonomy.

To the best of one's knowledge, no study combined analyzed stakeholders, institutions, value chain, and PESTEL factors on REEs and the market of Nd-Fe-B PMs to make a set of institutional interventions. This contributes to a further understanding of institutional development's role in the research field of CRMs, REEs, and Nd-Fe-B PMs.

In this thesis, the Williamson framework provided the necessary structure for the institutional analysis and the developed institutional interventions. Consequently, this study makes a noteworthy contribution to the field of institutional economics by offering a practical case and emphasizing the efficacy of the Williamson framework.

8.2.2 Societal Implications

First of all, this thesis could help in the quest for EU material security for the energy transition, as the research addressed how the EU could improve its autonomy regarding access to REE for achieving material security in the context of the energy transition. The actor, institution, value chain, and factor analyses pointed out the main issues in the REE system. Thereafter, institutional interventions were developed to help overcome some of the identified issues in the earlier analyses. Political and industrial decision-makers could use this research's findings and institutional interventions to inspire their policy-making. Furthermore, this research contributed to establishing more awareness regarding the problem's urgency by publishing it to the TU Delft repository and spreading and discussing the findings with friends, family, and fellow students.

The restructuring of supply was a recurring theme during the expert interviews. As a consequence of the Russian-Ukrainian war, the COVID-19 pandemic and the European energy crisis led to a shift of the embedded beliefs in open and free markets in the EU. E1 even calls the current situation "*a new Cold War*" and "*the end of globalization*." She emphasized, just as almost all other respondents, that this would have far-reaching consequences for society. Furthermore, current EU policies, such as the diversification of supply through strategic partnerships with like-minded countries, are expected to intensify further the tendency of global block-building (Hool et al., 2023). A deglobalized world has enormous implications for the Nd-Fe-B PM value chain, as 94 percent of the global supply is manufactured in China alone.

Thereby posing a significant risk of Chinese exploitation of this dominance; they could, e.g., flood the EU market with low-priced Nd-Fe-B PMs, affecting EU competitiveness, impose trade restrictions, low production quotas, or ban REE and magnet exports altogether (Carrara et al., 2023), which all would hamper the energy (and digital) transition in the EU.

Furthermore, this study poses questions about the feasibility of the current 2030 benchmarks of the CRMA for REEs, especially for recycling [E1, E3, E5, E6, E7]. Therefore, this research further highlights the necessity of custom-made REE-specific and realistic targets, including looking beyond 2030.

Current EU policies are predominantly focusing on supply security and supply-side policies. According to E3 and E7, policies should shift their emphasis to the demand side instead. Both respondents highlighted the need for 'de-growth' and shifting policy focus to "*refuse, rethink, reduce, and repair*" instead of recycling alone. E7 encourages us to make a distinction between what we need and what we want as a society.

"We have to ask ourselves in policy a wider question: where are we trying to get to? Are we trying to keep the growth show on the road?"- E7

If implemented, this would have significant repercussions for society, requiring a shift in consumption habits, transportation norms, energy needs, and manufacturing. E3 specifically advocates for shared mobility and public transport investments to make individual car ownership obsolete. Moreover, proposing generator and motor designs prioritizing modularity and enhanced repairability could redefine how technology is manufactured and maintained. For instance, making these technologies more disassembly-friendly could significantly extend their lifespan and reduce waste. Metabolic et al. (2021) highlight the potential of a rigorous shift to demand-side policies, as implementing a combination of circular strategies could drop EU demand for Nd from 15 percent to 1.1 percent of the global demand for PMs used in EV motors and wind turbine generators. Therefore, while demand-side policies show promise in addressing critical issues related to REEs, policymakers must comprehensively address and navigate their societal repercussions.

Additionally, this study identified many uncertainties concerning establishing domestic supply capabilities in REE mining, processing, recycling, and magnet manufacturing. It became evident that significant industrial policies and institutional interventions are required to address these uncertainties, as the free market alone is likely to be incapable of resolving these challenges by itself [E1 – E7].

