EU Critical Raw Materials Act: too ambitious or not ambitious enough?

A case study on the implications of the three Critical Raw Material Act proposals on satisfying demand for neodymium in wind turbines more sustainably through recycling in Germany

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Abstract

The mitigation of climate change and the transition to a more sustainable and circular use of resources are two of the largest challenges of our time. To this end, the European Commission proposed the Net Zero Industry Act (NZIA) and Critical Raw Materials Act (CRMA) in March 2023 as further pillars to its Green Deal. While the NZIA focuses on establishing supply chains for net-zero technologies, the CRMA aims to maintain access to the necessary materials. However, these so-called Critical Raw Materials (CRMs), are not only required for net-zero technologies but also for numerous other applications. To ensure their growing demand can be met more sustainably, the European Commission CRMA proposal states that 15% of total CRM consumption in the EU must be satisfied through recycled materials by 2030. In response to the Commission's proposal and as part of the legislative process, the European Council proposed a more ambitious target of 20% of demand to be satisfied through secondary materials. The European Parliament's proposal takes a slightly different approach in that it suggests a 45% target for recycling all waste streams, rather than focusing on a set share of consumption.

Given the current dynamic nature of the legislative process, no publicly available literature exploring the extent to which the three proposals can contribute to meeting CRM demand more sustainably could be identified. Hence, the objective of this thesis is to quantify and analyze the implications of each recycling target, leading to the following research question: "*How do the Critical Raw Materials Act recycling targets proposed by the European Commission, Council and Parliament compare in their contribution to meeting future demand more sustainably?".* To address this question, a case study on closed-loop neodymium recycling of NdFeB magnets in onshore and offshore wind turbines in Germany between 1989 and 2045 is performed. To map past and expected future neodymium stocks and flows, a dynamic material flow analysis (dMFA) is used. Building on a business-as-usual model without any recycling, explorative scenarios are developed reflecting each of the three CRMA proposals for recycling.

The results reveal that under the expected flow dynamics, the achievement and effectiveness of the targets depends on the time period considered. Because neodymium demand is expected to increase significantly over the upcoming decade, the Parliament's targets are the most realistic until 2030, given that they are defined relative to actual waste streams. In contrast, achieving the Commission's and Council's consumption-based targets is comparably unrealistic, due to the fact that not enough waste streams will be available to satisfy 15 or even 20% of the rapidly growing demand. Extrapolating the targets of the Commission and Council beyond 2030, shows that they are achievable from around mid-2030 onwards. Regardless of the scenario, recycling rates need to increase significantly and rapidly. To meet the Commission's and Council's targets in particular, recycling rates of up to 100% until 2035 must be realized. Compared to current recycling rates of below 1%, this appears highly ambitious.

Policy makers are advised to establish targets beyond 2030 and to support relevant stakeholders in creating a recycling infrastructure, both financially and through favorable framework conditions. Future research should explore whether the specific trends observed in this case study also apply to other strategic applications and materials. Moreover, research on how product-life extensions could contribute to decreasing demand for primary materials in the short- to medium-run should be conducted.

Key words: *Critical Raw Materials, EU Critical Raw Material Act, Green Deal, renewable energy, wind energy, neodymium, permanent magnets, recycling, circular economy*

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Abbreviations

Abbreviation	Definition
BWE	Bundesverband Windenergie
CMU	Critical Material Use Rate
CRM	Critical Raw Materials
CRMA	Critical Raw Materials Act
DFIG	Doubly-Fed Induction Generator
dMFA	dynamic Material Flow Analysis
EEG	Erneuerbare-Energien-Gesetz (Renewable Energy Act)
EU	European Union
GHG	Greenhouse Gases
GW	Gigawatts
HREE	Heavy Rare Earth Element
LREE	Light Rare Earth Element
MFA	Material Flow Analysis
MRI	Magnetic Resonance Imaging
MW	Megawatts
NdFeB magnet	Neodymium-Iron-Boron magnet
NZIA	Net Zero Industry Act
PGM	Platinum Group Metal
PMSG-DD	Permanent Magnet Synchronous Generators Direct Drive
PMSG-HS	Permanent Magnet Synchronous Generators High Speed
PMSG-MS	Permanent Magnet Synchronous Generators Medium Speed
REE	Rare Earth Elements
SCIG	Squirrel Cage Induction Generator
sMFA	static Material Flow Analysis

1 Introduction

The world currently faces a number of tremendous challenges. Two of these challenges are the mitigation of global warming and climate change and the transition to a more sustainable use of resources. It is well-established that emissions from various types of greenhouse gases (GHG) increase average global temperatures, leading to severe environmental, social, and economic impacts (IPCC, 2014). Evidence suggests that 25% of global GHG emissions are attributed to electricity and heat production, 24% to agriculture, forestry, and other land use, 21% to industry and14% to transportation, 6% to buildings and 10% to other energy (US EPA, 2022). In addition to GHG emissions, resource depletion and pollution into air, soil and water have further devasting consequences for the environment and human health (UNEP, 2017; World Bank, 2023). To limit all types of emissions and to mitigate the rapid depletion of resources, governments have committed themselves to a large number of different ambitious climate and environmental targets (UNEP, 2017; UNFCC, 2015).

In addition to while also contributing to global commitments such as the Paris Climate Agreement, the European Union (EU) is pursuing its ambitious Green Deal strategy. As one of the Green Deal's main objectives, the EU aims to become the first continent with net-zero emissions by 2050. Considering that energy was responsible for approximately 25% of the union's GHG emissions in 2021, transportation for 21%, industry for 21%, residential and commercial activities for 12% and agriculture for 10% (Statista, 2023), decarbonizing the energy grid could bring the EU considerably closer to achieving this net zero target. To this end, the EU has set an intermediate target of 45% renewable energy for 2030 (European Commission, 2022). In addition to goals of decarbonizing the energy grid, the Green Deal also aims to establish more sustainable extraction, use and end-of-life treatment of raw materials. For this, a number of strategies and directives targeting battery value chains, chemicals, agriculture, and circular economy have been put into place (European Council, 2023b).

Despite the importance of decarbonizing the energy grid to lower GHG emissions, the roll-out of renewable energy technologies is associated with challenges and trade-offs. To reach the EU's 45% renewable energy target, the current share of 22.2% renewable energy (EEA, 2022) must be more than doubled within the next six years. This increase will not only translate into a high demand for concrete, steel, plastics, glass, and other bulk materials, but also into a sharp rise in demand for certain elements including rare earth elements (REEs), platinum group metals (PGMs) as well as lithium, cobalt, and nickel (Bobba et al., 2020). Many of these elements, however, are also increasingly needed in a range of other sectors, including e-mobility, digital technologies, robotics, 3D-printing, defense, and space (Bobba et al., 2020). In addition to the large volume of resources need to satisfy the demand across all these sectors, the EU faces the challenge of being highly dependent on international suppliers, most notably on China. Six numbers demonstrate this dependence particularly well: 89% of solar module components and 56% of wind turbine components are produced in China (Bobba et al., 2020), China controls 60% of all rare earth oxide mining, 87% of all rare earth oxide processing, 91% of rare earth metal production and 94% of permanent magnet production (Gauß et al., 2021a).

To ensure that growing demand for these materials is satisfied while import dependencies are reduced and adverse environmental impacts along the entire value chain are avoided, the European Commission has proposed the Net Zero Industry Act (NZIA) and Critical Raw Materials Act (CRMA) in March 2023 as further pillars to its Green Deal (European Commission, 2023). The NZIA's goal is to strengthen the European ecosystem and industry for net zero technologies so that by 2030, 40% of the EU's required net zero technologies are produced domestically (Proposal for a Regulation Net Zero Industry Act, 2023). A prerequisite for achieving the targets specified by the NZIA, is maintaining access to the necessary material resources. To this end, the CRMA proposes a number of targets, including the goal that by 2030, 15% of all Critical Raw Material consumption in the EU must be sourced from recycled materials (Critical Raw Materials Act, 2023).

As part of the still on-going legislative process, the European Council and European Parliament need to accept the Commission's proposal or find a different compromise. While both the Council and Parliament welcomed the proposal, the Council has suggested increasing the mandatory share of recycled material to 20%. In contrast to the Commission's and Council's consumption-based targets, the European Parliament has suggested a slightly different approach, according to which 45% of strategic materials in waste streams need to be recycled by 2030 (European Council, 2023a; Simon, 2023). Although the final agreement between the three European bodies is still pending as of September 2023, it is clear that achieving the targets requires a significant transition in material sourcing, production, and end-of-life treatment within Europe. Against this background, this thesis will address questions relating to the extent to which each of the three proposals can contribute to satisfying demand more sustainably.

