Processing Rare Earths for Europe’s Wind Power

Scenario Analysis of EU Self-Sufficiency under the Critical Raw Materials Act

E.M.S. Tacken
29/10/2025

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Scenario Analysis of EU Self-Sufficiency under the Critical Raw Materials Act

By

E.M.S Tacken

Student number UL:	3995472
Student number TUD:	4952855

In partial fulfilment of the requirements for the degree of:

Master of Science
in Industrial Ecology

at Leiden University and Delft University of Technology,
to be defended publicly on 29-10-2025

Supervisors:	Prof.dr. E.G.M. Kleijn,	Leiden University
	Dr. B. Sprecher,	TU Delft
	J.M. Koese MSc,	Leiden University

TU Delft Universiteit Leiden

Preface

Writing this thesis has been both a challenging and rewarding journey. Although research and writing were not always what came most naturally to me, exploring such a current and dynamic topic kept me motivated throughout. Following the developments around the critical raw materials in the news while writing made the work feel particularly interesting and relevant.

I would like to express my sincere gratitude to my supervisors Prof. dr. E.G.M. Kleijn, Dr. B. Sprecher, and J.M. Koese MSc for their guidance, constructive feedback, and valuable discussions throughout this process. I am also thankful to my study advisor Paula for the continuous support during my studies.

A heartfelt thanks goes to my friends for their encouragement, company during study days, and much-needed distractions along the way. I am deeply grateful to my family for their support, especially my parents and sister for always cheering me on and for the "workation" in the Ardennes, and my grandparents for letting me work from their place for a few quiet days. Special thanks to Odile, and to John, Julie, and Anne for their time and effort in proofreading this report.

Completing this thesis has been a valuable experience that marks the end of my master studies. Industrial Ecology turned out to be such an exciting and fun field, full of people with interesting ideas, good humour, and a shared drive to make a difference. I've really enjoyed being part of that community and learning from everyone I met along the way.

Elisa Tacken

Delft, October 2025

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Abstract

As Europe accelerates its energy transition, securing access to critical raw materials has become a strategic priority. Rising geopolitical tensions and supply chain vulnerabilities have brought the issue of strategic autonomy to the forefront of EU policy. Rare Earth Elements (REEs), particularly neodymium and praseodymium, are critical materials essential for permanent magnets in wind turbines, yet their supply chains remain concentrated outside Europe. To reduce this dependency, the Critical Raw Materials Act (CRMA) sets a 2030 benchmark of 40% domestic processing. Yet, it remains uncertain whether future demand from Europe's expanding wind sector can be met through domestic processing.

This study assessed to what extent the European Union can meet the growing demand for Nd and Pr from wind power technologies through domestic processing, and how this aligns with the CRMA targets. A dynamic Material Flow Analysis (dMFA) was developed to simulate material flows between 2010 and 2050 under three scenarios combining different wind deployment and material intensity assumptions. A new dataset of operational and planned European REE processing facilities was compiled and compared with projected demand from the wind, electric-vehicle, and other sectors.

EU27 processing capacity is currently concentrated in Estonia. Announced projects within the EU indicate an expansion by 2030, with slight further growth towards 2050. Including capacity in non-EU member states like the UK and Norway would raise continental capacity even more, though all announced projects face risks of cancelation, delay, or downsizing.
If all domestic REE processing capacity was hypothetically available to the wind energy sector, the EU could meet 100% of wind Nd and Pr demand by 2030 across scenarios. This upper bound illustrates technical feasibility but ignores cross-sector competition. When processing capacity is shared with electric mobility and other sectors, outcomes diverge by scenario. The CRMA's 40% domestic processing benchmark is achievable for the wind sector in 2030 and 2050 under the Low-Demand Scenario. However, under a High-Demand Scenario it is not achieved in 2030 and falls well short by 2050 as demand growth outpaces capacity additions. This indicates that, while processing is not the immediate bottleneck for Europe's clean-energy transition, it becomes a constraint in high-growth futures if planned facilities are delayed or demand outpaces expansion.

The study highlights that achieving true self-sufficiency requires more than expanding processing capacity alone. A critical dependence lies downstream: without competitive permanent-magnet manufacturing, domestically processed Nd and Pr will continue to be exported and re-imported as magnets, eliminating the benefits for EU resilience. In addition, strengthening cross-sectoral coordination, integrating recycling, and establishing regional partnerships with the UK and Norway are essential to reduce systemic dependency on external suppliers.

Overall, the findings provide a structured, data-driven baseline to evaluate Europe's progress under the CRMA and identify conditions under which the EU's processing ambitions can support a secure and sustainable wind energy supply chain.

Keywords: Critical Raw Materials Act, Rare Earth Elements, Wind Energy, Material Flow Analysis, Self-Sufficiency

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List of Abbreviations

CRMA	Critical Raw Materials Act
CRM	Critical Raw Material
dMFA	Dynamic Material Flow Analysis
EoL	End-of-Life
EU	European Union
EU27	The 27 Member States of the European Union
EU REF	EU Reference Scenario
EV	Electric Vehicle
GHG	Greenhouse Gas
HDS	High Demand Scenario
IEA	International Energy Agency
JRC	Joint Research Centre (European Commission)
LDS	Low Demand Scenario
LREE	Light Rare Earth Element
MDS	Medium Demand Scenario
MFA	Material Flow Analysis
Nd	Neodymium
NdFeB	Neodymium-Iron-Boron (magnet type)
PM	Permanent Magnet
PMSG	Permanent Magnet Synchronous Generator
Pr	Praseodymium
REE	Rare Earth Element
REO	Rare Earth Oxide
UK	United Kingdom

1 Introduction

Energy is crucial for modern society, but current practices significantly harm the environment as the energy sector contributes over 75% of total greenhouse gas emissions in the European Union (EU) (European Commission, 2023b). As one of the most pressing global challenges, climate change asks for urgent action to reduce greenhouse gas (GHG) emissions. The EU aims to achieve carbon neutrality by 2050, which will require a shift from fossil fuels to renewable technologies such as hydroelectric, solar photovoltaic (PV), and wind energy (European Commission, 2023b).

The rapid expansion of renewable energy technologies has driven a substantial rise in demand for specific materials. Wind and PV technologies, for example, depend heavily on minerals like rare earth elements, copper, nickel, and cobalt for their production (European Commission, 2020). Since mining capacity cannot be scaled up rapidly, the anticipated growth in renewable energy capacity will increase the demand for these materials, intensifying pressure on resources. As the International Energy Agency highlights in their Global Critical Minerals Outlook (IEA, 2024a), clean energy applications are the primary drivers of demand growth for critical minerals, yet supply chains remain undiversified. This means future supply is not guaranteed due to geopolitical, environmental, and social risks and challenges. To tackle these challenges the European Commission identified a list of critical raw materials (CRMs) containing raw materials that are of economic significance and exposed to a high supply risk (European Commission, 2024).

With the identification of CRMs, the EU has taken a proactive approach by enacting the Critical Raw Materials Act (CRMA) which aims to enhance the EU's strategic autonomy in critical raw materials. To ensure a secure and sustainable supply, the CRMA seeks to regulate the management of these materials and guide industry practices (Hool et al., 2024). The legislation sets ambitious benchmark targets for domestic extraction, recycling, processing, and import dependence. By increasing strategic autonomy in CRMs, the EU aims to mitigate the risks associated with the growing demand for these essential materials, which are vital for the green transition (European Commission, 2024).

As the EU seeks to reduce reliance on imports, domestic extraction and recycling potential are progressively studied. However, less is known about future processing capacity within Europe (Ciacci et al., 2019; Lewicka et al., 2021; Rizos et al., 2024). This research focuses specifically on domestic processing of CRMs to support the growing demand from renewable technologies, with a case study on wind turbines and their use of REEs in permanent magnets.

1.1 The Case of Wind Turbines and Rare Earth Elements

Wind energy plays a central role in the EU’s decarbonisation strategy and is designated as a strategic sector under the CRMA. As the EU scales up its renewable energy capacity, wind power is expected to grow substantially. Globally, wind power is projected to become the second-largest renewable energy source after solar photovoltaics, making it a key technology in the global energy transition (IRENA and NUPI, 2024).

A defining characteristic of modern wind turbines, especially direct-drive models, is their reliance on permanent magnets made from REEs. These magnets offer high efficiency and reliability, attributes that are particularly valuable in offshore wind turbines, where the EU holds a leading position in both deployment and manufacturing (Díaz & Guedes Soares, 2020).

The main REEs used in wind turbine magnets include light rare earth element (LREE): neodymium (Nd) and praseodymium (Pr), and heavy rare earth elements (HREE): dysprosium (Dy) and terbium (Tb). These rare earth elements are identified as highly critical at global, as well as EU level (Carrara, Alves Dias, et al., 2020; Carrara, Alves, et al., 2020; IEA, 2024a; IRENA and NUPI, 2024). Nd serves as the primary magnetic material, accounting for approximately 30% of magnet weight and is typically combined with Pr in NdPr alloys. Dy and Tb are added in smaller quantities to improve the magnet's thermal stability and coercivity, which is their resistance to demagnetisation at high temperatures. This is particularly important in direct-drive and offshore wind turbines, where magnets operate under high thermal and mechanical stress (Alves Dias et al., 2020; Heim & Vander Wal, 2023; Mc Govern et al., 2024). Because of their material dominance and interlinkage, the Nd and Pr are the focus of this research.

Focusing on the wind energy sector provides a relevant case to explore the broader question of CRM strategic autonomy. Wind energy is a strategic growth area within the EU, and its deployment trajectory is relatively well documented. Moreover, the sector is a significant and growing consumer of REEs, particularly through its use of permanent magnets. As such, the wind sector serves as a valuable starting point for understanding the potential and limits of EU self-sufficiency targets under the CRMA.

1.2 Literature Review and Policy Landscape

1.2.1 Policy analysis

To understand the implications of the CRMA for the permanent magnet supply chain, it is important to understand the benchmarks set by the European Commission (2024). The CRMA establishes the following targets by 2030:

- 10% of annual consumption from domestic extraction,
- 40% from domestic processing,
- 25% from domestic recycling,
- and a maximum of 65% reliance on a single third country for any strategic raw material.

The following key definitions apply to the CRMA benchmarks:

- **Processing** refers to "all physical, chemical and biological processes involved in the transformation of a raw material from ores, minerals, plant products or waste into pure metals, alloys or other economically usable forms, including beneficiation, separation, smelting and refining, and excluding metal working and further transformation into intermediate and final goods;"
- **Recycling** involves "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations;"
- **Annual consumption of strategic raw materials** refers to "an aggregate of the amount of strategic raw materials consumed by undertakings established in the Union in processed form, excluding strategic raw materials incorporated in intermediate or final products placed on the Union market;"

It is important to note that the CRMA governs raw materials only. Permanent magnets are intermediate products, so the REE they contain are not counted in the CRMA's "annual consumption of raw materials".

This excludes rare earth elements in PMs from the processing and recycling benchmarks. This implies that the CRMA does not directly incentivise domestic PM processing or recycling.

The Clean Industrial Deal (European Commission, 2025b) complements the CRMA by committing over €100 billion to build EU-based clean manufacturing and enhance circularity. It also introduces demand aggregation mechanisms and a new EU Critical Raw Material Centre. These measures aim to strengthen domestic production and supply chain resilience for clean tech industries, including wind turbines.

1.2.2 Material Demand Projections

Numerous studies at both global and EU level have quantified the future material demand associated with the energy transition. For example, the International Energy Agency developed global projections to 2050 for the demand and supply of key energy transition CRMs based on the technology and policy trends (IEA, 2024a). The IEA projects that demand for critical minerals could quadruple by 2040 in net-zero scenarios, driven largely by clean energy deployment. Several other studies show the future rise of material requirements of wind energy on a global scale (Díaz & Guedes Soares, 2020; C. Li et al., 2022). At EU level, the European Commission (2020) assessed CRM criticality and mapped global supplying countries. The study shows the major EU suppliers of materials in extraction and processing stage, and revealed a high reliance on China alongside an increased use of secondary raw materials within the EU. These findings highlight the need for strategic interventions to enhance material supply security and processing capacity within the EU. Carrara et al. (2023) have modelled material requirements for renewable energy technologies under different policy pathways, identifying potential bottlenecks in the availability of key resources such as rare earth elements (REEs).

While most studies focus on material demand projections for end-use technologies such as wind and solar, few examine the processing infrastructure required to supply these materials in usable form. This study extends existing research by incorporating the domestic processing stage in the analysis, offering new insight into the self-sufficiency and strategic resilience of the EU's clean energy supply chain.

1.2.3 Supply Chain

This section provides an overview of the CRM supply chain with a focus on permanent magnet production and wind turbine manufacturing. The supply chain consists of three main stages: mining, processing and manufacturing. A simplified visualisation of the supply chain in given in figure 1-1 (Brian Hendrich et al., 2024).

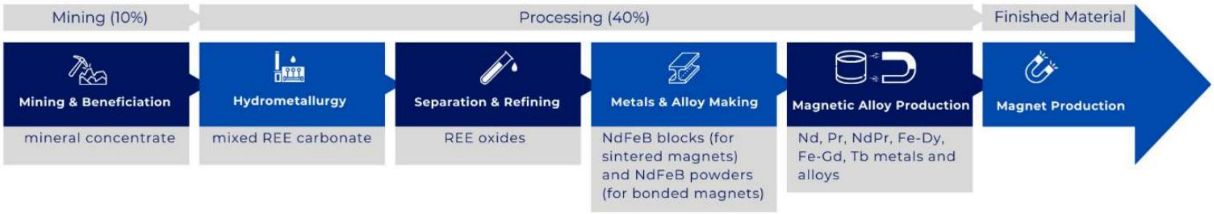


Figure 1-1. The mine-to-magnet value chain. Adapted from EU CRMA: Opportunities, challenges, viability and next steps (Brian Hendrich et al., 2024).

Throughout the PM supply chain, the EU's strong dependence on a single external supplier creates strategic vulnerabilities (Gauß et al., 2021). Past events, such as China's export restrictions on rare earths in 2011 (Sprecher et al., 2015), and more recent geopolitical tensions (Bradsher, 2025), have exposed the fragility of global supply chains and highlighted the need for improving their resilience.

Mining

The production or mining phase of the supply chain is not the primary focus of this research, as the production of minerals is quite widely studied. For example, BGS World mineral production (Idoine et al., n.d.) quantifies the global production of minerals and provides insight in the production locations.