8.3 Research Limitations

The first and most eminent limitation of this study is rooted in the institutional interventions of *Chapter 7*. The researcher conducting this thesis lacks a comprehensive and complete understanding of the intricate nature of this system and the myriad of organizations affected by these interventions. Dozens of EU and Member State policy officials are actively engaged in similar topics, making it presumptuous to assume that a single master's student could possess superior knowledge compared to their collective expertise. However, to mitigate this research limitation, expert interviews were conducted to gather more in-depth insights on this topic. These interviews provided detailed perspectives on the current constraints impacting European autonomy in REEs and Nd-Fe-B PMs and gave their opinions on potential policy interventions. Nevertheless, the suggested interventions should be viewed as indicators of policy possibilities. A more nuanced and comprehensive evaluation of institutional interventions is crucial.

Secondly, as indicated in the methodology section, only seven interviews have been conducted due to limited time, making it harder to generalize the findings and lower the external validity of the research. Moreover, more diverse respondents could lead to additional results and reduce biases.

Thirdly, in this thesis, predominantly in *Chapter 4,* the REE value chain analysis, a multitude of sources are used. This could potentially have led to data inconsistencies or discrepancies. To mitigate for these risks, data is often cross-verified from different sources, and found discrepancies and variations are explained.

Fourthly, *Chapter 5* introduces the REE system, which might be perceived as superficial and lacking depth, e.g., the limited comparison of the policies by only accounting for the US, China, and the EU. This analysis prioritized what was perceived as the most relevant actors and policies. Consequently, this may have led to the exclusion of other significant actors and policies. Furthermore, there's some redundancy across the four analyses, notably concerning the CRMA and certain REE value chain activities. To avoid such overlap, the four analyses have been meticulously scoped, and the inclusion of section references aims to prevent redundancy and aid in navigating between relevant sections.

Fifthly, *Chapter 6* discusses constraining and enabling factors for European REE autonomy. It is crucial to acknowledge that within the intricate system of REEs in the EU, numerous additional variables contribute, which this study may not encompass due to its focus on the most apparent and seemingly pivotal factors. Additionally, this study is grounded in present understanding and current demand scenarios, assuming no substantial technological advancements or shifts in demand. Furthermore, the distinction between an enabling and constraining factor might be oversimplified, as certain elements, like environmental regulations, high REE-prices, and escalating geopolitical tensions, blur the line between their enabling or constraining influence.

Sixthly, this thesis was compiled in 2023; the rapid evolution of technology, industry, and policies in the CRM system could mean that the information presented here might not perfectly represent the current landscape (anymore) as policies are being developed at the time of writing.

9. CONCLUSION

The objective of this research was to investigate the measures implemented by the EU to enhance its REE supply chain autonomy within the context of the EU's energy transition and to identify potential additional measures that can be taken to strengthen this strategy. This research aimed to identify institutional interventions to improve the EU's REE autonomy. This chapter uses perceptions from the analyses and expert interviews to answer the sub-questions and form an adequate answer to the main research question.

9.1 Answering the Sub-Questions

SQ1: *How is the global REE and Nd-Fe-B PM value chain constructed, and what are the main issues?*

This study delineates seven main value chain stages. The primary challenge of the REE value chain is the pre-eminence of China's control across all its stages. Notably, 87 percent of all the global REOs and 91 percent of the REEs are processed, and 94 percent of Nd-Fe-B PM manufacturing happens in China. China's vast influence extends downstream, particularly in Nd-Fe-B PM production, wind turbine, and EV manufacturing. Given China's dominance, future shifts in their control seem unlikely due to their well-established industry scale. The critical issues identified include single-country dependency, rising demand for Nd-Fe-B PMs, challenges in recycling and circular design, obstacles in new project establishment, including high cost, stringent environmental regulations, and the need for skilled labor. These concerns, primarily concentrated during the processing stage, underscore the complex barriers to achieving a resilient REE value chain.

SQ2: *What is the current state of the rare earth element system inside the European Union, and how do existing institutions and stakeholders influence the system?*

Existing stakeholders and institutions heavily influence the current state of the REE system within the EU. Fifteen main stakeholder types were identified, and numerous policies and institutions were analyzed. *Chapter 4* highlighted Chinese dominance in the upstream REE market. The global REE landscape revolves around three major geopolitical entities: the EU, China, and the US. China's longstanding strategic focus, encompassing credit lines, subsidies, partnerships, geopolitical influence, technology, infrastructure, and regulatory flexibility, has secured its pre-eminence. The US is actively endeavoring to catch up, recognizing the strategic significance of REEs, while the EU, too, acknowledges the imperative of strategic autonomy and has initiated measures such as the CRMA and the NZIA. CRMA and NZIA creating benchmarks, simplifying permitting procedures, focusing on sustainability, circularity, and risk mitigation. However, criticized for its vagueness in terms of implementation, unfeasible benchmarks, challenges in private investment, fiscal alignment, and levelling the playing field.