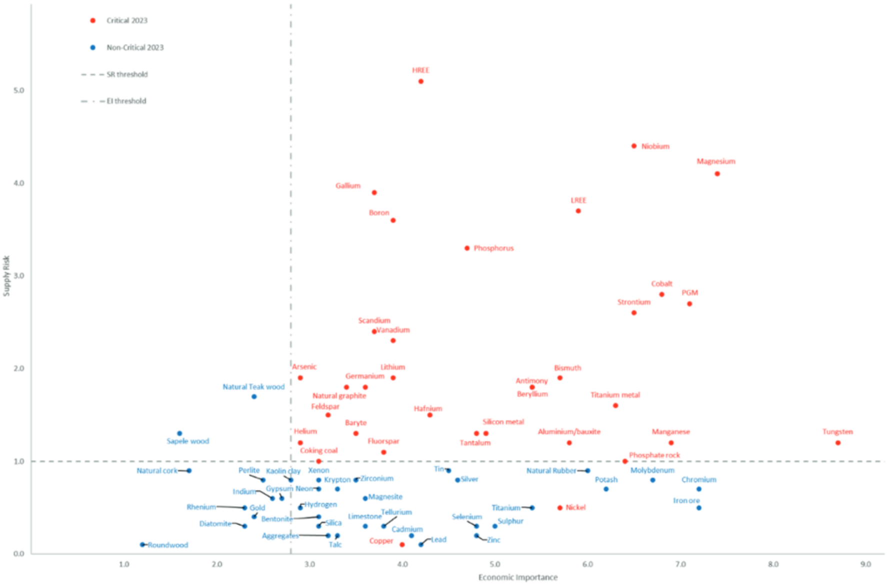
1.1 Critical Raw Materials

Critical Raw Materials are materials considered to have a high strategic and economic importance for the EU (European Commission, 2020a). Although the technologies needed to address many of the mentioned challenges rely on bulk materials such as steel, limestone, and other aggregates, many of them also require specific elements. For instance, heavy and light rare earth elements (HREE and LREE, respectively), including neodymium, dysprosium, or praseodymium used in permanent magnets, PGMs and metals like tantalum or titanium are classified as CRMs (Hofmann et al., 2018). Since 2011, the EU has hence been monitoring and quantifying the supply risk of CRMs. The most recent overview of the considered materials and their degree of criticality are provided in Figure 1.

A material's degree of criticality depends on its economic importance and specific supply risk. The economic importance is based on the allocation of raw materials to specific and strategically important end-uses and the economic value-added individual materials provide and is corrected by the substitution index (European Commission, 2020a). In other words, the more important and non-substitutable a material and the higher its value-added is, the greater its economic importance. A material's supply risk is determined by the EU's import reliance, in which the concentration of primary material supply from raw material producing, governance performance and trade aspects of producing countries is considered (European Commission, 2020a). The degree of criticality is not determined by geological abundance of materials. In fact, some critical material deposits are very abundant (Alves Dias et al., 2020; Balaram, 2019) but simply remain untapped for economic, technological, or environmental reasons. An example illustrating this is that even though only 38% of global REE deposits are located in China, China nevertheless extracts and produces 85% of global supply (LePan, 2021). This high degree of dependence on China as a single exporter, in combination with its governance performance and the currently low recycling rates of REEs, classify them as having a very high criticality.

Figure 1

EU Critical and Non-Critical Raw Materials (as of 2023)



Note. Figure from Grohol et al. (2023). Nickel and copper do not meet thresholds for CRMs but are nevertheless included as Strategic Raw Materials.

1.2 Renewable energy

The term *renewable energy* refers to energy sources that are naturally replenished (Dillemuth, 2022), providing an alternative to fossil fuel-based energy sources (Ciucci, 2023). Renewable energy sources include solar, wind and hydroelectric power, as well as ocean energy, geothermal energy, biomass, and biofuels (Ciucci, 2023). In contrast to the commonly-cited low- or zero-carbon energy sources, the term renewable energy does not include nuclear energy (Dillemuth, 2022). Although biomass is by far the largest renewable energy source in the EU in 2023 (EEA, 2023), wind and solar power are among the most rapidly expanding sources, already generating 22% of total EU electricity in 2022 (van Halm, 2023).

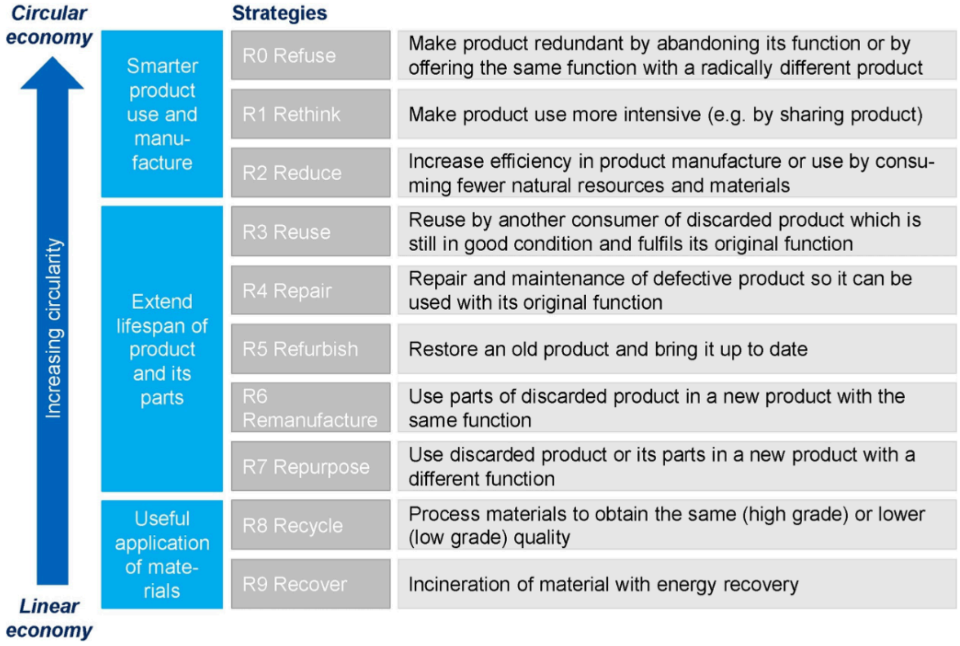
1.3 Circular economy

To facilitate the transformation towards a climate neutral and low-emission European economy by 2050, the establishment of a circular economy is one of the Green Deal’s pillars (European Council, 2023b). The concept of a *circular economy* can be understood as an economic system in which the lifecycle of products, parts and materials is extended, and material consumption, waste, and losses are minimized (European Parliament, 2023; Morseletto, 2020). Closing material loops successfully has the potential to decouple economic activity from primary resource consumption and environmental degradation (Larrain et al., 2020; Morseletto, 2020). Establishing a circular economy can hence be understood as a systemic shift from the currently predominant linear economy following a “take-make-use-dispose” approach to one in which material cycles are established (European Parliament, 2023). A circular economy is associated with lower GHG emissions, less disruptions and emissions to the environment and increased employment opportunities in the long run (European Parliament, 2023).

Within the concept of a circular economy, academics and practitioners often refer to and implement so-called *R-Strategies* (Kirchherr et al., 2017; Morseletto, 2020). R-Strategies are frameworks combining the core principles of a circular economy (Larrain et al., 2020). While some of these frameworks include only three or four individual principles (Kirchherr et al., 2017; Morseletto, 2020), others are more elaborate; Kirchherr et al. (2017), for instance, follow the 9R-Framework. The 9R-Framework is subdivided into three different categories to distinguish different phases along the value chain (Figure 2).

Figure 2

9R-Framework of principles for a circular economy



	Strategies	
Smarter product use and manufacture	R0 Refuse	Make product redundant by abandoning its function or by offering the same function with a radically different product
	R1 Rethink	Make product use more intensive (e.g. by sharing product)
	R2 Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of product and its parts	R3 Reuse	Reuse by another consumer of discarded product which is still in good condition and fulfils its original function
	R4 Repair	Repair and maintenance of defective product so it can be used with its original function
	R5 Refurbish	Restore an old product and bring it up to date
	R6 Remanufacture	Use parts of discarded product in a new product with the same function
	R7 Repurpose	Use discarded product or its parts in a new product with a different function
Useful application of materials	R8 Recycle	Process materials to obtain the same (high grade) or lower (low grade) quality
	R9 Recover	Incineration of material with energy recovery

Note. Figure from Kirchherr et al. (2017).