On a European level, several studies address the domestic mining potential of the EUs natural reserves and strategies to diversify supply chains. For example, Lewicka et al. (2021) study the possibilities of domestic production of CRMs in the EU and Altamura et al. (2023) explore the sourcing of CRMs from mining, mineral processing, and metallurgical residues within the EU. Koese et al. (2025) have focussed on the EU and Electric Vehicles. Koese concludes that the projected extraction of cobalt, natural graphite and REE (Rare Earth Elements), will probably not reach 10 % of the EU demand in 2030. To increase the EU's self-sufficiency, CRM extraction in Europe needs to increase, in parallel with implementing circular economy efforts to reduce material demand.

Processing

The CRMA does not specify which stages of the supply chain are defined as 'processing' for specific materials and final goods. This lack of a standardised definition highlights the need to establish a clear and consistent scope for the materials analysed in this study.

The EU is heavily reliant on imports for several CRMs, including LREE. The import reliance is 100% for extracted and processed LREE (European Commission, 2023a). Despite this dependency, no notable efforts exists to quantify and map processing facilities and capacities for CRMs within the EU.

Given the EU's high import dependency, strengthening domestic processing capacity is crucial for supply chain resilience. However, the strategic need for domestic processing depends not only on resource availability, but also on the location of downstream manufacturing. Since reshoring manufacturing industries is a long-term and complex process, increasing refining capacity is most relevant for materials directly supporting EU-based production (Gregoir, L., & van Acker, K., 2022).

Magnet and wind turbine manufacturing

The manufacturing of rare-earth permanent magnets is predominantly concentrated outside the EU. As of 2019, global production reached approximately 130,000 tonnes, yet the EU had only 1,000 tonnes of domestic capacity, importing over 16,000 tonnes annually from China according to Carrara et al. (2023). Gauß et al. (2021) estimate the EU's dependency on Chinese-produced permanent magnets at 98% of its supply. High production costs limit the competitiveness of European-made magnets. The price difference between EU- and China-produced magnets is estimated at 20–30%, depending on the application (Carrara et al., 2023).

In parallel, the EU has an established wind turbine manufacturing base, with average annual production of approximately 10,500 turbines between 2013 and 2023. Key manufacturing countries include Germany, Denmark, Spain, the Netherlands, France, Italy, Portugal, Estonia, and Ireland (Eurostat, 2025). Despite this strong industrial presence in wind turbine assembly, the supply chain for components such as magnets remains highly import-dependent. This mismatch illustrates a core vulnerability: while the EU produces large volumes of wind turbines domestically, it relies primarily on China for one of the most critical components.

1.2.4 Circularity and Recycling

The recycling of rare earth elements is a potential strategy for reducing EU dependency on primary imports. However, less than 1% of REEs are currently recycled in the EU, largely because of the absence of specialised collection, processing, and re-alloying infrastructure (Carrara et al., 2023).

In the case of permanent magnets used in wind turbines, recycling faces an additional bottleneck: most PM manufacturing takes place outside the EU. This means that even when end-of-life wind turbines become available for recycling, there is a risk that PMs will be exported for treatment. This would undermine EU goals for circularity and strategic autonomy, as outlined in the CRMA.

As show in figure 1-2, many recycling operations for PMs overlap with processing steps, such as refining and re-alloying. This means that investing in recycling infrastructure would also contribute to domestic processing capacity. Strengthening these linked operations could help the EU not only meet its 25% recycling benchmark, but also improve its ability to achieve the 40% domestic processing target under the CRMA.

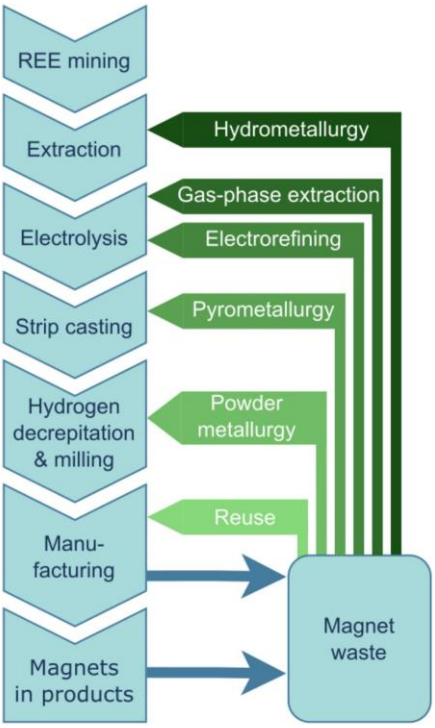


Figure 1-2. Overview of NdFeB recovery methods and entry points into the primary supply chain. Adapted from Koese et al. (2025).

Technical and economic barriers to PM recycling remain, including low collection rates, complex separation processes, and high costs (Rizos et al., 2024). Nevertheless, the policy landscape is evolving: Articles 28 and 29 of the CRMA introduce provisions to improve magnet recyclability by requiring information on magnet composition and recycled content (European Commission, 2024). These measures aim to facilitate future recycling efforts and support infrastructure development within the EU.

1.3 Knowledge gap

As discussed in section 1.2.1, there is a contradiction between EU policy targets and supply chain realities: REEs in PMs are recognised as critical due to their economic importance and supply risk, yet they fall outside the CRMA’s scope due to their classification as intermediate products. As a result, the CRMA may do little to address actual supply risks for the EU wind energy sector. However, the Clean Industrial Deal presents an opportunity to stimulate new PM production and processing capacity in the EU. The material demand from the EUs growing wind power capacity offers an entry point for building this capacity. This would allow CRMA benchmarks to become relevant over time as domestic consumption of raw materials grows.

Beyond this policy mismatch, there is a knowledge gap in the academic and industrial literature regarding the status of domestic CRM processing capacity in the EU. Despite the urgency of securing CRM supply chains, domestic processing capacity remains poorly quantified and analysed, both in terms of current infrastructure and future outlook.

At the same time, the EU remains heavily dependent on non-European supply chains for mining, processing, and magnet production. This dependence is well-documented, but few studies provide a quantitative assessment of how these sector specific material demand and processing bottlenecks might impact the EU's ability to achieve policy goals.

This thesis addresses these gaps by:
- quantifying material demand (Nd and Pr) from wind turbines under multiple deployment scenarios,
- mapping current and planned EU processing capacity for Nd and Pr,
- evaluating whether domestic processing can meet wind sector demand,
- and analysing what this means for EU policy targets on critical raw materials.

1.4 Objective and Research Questions

The objective of this research is to evaluate the extent to which the European Union can meet future demand for critical raw materials from wind energy technologies through domestic processing, using dynamic Material Flow Analysis (dMFA). By doing so, the research seeks to contribute insight into the feasibility of achieving EU policy targets and to identify limitations and opportunities for improving supply chain resilience in the wind sector.

Main question:
To what extent can the European Union meet the growing demand for critical raw materials from wind energy technologies through domestic processing, under different deployment scenarios, and how does this align with the targets set in the Critical Raw Materials Act?

Sub-questions:
1. Which critical raw materials are relevant for wind turbine technologies, and what are the key processing stages and trade dependencies within their supply chains?
2. What is the current and planned domestic processing capacity for these materials within the EU, and how can it be quantified?
3. How does the demand for critical materials from wind turbines evolve under different deployment scenarios, and how does this compare to available domestic processing capacity?
4. What are the implications of the model outcomes for EU policy targets on domestic CRM processing, and what factors may constrain or enable meeting these targets under different future scenarios?

2 Methodology

To address the main research question, this study conducts a dynamic Material Flow Analysis (dMFA). MFA is a widely used method in Industrial Ecology for modelling material stocks and flows over time. It enables scenario-based analysis of future demand and end-of-life trends, supporting policy development for recycling and resource efficiency (Deng et al., 2023; Elshkaki & Graedel, 2013; Müller et al., 2014). The method allows the modelling of future demand under multiple demand scenarios while linking it to processing infrastructure, making it a well-suited method to assess the feasibility of meeting the EU's Critical Raw Materials Act targets.

This chapter explains how the MFA method is applied to answer the research questions. It begins with an overview of the research framework and proceeds to define the model's scope, structure, and scenarios. The next sections describe how the necessary data was collected, processed, and quantified. Section 2.4 explains how results are evaluated in relation to EU policy targets, and discusses how uncertainty is addressed through sensitivity analysis.

2.1 Research framework

The MFA in this study broadly follows the framework described by Van Der Voet (1996), who identifies three main steps in conducting a substance- or material flow analysis:

1. System's Definition: Establishing the scope, boundaries, and structure of the system.
2. Quantification: Collecting data to quantify stocks, flows, and parameters, and modelling the system.
3. Interpretation: Evaluating the robustness of the results, translating into policy relevant terms and linking to policy instruments.

Figure 2-1 presents a schematic overview of the research framework, linking the modelling steps to the sub-research questions, the thesis chapters, and the outputs generated at each step.

The process begins with identifying the knowledge gap and formulating the research questions, based on the literature review. From there, the scope and system boundaries are established, and a conceptual model is developed. Data collection and parameter quantification then enable the development of a formal model. This is implemented in Python to produce a computational model capable of simulating future material flows and comparing them to available processing capacity. Model results are interpreted in relation to the CRMA targets and the broader context of strategic autonomy and industrial policy. A sensitivity analysis is used to test how results respond to uncertainties in key assumptions.

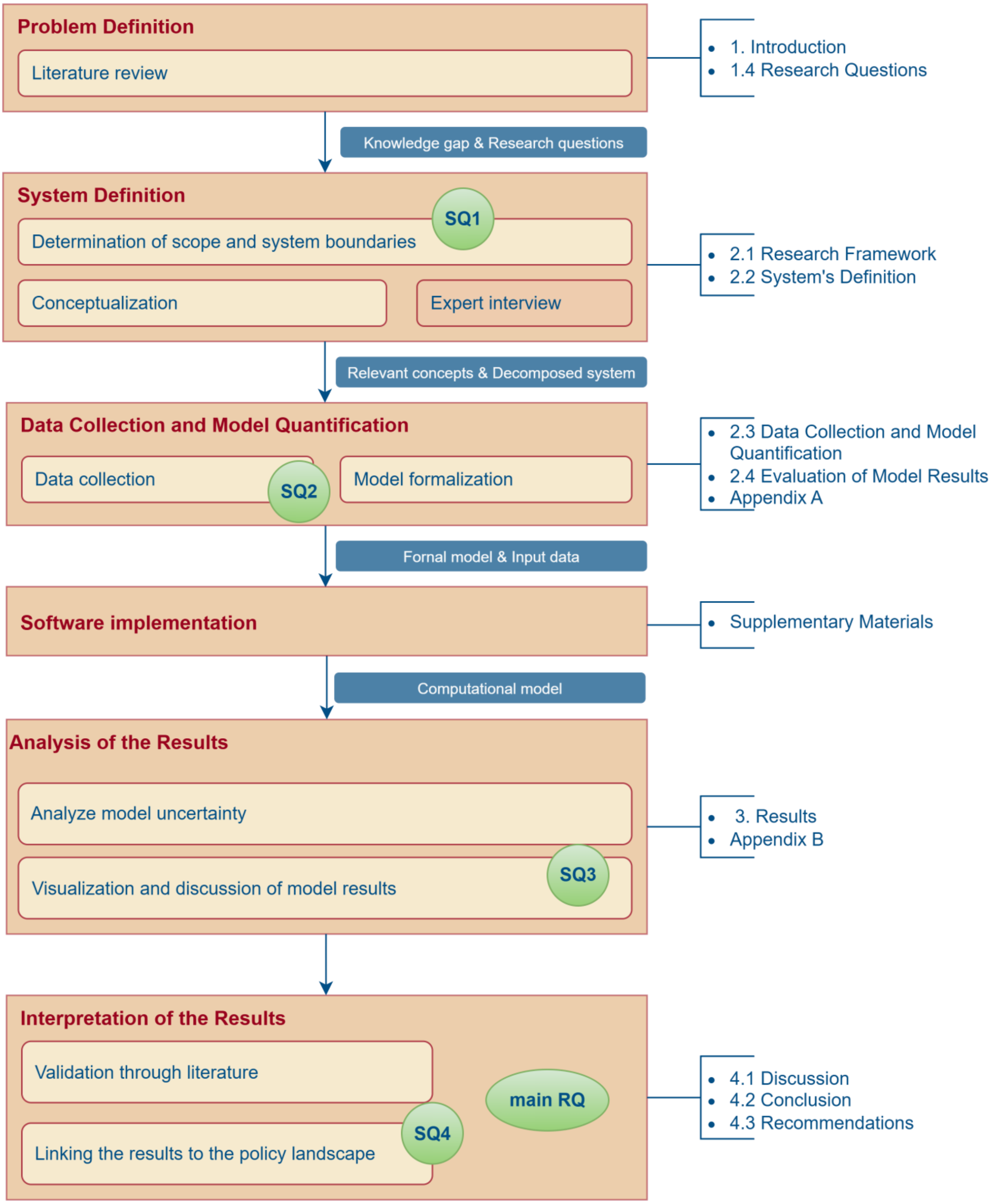


Figure 2-1. Research Framework linking research questions, modelling steps, and outputs.

2.2 System's Definition

2.2.1 Scope

The system boundaries are defined along three dimensions: geographical, temporal, and technical:

Geographical:

The geographical scope is limited to the EU27 countries, because the CRMA applies to the EU's member states (European Commission, 2024). For the processing capacity data collection a broader scope is considered, by including all facilities planned in the European continent to provide a more complete picture of the developments in the sector.

Temporal:

The scope of the model are the years 2010-2050 because of availability of historical data and the important policy target milestones 2030 and 2050 for the CRMA and Clean Industrial Deal. However, for the installed wind capacity, more data is available, so a larger historical time period is encompassed. For more details on the data sources and timeframe of the model see section 2.3.

Technical:

As previously mentioned in the introduction, the technical scope of the model focusses on rare earth elements in the wind energy sector. The technicalities are further defined as follows:

- **Applications:** Both onshore and offshore wind turbine are included in the model. They are modelled separately due to their different technological features and market development outlooks. Offshore turbines are typically larger and more likely to use permanent magnet generators, leading to different material intensities (Alves Dias et al., 2020).
- **Turbine types:** The model focuses on wind turbine types that use permanent magnet generators, namely direct-drive PMGs (D-PMSG) and hybrid drive PMGs (E-PMSG) (C. Li et al., 2022; Mc Govern et al., 2024). While other turbine types can also contain REEs, they are excluded to limit model complexity and focus on the most material-intensive technologies. As a result, the total REE demand from wind may be somewhat underestimated.
- **Processes:** The level of technical detail is kept general, consistent with the study's policy-oriented scope and large spatial and temporal coverage. The model does not include details on mining, magnet production, or other downstream applications. It focuses on the processing of raw materials into separated rare earth oxides (REOs), in line with the CRMA's definition of "processing". These steps include beneficiation, separation, and refining (Brian Hendrich et al., 2024).
- **Materials:** The model focusses on light rare earth elements neodymium (Nd) and praseodymium (Pr). These materials are selected based on their high criticality and role in EU wind energy supply chain, as discussed in section 1.1.