SQ3: *What are the main factors and developments, influencing the EU's REE autonomy?*

The research on the main enabling and constraining factors influencing the EU's autonomy regarding REEs reveals a complex landscape. Geopolitical tensions and resource nationalism potentially hinder the EU's access to REEs, notably due to strained trade relations between the US and EU with China. However, the growing awareness of the need for an open, strategic, autonomic EU and the legislation in the form of the CRMA stand as significant enabling developments. The legislation sets benchmarks, simplifies permitting procedures, and focuses on sustainability and circularity, although it faces challenges in its implementation, such as bureaucracy and lack of fiscal alignment. The viability of REE projects in Europe depends on actual 'EU-made' demand and overcoming the lack of a level playing field with other global markets. The issue of resource nationalism, substitution difficulty, and the high energy and material needs in Europe compound these challenges.

SQ4: *How can institutional interventions enhance the autonomy in the EU regarding access to REE, and who is responsible?*

The existing EU policy mitigates dependencies by Maintaining and improving external relations, Establishing domestic supply, Improving circularity, Supporting substitution and alternative solutions, and Monitoring and stockpiling. This study identified challenges for each strategy and provided institutional interventions to elucidate them, it can furthermore be concluded that all the five strategies are imperative for significant autonomy enhancement.

Firstly, introducing supply diversification incentives, in order to effectively stimulate private demand for diversified supply. Furthermore, the augmentation of strategic partnerships with REE-rich, EU-friendly countries.

Secondly, for the establishment of domestic supply capabilities, it is crucial to introduce regulations that incentivize companies to embrace internal capacity, as there is a lack of demand for domestic extraction, processing, manufacturing, and recycling. These regulations should aim to level the playing field between the EU, China, and the US. Furthermore, the inclusion of a Nd-Fe-B PM domestic manufacturing benchmark in the CRMA, raising public acceptance, expanding funding, standardizing long-term contracts, and introducing low-energy zones should all help the EU establish a competitive internal REE capacity.

Thirdly, a circular strategy should encourage effective Nd-Fe-B PM demand reduction. Furthermore, EoL practices such as EV motor, and wind turbine generator disassembly, Nd-Fe-B PM collection, and recycling should all be incentivized by including magnet grade as a CRMA PM labeling requirement, establishing Nd-Fe-B PM collection targets, providing incentive structures for circularity, standardize circularity by design, introducing extended producer responsibility, and expand support programs. Lastly, the introduction of an export ban on EoL Nd-Fe-B PMs should effectively prevent existing secondary sources from being relegated as scrap to third countries.

Fourthly, manufacturers in the EV and wind turbine sectors (especially in offshore applications) exhibit a preference for Nd-Fe-B PM applications owing to their distinctive properties. These properties, such as higher efficiency, increased durability, and lower operating costs, tend to outweigh the initial associated expenses. Therefore, increased funding for more R&D and innovation for substitutes is desirable. Moreover, substitutes could be incentivized.

Fifthly, presently, there exists a notable deficiency in communication, transparency, and clarity among industry stakeholders, Member States, and the EU regarding strategic stockpiling. The responsibility for this crucial task remains ambiguous, and there is a lack of precision regarding the specific quantities and types of materials deemed necessary for effective strategic stockpiling. Therefore, the EU should investigate obligation possibilities for Member States to monitor and strategically stock Nd-Fe-B PMs.

9.2 Answering the Main Research Question

How can the European Union improve its autonomy regarding its access to rare earth elements for achieving material security in the context of the European Union's energy transition?

Several overarching institutional interventions accelerate the general progress of achieving strategic autonomy. These include introducing sub-benchmarks per individual CRM, improving understanding within governmental entities, increasing overall investment, and acknowledging the criticality for the EU to extend its policy horizon beyond 2030, given the long-term impacts of most proposed interventions.