The first category *smarter product use and manufacturing* includes the principles of *refusing* products by making them redundant, *rethinking* products by increasing product use intensity and *reducing* product and material use, for instance, by increasing material efficiency. The second category is *extension of products' and parts' lifespans* and activities such as *reuse* and *repair*, as well as *remanufacturing* and *repurposing*. While *remanufacturing* refers to treating parts of discarded products in a factory so that they can be reused as a new product of the same function, *repurposing* relates to using parts of a product in a different product with a new function. The third category, *useful application of materials,* comprises *recycling* and *energy recovery* for waste otherwise landfilled or incinerated without heat recovery (Morseletto, 2020). *Recycling* refers to treating products mechanically or chemically so that the same or lower grade material is obtained (Kirchherr et al., 2017; Larrain et al., 2020). Within recycling, a further distinction can be made between closed- and open-loop recycling: Closed-loop recycling refers to obtaining a high enough quality to replace the primary material in the same product and open-loop recycling refers to recycling in which the quality and properties of the material change (Larrain et al., 2020). This decrease in material quality and functionality is also referred to as down-cycling.

Following Kirchherr et al. (2017), the categories and individual principles follow a hierarchy, with recycling and energy recovery being the least-desired options. Recycling and energy recovery are the least-desired processes, because, although they generate some material and energy flows for further use, they are associated with significant emissions, low yield rates and no fundamental influence on promoting more circular production and consumption patterns in general (Morseletto, 2020). Despite this relative undesirability, most recycled materials have environmental advantages over primary materials (Geyer et al., 2016) by preventing pollution and GHG emissions, conserving natural resources and avoiding landfilling and incineration (EPA, 2022). For instance, studies comparing primary NdFeB magnet production with recycling NdFeB magnets reveal that recycled magnets score significantly better across most impact categories (Sprecher et al., 2014) and are associated with significant energy and CO_2 savings (Jensen, 2019).

In this thesis, all materials originating from primary mining and used in an application for the first time are referred to as *primary materials*. All materials that have undergone a reuse, refurbishing, remanufacturing, or recycling process are referred to as *secondary materials*.

1.4 Critical Raw Materials Act

As described above, the Commission presented its proposal for a CRMA in March 2023. According to the proposal, the CRMA's goals are to "increase and diversify the EU's critical raw materials supply" and to "strengthen circularity, including recycling". More specifically, President of the European Commission Ursula von der Leyen says that the CRMA will "significantly improve the refining, processing, and recycling of critical raw materials" (European Commission, 2023b). In essence, the Commission's proposal includes four targets: (1) at least 10% of the EU's annual consumption needs to be from EU extraction, (2) at least 40% of the EU's annual consumption needs to be from EU processing, (3) at least 15% of the EU's annual consumption need to be from domestic recycling and (4) no more than 65% of the EU's annual consumption of any one material is allowed to be processed by a single third country (Critical Raw Materials Act, 2023).

Given the nature of the EU policy making process, proposals by the Commission need to be accepted by the European Council and European Parliament as well. Only once the three bodies reach an agreement, does the CRMA become enacted and thereby binding for EU member states. In the case of the CRMA, the Council has generally welcomed the proposal June 2023; however, it proposed a number of changes, including more ambitious targets. Specifically, it proposes to raise the share of secondary materials satisfying domestic demand from 15 to 20% (European Council, 2023a). In contrast to the Commission's and Council's approach of setting targets on the share of inflows being recycling, the Parliament reversed the logic by instead proposing a target whereby 45% of all the EU's waste streams including CRMs must be recycled (Simon, 2023). Even though the final outcome of the negotiations between the European Council and Parliament for the specific targets are still pending, the CRMA will constitute a substantial new legislation with far-reaching implications.

Overall, the Commission's CRMA proposal has been welcomed by many EU member states, including Germany, France, Italy, and the Netherlands (BMWK, 2023b; Ministerie van Buitenlandse Zaken, 2023). The fact that supply chain security of CRMs receives more attention is also appreciated by industry representatives and researchers (BDI, 2023; BMWK, 2023c; Wuppertal Institut, 2023). At the same time, the targets are considered very ambitious (BMWK, 2023c; Levinger, 2023) and criticism has been voiced that the CRMA focusses too much on recycling and does not place enough emphasis on other circularity principles or a more comprehensive circular economy strategy (BDI, 2023; Wuppertal Institut, 2023).

1.5 Societal relevance and connection to industrial ecology

The research conducted in this master thesis has a clear social relevance. The urgency and importance of decarbonizing all economic sectors and of transitioning to a more sustainable use of resources is well-documented through the already far-reaching adverse social, economic, and environmental impacts of climate change and high levels of pollution (IPCC, 2014; UNEP, 2017). Although the scaling of renewable energy technologies is crucial to decrease GHG emissions, the resulting increase in resource consumption also needs to be addressed. To this end, transitioning to a circular economy, in which material loops are closed and waste is minimized, could be one solution. The benefits of a circular economy are not only of environmental nature, but also include a number of positive social benefits. For instance, negative impacts such human rights violations, physical and psychological harm, and economic exploitation often caused during primary material extraction and processing, could be lowered (Bittner et al., 2023; BUND, 2022; Stewart, 2020). In a European context, the transition to a circular economy could have favorable socio-economic benefits, for instance, projections find that up to two million jobs could be created (Hinton-Beales, 2020). Moreover, decreasing reliance on primary materials through greater circularly would also contribute to the EU's supply chain diversification strategy, thereby lowering economic and geo-political dependencies and risks.

The topic of this research also integrates many of the industrial ecology perspectives. Industrial ecology studies the relationships between society, the economy, and the environment. By systematically quantifying and assessing material and energy flows between nature and the technosphere, it aims to reconcile human development with environmental responsibility, without losing sight of socioeconomic parameters (ISIE, n.d.). In conducting this research on how demand for CMRs can be met more sustainably, all three industrial ecology dimensions are integrated. The environmental perspective is considered through the general research context of scaling technologies to mitigate climate change and methods to ensure this scaling does occurs as environmentally sustainable as possible. The economic perspective is implicitly addressed through the wider context of establishing a circular economy, as this would entail a transition away from the current economic system to a more resource-efficient one. This transition would have far-reaching economic consequences, given that new infrastructures, businesses opportunities and supply-chains may develop. Although the social implications are not the focus of this research, the ones described above are nevertheless of great relevance.

1.6 Literature review

The following section provides an overview of the literature on CRM demand in the EU in general and for renewable energy sources specifically. Because the scaling of renewable energy technologies and the implication of the CRMA occurs on the level of individual member states, research on CRM demand on a state-level is also discussed. Finally, research on strategies of how primary demand for CRMs required for renewable energy sources can be lowered is presented.

1.6.1 CRM demand in the EU

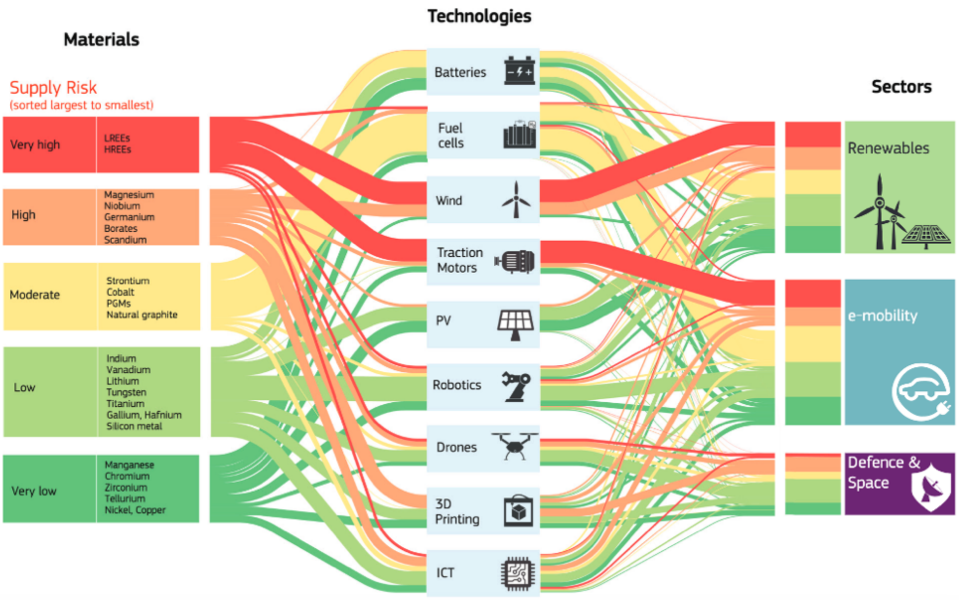
As part of its Foresight Study (Bobba et al., 2020), the EU has identified three sectors for which access to CRMs is of particular strategic importance and projected their future demand for them across nine core technological applications (Figure 3). The analysis reveals that compared to the total 2020 EU-wide CRM consumption, e-mobility and renewable energy sector alone may result in an up to 50-fold increase in lithium demand, almost 15-fold increase in cobalt demand, more than 10-fold increase in dysprosium and more than 4-fold increase in neodymium demand by 2050. With respect to just scaling renewable energy sources, solar energy would increase demand for tellurium 8-fold, demand for germanium 4-fold and demand for indium and gallium almost 2-fold by 2050. According to the authors, scaling wind energy in the EU, could increase dysprosium demand 6-fold, neodymium demand 3-fold and praseodymium demand 2-fold by 2050.