2.2.2 Model structure

The dMFA model consists of two interconnected subsystems:

Wind Capacity Subsystem

This subsystem simulates the annual inflow, stock, and outflow of installed wind power capacity in the EU (both onshore and offshore). The stock of installed capacity is based on scenario data, while decommissioning is modelled using lifetime distributions. This determines the yearly retirements and additions of capacity in megawatts.

Material Use Subsystem

The material use subsystem translates wind capacity inflow into annual material demand for Nd and Pr by combining the annually deployed capacity with:

- Turbine technology market shares (e.g., direct-drive vs geared)
- Material intensities per turbine type (kg Nd and Pr per MW)

The annual material demand is then compared to available domestic processing capacity. To assess wind energy's realistic share of this capacity, the model includes allocation assumptions, described in more detail in section 2.4.

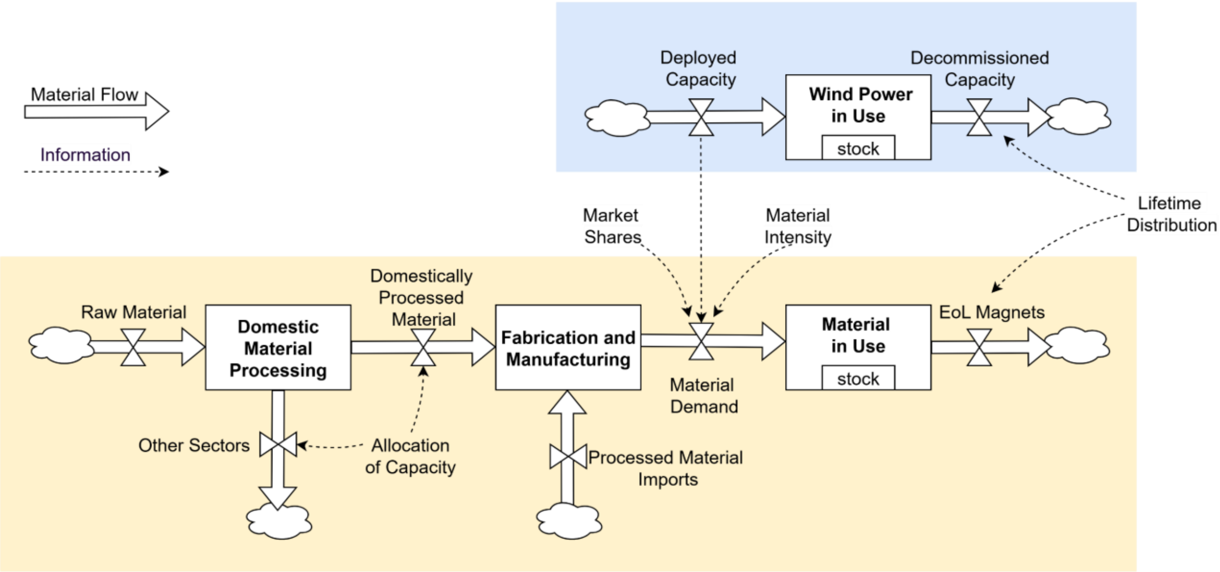


Figure 2-2. Stock-flow diagram of the interconnected subsystems: the Wind Capacity Subsystem (blue) and the Material Use Subsystem (yellow).

A link to the python model is provided in Appendix A.

2.2.3 Scenarios

The analysis uses three demand scenarios, varying in scale and policy ambition. The scenarios are combinations of two wind deployment scenarios, and two scenarios for the intensity of material demand, based on published studies and forecasts by the European Commission and the Joint Research Centre (Alves Dias et al., 2020; European Commission et al., 2021).

Each scenario defines a different combination of installed wind capacity growth and technological and market developments affecting material demand of Nd and Pr metal per megawatt.

Table 2-1. Scenario definitions combining wind power deployment and material demand intensity assumptions.

Scenario	Wind power installed capacity	Material demand intensity
Low Demand Scenario	Low	Low
Medium Demand Scenario	High	Low
High Demand Scenario	High	High

Low Demand Scenario (LDS)

This scenario assumes moderate growth in installed wind power capacity, following the EU Reference Scenario 2020 (European Commission et al., 2021). It incorporates optimistic assumptions about technological advancements resulting in reduced material use, and a substantial market share for alternative generator types that do not rely on permanent magnets. As a result, demand for LREEs remains relatively low (Alves Dias et al., 2020).

Medium Demand Scenario (MDS)

This scenario represents a mid-range projection. It assumes high wind power deployment in line with policy goals under REPowerEU, the 2050 Climate Target Plan (MIX scenario), and the EU Offshore Strategy. Along large wind capacity growth, the MDS retains the same low material intensity assumptions as in LDS. It reflects a future where wind energy expands rapidly, but material demand limited is through efficiency gains and innovation.

High Demand Scenario (HDS)

The HDS combines ambitious wind energy expansion with slower technological development. Wind deployment projections follow REPowerEU and other climate policy goals, identical to the MDS. Material intensity remains high due to limited breakthroughs in generator design and a growing reliance on permanent magnet generators. This scenario presents the most challenging outlook for material supply.

2.3 Data Collection and Model Quantification

This section describes the input data, sources, assumptions, and processing steps used to quantify the variables in the dynamic stock-driven material flow model.

2.3.1 Wind Capacity

Installed wind power capacity is the core input for the model’s stock-driven structure. It determines the annual inflow of new turbines and decommissioning flows, which in turn drive material demand. Installed capacity data is available in five-year intervals between 2005 and 2050. Capacity is assumed to start from 1990, interpolated using Piecewise Cubic Hermite Interpolating Polynomial (PCHIP) to create smooth, annual time series. The third parameter is the wind turbine lifetime, which is modelled using a Weibull distribution to simulate realistic decommissioning patterns over time.

Table 2-2. Input parameters for modelling annually deployed wind power capacity in the EU27, including numerical values and data sources.

Parameter	**Unit**	**Value**		**Source / Notes**
Installed capacity	GW	*LDS:* EU REF Scenario 2020	*MDS & HDS:* Scaled from LDS: 1.5× (2030), 2.5× (2050)	Carrara et al. (2023), European Commission (2021)
Time series	Years	1990-2050		WindEurope (n.d.) PCHIP interpolation
Average lifetime	Years	Onshore: 25, Offshore: 30		Alves Dias et al. (2020), Carrara et al. (2020)
Distribution type	-	Weibull		Van Nielen et al. (2023)
Shape parameter	-	k = 3		Van Nielen et al. (2023)
Scale parameter	-	Computed from mean: $s = \mu / \Gamma(1 + 1/k)$		

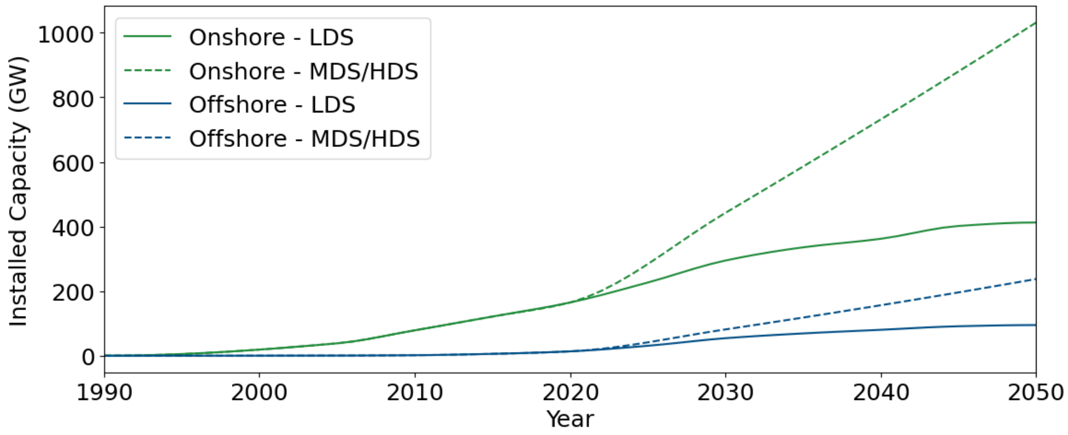


Figure 2-3. Historical and projected total installed wind power capacity in the EU27.

<u>Limitations and Uncertainties</u>

Installed capacity data prior to 2005 relies on interpolation and assumptions due to limited historical records. In addition, long-term projections beyond 2035 carry increasing uncertainty, as they are influenced by evolving EU policy objectives, technological developments, market dynamics, and potential constraints in wind power deployment.

2.3.2 Material Demand

The annual material demand for neodymium and praseodymium is calculated by linking newly installed capacity to component-level material intensities and turbine market shares.

Material intensities are based on Mc Govern et al. (2024), by using the average values (kg/MW) for turbine types using permanent magnet synchronous generators (PMSG). Different intensities are applied depending on the turbine type (e.g., D-PMSG vs E-PMSG). The historical material intensities depicted in Table 2-3 are assumed to remain constant over time, while scenario-specific reductions are applied in future projections to reflect expected technological improvements.

Table 2-3 Material intensity estimates of neodymium (Nd) and praseodymium (Pr) per turbine type in kg/MW (Mc Govern et al., 2024).

	Nd	**Pr**
Type D-PM DD-PMSG	180	35
Type E E-PMSG	50	4

PM turbines began entering the market at notable scale around 2010. Historical market share data for turbine technologies between 2010 and 2018 is drawn from Carrara et al. (2020), with separate trends identified for onshore and offshore installations. Future market shares are scenario-dependent: the Low Demand Scenario assumes a greater adoption of alternative technologies alongside improvements in material efficiency, while the High Demand Scenario reflects an increasing dominance of PMSG-based turbine types. Details on the historical and future market shares used in the analysis are given in Appendix B.

The assumptions used in the material demand subsystem for both scenarios are summarised in Table 2-4.

Table 2-4 Assumptions for material demand under Low, Medium, and High Demand Scenarios (Alves Dias et al., 2020; Mc Govern et al., 2024).

Parameter	**Unit**	**LDS & MDS**	**HDS**
Nd intensity reduction	kg/MW/a	0.05	0
Pr intensity reduction	Kg/MW/a	0.05	0
Market shares Onshore	%	0.41 (2030), 0.52 (2050)	0.52 (2030), 0.65 (2050)
Market shares Offshore	%	0.48 (2030), 0.44 (2050)	0.95 (2030), 0.95 (2050)

Annual Nd and Pr material demand for both onshore and offshore wind is calculated as:

$$Material\ Demand(t) = \sum_i (Deployed\ Capacity_i(t) \times Market\ Share_i(t) \times Material\ Intensity_i(t))$$

Where i denotes each turbine type.

Limitations and Uncertainties

Market share data beyond 2018 is extrapolated based on scenario-specific assumptions, introducing uncertainty in long-term projections. Additionally, the dataset does not account for potential disruptive innovations in turbine design that could significantly alter future technology mixes. Material intensity values are based on industry averages and do not capture manufacturer-specific differences or design optimisations, which may lead to under- or overestimation of actual material use.

2.3.3 Processing Capacity

As outlined in the introduction, the availability of reliable data on REE processing capacity in the EU represents a knowledge gap. Therefore, a bottom-up data collection approach was undertaken to quantify current and future processing capacity in the EU.

Data on individual processing facilities and planned project was collected until April 2025. The main sources of data were the S&P Capital IQ Pro database (*S&P Global Market Intelligence*, 2025) and the list of selected strategic projects under the CRMA (European Commission, 2025c). Additional information was obtained from company reports, scientific papers, and trade journals.

These sources provided insights into project ownership, location, operational status, covered processes, projected output capacities, and expected commissioning dates. Facilities were included if they process light rare earth elements (LREEs), specifically neodymium and praseodymium, in a form relevant for permanent magnet production (i.e., separated REOs).

The analysis includes both operational and planned facilities, and while the research focuses on the EU27, projects in European non-EU countries such as the UK and Norway were also recorded. This broader scope was included to provide a more comprehensive picture of regional developments in the sector, but only capacity within the EU27 is used in the comparison with material demand and the self-sufficiency analysis.

Data Processing and Quantification

To enable integration into the model, capacity data was standardised and generalised for three benchmark years: 2020, 2030, and 2050. The facilities' throughput was harmonised and expressed in tonnes per year of separated magnet REO (t REO/a), specifically NdPr-oxide equivalent, as this is the most commonly reported unit for processing capacity. No further breakdown was made by specific process technologies, due to heterogeneity in reporting and limited availability of disaggregated process data. More detailed assumptions and facility-level sources are included in Appendix C.

In addition to numerical data, a geographical map was created showing the spatial distribution of REE processing facilities and their capacities in 2020, 2030, and 2050. This provides spatial insight into the industrial landscape, highlights potential geographic clustering of infrastructure, and supports interpretation of regional policy implications.

Finally, to ensure comparability with material demand, all processing capacities were converted from separated NdPr-oxide to Nd + Pr metal equivalent. The metal content was taken as a fraction of the oxide weight: for neodymium, Nd metal corresponds to 0.857 × Nd_2O_3, and for praseodymium, Pr metal corresponds to 0.828 × Pr_6O_{11}. Assuming a didymium composition of 75 % Nd and 25 % Pr (Heim & Vander Wal, 2023), this results in a factor of **0.85** for the conversion between NdPr-oxide and Nd + Pr metal.

Limitations and Uncertainties

Data on processing capacity is fragmented, largely based on open sources, and often commercially sensitive. Planned projects carry uncertainty, as delays, downsizing, or cancellations are common and influenced by shifting policy support. Specific processing technologies are not distinguished due to limited data availability and the model's macro-scale focus.

2.3.4 Allocation Assumptions

To assess how much of the EU's processing capacity for Nd and Pr can realistically serve the wind energy sector, this study applies two allocation approaches:

Full allocation:

As a theoretical starting point, the material demand is compared to 100% of the processing capacity, assessing the hypothetical case for if all LREE processing capacity is available for the wind energy sector.