To incentivize supply diversification and internal capacity development, policymakers should carefully consider implementing regulations such as product longevity standards, dematerialization requirements, and import tariffs. While these measures may effectively incentivize the market, financial structures, particularly OPEX subsidies, are effective in reducing production costs. However, policymakers must tread cautiously, considering potential downsides such as resource nationalism and fiscal policy variations among Member States. Expanding funding programs and public-private partnerships is essential for advancing innovation and sustainable development.

Implementing the CRMA, and the institutional interventions requires significant financial backing and the implementation of robust incentive structures to encourage investment and consumption. While a substantial part of this responsibility lies with individual Member States, it is crucial for the European Commission to clearly define incentive frameworks. Effective communication at the EU level is imperative to establish policy alignment and mitigate the risk of creating an uneven playing field within the EU itself. A strategic approach should ensure that incentives are coordinated, transparent, and collectively contribute to the overarching goal of open strategic autonomy, preventing disparities and fostering a harmonized policy landscape across the EU.

With these insights, policymakers can improve open strategic autonomy regarding access to REEs in the EU and its Member States while dealing with the complexities of the EU's REE and Nd-Fe-B PM system.

9.3 Recommendations

The findings of this study hold particular relevance for three primary knowledge user groups: policymakers, companies, and, based on the outlined limitations in *Section 8.3*, recommendations are offered for future research.

9.3.1 Recommendations for Policymakers

The European Commission and EU Member State policymakers are strongly urged to earnestly consider the presented institutional interventions and the insights derived from this study. They are advised to actively refine and implement these interventions to improve the EU's autonomy regarding REEs.

9.3.2 Recommendations for Companies

In light of the thesis findings, a robust recommendation is made for Nd-Fe-B PM users, including manufacturers of wind turbines and EVs, to adopt a more strategic approach to supply security, taking inspiration from initiatives such as Tesla's (*Section 6.4*). In the contemporary geopolitical landscape, companies ought to consider not only price and performance but also prioritize the assurance of a stable supply.

9.3.3 Recommendations for Future Research

This thesis has yielded valuable insight that can pave the way for future research. The findings not only lay the groundwork for expanding upon the current work but also open avenues for exploring new and uncharted areas of research. This section discusses these avenues for further research.

Firstly, future studies could delve even deeper into the complexities of the specific institutional systems involved, as adopting institutional interventions has vast implications on geopolitics, the global economy, society, and the environment. This could be achieved by enhancing the findings' generalizability by extending the scope and the quantity of expert interviews, including more industry experts, policy officials, and other stakeholders.

Secondly, the rapidly evolving nature of this research domain asks for continuous updates of the findings. Moreover, a more nuanced and comprehensive approach to studying the constraining and enabling factors for the EU REE autonomy should be pursued, including considering variables beyond the most apparent factors. Consistent forecasting of potential technological advancements and shifts in demand would provide policymakers with the most accurate findings.

Thirdly, *Chapter 5* could be expanded by adding more policies, actors, and countries into the institutional and stakeholder analysis. Resulting in a more complete perspective of the global REE system and its dynamics.

Fourthly, there is currently a deficiency in comprehending the cost implications of attaining open strategic autonomy. Subsequent studies could thus center on scrutinizing the costs linked to the recommended institutional interventions, including the pathways for Nd-Fe-B PM substitution. Such an analysis would not only offer a more transparent understanding of the desirability of various options but also provide a definitive answer on whether the additional costs and supply risks associated with Nd-Fe-B PMs are justified.

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APPENDIX A

Table A1: *Research approaches and their comparison with the chosen qualitative approach.*

RESEARCH APPROACH	ARGUMENTATION
CASE STUDY	The case study approach consists of an in-depth analysis of a specific case. Although this approach provides contextual and qualitative understanding, it would probably lack in generalizability, since it is perhaps not be able to capturing the bigger picture and dynamics with regards to the REE market.
QUANTITATIVE	A quantitative approach could provide this research with valuable information as it is a great tool for evaluation, and identification of patterns and relationships. However, a quantitative approach alone is likely to lack stakeholder perspectives and qualitative insights.
EXPLORATORY	The exploratory research approach is also not a perfectly suited as there is no lack of theory, and the problem is already quite clear. Moreover, this approach lacks the systematic analysis that is required to address the complexity of the EU's REE dependency issue.
MODELLING	A design approach has the potential to generate innovative ideas and recommendations. However, relying solely on a design approach without a comprehensive analysis of the current state of the market and the feasibility of different options may result in less informed and less effective policy options. Furthermore, designing a strategy will be too demanding for this project.
DESIGN	A design approach has the potential to generate innovative ideas and recommendations. However, relying solely on a design approach without a comprehensive analysis of the current state of the market and the feasibility of different options may result in less informed and less effective policy options. Furthermore, designing a strategy will be too demanding for this project.