In addition to research into CRM demand on the EU-level, numerous studies have disaggregated these demand-supply dynamics for renewable energy technologies to the level of individual EU member states (Cao et al., 2019; Ciacci et al., 2019; Glöser et al., 2016; Guyonnet et al., 2015; Rademaker et al., 2013; Shammugam et al., 2019; van Exter et al., 2018; Wuppertal Institut, 2014). Because it ultimately lies in the responsibility of the individual states to translate the targets into national laws and to achieve the targets (in addition to their own strategies and policies), mapping future demand and supply dynamics can yield valuable insights. Despite the shared targets, the large internal market, and the intertwined supply chains in the EU, monitoring and projecting these dynamics on a country-level provides member states with the opportunity to better plan and evaluate its expansions, to identify supply bottlenecks early on and to develop strategies to mitigate any potential supply-issues.

One example of a country-level study is an investigation by Cao et al. (2019) in which a material flow analysis (MFA) quantifying material stocks and flows needed for different energy scenarios in Denmark was conducted. While demand for all bulk and critical materials was expected to increase in five of the six scenarios, the wind scenario (assuming a massive electrification of transportation and heating sectors) and the hydrogen scenario (assuming hydrogen technologies are used to convert wind energy into hydrogen for further hydrogenation of carbon sources) specifically, also entailed a large increase in CRM demand. For instance, the analysis expected a more than two-fold increase in demand for neodymium by 2048, compared to 2018 levels. Scenario analyses like these reveal that achieving Denmark's ambitious target of 100% renewable energy by 2050 could be at risk due to the high supply

Figure 3

Critical Raw Material demand for strategic sectors in the EU



Note. Figure from Bobba et al. (2020).

chain risk. Based on this, strategies related to more secondary materials sourcing or to decreasing the market share of wind turbines relying on CRM intensive permanent magnets or to increasing lifespans can be suggested.

Similarly, a number of papers investigating CRM demand-supply dynamics in the Netherlands have been published. For instance, van Exter et al. (2018) investigated the 22 most common metals in wind turbines and solar technologies. The authors found that for the Netherlands to achieve its renewable energy targets by 2030, annual demand for neodymium, terbium and praseodymium would roughly triple and the demand for dysprosium would more than double. With respect to global demand for these metals, the authors argued that if all countries were to roll-out renewable energy at a similar pace to the Netherlands, a significant material shortage would arise. To avoid this from happening, the authors suggested material substitution, improvements in circular design, accelerating recycling efforts and developing a European mining industry to lower import dependency and to increase available supply.

Another country whose CRM demand has been widely studied is Germany, considering the size of its economy and the resulting demand for renewable energy sources like wind and solar power. As early as 2014, the Wuppertal Institut (2014) investigated the material demand associated with different types of renewable energy technologies in Germany. For solar energy, assuming high or very high expansion pathways, the study projected a 5-fold increase in indium demand per decade between 2011 and 2050 compared to 2001-2010 cumulative demand. The study's high-demand scenario for wind energy reflected current wind energy targets closest and projected a demand of over 750 tons of neodymium for onshore and 1200 tons of neodymium for offshore turbines between 2041 and 2050. These results are in line with a more recent study, expecting a cumulative neodymium demand of 20,000 tons between 2018 and 2050, under the "REMOD" scenarios closest to current expansion targets in Germany (Shammugam et al., 2019). Under these scenarios, the study also reported an annual neodymium demand of approximately 240 tons in 2018, 500 tons in in 2030 and 1000 tons in 2045 (Shammugam et al., 2019).

1.6.2 Research and progress on meeting growing CRM demand more sustainably

In response to the growing demand for CRMs, strategies for how this demand can be satisfied more sustainably are increasingly addressed by academics and practitioners. Despite the widespread consensus that primary CRMs will need to be sourced over the next decades to achieve the EU's fast-growing demand for them (Gauß et al., 2021a; van Exter et al., 2018), decreasing the reliance on primary materials through replacing them with secondary materials could nevertheless contribute to mitigating some adverse environmental impacts of the required raw material consumption (Contreras Lisperguer et al., 2020; European Commission, 2020b; Gauß et al., 2021a). Following the 9R framework described above, notable advancements in smarter material use, very limited progress with strategies for lifespan extensions and mixed successes with recycling in renewable energy applications are discussed.

In terms of smarter manufacturing, improvements in material efficiency for solar modules can be observed and promising projections for CRM-intensive permanent magnets have been made. For instance, the poly crystalline silicon consumption per solar cell has declined from 16g/Wp to almost 2.5g/Wp, since 2004, reflecting an increase in material efficiency of 87% (Fraunhofer ISE, 2023). In other words, although the absolute demand for silicon is growing, its application in solar cells has become more efficient. For permanent magnets, Pavel et al. (2017) mention a company that has decreased the amount of dysprosium in their turbines to 1%, compared to industry averages of 4.4%. Similarly, Shammugam et al. (2019) project that by 2050, permanent magnets will only consist of 20% neodymium, compared to 31% in 2018. Moreover, research into alternative magnetic materials (Balaram, 2019) and the continued market establishment of CRM-low generator types, including different types of electrically-excited generators, Squirrel Cage Induction Generators (SCIG) or Doubly-Fed Induction Generators (DFIG) have may decrease the reliance on REEs.

The advancement of lifespan extension principles for solar modules and wind turbines is limited in Europe. For solar modules, specifically, the currently predominant lamination and encapsulation design makes any efforts of reuse, repair, or refurbishment difficult without significant processing (Farrell et al., 2020). As a result, most efforts are directed at separating the materials and recycling them subsequently (Farrell et al., 2020). Similarly, even though the obstacles are of different nature, no commercialized technology or infrastructure for reusing, refurbishing or remanufacturing NdFeB magnets from wind turbines is in place (Rizos et al., 2022). Although, in particular, the high end-of-life collection rate of wind turbines (Rizos et al., 2022) and their high concentration of REEs provide a good opportunity for refurbishing und remanufacturing (UBA, 2019), lack of design for dismantling and safe demagnetization are cited as obstacles to their large-scale roll-out (Alves Dias et al., 2020).

With respect to recycling, although the overall progress is more advanced, reported recycling rates remain low. Recycling CRMs in solar modules and NdFeB magnets has not only been subject to attention by academics and policymakers (Critical Raw Materials Act, 2023; Mulazzani et al., 2022; Yang et al., 2017), but also a number of pilot projects or small-scale facilities have already been established (Crownhart, 2021; Critical Raw Materials Act, 2023; Fraunhofer, 2022; SusMagPro, n.d.). Despite this, the share of end-of-life solar modules being recycled is currently around 10% (Mulazzani et al., 2022) and recycling activities for REEs such as those used in NdFeB magnets are not yet commercialized (Yang et al., 2017) and lie below 1% in Europe (Alves Dias et al., 2020; Cao et al., 2019; UBA, 2019). With respect to magnet recycling, some sources claim magnet recycling rates of up to 98%, when in fact, this is usually open loop recycling (Shammugam et al., 2019) or down-cycling into dissipative uses such as the steel or cement industry (Guyonnet et al., 2015). Overall, these low recycling rates are unfortunate, given that in theory, 94.4% of aluminum, 85.7% of silicon, 80.6% of silver and 89.9% of copper in crystalline silicon solar cells (Mulazzani et al., 2022) and around 90% (Habibzadeh et al., 2023) of CRMs in permanent magnets could be recycled.