Partial allocation:

In practice, it is likely processing capacity is shared across multiple sectors. To realistically asses the processing capacity available for the wind sector, competing demand from other sectors is included in the scenarios.

Most Nd and Pr consumed in the EU are used in permanent magnets: estimates range from 80% (SCRREEN2, 2023) to 97% (van Nielen et al., 2023). The EU imports roughly 18,000 tonnes of PMs annually, which consist for ~30% of Nd/Pr, corresponding to around 6,000 tonnes of Nd/Pr consumption in the EU (Gauß et al., 2021; van Nielen et al., 2023; Vasileios Rizos et al., 2022). Approximately 10% of NdFeB magnet demand is attributed to wind energy, forming the baseline allocation used in this study.

The e-mobility sector is the other major strategic end-use with high CRM supply risk (Carrara et al., 2023). Material demand in this sector depends on technological advancements and political ambitions regarding their development, just like the renewable energy sector, resulting in a wide range of future scenarios. In addition, the e-mobility sector has a strong domestic EU manufacturing base (IEA, 2025b), making it a relevant case for domestic material processing.

EV motors and wind turbines drive the demand for REEs, and development in other sectors is driven by broader market dynamics and is expected to grow more gradually and predictably. For this reason, these sectors are aggregated into a single category in the model. This 'other sectors' category covers applications such as ICT, defence, healthcare, and consumer electronics. Growth in other sectors was modelled using annual rates of 3% and 10%, representing the lowest and highest historical growth rates reported by Alves Dias et al. (2020). These values serve as upper and lower boundaries to explore the potential range of outcomes, rather than realistic forecasts of future growth.

For this research step, the model focusses on just the Low Demand Scenario and High Demand Scenario, to explore the range of outcomes. The scenario specific parameters are given in Table 2-5.

Table 2-5. Assumptions for projected material demand in the electric vehicle sector and other sectors across scenarios.

	Unit	**LDS**	**HDS**	**Source/Notes**
EV Nd/Pr material demand	t/a	2020: 437 2030: 1634 2050: 2186	2020: 437 2030: 2916 2050: 4025	Carrara et al. (2023)
Growth rate other sectors	%/a	3%	10%	Alves Dias et al. (2020) (based on historical range; exploratory bounds)

Limitations and Uncertainties

It is assumed that no process losses occur during LREE processing, as such losses are generally captured and recovered internally (Kumari & Sahu, 2023). Due to data constraints, intermediate trade flows and final product locations are not distinguished, processing is assumed to occur within the EU when capacity exists.

2.3.5 Permanent Magnet Manufacturing

Permanent magnet manufacturing represents a critical link in the rare earth supply chain and plays a decisive role in achieving strategic autonomy. As noted earlier, domestic processing alone does not guarantee reduced import dependence if the processed materials are subsequently exported for magnet production and later re-imported as finished or intermediate products.

To assess the current state of this stage in the supply chain, desk research was done, including outreach to companies in the industry. More than twenty companies were contacted by email to gather information on existing and planned production capacity. The response was limited, with only one company interview providing insight into the current market situation. The main takeaway was that large-scale domestic magnet manufacturing remains virtually absent in the EU, primarily due to high production costs and limited competitiveness with Asian suppliers. According to the interviewee, significant expansion would likely only occur under crisis conditions or through targeted policy incentives (Anonymous Participant, personal communication, 15 April, 2025).

The few facilities identified through desk research illustrate the fragmented and small-scale nature of the European magnet industry. There a few bigger facilities planned or in the process of starting up:

- Neo Performance Materials recently opened a facility in Narva, Estonia, with an initial capacity of around 2,000 t/a and plans to expand to 5,000 t/a as part of a "mine-to-magnet" strategy in combination with their processing facility in Sillamäe (Argus, 2023).
- In France, MagFactory in Noyarey focuses on magnet-to-magnet recycling (Magnetics Magazine, 2024a, 2024b). Their aimed capacity is 500 tons of high-performance sintered magnets per year by 2027. Since MagFactory also processes materials, it is included in the capacity analysis described in section 2.3.3.

Several smaller manufacturers are operational in Slovenia (Magneti, Kolektor), Germany (Vacuumschmelze, Magnetfabrik Schramberg), and Finland (Neorem). Their total output in 2019 was estimated at only about 1,000 t/a, compared to roughly 16,000 t/a of magnets imported from China each year (Carrara et al., 2023).

Because future domestic manufacturing capacity could not be comprehensively quantified, this study assumes that all domestically processed materials are used in local magnet production. As a result, the analysis focuses on processing capacity and end-use demand, without explicitly modelling intermediate manufacturing stages. This assumption may present a somewhat optimistic view of European self-sufficiency, since true independence depends not only on processing but also on retaining value within the downstream manufacturing stages. Addressing this gap is an important subject for follow-up research.

2.4 Evaluation of Model Results

2.4.1 Self-Sufficiency

The primary objective of evaluating the model results is to determine whether the EU can meet future demand for critical raw materials from wind energy technologies through domestic processing. To assess this, modelled material demand from wind turbines is compared against available domestic processing capacity under different allocation assumptions.

The key performance indicator is the self-sufficiency ratio: the share of total wind sector material demand that can be met through domestic processing. This is calculated for each scenario and expressed as a percentage of total demand. Results are then benchmarked against the CRMA target of 40% domestic processing by 2030, and further improvement toward self-sufficiency by 2050.

2.4.2 Sensitivity Analysis

To assess the robustness of the model outcomes, a sensitivity analysis was conducted focusing on two main aspects: (1) the calculation of wind-sector material demand and (2) the estimation of EU self-sufficiency levels.

First, the uncertainty in the wind-sector material demand calculation was explored using a Monte Carlo simulation. The input variables were varied by applying uniform distributions, with ranges of ±10% or ±20% depending on the confidence in the underlying data or assumption. In total, 200 runs were performed, and the results are presented as confidence intervals (5–95%, 10–90%, and 25–75%), which illustrate the spread and reliability of the modelled demand trajectories.

Second, the uncertainties in the self-sufficiency calculations were assessed by systematically varying the parameters that determine the share of processing capacity available to the wind sector. Specifically, EV sector demand, other sector demand, and the initial allocation of processing capacity to wind were adjusted by ±10%. The resulting outcomes were expressed as a percentage change relative to the baseline results, to give insight into which parameters have the greatest influence on the self-sufficiency indicators.

3 Results

3.1 Wind Power Capacity

The first result is the projection of the power added to the EU wind turbine fleet, which forms a foundation for the rest of the models calculations. Figure 3-1 presents the modelled annual deployment of wind power capacity in the EU27 for the Low Demand Scenario (LDS) and the Medium/High Demand Scenarios (MDS/HDS), differentiated between onshore and offshore technologies.

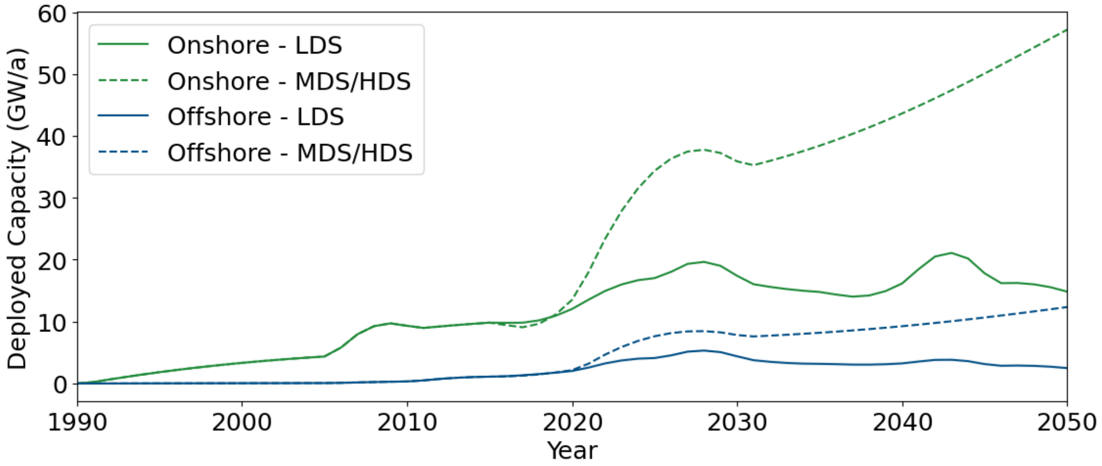


Figure 3-1. Modelled annual deployment of wind power capacity in the EU27 by scenario, showing onshore and offshore contributions.

In the MDS/HDS, annual deployment continues to rise steadily, with a steeper increase observed for onshore wind compared to offshore. In the LDS, annual additions stabilise at approximately 15 GW/year for onshore and 3 GW/year for offshore technologies. The oscillations visible in the curves are a result of the lifetime distribution modelling. The Weibull distribution used to represent turbine retirements introduces cyclical peaks when large capacity cohorts reach their end-of-life and are replaced.

These results reflect the different policy ambitions embedded in the scenarios and the growth trajectories of onshore and offshore wind. In all scenarios, onshore deployment remains the dominant contributor to total annual installations, though offshore growth is proportionally higher in the higher demand pathways. These deployment trends directly shape the material demand trajectories discussed in Section 3.2.

3.2 Material Demand

The transition to wind energy substantially drives demand for light rare earth elements, which is quantified by combining the annual deployment of new wind capacity and the material intensity of the turbine fleet. Figure 3-2 shows the modelled annual demand for Nd and Pr in each scenario.

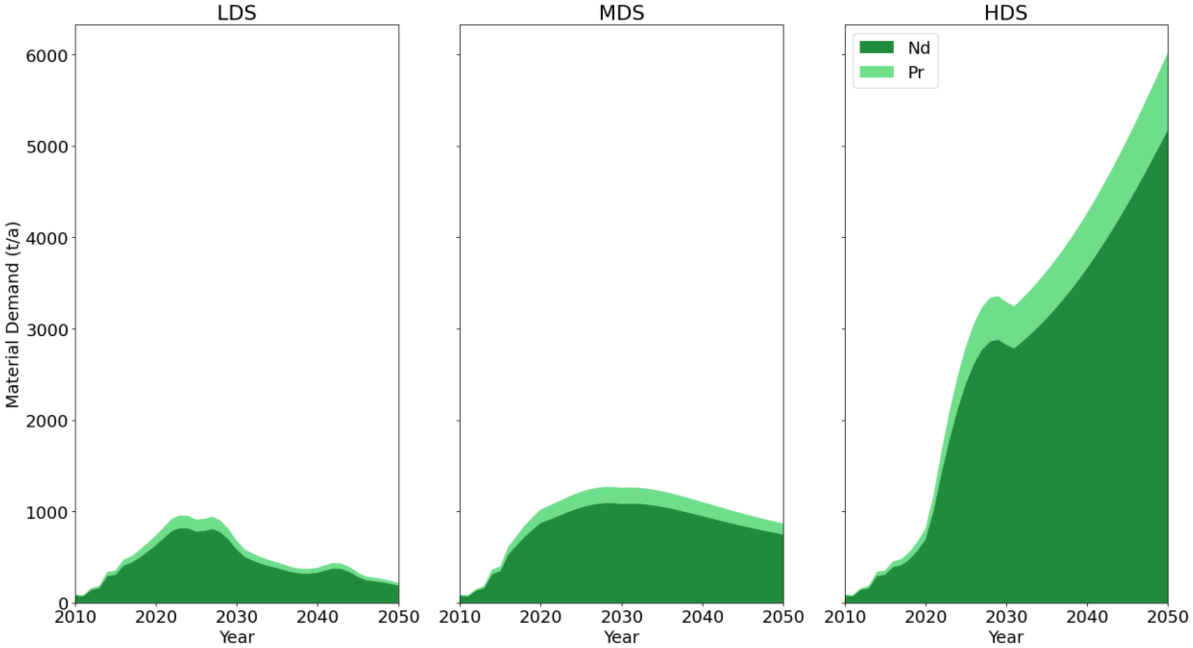


Figure 3-2. Modelled annual demand for neodymium (Nd) and praseodymium (Pr) in the EU27 under Low, Medium, and High Demand Scenarios.

In the LDS and MDS, material demand growth is limited, peaking around 2025–2030 before stabilising or declining slightly. This indicates that under moderate deployment rates and continued efficiency improvements, material flows could become predictable, enabling better planning for processing capacity and recycling systems. The HDS, however, projects a tripling of demand by mid-century compared to MDS, reaching over 5,000 t/a of Nd by 2050. Such growth would significantly increase supply pressure and require significant expansion of domestic processing capacity to ensure 40% self-sufficiency. However, it would also result in much larger in-use stocks of material. In the long term, these stocks could make domestic recycling more viable, potentially reducing dependence on primary supply. The influence of recycling dynamics on the system will be revisited in the discussion.

The peak in material demand between 2020 and 2030, particularly visible in the HDS, results from the lifetime dynamics modelled through the Weibull distribution. As the first cohort of turbines reaches end-of-life, a wave of replacements coincides with the addition of new capacity, temporarily amplifying total material demand.

For context, the International Energy Agency (IEA, 2025a) projects global Nd and Pr demand for clean energy applications to exceed 60 and 10 kt/a respectively by 2050, under its Net Zero scenario. In HDS, EU demand alone could account for close to 10% of global Nd demand. This points to the importance of securing supply chains, especially given the concentration of current global processing capacity outside the EU.

The material demand projections in Figure 3-2 are compared to domestic processing capacity in Section 3.3, where we assess whether projected domestic facilities can meet these varying levels of demand.

3.3 Processing

At present, domestic processing of LREEs within the EU is limited to a single operational facility: the Silmet plant in Estonia, operated by Neo Performance Materials. This facility has an annual capacity of 750 tonnes of separated NdPr rare earth oxides (REO). However, the European processing landscape is expected to change significantly over the coming decades, with several projects announced or under development both within and beyond the EU. Within the EU27, most planned capacity is located in France. Beyond the EU, the United Kingdom and Norway have announced several projects, with planned capacities that exceed those currently expected within the EU27.

Figure 3-3 illustrates the geographical distribution of current and planned processing capacity in Europe. In 2020, total EU27 capacity was around 750 t REO/a, entirely from Estonia. By 2030, announced projects could increase EU27 capacity to almost 7,900 t REO/a, with further increases to over 8,500 t REO/a projected by 2050. Including non-EU European countries, total continental capacity could exceed 17,000 t REO/a by 2050, assuming all projects proceed as planned.