Table A2: *All REEs with their application (EPA, 2012)*

ELEMENT	ATOMIC NUMBER	INDUSTRY	APPLICATION
SCANDIUM	21	Aerospace, lightning	Metal alloys in the aerospace industry, additives in mercury-vapor lamps, and metal halide lamps.
YTTRIUM	39	Lightning, medicine, defense, clean energy	Metal alloy, microwave communication for satellites, fuel efficiency, color televisions, computer monitors, temperature sensors, ceramics
LANTHANUM	57	Clean energy, catalyst, glass	Batteries, EV batteries, digital cameras, laptop batteries,
CERIUM	58	Catalyst, lightning	Lens polishes, metal alloy, catalyst
PRASEODYMIUM	59	Magnets, lightning, laser, glass	Improves magnet corrosion resistance/wind energy, searchlights,
NEODYMIUM	60	Magnets, laser, glass, clean energy	High-power magnets/wind energy
PROMETHIUM	61	Luminous paint, nuclear batteries	
SAMARIUM	62	Magnets, lasers, neutron capture	High-temperature magnets,
EUROPIUM	63	Lightning, lasers	Liquid crystal displays (LCDs), fluorescent lighting
GADOLINIUM	64	Clean energy, catalyst, lightning, magnets	Electrolyte for solid oxide fuel cells
TERBIUM	65	Magnets, clean energy, lightning, laser, defense	Used for wind energy
DYSPROSIUM	66	Magnets, clean energy, lasers, hard disk drives	High-power magnets/ wind energy
HOLMIUM	67	Lasers, magnets	Highest power magnets known
ERBIUM	68	Infrared lasers, fiber-optic	
THULIUM	69	Lightning, lasers	
YTTERBIUM	70	Infrared lasers, nuclear medicine, monitoring earthquakes	Portable X-ray units
LUTETIUM	71	Lightning, catalyst,	LED light bulb