1.6.3 Recycling potentials to meet CRM demand sustainably

Because recycling nevertheless remains the focal point of most supposed circular economy policies (Mulazzani et al., 2022), a large body of literature has investigated the extent to which demand could be satisfied through secondary materials. Many of these studies (see for example Alves Dias et al., 2020; Ciacci et al., 2019; Rademaker et al., 2013), however, implicitly assume that all materials reaching their end-of-life can be fully recycled, even though in reality a lack of infrastructure, technologies and unavoidable losses inhibit complete or even substantial recycling. Although the precise values reported deviate from each other due to their different underlying assumptions, most studies suggest that even in the most optimistic scenarios, the imbalance between CRM demand and secondary material supply will remain significant. For instance, the International Energy Agency predicts that between 2031 and 2040, solar module recycling could satisfy 5.9% of silicon demand under its Net Zero Scenario and up to 33.7% between 2041 and 2050 in Europe (IEA, 2022). In their calculations, the authors assume material intensity improvements of 30% for silicon and 75% for silver, as well as recovery rates of 85%.

For secondary REEs, a study by Rademaker et al. (2013) projects a 10% potential recycling supply (defined as the ratio between end-of-life neodymium and neodymium demand) globally for NdFeB magnets in wind turbines. On the EU-27 level, the authors project that across all applications, the potential recycling supply will decrease between 2011 and 2020 and begin increasing again in the late 2020s. A more recent study by Alves Dias et al. (2020) finds that up to 50% of electric traction motors and nearly one third of clean energy technologies (wind turbines and electric vehicles) could be satisfied through recycled neodymium by 2050. This, however, is only achievable if the “recycling system is significantly improved” (Alves Dias et al., 2020).

A similar rate is reported by an investigation on European neodymium flows for wind turbines, finding that secondary neodymium could supply up to 50% of current neodymium demand if latent potentials were turned into actual capacity (Ciacci et al., 2019). A slightly less optimistic scenario is developed by Rizos et al. (2022), finding that recycling wind turbines with a collection rate of 90-99% and a disassembly efficiency of 90 and 95%, could yield less than 1000 tons of NdFeB magnet secondary supply by 2030 and approximately 4000 tons by 2050. In their study on energy scenarios in Denmark, Cao et al. (2019) argue that while the current 'circularity potential' (defined as the ratio between outflows and inflows) of secondary neodymium and dysprosium lies at 0.24 and 0.26%, respectively, in 2018, may peak at 45.5 and 51.31% and is expected to decline to 39% and 47% by 2048 under the hydrogen and wind scenarios. The authors explain the peak and later decline by the increasing secondary supply from decommissioned wind turbines and lower material intensity in new turbines (Cao et al., 2019).

1.7 Scientific relevance and research gap

The preceding literature review reveals numerous studies have investigated demand-supply dynamics and the associated supply risks of CRMs in the EU. Likewise, many investigations have studied the extent to which various circular economy principles could mitigate the imbalance between growing demand and limited secondary material supply on both the EU, as well as member state-level. However, a significant knowledge gap persists in the context of the recent CRMA proposals and their ambitious recycling targets for 2030: to date, no research has systematically investigated the implications of the proposed targets. In other words, the role that each of the proposed targets could play in satisfying growing demand for CRMs more sustainably through secondary materials has not yet been explored. Given that the Commission's and Council's proposals take a consumption-based approach (i.e., a certain percentage of demand needs to be satisfied through secondary materials) and the Parliament's proposal takes an end-of-life approach (i.e., a certain amount of waste streams needs to be recycled), research on how these approaches and their specific targets compare, can provide novel insights for both the academic debate, as well as for policy makers.

In addition to this main research gap, previous literature on recycling potentials related to CRMs often falls short of exploring and analyzing required recycling rates in the necessary depth. In other words, what many studies quantifying potential secondary material supply share (Cao et al., 2019; Ciacci et al., 2019; Glöser et al., 2016; Rademaker et al., 2013), is that they calculate secondary material volumes solely based on end-of-life streams. In determining the share of demand that could be satisfied through recycling, they calculate a ratio of waste streams (outflows) to demand (inflows). While this may provide reasonable long-term estimates of latent potentials, the meaningfulness of these calculations is limited for short-term assessments. The reason for is that using such a simplified ratio implicitly assumes a 100% recycling rate of all waste streams. Because recycling rates rarely reach 100% in reality, relying only on such a ratio is likely to overstate recycling potential in the short- to medium-run.

1.8 Research objectives and questions

To address the identified knowledge gaps, the overarching objective of this research is to compare the implications of the different CRMA recycling proposals from the Commission, Council and Parliament. More specifically, this thesis aims to explore the potential contribution that achieving the proposals has on meeting demand for CRMs more sustainably. In doing so, this thesis will also consider and discuss the specific recycling rates necessary to achieve the targets.

To achieve this research objective, the following four core steps are conducted: (i) quantification of past and current CRM demand, (ii) quantification of expected future CRM demand, (iii) quantification of CRMs reaching their end-of-life, and (iv) development and analysis of different recycling scenarios. Essentially, the first step is aimed at exploring how much CRMs have been installed annually until today. The second step quantifies how CRM demand is expected to develop in the future. The third step builds on the first and second step, by determining the amount and point in time that CRMs will reach their end-of-life. This, in turn, yields the basis for the fourth step which is to develop recycling scenarios based on the three proposals outlined above and to compare their implications for satisfying demand more sustainably.

Following these objectives, the guiding research question of this research is:

How do the Critical Raw Materials Act recycling targets proposed by the European Commission, Council and Parliament compare in their contribution to meeting future demand more sustainably?

Based on the four core steps (i) – (iv) outlined above, the following sub-questions are posed:

1. *How has CRM demand developed over time?*
2. *How is CRM demand expected to develop?*
3. *When are which amounts of CRMs expected to reach their end-of-life?*
4. *How much secondary CRMs would be generated under the proposed targets?*

1.9 Structure of research

The further thesis is structured as follows: First, the Methodology introduces the case study of wind turbine permanent magnet recycling in Germany. It then provides and overview of the theoretical framework of dynamic Material Flow Analyses (dMFA) and describes the respective scenarios and data processing steps. The Results presents the outcomes of each scenario first and then compares the individual scenarios to address the main research question. The Discussion section interprets the results with respect to their broader implications, derives a number of policy recommendations and reflects on the limitations of this research. The Conclusion will summarize the core findings and Suggestions for future research will discuss which questions remain unanswered and require further exploration.

2 Methodology

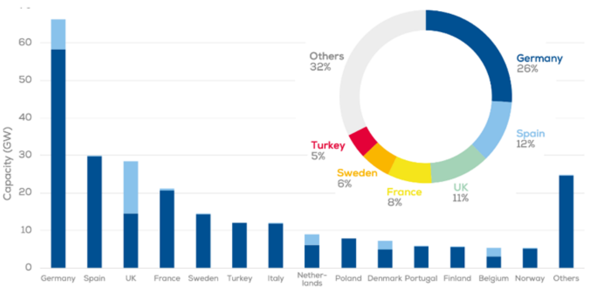
This chapter begins by introducing the case study. It then defines the scope, provides an overview of the methodology used to address each research sub-question, outlines the data requirements, and discusses the data quality. Lastly, it describes the sensitivity analyses performed.

2.1 Case study: neodymium in NdFeB permanent magnets for wind turbines in Germany

To address the research question on the extent to which achieving the proposed CRMA recycling targets can contribute to satisfying demand more sustainably, the application of NdFeB permanent magnets in wind turbines in Germany is used as a case study. More specifically, this study focuses on the LREE neodymium, which, in combination with other CRMs such as boron, dysprosium and praseodymium is an essential element for these powerful magnets (Bobba et al., 2020). Although neodymium demand for wind turbine magnets only makes up 16% of total neodymium demand in Europe (Ciacci et al., 2019), the scaling of wind energy and the simultaneously decreasing demand for other applications such as hard disks implies that the share will continue growing over the next decades (UBA, 2019).

Figure 4

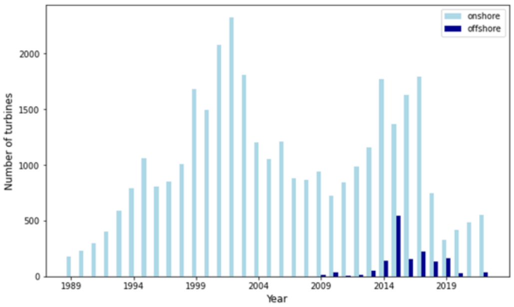
Total capacity of wind power installed across Europe in 2022



Note. Figure from WindEurope (2023). Germany has the most installed capacity of wind power in Europe, making it particularly suitable for a case study.

Figure 5

Absolute number of wind turbines installed in Germany



Note. Annual number of wind turbines installed in Germany peak in 2002 for the first time and again between 2014 and 2016. First offshore turbines are installed in 2009.