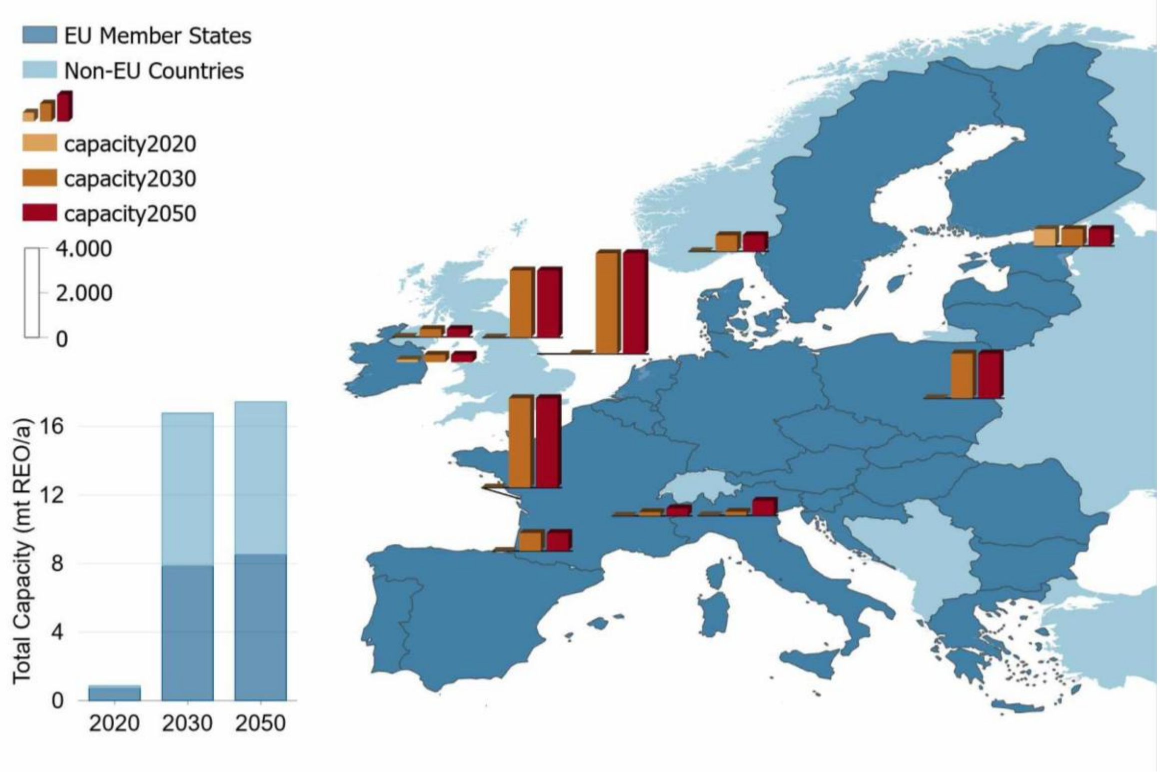


Figure 3-3. Geographical distribution and capacity of current and planned REE processing facilities in Europe for 2020, 2030, and 2050.

Although the projected increase between 2020 and 2030 appears substantial, it mainly reflects the concentration of recently announced and ongoing projects under the Critical Raw Materials Act and national industrial programmes. As of 2025, only a small share of these facilities is operational, while most are still in various stages of permitting, financing, or construction. Since delays or downsizing of projects is common, it is possible part of the planned capacity fails to materialise on schedule. As a result, the availability of domestic processing by 2030 could be significantly lower than projected, which would directly affect the self-sufficiency results discussed in Section 3.4.

Table 3-1. Overview of selected REE processing projects in Europe, including location, process type, capacity, and status.

Project	**Location**	**Main process**	**Capacity (separated NdPr-oxides)**	**Year / Status**
CAREMAG	Lacq, France	Processing/Recycling	800 t REO/a	From end of 2026
Ionic Rare Earths Ltd.	Belfast, UK	Recycling	350 t REO/a	From 2026
Less Common Metals	Cheshire, UK	Processing (alloy production)	120 t REO/a - 330 t REO/a	In operation, currently expanding
LIFE-22-ENV- IT-INSPIREE	Pieve Fissiraga Lodi, Italy	Recycling	160 t REO/a – 650 t REO/a	From 2027, full capacity in 2032
MagFactory	Noyarey, France	Recycling	165 t REO/a - 330 t REO/a	From 2027
Mkango Resources	Pulawy, Poland	Separation	2000 t REO/a	Awaiting permit
Neo Performance Materials	Sillamae, Estonia	Separation	750 t REO/a	In operation
Peak Rare Earths	Teesside, UK	Separation	3000 t REO/a	From 2025
Pensana	Saltend, UK	Processing	4500 t REO/a	From 2024
REEtec	Herøya, Porsgrunn, Norway	Separation (incl. recycling)	720 t REO/a	From 2025 (second plant planned for 2027, capacity unknown)
Solvay	La Rochelle, France	Processing	4000 t REO/a	From 2025

The processing facilities listed in Table 3-1 differ in terms of feedstock and technology. Some focus on processing primary ores and concentrates, while others are based on recycling end-of-life products or use a combination of both. These differences affect the type of input material, maturity of the processing technology, and the scalability of capacity. However, in this study all facilities are treated as processing capacity expressed in separated Nd/Pr-oxide equivalent. The potential implications of this simplification are addressed in the discussion section.

While planned projects indicate a substantial increase in potential processing capacity, actual contributions will depend on realisation timelines, technological readiness, and policy support. Delays or cancellations are already observed for some CRMA strategic projects, and could limit availability. In addition, parts of the announced capacity may be tied to existing or future agreements with non-EU partners or specific offtakers, meaning that certain volumes could be reserved for other purposes or export rather than available for EU domestic use.

3.3.1 Full allocation

When assuming that all available domestic LREE processing capacity is allocated exclusively to the wind sector, the EU could, in the future, easily meet 100 % of its projected demand across all scenarios considered. The shortfall around 2020 will be made up by newly commissioned capacity, creating a significant surplus by 2030. While this illustrates the technical feasibility of meeting demand domestically, it represents an unrealistic scenario, as it disregards competing demand from other sectors such as electric vehicles. The result therefore serves as an upper bound for the potential contribution of domestic processing to the wind sector.

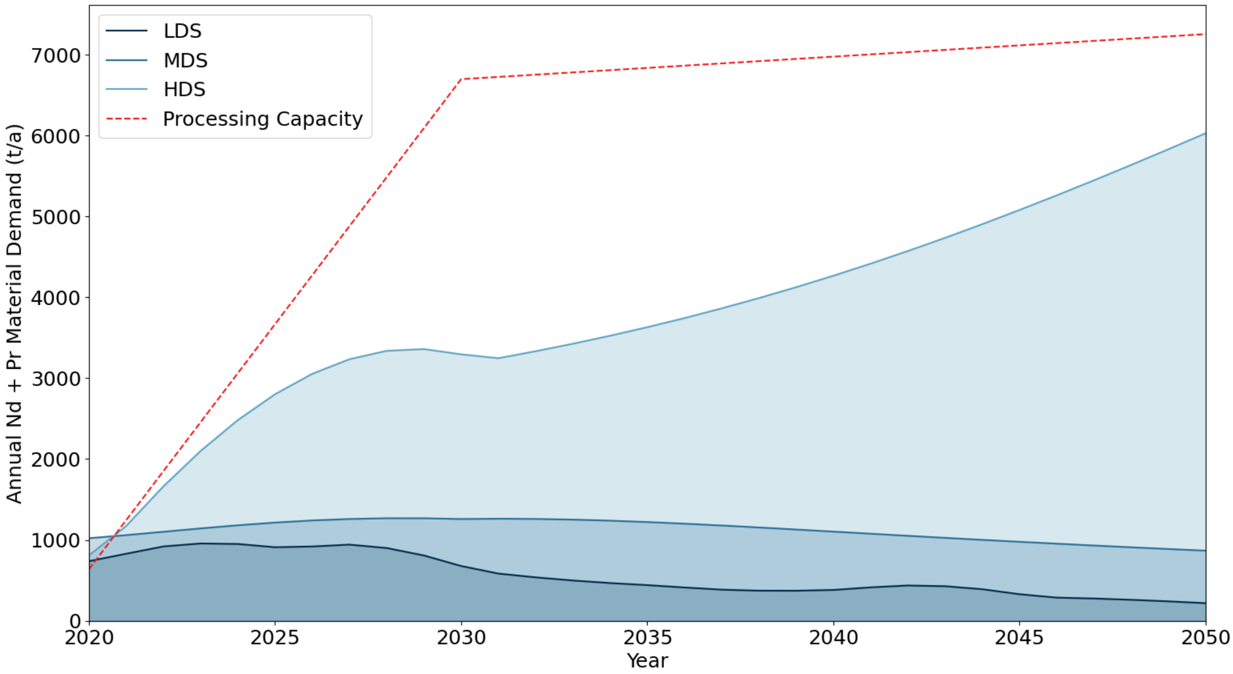


Figure 3-4. Modelled annual demand for neodymium and praseodymium of the wind sector under Low, Medium, and High demand scenarios, compared to total domestic processing capacity (in Nd and Pr metal equivalent).

The small differences in material demand between scenarios in 2020 result from the modelling method and data availability. Historical market share data for turbine technologies were only available up to 2018, after which values were extrapolated to 2020 based on scenario-specific assumptions. As a result, slight variations arise in the modelled material intensities and technology shares at the start of the simulation period, even though overall installed capacity is the same across scenarios.

3.3.2 Partial allocation

When demand from other sectors is taken into account, the situation changes significantly. Figure 3-5 illustrates this scenario, whereby demand from the wind sector, the EV sector and other sectors have been included. This clearly shows that the projected demand from other sectors may become much higher than the demand from wind only. This indicates that the full allocation scenario of paragraph 3.3.1 is not realistic due to the competition on the NdFeB-magnet market.

The growth rates applied for “other sectors” (3% and 10%) represent historical lower and upper bounds reported in literature (Alves Dias et al., 2020) and are used to capture a range of outcomes rather than exact forecasts. As a result, total demand in the HDS may be somewhat overestimated, but this provides an upper boundary to test the resilience of domestic processing capacity under extreme growth conditions.

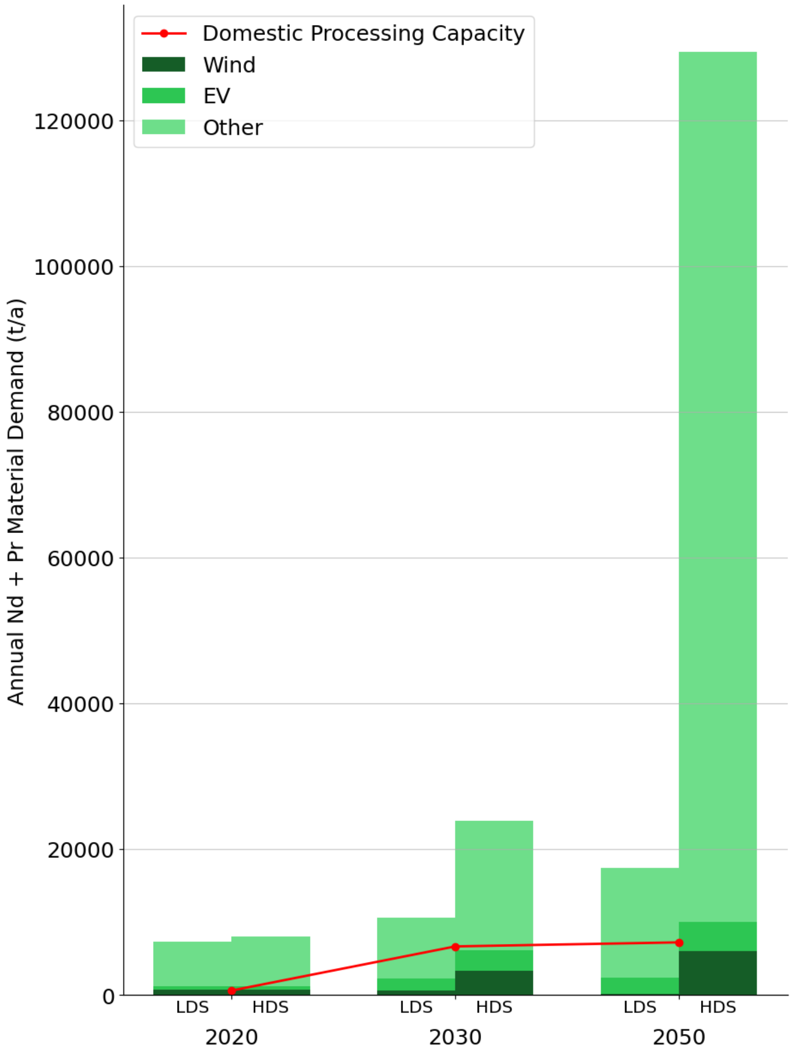


Figure 3-5. Projected material demand for neodymium and praseodymium (metal equivalent) across the wind, electric vehicle, and other sectors under the Low (LDS) and High (HDS) Demand Scenarios, compared to projected domestic processing capacity.

3.4 Self-Sufficiency

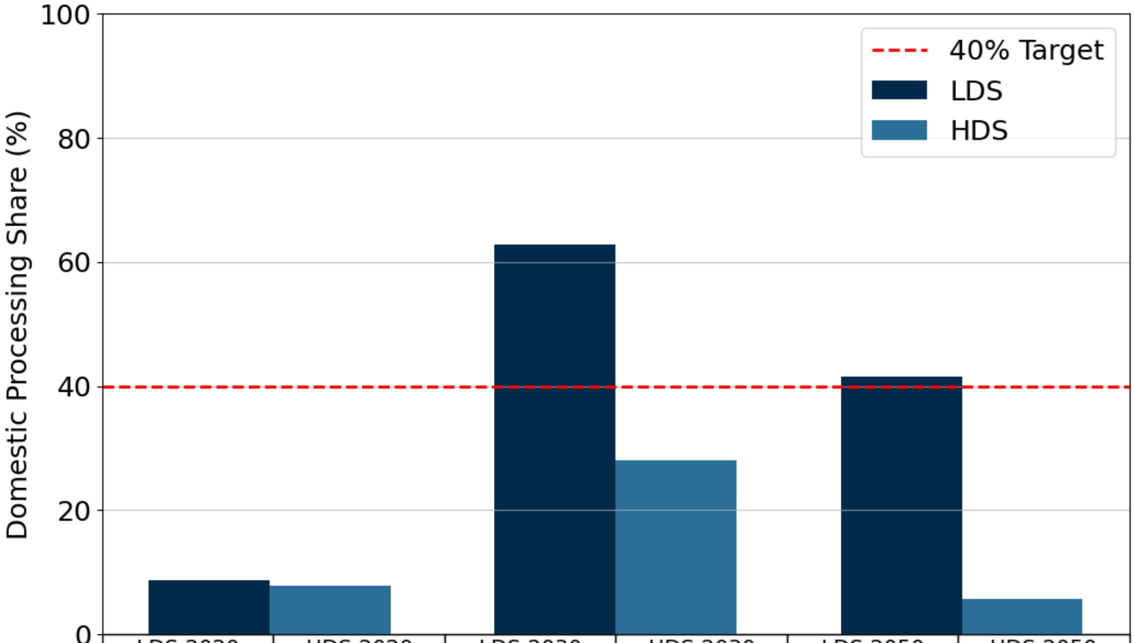
Paragraph 3.3 brings the LREE demand for the wind sector in perspective by looking at the overall domestic demand. This is important since the scope of the CRMA goals are the total LREE demand and not wind demand only.