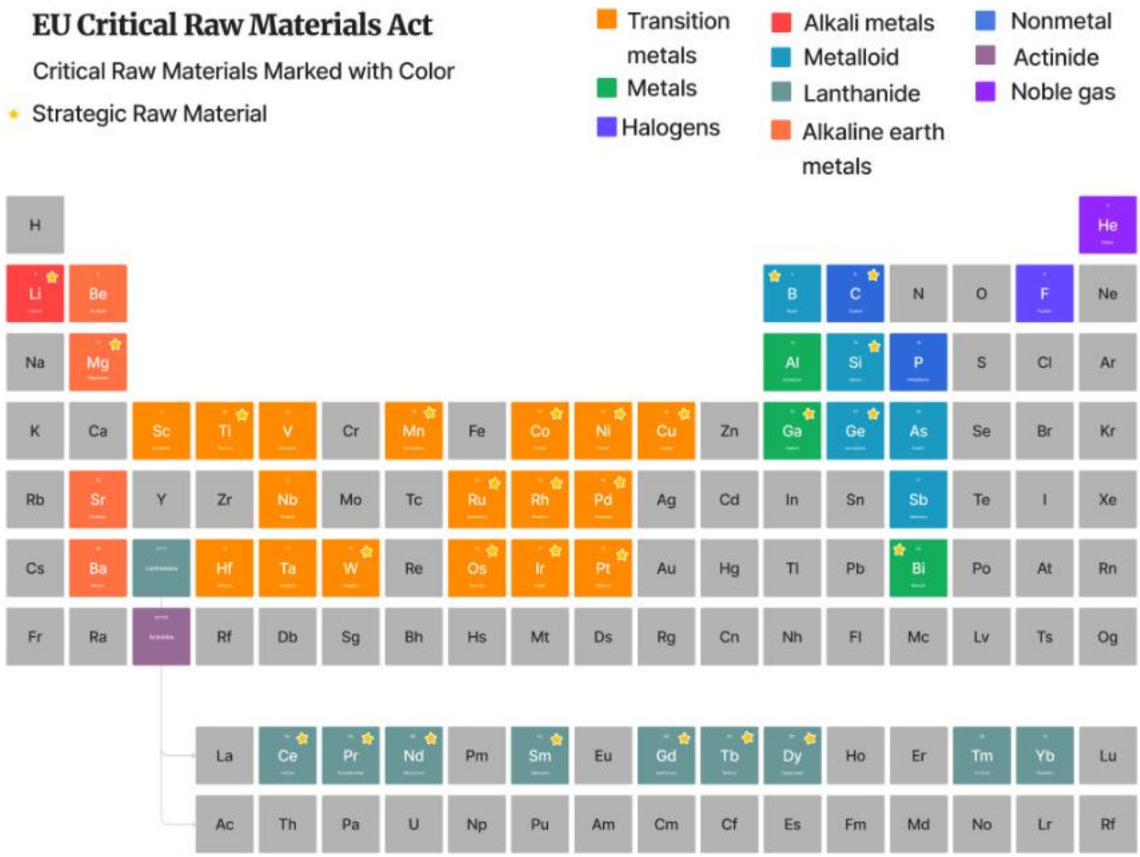

Figure A1: *Critical elements for the energy transition, including their application (European Commission, 2023)*

APPENDIX B

Interview protocol

Introduction

- My name is Timo Maassen, and I am working on my thesis project for my master's in Complex Systems Engineering and Management at the Technology Business and Management faculty of the University of Technology in Delft, the Netherlands. I am focusing on improving the European Union's independence in the field of rare earth elements, with the aim of enhancing future energy security.
- Thank you for your time
- Explanation of research project, goal of interview and study
- Request for consent

Questionnaire

1. Who are you, how would you describe your job, and can you briefly introduce how you are connected with Rare Earth Elements (REEs)?

2. What is your view on the current REE global value chain?
    a. Could you describe the current situation of the EU regarding REEs?
    b. What strategy are the other global power unroll?
    c. To what extent is a pan-European approach desirable?
    d. How do EU Member States differ in their approach/vision toward REE autonomy?

3. What, in your opinion, are the success factors for the EU to improve its self-sufficiency in the REE supply chain?

4. How could EU and national policies help to make the EU (and its Member States) more self-sufficient with regards to REEs?
    a. What is your view to the current EU 'critical raw materials act' directives?
        i. Are they feasible?
        ii. How could they effectively be achieved (by which means/measures)?
            (E.g. subsidies, enforcements, price incentives)

-- Should policy be aimed at different sectors/industries (prioritization)

5. What are further measures that could help the EUs autonomy in REEs, and what is your take on the following measures?
    a. In terms of <u>diversifying supply</u>, what role do you see for strategic international alliances, considering the potential trade-offs between human rights and material/energy security?
        i. How to deal with higher prices? (Competition with e.g. Japan and US for more expensive non-Chinese REEs)
    b. How do you view the potential impact of <u>trade restrictions</u>, such as tariffs or export quotas, on the EU's pursuit of REE self-sufficiency?
    c. To what extent do you think strategic <u>stockpiling</u> of REEs is a viable strategy for the EU to ensure a stable supply
    d. Regarding the <u>circular economy</u>, how do you perceive the challenges and opportunities in establishing a robust REE recycling industry, and what policies or incentives could support its growth?
        i. What about circularity by design?
    e. To what extent could R&D, and technological development such as REE content reduction or REE substitution play a role, and how could these be incentivized?

6. What role does European values play in achieving a more self-sufficient EU in REEs?
    a. In your view, what strategies or approaches can effectively address public concerns and resistance, particularly in relation to mining and processing practices of REEs?
        i. What about the role of media and political representation?

7. Can you think of any innovative policy measures or interventions, not covered in our discussion, that could significantly contribute to the EU's REE autonomy?

8. Who do you recommend interviewing further in this research?

9. Any remarks with regards to this interview?

End

- Thank you for the participation
- For any further questions, feel free to contact me, under the following e-mail: t.j.maassen@student.tudelft.nl

APPENDIX C

**Informed consent form – Interview master thesis "Exploring European Union rare earth element
Independence"**

You are being invited to participate in a research study titled thesis "Exploring European Union rare earth element independence." This study is being done by Timo Maassen from the TU Delft.