This case study has been selected for two main reasons. First, Germany has been among the first European countries to implement and scale-up both onshore and offshore wind energy (WindEurope, 2023). Compared to other European countries (Figure 4), this makes Germany not only the country with the most installed capacity in 2022, but also implies that first generations of turbines reach their end-of-life and are retired. Even though the amount of neodymium collected from existing end-of-life wind turbines is only marginal compared to current demand for new magnets (Section 2.4.2), the volume of neodymium becoming available for recycling is expected to increase over the upcoming years. Second, permanent magnets in wind turbines are suitable for recovering materials and parts. Unlike other applications, permanent magnets in wind turbines are large (ranging between 80 – 600 kg/MW with 30% neodymium content), have a near 100% end-of-life collection rate (Nüsslein, 2020; Ortegon et al., 2013; Wuppertal Institut, 2014) and are dismountable (Jensen, 2019). This low proliferation and high material concentration increases the technological and economic feasibility of recycling NdFeB magnets.

2.1.1 Onshore and offshore wind energy in Germany

In Germany, onshore wind turbines were first installed in the late 1980s. Although the precise numbers of installed turbines between 1985 and 1990 differs marginally between sources (BWE, 2022; WindEurope, 2023), data published by the Bundesverband WindEnergie (BWE) states that, cumulatively, 177 turbines were installed by 1989 and a further 228 were added in 1990 (BWE, 2022). According to BWE data, the number of installed turbines reached a first peak around 2001/2002, with 2079 and 2321 wind turbines installed annually, respectively. The average capacity per turbine in these years was between 1.3 MW and 1.4 MW. Over the next decade, additions in onshore turbines dropped, peaked again around 2014-2017 and then experienced a bust due to the amendments to the Erneuerbare-Energien Gesetz (EEG) in 2017 (Rueter, 2019). Since then, annual additions have been increasing again, however, have not yet reached peak levels (Figure 5). In 2022, 551 new turbines with an average capacity of 4.3 MW were installed.

With respect to offshore turbines, the first ones were constructed in 2008, and the first wind park was connected to the grid in 2010 (WindEurope, 2023). However, this thesis follows the BWE reports and so installations from 2009 onwards are considered in this thesis (Figure 5). A first peak in installations was reached in 2015. Since then, the annual additions dropped, with only 38 offshore turbines constructed in 2022 (BWE, 2022). While average capacity of offshore turbines in 2008 was approximately 5 MW, this almost doubled by 2022, reaching an average of 9 MW (BWE, 2022).

To achieve its national climate neutrality and renewable energy goals, the German federal government has raised its wind capacity targets significantly in 2023 as part of the most recent amendment to the EEG. Following these targets, an additional 57 GW onshore and 22 GW offshore capacity need to be

Table 1

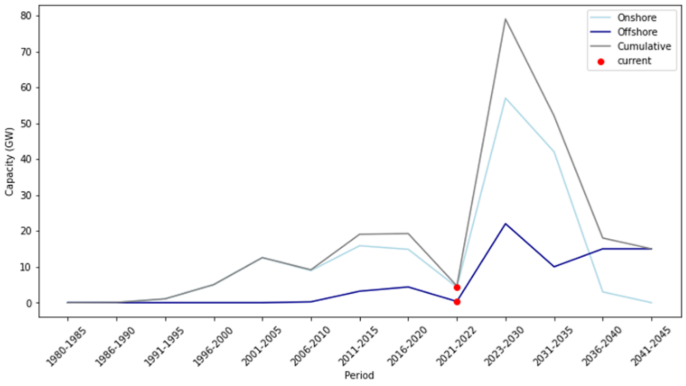
German federal wind power expansion targets specified in the EEG until 2045

Year	Onshore		Offshore	
	Target capacity	Additional capacity required until year	Target capacity	Additional capacity required until year
2030	115 GW	57 GW	30 GW	22 GW
2035	157 GW	42 GW	40 GW	10 GW
2040	160 GW	3 GW	55 GW**	15 GW
2045	160 GW*	0 GW	70 GW	15 GW

Note. *The EEG only specifies targets until 2040, hence it is assumed that the target remains the same for 2045. **The EEG only specifies targets for 2035 and 2045, hence the target assumed for 2040 reflects the mean between the 2035 and 2045 target.

Figure 6

Additional onshore and offshore capacity installed per period to date and according to German federal targets until 2045



Note. The periods reflect five-year increments, except for 2021-2022 and 2023-2030. This is due to the Federal targets published in 2023 encompassing the period 2023-2030. The cumulative amount shows the annual cumulative net addition, not the total capacity installed.

installed between 2023 and 2030 (Table 1 and Figure 6). Spread evenly across these seven years, this translates into approximately 7.1 GW additional onshore and 2.8 GW offshore capacity to be installed annually. Compared to the installed capacity of 58 GW onshore and 8 GW offshore capacity in 2022 (BMWK, 2023a), the raised targets imply that capacity needs to be increased significantly. Figure 6 visualizes this significant increase clearly, by showing how annual capacity additions have developed until today and how they would need to continue developing according to the EEG targets.

2.1.2 End-of-life treatment of wind turbines in Germany

When it comes to end-of-life treatment of wind turbines in Germany, progress is limited. Even though the Bundes-Immissionsschutzgesetz (German Federal Emission Control Act) postulates all turbines need to be deconstructed (Bundes-Immissionsschutzgesetz, 1974) and even though recycling rates of around 80% percent are commonly reported (Nüsslein, 2020), closer inspection reveals that in particular the recycling of turbines does not occur as successfully in reality. In fact, large-scale recycling approaches are not commercialized yet (Paulsen & Enevoldsen, 2021) and the cited rates of 80% typically refer to the total mass of wind turbines and not to the average rates across components and parts (Velenturf, 2021). Hence, the question arises what the recycling rate CRMs from wind turbines is.

With respect to the recycling of CRMs, and specifically of neodymium from NdFeB magnets, progress is very limited. In fact, research reveals that currently no recycling of permanent magnets occurs on a commercial scale in Germany (UBA, 2019). This is in line with European research mentioned above, reporting neodymium recycling rates of below 1% (Alves Dias et al., 2020). For the year 2019, the UBA (2019) reported 800 tons of post-consumer NdFeB magnet from various types of end-of-life NdFeB magnet streams in Germany. Of these 800 tons, the authors consider 730 tons to have a “theoretical recycling potential”. The authors further estimate that 91% of these are exported or dissipate as finely dispersed dusts in the steel scrap industry. Although a large fraction of steel scrap is recycled (EuRIC AISBL, 2020) the individual elements of neodymium and other CRMs can no longer be separated and recovered. The remaining 70 tons of post-consumer material are sludges containing NdFeB magnets and other production waste are also exported to countries such as Japan or China (UBA, 2019). Note that although the CRM recycling rate is reported to be lower than 1% in Germany, for the purpose of this thesis, the rate is assumed to be 1% for modelling and computational purposes.

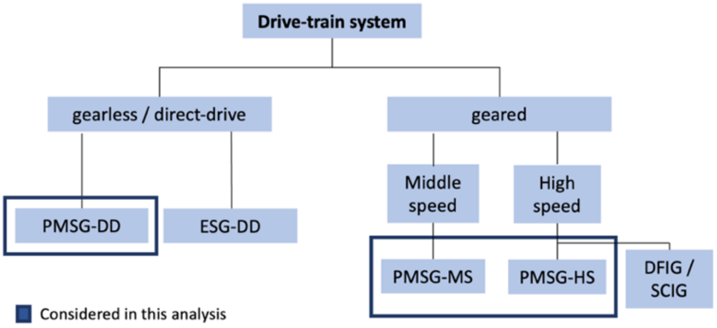
While the CRMA targets currently discussed are far more comprehensive and substantial, it is worthwhile to note that Germany developed its first Bundesrohstoffstrategie (Federal Raw Material Strategy) in 2010 (BMWi, 2019). With the goal of addressing raw material issues holistically and in close cross-department cooperation, the Bundesrohstoffstrategie lays the foundation for a regulatory framework to maintain access to critical resources. Because the measures following the strategy mainly testify to the matters growing importance, the initial strategy was expanded, and 17 additional measures were adopted in 2020. These measures include the funding of research projects, the promotion of primary raw material extraction in Germany’s and Europe’s metal sector, the establishment of a dialogue process with industry representatives to increase the use of secondary materials from recycling and the strengthening of a circular economy based on recovery and reuse. Since most of the measures are not legally binding and their implementation in parts is hard to quantify and track, it is difficult to assess its overall success. Given the currently still very limited roll out of a recycling infrastructure in particular, it can be expected that the EU’s CRMA will become a far greater accelerator of a more responsible and effective use of raw materials.