But what does this mean for answering research question 4, more specifically, could the CRMA benchmarks of 40% domestic processing be achieved for the wind sector? In order to answer this question, the allocation of processing capacity per analysed sector (wind, EV and others) was modelled based on the projected demand from these sectors. The processing capacity allocated to each sector is based on the market share of the sector, detailed assumptions are attached in Appendix D.

The wind sector material demand and the allocated processing capacity are combined in Figure 3-6 which shows the percentage of domestically processed material. The results show that the EU starts from a situation where CRMA benchmarks are far from met. Under the assumptions of this study, this situation will change by 2030. For the LDS, the EU 40% target can be met, and for the HDS domestic processing can account for nearly 30% of demand. This improvement is mainly driven by the projected increase in processing capacity between 2020 and 2030. However, the results depend strongly on whether the announced capacity additions are actually realised, as many projects are still in early stages of development and may face delays or cancellation.

By 2050, domestic processing capacity could fall well short of meeting the CRMA target. In the LDS, self-sufficiency remains around the 40% benchmark, whereas in the HDS it drops below 10%. This is because the growth in processing capacity cannot keep up with the large growth in demand. As discussed, this scenario assumes very large growth in other sectors and these results highlight the sensitivity of self-sufficiency outcomes to these assumptions.

Please note that this is the share of domestically processed material for the wind sector only. Whether the 40% target is met for the other sectors is out of scope for this study.



	LDS 2020	HDS 2020	LDS 2030	HDS 2030	LDS 2050	HDS 2050
40%	-231	-260	+155	-397	+3	-2073
100%	-674	-745	-252	-2373	-128	-5688

Figure 3-6. Share of wind sector material demand met through domestic processing capacity under the Low Demand Scenario and High Demand Scenario, with partial allocation assumed, in 2020, 2030, and 2050. Bars show the percentage of demand covered relative to the CRMA benchmark of 40%. The table below the chart reports the corresponding shortfall (negative) or overcapacity (positive) in tonnes of Nd + Pr metal per year (t/a).

3.5 Sensitivity

The sensitivity analysis consist of two cases. The first case assesses the uncertainty of the material demand forecasts. The results of the Monte Carlo simulation in Figure 3-7 show the uncertainty for multiple percentiles. Uncertainty for the High Demand Scenario is relatively high compared to the other scenarios, and progressively increases over time.

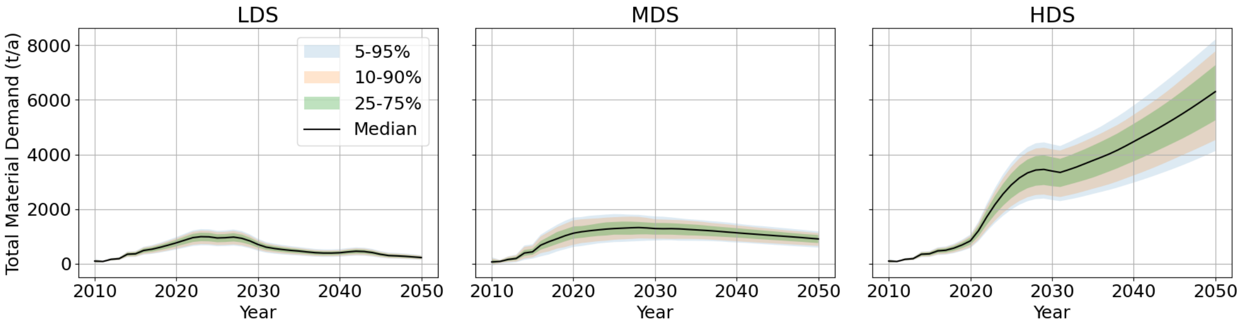


Figure 3-7. Uncertainty ranges (5–95%, 10–90%, and 25–75% percentiles) for projected material demand from wind turbines under Monte Carlo simulations.

The second case of the sensitivity analysis assesses the effect of the main assumptions on the self-sufficiency projections presented in paragraph 3.4. Table 3-2 shows the relative effect of slight changes in the input variables on the domestically processed material share, as a percentual change.

Table 3-2. Sensitivity of wind sector self-sufficiency outcomes to ±10% changes in electric vehicle demand, other sector demand, and initial processing capacity allocation. Values indicate the percentage point change in the share of domestically processed material relative to the baseline case.

	LDS 2030	LDS 2050	HDS 2030	HDS 2050
EV demand -10%	1.0	0.6	0.7	-0.3
EV demand +10%	-1.0	-0.6	-0.7	0.3
Other sectors -10%	2.3	7.8	6.9	28.4
Other sectors +10%	-2.3	-7.3	-6.6	-22.3
Initial allocation -10%	-9.4	-10.2	-8.9	-10.8
Initial allocation +10%	9.2	10.3	8.6	11.0

The assumption on initial allocation of processing capacity has the largest influence on the outcomes. A ±10% change in the initial allocation shifts the share of domestically processed material for wind by roughly ±9–11 percentage points across all scenarios. This means that the allocation assumption alone can determine whether the 40% CRMA benchmark is met, particularly in marginal cases such as HDS 2030.

The second most influential factor is demand from other sectors, with its effect becoming more pronounced towards 2050, especially under the HDS scenario. This can be explained by the strong growth in other sector demand in HDS 2050. Since the absolute demand in this year and scenario is very high, ±10% changes have a large effect on the remaining capacity available for wind.
As expected, if demand from other sectors (including EVs) is lower, more capacity remains available for the wind sector, and vice versa.

Variations in EV demand only lead to relatively small changes in the allocation to wind. This implies that the wind sector's share of processing capacity is less sensitive to EV demand, because total demand is dominated by other sectors. Especially in the 2050 HDS results, the effect of the 'other sector' demand is strong, implying that competition for limited processing capacity is an important factor in high material demand futures.

4 Discussion & Conclusion

4.1 Discussion

This section discusses and interprets the results of this research per topic, followed by the implications and limitations.

4.1.1 Wind Power Capacity & Material Demand

The results show a strong contrast between scenarios. In the LDS and MDS, demand stabilises after 2030, suggesting predictable material flows that could support planning for processing and recycling infrastructure. In the HDS however, neodymium demand exceeds 5,000 t/a by 2050. This highlights how sensitive the demand based-policy targets are to deployment assumptions.

While the HDS assumes rapid offshore expansion and continued reliance on permanent magnet technologies, recent political and market signals suggest that such high-demand futures may be less realistic. For example, investment interest for offshore projects has weakened, as seen in stalled tenders in the Netherlands and Denmark, and concerns over financial risks raised by operators like TenneT (Koster, 2025; Van Gestel, 2025; WindEurope, 2024). In addition, the re-election of Donald Trump in the US is expected to reduce momentum in global renewable investment, indirectly slowing European offshore deployment. For instance, Trumps order to stop U.S. offshore wind projects, affecting several European companies (Plumer & Friedman, 2025; Twidale, 2025). Taken together, these trends suggest that wind deployment may align more closely with LDS or MDS pathways, where material demand grows at a more moderate pace.

When compared to previous forecasts, the modelled capacity trajectories are comparable with IEA and WindEurope projections for 2030 (2024b; 2025), although the IEA anticipates a stronger offshore share. In terms of material demand, this study aligns with Carrara et al. (2023) under the LDS, while the HDS diverges after 2030 due to its higher deployment scale and limited efficiency improvements.

The assumptions on market and technology development largely reflect the current state of industry practice. Because permanent magnet materials are highly critical, several actors are investing in technological innovation to reduce REE use. Such advancements, whether through material substitution or improved magnet efficiency, could substantially lower future demand (Ghorbani et al., 2025; Heim & Vander Wal, 2023). This highlights that material criticality is not static but evolves with innovation and market feedback.

Finally, the HDS results imply a large build-up of in-use stocks. While it poses a challenge for material supply, it could support higher recycling shares in future, easing primary supply pressure. Depending on the recycling method (direct re-use of magnets or metallurgical recovery) processing capacity will need to adapt accordingly.

4.1.2 Processing Capacity

Planned EU processing capacity, based on known projects, grows rapidly to 2030 but then levels off. While additional projects may be announced in the coming years, long-term projections remain uncertain due to frequent delays and cancellations (Liu et al., 2023). As noted in Section 1.3, very few studies quantify European processing capacity, underlining the relevance of this analysis despite the gaps in available data. Overall, the results highlight that processing expansion is not purely a technical challenge but also a question of timing, coordination, and investment stability.

Primary vs. Secondary

A methodological limitation of this study is that no distinction is made between primary and secondary (recycling-based) processing capacity. In practice, these categories differ in several aspects. Recycling capacity is constrained by the availability and collection of end-of-life products and may therefore expand more slowly than primary processing, which depends on mine production and trade flows. The recycling stream lags demand growth because products only return after long lifetimes and is further influenced by collection rates and logistics. Moreover, recycling technologies are generally less mature and less scalable in the short term (Ghorbani et al., 2025). Treating both sources equally may therefore lead to an overestimation of short-term supply and responsiveness to demand growth.

Recycling input streams may contain more dysprosium (depending on the EoL product and magnets generation), taking up processing capacity, which results in overestimating Nd/Pr outputs for recycling facilities (Heim & Vander Wal, 2023). From an environmental perspective, aggregating primary and secondary processing masks the fact that recycling generally has lower carbon and environmental footprint, which means that sustainability benefits of a higher share of secondary processing are not captured in the results.

Importantly, in terms of self-sufficiency, primary processing substitutes imports of processed materials but still relies on imported ores or concentrates (if domestic extraction is not scaled up), whereas recycling reduces import dependence throughout the supply chain by closing material loops. Although both categories contribute equally toward the 40% domestic processing target under the CRMA, recycling provides additional self-sufficiency and circular-economy benefits that are not captured in this analysis.

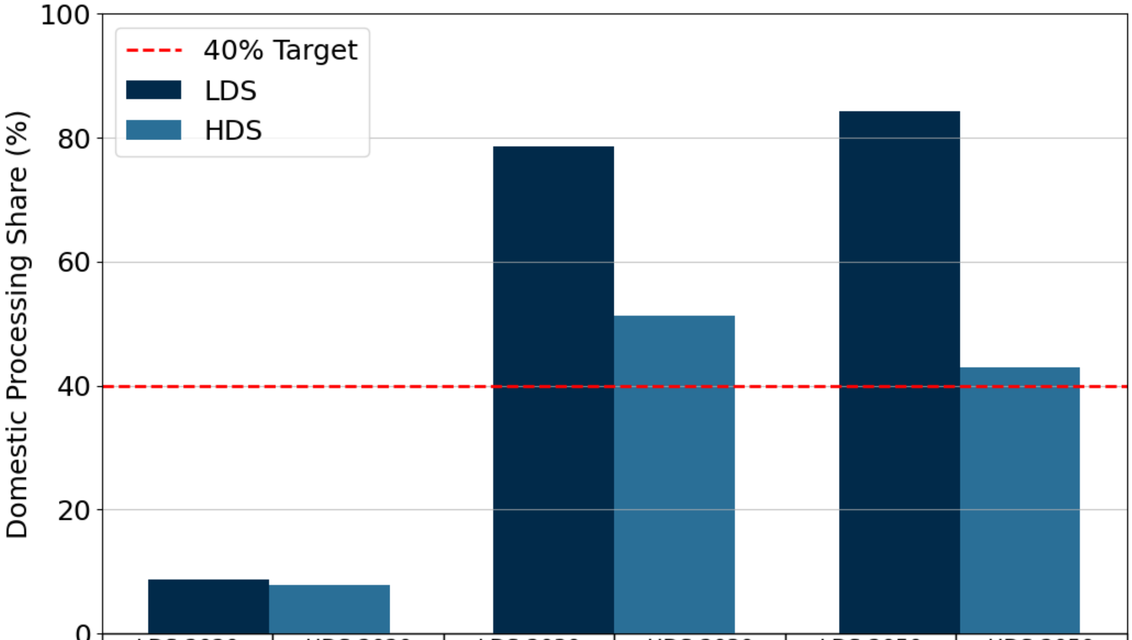
While this simplification allows for a consistent comparison of capacity and demand, the results should be interpreted with these limitations in mind; If only primary capacity is considered scalable in the near term, effective domestic processing may be lower than the results suggest.

Sectoral Competition

The results show that competition with other sectors strongly influences the share of processing capacity available to the wind sector. While full allocation would allow the EU to meet CRMA benchmarks with ease, partial allocation shows a more constrained picture, especially in high-demand scenarios. The assumed growth in other sectors may overestimate total material demand toward 2050, but this approach remains useful to explore the upper and lower bounds of system robustness.

Interestingly, the sensitivity analysis indicates that fluctuations in EV demand alone do not substantially alter the wind sector's access to processing capacity. Instead, growth in the broader category of "other sectors" (including electronics, robotics, consumer appliances, and defence applications) has the largest impact. These sectors are expected to grow steadily, and compared wind or EVs, they often involve a dispersed manufacturing base, making it difficult to prioritise or steer supply. This implies that in a high-demand future, competition from this collectively large sector could form a more significant constraint to wind-sector self-sufficiency than competition with EVs.

To further illustrate this effect, an additional sensitivity case was modelled for the self-sufficiency analysis previously shown in Figure 3-6, in which demand from other sectors was held constant over time (0% growth). As shown in Figure 4-1, removing growth in other sectors substantially increases the domestic processing share for the wind sector, particularly under the High Demand Scenario. This highlights that assumptions on competing sectoral demand are a key determinant of whether the CRMA benchmark is met.