The purpose of this research study is to investigate the measures implemented by the EU to enhance its rare earth element supply chain independence within the context of the EU's energy transition, and to identify potential additional measures that can be taken to strengthen this strategy. and will take you approximately 60 minutes to complete. The data will be used for my master thesis, and educational uses.

I will be asking you to provide information regarding the topics related to EUs rare earth element system (institutional, political, economical, social, technical, environmental, legal.

As with any online activity the risk of a breach is always possible. To the best of our ability your answers in this study will remain confidential. To ensure maximum safety, we will reduce potential risks by collecting and retaining the minimum amount of personal information required. The gathered data will be stored in a secure storage solution approved by TU Delft and kept in a private TU Delft OneDrive location, with exclusive access granted solely to the research team. Before being included in the thesis report, all interview data will undergo anonymization, which means any identifiable information such as names and email addresses will be removed. The final thesis report will be published in the TU Delft thesis repository including the anonymous summary and will be publicly accessible.

Your participation in this study is entirely voluntary and you can withdraw at any time. You are free to omit any questions. After conducting the interview, I will share a summary of it with you. You have the freedom to ask for specific parts to be removed from the summary before it is included in the thesis report. Rest assured that the summary will be completely anonymous, protecting your identity, and send for agreement. If needed, modifications can be made.

Regarding other personal data collected during the project, such as audio/video recordings, notes, and the participant list, I will ensure its deletion within three years after the project's completion at the latest. This data will be maybe be reused for further scientific research in the domain of institutional rare earth dependence.

However, if an extension to retain the data is needed, we will always seek your consent first to continue using the information beyond the initial period. Your consent is of utmost importance to us in any data-related decisions.

For any questions or complaints regarding the research, feel free to contact us:

- Researcher: Timo Maassen (t.j.maassen@student.tudelft.nl)
- Supervisor: Jaco Quist (j.n.Quist@tudelft.nl)

PLEASE TICK THE APPROPRIATE BOXES	Yes
A: GENERAL AGREEMENT – RESEARCH GOALS, PARTICPANT TASKS AND VOLUNTARY PARTICIPATION	
1. I have read and understood the study information above, or it has been read to me. I have been able to ask questions about the study and my questions have been answered to my satisfaction. I consent voluntarily to be a participant in this study and understand that I can refuse to answer questions and I can withdraw from the study at any time, without having to give a reason.	☐
2. I understand that taking part in the study involves an audio-recorded or video-recorded interview.	☐
3. I understand that the study will end in Fall 2023.	☐
B: POTENTIAL RISKS OF PARTICIPATING (INCLUDING DATA PROTECTION)	
4. I understand that taking part in the study also involves collecting specific information such as name, and email address and audio or video recordings.	☐
5. I understand that the following steps will be taken to minimise the threat of a data breach, and protect my identity in the event of such a breach: anonymisation of the summary of the interviews before publication, secure data storage on the TU Delft OneDrive, and access to the recordings are limited to the research team.	☐
6. I understand that any personal information collected from me, which could identify me, such as my name and email address, will be strictly kept within the research team and not shared with anyone else. Furthermore, I understand that the identifiable personal data I provide will be securely destroyed once the project reaches its completion. However, anonymized transcriptions may be retained for up to three years after the project's conclusion. In the event that an extension to retain the data is necessary, I will be asked for my consent before any extended use of the data takes place. My consent will be sought as a priority in any decision involving the usage of the data beyond the original timeframe.	☐
C: RESEARCH PUBLICATION, DISSEMINATION AND APPLICATION	
7. I understand that the aggregated and anonymized information I provide during the research study will be utilized for a master's thesis report, which is intended to be published in the TU Delft thesis repository. However, it's important to note that only summaries that have been anonymized, removing any personal identifying details, will be included in the final report for publication.	☐
8. I agree that my responses, views, or other input can be quoted anonymously in research outputs.	☐
D: (LONGTERM) DATA STORAGE, ACCESS AND REUSE	
9. I give permission for the summary of the interviews that I provide to be archived in TU Delft repository so it can be used for future research and learning. I understand that access to the TU Delft repository is public.	☐

Signature

____________________________ ____________________________ ________

Name of participant Signature Date

Study contact details for further information:
Timo Maassen
t.j.maassen@student.tudelft.nl or the thesis supervisor Dr.ir Jaco Quist j.n.quist@tudelft.nl