2.2 Temporal and technological scope

The temporal scope of this research is 1989 to 2045. Even though the first onshore wind turbines were installed in the late 1980s, 1989 marks the beginning of their commercial scaling in Germany (BWE, 2022; WindEurope, 2023). Due to a lack of more precise earlier data, 1989 will therefore be the first year considered in the analysis. For offshore wind turbines, singular turbines were first installed in 2008 but because the BWE documentation begins 2009, installations from 2009 onward will be considered in

Figure 7

Wind turbine generator types



Note. Figure adapted from Glöser et al. (2016) and Wuppertal Institut (2014). The overview only shows some of the most common generator types.

this thesis (WindEurope, 2023). The most recent available data for both on- and offshore wind turbines is from 2022 (BWE, 2022). To address the second and third research sub-questions, the scenarios explored continue until 2045. Even though the CRMA only outlines targets for 2030, the year 2045 is nevertheless chosen as the upper limit, as it coincides with the German expansion targets. Given the ongoing and dynamic legislative process and research context, the Commission's proposal from March 2023, the Council's proposal from June 2023 and the Parliament's proposal from September 2023 are used. In other words, any changes to these proposals or compromises found after September 2023 are not considered in this investigation.

With respect to the technological scope, the case study is narrowly focused on closed-loop recycling of neodymium in NdFeB magnets used in on- and offshore wind turbines. Because wind turbine generators can either be electrically or magnetically excited (Figure 7), this research considers only permanent magnet synchronous generators with direct drive (PMSG-DD), geared medium speed permanent magnet synchronous generators (PMSG-MS), and geared high speed permanent magnet synchronous generators (PMSG-HS). Based on the recycling targets specified by the proposals, this research investigates only closed-loop recycling and none of the other R-Strategies discussed above.

2.3 Data processing steps

To address the overarching research question, a material flow analysis (MFA) is performed. MFAs are a widely used approach to systemically quantify and model material stocks and flows within a specific region (Ciacci et al., 2019). MFAs allow to determine a region's reliance on imports, material losses along supply chains and recycling potentials (Guyonnet et al., 2015). Within MFAs, one can distinguish between static MFAs (sMFAs) and dynamic MFAs (dMFAs). sMFAs are snapshots of material stocks and flows within a defined system at a particular point in time. sMFAs typically quantify material flows throughout their entire value chain based on mass balance principles. The quantified material flows typically begin with raw material extraction, cover the identified material processing and manufacturing steps, include all material applications and end with end-of-life treatments. Within the defined system boundaries, material imports and exports, material accumulation in individual processes and material cycles (for instance, by means of recycling) are accounted for. (Fishman, 2023c)

In contrast to sMFAs, dMFAs provide insights into the behavior of stocks and flows over time and do not map the entire supply chain. Rather, dMFAs focus on an individual process or application and quantify inflows and outflows specific to an individual process. dMFAs allow to analyze how and why stocks and flows change, what their age, compositions and characteristics are, how future demand and supply, urban mines and material accumulation may develop and where circular economy and resource efficiency potentials lie (Fishman, 2023a). An important distinction specific withing dMFAs is between stock- and flow-driven models. While stock-driven dMFAs use annual stock data to determine the level of inflows, flow-driven dMFAs use inflow time series data to determine the level of stock. Despite their different input requirements, the final outcomes of the models are identical (Fishman, 2023a).

Table 2

Sub-questions and translation into case study

Sub-Question	Translation into case study
1. How has CRM demand developed over time?	Quantification of neodymium installed until today (1989 and 2022).
2. How is CRM demand expected to develop?	Quantification of expected annual neodymium demand (2023 – 2045).
3. When are which amounts of CRMs expected to reach their end-of-life?	Calculation of past and expected end-of-life flows of neodymium (1989 - 2045).
4. How much secondary CRMs would be generated under the proposed targets?	Scenario analysis based on proposals by European Commission, Council and Parliament over time (1989 – 2045)

In this thesis, a flow-driven dMFA is conducted. Table 2 provides an overview of the sub-questions and their translation into the context of this case study. In line with MFA terminology and its principles described below, material consumption and expected demand are henceforth be referred to as inflows and material waste or end-of-life streams are referred to as outflows. The accumulation of materials during their use phase in wind turbines is the stock.

In line with previous dMFAs on wind turbines (Cao et al., 2019; van Nielen et al., 2023), a Weibull probability distribution is selected for the survival function sf. Survival curves reflect the amount of each cohort's neodymium inflow that survives over time. Once the survival curve is scaled to the inflow of a given year, the curve's parameters (mean and standard deviation) are set according to the application. With respect to the lifespan (mean) of NdFeB magnets in wind turbines, 20 years is assumed. Even though the potential lifespan of wind turbines can be up to 30 years, the expiration of subsidies and rapid efficiency improvements imply that, on average, turbines are decommissioned after 21 years in Germany (BWE, 2022). Because average lifespans have been increasing over the past years (Wipfler, 2022), a mean of 20 years is nevertheless assumed. This lifespan assumption is in line with previous literature on wind turbines in Germany (Glöser et al., 2016; Shammugam et al., 2019). Further, standard deviation is set at four, following models provided by Fishman (2023a).

Using the Weibull probability distribution and the total number of years under investigation, a survival curve matrix is created to reflect the percentage of each cohort's survival over the time period studied (Appendix A). Multiplying each cohort's inflows with the respective survival percentage yields the cohort's survival matrix (Appendix A). Summing the individual cohort's inflows that have survived until a given year yield the stock (Appendix A). Following this logic, the inflow and survival curve are exogenous variables, and the stock is endogenous (i.e. calculated through the model). The generalized and formal definition of this relationship is given in Equation 1, where $stock(y)$ relates to the total amount neodymium in a given year y in Germany, $inflow(\tau)$ refers to sum of neodymium from each cohort that has survived until year y assuming a Weibull distribution survival function sf:

Equation 1: $stock(y) = \sum_{\tau=y_0}^{y}[inflow(\tau) * sf(y-\tau)]$

Based on the time series data of stock computed using Equation 2, mass balance principles are applied to determine the annual net additions to stock (NAS) and annual $outflow$ (Equations 3 and 4). The outflow indicates the amount and point in time a material reaches becomes available for recycling or other end-of-life treatment.

Equation 2: $NAS(y) = stock(y) - stock\ (y-1)$

Equation 3: $outflow(y) = inflow(y) + NAS(y)$

In Sections 2.3.1 – 2.3.2, a detailed overview of all additional steps required to address the sub-research questions using the generalized model is provided. This includes the processing of raw data to compute the historic inflow time series data (sub-question 1), expected future inflow timeseries data (sub-question 2) and the exploratory scenario analysis (sub-question 4). Sub-question 3 requires no additional steps; it can be addressed through Equation 3 across all scenarios.

2.3.1 Additional data processing steps for sub-question 1: CRM demand over time

To develop a dMFA model for the time period between 1989 and 2023, the annual neodymium *inflow* of onshore and offshore turbines is calculated first. Because the technical configurations and market shares of generators are different for onshore and offshore turbines, annual *inflow onshore* and *inflow offshore* in year *y* are computed using Equations 4 and 5 first and then summed in Equation 6 to yield the inflow described in the generalized model in Equation 1. In Equations 4 and 5, *j* is a categorical variable representing the different generator types PMSG-DD, PMSG-MS or PMSG-HS*, turbines* reflects the number of wind turbines installed, *capacity* relates to the average turbine capacity (in MW), *ms* is the market share (in percent) of installed turbines of generator type *j, weight* is the mass of the permanent magnet type *j* (in kg/MW) and *nd* is relative content on neodymium in NdFeB magnets (in percent). After *inflow(y)* is calculated in Equation 6, its unit converted from kilograms to tons.

Equation 4: $inflow\ onshore(y) = \sum_{j=1}^{3}(turbines_j(y) * share_j(y) * \ capacity_j(y) * weight_j\ (y) * nd(y))$

Equation 5: $inflow\ offshore(y) = \sum_{j=1}^{3}(turbines_j(y) * share_j(y) * capacity_j(y) * weight_j\ (y) * nd(y))$

Equation 6: $inflow(y) = \ inflow\ onshore(y) + inflow\ offshore(y)$

One limitation common to flow-driven models is that initial stocks are often unknown, leading the model to underestimate outflows and overestimate NAS (Fishman, 2023b). This can occur whenever it is infeasible or not possible to model all historic stocks and flows. In the context of this study, however, this underestimation of outflows is not an issue, given that data on first neodymium inflows to wind turbines is in fact available and used.