	LDS 2020	HDS 2020	LDS 2030	HDS 2030	LDS 2050	HDS 2050
40%	-231	-260	+262	+372	+97	+177
100%	-674	-745	-145	-1604	-34	-3439

Figure 4-1. Sensitivity of domestic processing share to demand growth in other sectors. Results are shown for a case where other sector demand is held constant (0% annual growth), compared to baseline allocation assumptions. The higher processing shares illustrate how growth in competing sectors significantly limits the capacity available to the wind sector, especially under the HDS.

Policy Dimension and Geopolitics

Policy implications arise from both risks and opportunities. Planned capacity outside the EU, particularly in Norway and the UK, exceeds most EU27 projects, highlighting the value of strategic partnerships. At the same time, Europe remains exposed to geopolitical risks, as seen in the reliance on the Estonian facility located close to the Russian border. This dependence highlights that processing capacity is not only a matter of quantity but also of strategic location and political stability.

Together, these factors demonstrate that the future adequacy of EU processing capacity depends as much on governance and coordination as on the physical expansion of facilities, which connects directly to the following discussion on self-sufficiency.

4.1.3 Self-Sufficiency and Systemic Dependency

The results show that the 40% domestic processing benchmark can be met by 2030 under the LDS, but not under the HDS. However, "meeting" this benchmark does not guarantee genuine autonomy. True self-sufficiency goes beyond processing alone: Europe currently lacks large-scale permanent magnet manufacturing and remains dependent on external suppliers for downstream products. Expanding the

EU processing capacity as an isolated achievement without parallel investments in magnet production and integration into end-use manufacturing (e.g., wind turbines, EV motors).

From a policy perspective, the findings indicate that existing CRMA policy instruments appear broadly effective. If all currently planned projects are completed, domestic processing capacity could meet the 40% target under LDS conditions. Yet, this outcome depends critically on project realisation. As discussed in Sections 3.3 and 4.1.2, frequent delays, cancellations, and permitting challenges make the 2030 target uncertain in practice. Nonetheless, since LDS trajectories for wind deployment now appear more realistic (given recent market slowdowns explained in Section 4.1.1) the alignment between capacity expansion and demand growth may improve, increasing the likelihood of reaching the CRMA benchmark.

Even if the EU achieves 40% domestic processing, significant systemic dependencies will remain. Europe continues to rely heavily on China for upstream feedstock and magnet manufacturing, while technical know-how and refining technologies are also concentrated outside the EU. Recent export restrictions by China on rare-earth materials and technologies related to processing and separation illustrate how these dependencies extend beyond material supply alone, they also constrain Europe's ability to scale up its own industrial base (Corlin, 2025; A. Li, 2025). Such measures can temporarily incentivize domestic investment and policy momentum, yet their long-term impact depends on their persistence. If restrictions are relaxed or reversed, supply dependencies may simply reoccur, limiting the effect of short-term geopolitical shocks. Autonomy regarding critical raw materials therefor involves not only where processing occurs, but also who controls the technologies, supply contracts, and intellectual property.

To strengthen EU strategic autonomy, partnerships with nearby non-EU countries such as the UK and Norway provide opportunities: both to expand accessible processing capacity and to reduce reliance on China. This relates directly to another CRMA benchmark, which states that no more than 60% of supply should come from a single country. Even if the 40% benchmark is met, the EU may still remain highly dependent on Chinese supply for the remaining share, highlighting the importance of supply diversification.

4.1.4 Implications and Limitations

This study, like any scenario-based analysis, is subject to both methodological and contextual limitations. The results should therefore be interpreted as indicative trends that illustrate possible trajectories rather than exact forecasts.

Scenario and Model Uncertainty
The analysis is built on long-term scenarios that inevitably carry uncertainty in underlying assumptions such as technology deployment, material intensity, and market development. The differences between the LDS, MDS, and HDS already illustrate how small variations in these assumptions can lead to large divergences in projected demand. In addition, material demand is highly sensitive to price volatility in rare-earth markets. Previous crises, such as the 2010 REE price spike (Sprecher, 2016), have shown how sudden market disruptions can alter technology choices and investment behaviour. These kinds of effects are not captured by the model.

Data and Methodological Limitations

Processing capacity data remain fragmented, commercially sensitive, and largely limited to publicly announced projects, particularly beyond 2030. Many planned facilities are still in early stages and may face delays or cancellations. The model also generalises processing technologies and assumes uniform efficiency across facilities, while in reality technological performance and scalability vary. Similarly, sectoral allocation relies on simplified proportional assumptions derived from secondary sources. These simplifications are necessary to ensure consistency across scenarios but limit the precision of quantitative outcomes.

Scope and External Dynamics

The political and market environment for critical raw materials is highly dynamic, and results may change quickly in response to new developments. For example, during the writing of this thesis, several new initiatives and policies were announced (e.g. the selected strategic projects under CRMA (European Commission, 2025c)). Events such as geopolitical conflicts, shifts in trade relations, or sudden policy changes could alter the feasibility of domestic processing and the structure of global supply chains in ways that are not captured in the model. Moreover, environmental impacts and secondary material flows were not assessed, although they are central to the EU's sustainability goals. As in-use stocks increase, recycling could become a key factor influencing future self-sufficiency but is not included in the model's scope.

Despite these uncertainties, the study provides a structured, data-driven baseline linking material demand scenarios to domestic processing capacity and EU policy benchmarks. The results are best understood as a directional insight showing how processing capacity, material demand, and policy targets interact under different futures. Future research can refine this baseline as better data become available, turning these indicative findings into actionable knowledge.

4.2 Conclusions

This study set out to assess to what extent the EU can meet the growing demand for critical raw materials from wind energy technologies through domestic processing, and how this aligns with the targets set in the Critical Raw Materials Act. A Material Flow Analysis was developed for the light rare earth elements neodymium and praseodymium, comparing material demand to domestic processing capacity. The following main research question guided this study:

"To what extent can the European Union meet the growing demand for critical raw materials from wind energy technologies through domestic processing, under different deployment scenarios, and how does this align with the targets set in the Critical Raw Materials Act?"

This question was explored through four sub-questions, each addressing a specific component of the analysis.

Sub-Question 1. *"Which critical raw materials are relevant for wind turbine technologies, and what are the key processing stages and trade dependencies within their supply chains?"*

The research identified neodymium and praseodymium as the most relevant critical raw materials for wind turbine technologies. These light rare earth elements are used in permanent magnet generators that dominate modern onshore and offshore wind turbines, particularly direct-drive designs. Their processing involves several key stages: beneficiation, separation, and refining. Together, these steps transform ores and concentrates into separated rare earth oxides and metals.

The CRMA defines processing as these upstream steps but excludes intermediate products such as permanent magnets. As a result, the Act indirectly addresses supply risks for the wind sector but does not directly incentivise magnet manufacturing or recycling. The EU remains highly dependent on China, which dominates mining, separation, and magnet production. Within Europe, permanent magnet manufacturing capacity is limited, meaning that domestically processed materials risk being exported and re-imported as finished magnets. This represents an important structural dependency in the supply chain.

Sub-Question 2. *"What is the current and planned domestic processing capacity for these materials within the EU, and how can it be quantified?"*

As of 2020, the EU's domestic processing capacity was limited to approximately 750 t REO/a, provided almost entirely by the Neo Performance Materials facility in Estonia. Several new projects have since been announced or are under development, e.g. in France and Poland, with additional capacity emerging in the UK and Norway. If all planned EU projects are realised, capacity could reach nearly 8,000 t REO/a by 2030. Including non-EU European projects would raise continental capacity even further. However, as of 2025, most of these projects remain in early stages of permitting or construction, and face the risk of delay or downsizing. Actual available capacity by 2030 could therefore be significantly lower than the announced figures.

Sub-Question 3. *"How does the demand for critical materials from wind turbines evolve under different deployment scenarios, and how does this compare to available domestic processing capacity?"*

The model results show that future demand for Nd and Pr is highly sensitive to wind-deployment trajectories. Under the Low and Medium Demand Scenarios, demand peaks around 2030 and then stabilises, offering opportunities for planning processing and recycling. In contrast, under the High Demand Scenario, demand keeps rising to 2050, driven by rapid offshore expansion and continued reliance on permanent magnet generators. This places pressure on supply but also creates a growing in-use stock that could later serve as a secondary material flow.

When compared with projected processing capacity, the analysis finds that, for the wind sector alone, processing capacity appears sufficient to meet demand across scenarios. However, once competition from electric mobility and other industries is considered, available capacity for wind becomes much more constrained.

Sub-Question 4. *"What are the implications of the model outcomes for EU policy targets on domestic CRM processing, and what factors may constrain or enable meeting these targets under different future scenarios?"*

The model indicates that the CRMA benchmark of 40 % domestic processing can be achieved for the wind sector under the Low Demand Scenario, but is unlikely to be met under the High Demand Scenario. Processing capacity therefore emerges not as an immediate bottleneck, but as a potential constraint in high-growth futures where demand outpaces capacity expansion.

Achieving and maintaining the CRMA targets will depend on the successful completion of announced projects, the coordination of capacity allocation across sectors, and the integration of processing with domestic magnet manufacturing. Without such integration, processed materials risk being exported, limiting the EU's strategic autonomy. Enabling factors include continued policy support under the CRMA and Clean Industrial Deal, investment certainty, and regional cooperation with non-EU partners such as the UK and Norway.

To answer the main research question, this study finds that the EU's 40 % domestic processing target appears technically feasible under moderate demand pathways, provided that current projects are realised and sectoral coordination improves. Under high-demand conditions, however, capacity shortfalls are likely, underscoring the need for adaptive governance and ongoing investment. Achieving true self-sufficiency will require more than capacity expansion, as it calls for integration of processing with magnet manufacturing and recycling to ensure that domestic processing contributes to strategic autonomy and does not become an isolated achievement. By quantifying EU processing capacity and linking it to material demand scenarios and policy benchmarks, this study provides a baseline for evaluating Europe's progress toward critical raw material self-sufficiency. It highlights the importance of continuous data collection, scenario monitoring, and cross-sectoral collaboration to guide the EU's path toward a resilient rare-earth supply chain.

4.3 Recommendations

The role domestic processing capacity plays in whether the EU can meet its CRMA benchmarks, differs under different material demand scenarios. While current plans may be sufficient in moderate demand pathways, high-demand futures require additional action, careful monitoring, and coordinated policies. The following recommendations are directed at policymakers and researchers.

4.3.1 For Policymakers

The recommendations for policymakers are divided into those that directly follow from the findings of this study, and those that represent broader, more general measures that are relevant to strengthening strategic autonomy.

Result-based Recommendations:

- Timely realisation of planned processing projects is essential. The model results show that the 40 % domestic processing benchmark can only be achieved under the Low-Demand Scenario if announced facilities are completed as planned. Policymakers should therefore continue to support and de-risk CRMA strategic projects to prevent delays or cancellations.
- Cross-sector coordination for processing capacity should be established. Competition with other sectors proved to be a decisive factor in determining whether sufficient capacity remains available for wind energy. Developing mechanisms to strategically allocate processing capacity, or to steer demand between sectors, could prevent critical industries from facing material shortages.
- Processing expansion should be linked to magnet manufacturing. The findings indicate that domestic processing alone does not ensure real self-sufficiency if refined materials are subsequently exported for magnet production. Policy support should therefore explicitly connect new processing facilities with downstream magnet manufacturing, enabling true supply-chain resilience within the EU.
- Data monitoring and transparency should be improved. Given the current uncertainty and fragmentation of available data, structured monitoring of European processing capacity could be

beneficial. Annual, verified reporting distinguishing between primary and secondary capacity would enable adaptive governance and progress tracking under the CRMA.

- Recycling should be recognised as a capacity booster. Under moderate demand trajectories, stabilising material flows after 2030 provide an opportunity to prepare for large-scale end-of-life recycling of wind turbines. Integrating recycling within the processing framework would help maintain self-sufficiency beyond 2030 and strengthen circular-economy outcomes.

Broader Recommendations:

- Deepen strategic partnerships with nearby countries such as the UK and Norway, where significant capacity is planned, as is already implemented for other CRMs (European Commission, 2025d).
- Sharpen recycling policy by explicitly including permanent magnets, which are currently excluded as 'intermediate products', in CRMA targets and enforcing Article 28/29 on recyclability and recycled content.
- Promote circular and modular turbine design for easy disassembly and recycling, preparing for the secondary material flow of future decommissioned turbines.
- Support innovation and material substitution for rare-earth-free magnet alternatives to reduce long-term REE dependency.
- Encourage regional industrial clustering of processing, magnet production, turbine assembly, and recycling to create synergies and lower costs.

4.3.2 For Future Research

Further research could strengthen the understanding of Europe's rare earth self-sufficiency and improve future scenario assessments by focusing on:

- Regularly updating demand and supply projections, incorporating new policy developments, technology trends, and project progress or delays.
- Expanding and refining data on European processing and recycling capacity, ideally through sector-specific studies and collaboration with project developers.
- Integrating environmental and economic dimensions into the model, for example by combining MFA with life-cycle or input–output analyses to assess carbon impacts and cost competitiveness.
- Including recycling flows explicitly, to capture the timing, scale, and potential contribution of end-of-life materials to future self-sufficiency.
- Assessing the potential for domestic magnet manufacturing, including industrial capacity, investment interest, and feasible timeframes for scaling up production.
- Analysing trade data for raw materials, processed materials, magnets, and final products to gain additional insight into actual self-sufficiency and circularity potential.

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Appendices

A. Model Repository

The model and supporting scripts developed for this thesis are openly available on GitHub:

Tacken, E.M.S. (2025). *Processing Rare Earths for Europe's Wind Power: Model Repository*.
Available at: https://github.com/elisatacken/IEThesis

The repository includes:
- Python code used for the material flow model
- Input datasets

All code is released under an open-source license for academic and non-commercial use.

B. Wind Turbine Market Shares

Historical market shares of permanent magnet wind turbines, based on (Carrara, Alves Dias, et al., 2020):

	2010	**2011**	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**
Onshore									
Type D-PM DD-PMSG	2	3	3	5	10	10	10	10	10
Type E E-PMSG	10	5	20	15	20	20	30	25	20
Offshore									
Type D-PM DD-PMSG	0	0	0	2	10	5	40	50	70
Type E E-PMSG	0	0	0	5	10	40	0	35	25

Future market shares of permanent magnets in wind turbines:

	Onshore			***Offshore***		
	LDS	*MDS*	*HDS*	*LDS*	*MDS*	*HDS*
2018	0.3	0.3	0.3	1	1	1
2020	0.3	0.3	0.3	1	1	1
2030	0.41	0.41	0.52	0.48	0.48	0.95
2050	0.52	0.52	0.65	0.44	0.44	0.95

C. Overview of Processing and Recycling Facilities in Europe

This appendix provides background information on current and planned REE processing and recycling facilities in Europe. The facilities described include operational plants, announced projects, and selected EU strategic initiatives under the Critical Raw Materials Act (CRMA).

To compare domestic processing capacity with projected demand for neodymium and praseodymium in permanent magnets, all reported figures were converted to a common unit: NdPr-oxide equivalent. The following assumptions and conversion factors were applied:

- **Oxides to metals:**
  The metal content is taken as a fraction of the oxide weight. For neodymium, Nd metal corresponds to 0.857 of the weight of Nd_2O_3, and for praseodymium, Pr metal corresponds to 0.828 of the weight of Pr_6O_{11}. Assuming a didymium mix of 75% Nd and 25% Pr (Heim & Vander Wal, 2023), a single factor of 0.85 was applied for conversion between NdPr-oxide and Nd+Pr metal.
- **Magnets to separated oxides:**
  Sintered NdFeB magnets are assumed to contain 30% REEs by mass. Of this fraction, 2% is heavy REEs (Dy/Tb) and 28% is Nd+Pr metal. This share was converted to NdPr-oxide equivalent using the 0.85 factor above.
- **Recycling feed:**
  For end-of-life products (in the projects consisting of HDDs and electric motors), recycled magnets are assumed to contain 5% Dy of the total REE fraction, with the remainder treated as Nd+Pr for conversion.

1. CAREMAG (Lacq, France)

CAREMAG is an EU strategic project scheduled to start operations at the end of 2026. The facility will recycle around 2,000 t/a of end-of-life rare earth magnets and refine 5,000 t/a of mining concentrates, with an expected output of ~800 t/a NdPr and ~590 t/a Dy and Tb oxides (Carester, n.d.).

The company has secured long-term offtake agreements, including a 2024 deal with car manufacturer Stellantis to supply more than 3,400 tonnes of REOs (Nd, Pr, Dy, Tb) over ten years, of which more than one-third will come from recycled materials. CAREMAG has also attracted international investment: Jogmec and Iwatani (Japan) committed up to €110 million, linked to an agreement for 50% of the facility's Dy and Tb output, equivalent to about 20% of Japan's future demand for these heavy rare earths (Obayashi, 2025; Shaw, 2025).

2. Ionic Rare Earths Ltd. (Belfast, United Kingdom)

Ionic Rare Earths Ltd. is developing a recycling facility with first deliveries expected in 2027. The plant is designed to process 1,200 t/a of feedstock, yielding about 400 t/a of separated magnet REOs, including 350 t/a Nd and Pr oxide, over a 20-year operating life. Feedstock consists mainly of end-of-life permanent magnets and magnet manufacturing waste. Target outputs include Nd, Pr, Dy, Tb, and mixed NdPr oxides. The company has established partnerships with Less Common Metals (UK) and Vacuumschmelze (Germany) to supply magnets containing 100% recycled REEs. A demonstration plant in Northern Ireland is already producing rare earth oxides, and additional feedstock will come from the

Makuutu heavy REE project in Uganda. The process relies on hydrometallurgical extraction and separation to refine high-purity magnet oxides (Iconic Rare Earths Limited, 2024; Jamasmie, 2024).

3. Less Common Metals (Cheshire, United Kingdom)

Less Common Metals produces rare earth metals and alloys, with a focus on Nd and NdPr. Current capacity is 110 t/a, expanding to 330 t/a Nd and NdPr metals (Magnetics Magazine, 2025). The facility emphasises recycling as a feedstock source and also processes heavy rare earths such as Tb and Dy (Innovation News Network, 2024).

4. LIFE-22-ENV- IT- INSPIREE (Pieve Fissiraga, Italy)

LIFE INSPIREE is an EU strategic recycling project focused on rare earth permanent magnets. The project aims to build partnerships with companies such as Neo Performance Materials, Stellantis, and Magneti Ljubljana to integrate recycled REEs into manufacturing processes. Initial operations are scheduled for 2027, with a capacity to recycle ~500 t/a of magnets, yielding about 170 t/a of separated REEs (Nd, Pr, Dy). By 2032, full operation is expected to increase output to ~680 t/a, contributing to the EU's goal of raising REE recycling rates from currently less than 1% (European Commission, n.d.).

Assuming a 5% Dy content in the recycled magnets, output of this project will be ~160 t/a in 2027 and ~650 t/a in 2032.

5. MagFactory (Noyarey, France)

MagFactory is a recycling-based permanent magnet production facility, operational since 2024. It focuses on manufacturing high-performance sintered NdFeB magnets entirely from recycled materials. Production capacity is expected to reach ~500 t/a by 2027 and ~1,000 t/a by 2030 of high-performance sintered NdFeB magnets (Magnetics Magazine, 2024b; Petit, 2022).

Assuming the magnets contain 30% REE, of which 2% Dy/Tb and 28% Nd+Pr metal, and converting the metal to oxides (Nd+Pr metals / 0,85), the output of Magfactory is expected to reach 165 t/a and 330t/a NdPr-oxide-equivalent by 2027 and 2030 respectively.

6. Mkango Resources (Pulawy, Poland)

The separation plant in Puławy is recognised as an EU strategic project and expected to start operations in 2027. The facility is designed to produce around 2,000 t/a of separated Nd/Pr oxides, along with approximately 50 t/a of Dy and Tb oxides in a heavy rare earth carbonate (European Commission, 2025a; Mkango Resources Ltd., n.d.).

7. Neo Performance Materials (Sillamäe, Estonia)

Neo Performance Materials operates the EU's first commercial rare earth separation facility at Sillamäe, Estonia. The site includes three plants: a light rare earth metals plant (capacity ~3,000 t/a), a rare metals plant (~700 t/a), and a metallurgy plant. While most feedstock is imported from outside Estonia (primarily Brazil, the United States, and Russia), the majority of output is exported to markets in the EU, USA, and Japan. Silmet products are used across multiple sectors, including automotive, aviation, electronics, and high-tech industries (Argus, 2023; Sillamäe linn, n.d.).

Of the 3000 t/a LREs, about a quarter is NdPr-oxides according to Reuters (2024), which roughly corresponds with rare earth oxide distributions according to Xie et al. (2014). Accordingly, NdPr-oxides output of the Silmet plant is assumed to be 750 t/a in this study.

In addition to supplying separated oxides, Silmet provides neodymium oxide for Neo's Magnequench operations in Asia. Material from Silmet is processed further in Thailand through a tolling agreement and used in permanent magnet powder production for facilities in Tianjin, China, and Korat, Thailand. Historically, a large share of Silmet feedstock has come from Russia, though Neo has been diversifying its supply sources (Neo Performance Materials, 2024).

Neo is also expanding in Estonia, with a new permanent magnet manufacturing facility under construction in Narva. This plant is intended to create a mine-to-magnet supply chain in Europe, supported by feedstock from Silmet and future recycling integration (Neo Performance Materials, 2023).

To secure long-term supply, the company is co-developing the Sarfartoq carbonatite deposit in Greenland and has established agreements with Energy Fuels in the United States, which ships mixed rare earth carbonate derived from monazite for processing at Silmet. This U.S.–EU supply chain, initiated in 2021, marked one of the first such links in decades (Argus, 2023).

8. **Peak Rare Earths (Teesside, United Kingdom)**

Peak Rare Earths is planning a separation facility at Teesside, with an expected output of 9,900–11,600 t/a REO equivalent, including 3,000–3,500 t/a of NdPr oxide. The more conservative expected capacity of 3000 t/a is used this study. Feedstock will come from a Tanzanian deposit, and the company also plans to integrate rare earth recycling at the site. Commissioning and ramp-up are scheduled to begin in December 2024 (Casey, 2018; Peak Resources, 2021).

9. **Pensana (Saltend, United Kingdom)**

Pensana is developing a separation facility at Saltend, UK, with a planned capacity of 12,500 t/a of separated rare earth oxides, including 4,500 t/a of NdPr (about 5% of the projected global market in 2025). The plant will be supplied with feedstock from Angola (Pensana Plc, 2022; Rani, 2021).

10. **REEtec (Porsgrunn, Norway)**

REEtec operates a rare earth separation facility at Herøya Industrial Park in Porsgrunn, Norway. The plant is closely aligned with the Swedish state-owned mining company LKAB, which is developing a significant rare earth deposit to provide feedstock. The facility focuses on producing separated NdPr oxides. A distinguishing feature of REEtec's process is its relatively low energy demand, and the exclusive use of hydropower. The first plant is scheduled to commence operations in 2025 with a capacity of approximately 720 tonnes per year of NdPr oxides. A second facility is planned for 2027, though its capacity has not yet been disclosed (Magnetics Magazine, 2024a).

11. **Solvay (La Rochelle, France)**

Solvay is developing a rare earth processing facility in La Rochelle, scheduled to begin operations in 2025. The plant will have an estimated capacity of 4,000-4500 t/a and is projected to cover around 30% of Europe's permanent magnet needs by 2030. The exact material mix is not published, however, since Solvay states it will be NdPr focussed and depend on orders, 4000 t/a is taken as the potential capacity for NdPr oxides in this study.

Feedstock will come from both primary and secondary sources: Hastings' Yangibana rare earth project in Western Australia (initially ~2,500 t/a) and recycled mixed rare earth oxides supplied by Cyclic Materials, with shipments beginning in late 2024. Solvay also aims to source up to 30% of materials locally through recycling end-of-life magnets from European motors (Belga News Agency, 2025; Marchandon et al., 2024; Smialek, 2025; *Solvay*, 2022; *Solvay*, 2024).

Additional projects (excluded from model):

Several projects were identified but excluded from the quantitative model due to insufficient information on capacity or timelines:

- **3R-Cycle (Finland)**
  A pilot project focused on critical metal leaching and recovery. No details are available on launch dates, planned capacity, or development stages (3R-Cycle, n.d.).
- **ReeMAP Project (Malmberget, Sweden)**
  A mining and processing initiative led by LKAB, targeting rare earth recovery from iron ore deposits with high phosphorus and REE concentrations. Operations are expected to start in 2026, with full-scale production foreseen in the 2030s. The project aims to supply up to 30% of current EU demand, but specific capacity figures are not available. Processing will be partly carried out by REEtec in

Norway and a second LKAB-owned facility in Luleå. A demonstration plant has already been established at the Luleå Industrial Park (Belda, 2023; LKAB, 2025).

These projects were excluded from the model because their future capacities and timelines remain highly uncertain. While they may eventually add substantial processing volumes to the European market, their omission ensures that the model results remain conservative and based on verifiable data.

D. Distribution of Processing Capacity under Partial Allocation

The allocation method is based on the relative market shares of the wind, EV, and other sectors in total European demand for neodymium and praseodymium. This approach assumes a proportional distribution of available processing capacity according to sectoral demand. Figures C-1 and C-2 show the processing capacity over time, and the distribution of the total capacity between sectors.

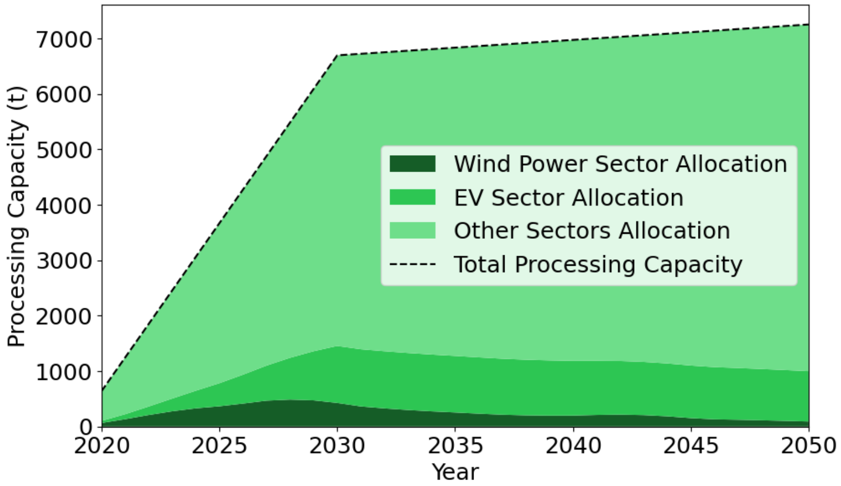

Figure C-4-2. Processing capacity allocation under the Low Demand Scenario.

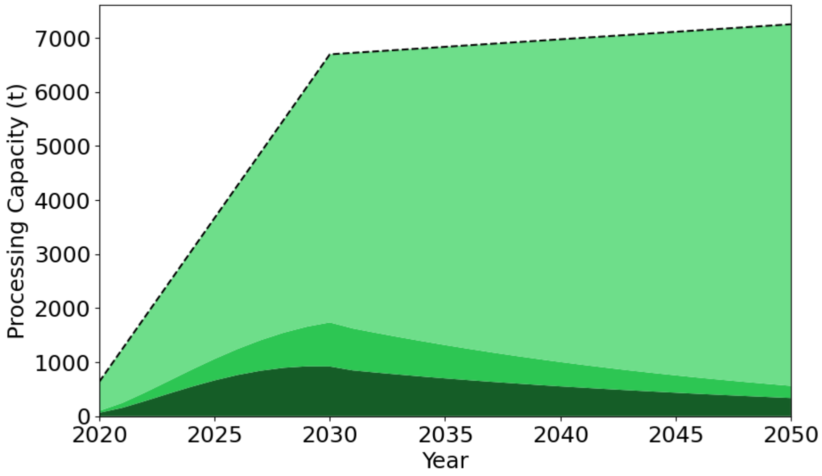

Figure C-4-3. Processing capacity allocation under the High Demand Scenario.

This method is a simplifying assumption. In reality, the distribution of processing capacity is unlikely to follow market shares alone. Economic value of end-products, long-term supply contracts, and targeted policy measures may strongly influence which sectors have access to processed materials. Thus, the partial allocation scenario should be seen as a baseline estimate of competition rather than a prediction of actual market outcomes. It is used to illustrate how competition between sectors can significantly affect the share of domestic processing available for wind turbines.