2.3.2 Additional data processing steps for sub-question 2: projected CRM demand

To quantify how neodymium inflows are expected to develop between 2023 and 2045, additional data relating to the German federal government's wind energy expansion targets (Table 1), expected average turbine capacity, future market shares per generator type, weight of permanent magnets and neodymium content are used. In line with the technological scope defined above, the weight of permanent magnets per generator type and neodymium content are assumed to remain at 2022 levels. All raw data used is provided in Appendix A.

The number of turbines needed to meet expansion targets is calculated using Equation 7, where *capacity per period* reflects expansion targets per period (as reported in Table 1) and *years per period* corresponds to the timesteps between the respective target years specified in the EEG (as reported in Table 1). Dividing the *capacity per period* by the number of *years per period*, yields the annual *average capacity addition*. As before, because *inflow* is computed separately for offshore and onshore wind turbines, Equation 7 needs to be performed for both, onshore and offshore capacities:

Equation 7: $average\ capacity\ addition\ (y) = \frac{capacity\ per\ period}{years\ \ per\ period}$

Once the necessary annual *average capacity addition* is calculated, this is translated into the required absolute number of onshore and offshore wind turbines. Because the number of turbines required to meet the capacity addition depends on the average capacity of individual turbines, average turbine capacities are determined first. For onshore wind turbines, a linear line of best-fit of the capacity growth per turbine between 1989 and 2022 is generated. Due to lack of reliable sources and projections, the annual growth rate is extrapolated until 2045 (Appendix A), yielding an average turbine capacity of 5.79 MW in 2045 (compared to 4.36 MW in 2022). For offshore wind turbines, BWE projects an average turbine capacity of 13 MW by 2025. The largest offshore wind turbine prototype revealed in 2023 has a capacity of 18 MW (Lewis, 2023). Given that precise projections of technological development are inherently uncertain, the 18 MW are used as the average installed capacity of offshore turbines in 2045. This assumption is approximately in line with other studies projecting offshore turbines with a capacity of 20 MW by 2050 (Shammugam et al., 2019). Linear extrapolation is used between the 13 MW average installed capacity expected for 2025 and the 18 MW in 2045 (Appendix A).

Based on these average capacities of wind turbines, *wt* (absolute number of wind turbines) that need to be installed annually to reach the *average capacity addition* is determined with Equation 8:

$$\text{Equation 8: } wt(y) = \frac{average\ capacity\ addition(y)}{average\ capacity\ per\ WT(y)}$$

Once the number of average capacity and absolute number of onshore and offshore turbines are computed and used to determine the inflow (Equations 4, 5 and 6), the dMFA model described above is extended for the time period 2023 - 2045.

2.3.3 Additional data processing steps for sub-question 4: scenario analysis

Given the recency and the ongoing legislative process of the CRMA, multiple exploratory scenarios are developed. The scenarios reflect the different proposals by the Commission, Council and Parliament. Scenario 1 reflects the Commission's proposal that 15% of domestic consumption (inflows) need to be sourced from secondary materials. Scenario 2 reflects the Council's proposal that 20% of inflows need to be sourced from secondary materials. Scenario 3 applies a recycling rate of 45% on all outflows as suggested by the Parliament. Since all three targets are set for the year 2030, two sub-scenarios per scenario are investigated in this thesis. The sub-scenarios explore the implications of the targets beyond 2030, i.e., if the targets remain constant until 2045 or if they increase over time. Table 3 provides an overview of the scenarios, and Sections 2.3.3.1-2.3.3.3 outline the methodologies and assumptions.

2.3.3.1 Scenario 1 and Scenario 2: European Commission and Council's proposals

The methodology for Scenarios 1 and 2 is identical, the only difference being the precise share of inflows that need to be sourced from secondary neodymium by 2030. To determine the amount of secondary neodymium that can be generated to replace primary materials by 2030, two main steps are performed.

In a first step, extrapolation is used to compute the annual share of secondary neodymium required before and after 2030. More specifically, the current share of 1% secondary neodymium in inflows is extrapolated to reach the proposed 15 and 20%, respectively, in 2030. As described above, the share of secondary neodymium is assumed to remain at 15 and 20%, respectively, for Scenarios 1.1 and 1.2. and assumed to increase further for Scenarios 1.2 and 2.2. For the latter two scenarios, the linear trend

Table 3

Descriptions of scenarios and sub-scenarios

Scenario	Description of scenarios	Description of sub-scenarios
Baseline	Business-as-usual, no recycling	none
Scenario 1	Reflects EU Commission's proposal: 15% of inflows need to be supplied from secondary material in 2030 (CMU rate = 15%)	Scenario 1.1: 15% CMU rate target remains constant between 2030 and 2045
		Scenario 1.2: assumed CMU rate trend between 2023 and 2030 extrapolated until 2045
Scenario 2	Reflects EU Council's proposal: 20% of inflows need to be supplied from secondary material in 2030 (CMU rate = 20%)	Scenario 2.1: 20% CMU rate target remains constant between 2030 and 2045
		Scenario 2.2: assumed CMU rate trend between 2023 and 2030 extrapolated until 2045
Scenario 3	Reflects EU Parliament's proposal: recycling 45% of all outflows	Scenario 3.1: 45% recycling rate target remains constant between 2030 and 2045
		Scenario 3.2: assumed recycling rate trend between 2023 and 2030 extrapolated until 2045

used to extrapolate between 2023 and 2030 is extended to 2045. In case that the extrapolated values exceed 100%, they are capped at 100% for the respective years.

The target shares for 2030, as well as the extrapolated shares for before and after 2030 are henceforth referred to as the Circular Material Use ratio (CMU). In principle, the ratio (Equation 9) is similar to the 'potential recycling supply ratio' used by Rademaker et al. (2013) and the 'circularity potential' used by Cao et al. (2019), in that it provides the share of inflows that is (supped to be) satisfied through secondary material flows. The term CMU is used for consistency and comparability purposes with Scenario 3, so that the different modelling outcomes use the same terminology.

Equation 9: $CMU(y) = \frac{secondary\ neodymium(y)}{inflows\ (y)}$

The second step is to quantify the amount of *secondary neodymium* needed to satisfy the 2030 targets, as well as the previously determined *CMU* rates. The equation for this (Equation 10) is as follows:

Equation 10: $secondary\ neodymium(y) = CMU(y) * inflow(y)$

In addition to quantifying the amount of secondary neodymium needed to satisfy the Commission's and Council's proposals, the recycling rate of outflows required to yield the desired amount of secondary neodymium is computed (Equation 11). Determining the corresponding recycling rate is crucial to determine whether the proposed targets are attainable within this narrowly defined case study of closed-loop NdFeB magnet recycling.

Equation 11: $recycling\ rate(y) = \frac{secondary\ materials(y)}{outflows(y)}$

For all years in which the $recycling\ rate > 1$, outflows are less than the amount of secondary neodymium required to satisfy the targets. For all years in which the $recycling\ rate < 1$, outflows exceed the desired amount of secondary neodymium and are hence theoretically possible (even if potentially unfeasible and unrealistic).

Appendix B (Figures 8 and 9) presents the extrapolated CMU rates of Scenarios 1.1, 1.2, 2.1 and 2.2.

2.3.3.2 Scenario 3: European Parliament's proposal

The methodology to explore the third scenario is slightly simpler than that for Scenarios 1 and 2. First, linear extrapolation is used to calculate the annual recycling rates between the 1% in 2022 and the desired rate of 45% for 2030. To explore how these dynamics develop beyond 2030, Scenarios 3.1 and 3.2 are created. Scenario 3.1 assumes that the recycling rate of 45% in 2030 remains at the same level until 2045. Scenario 3.2 assumes the recycling rate to continue increasing at the same rate as it did between 2023 and 2045. Using the annual recycling rates and the outflows as a basis, the amount of secondary neodymium that could theoretically be generated is computed (Equation 11):

Equation 11: $secondary\ neodymium\ (y) = \ outflows(y) * recycling\ rate\ (y)$

To analyze how the proposal by the Parliament compares to the proposals by the Commission and Council in terms of the share of primary materials inflows that can be replaced by secondary materials is calculated using the CMU as before (Equation 9).

Appendix B (Figure 10) visualizes the extrapolated recycling rates of Scenarios 3.1 and 3.2.

2.4 Data sources and quality

To develop the flow-driven dMFA model and scenarios described above, the core data need is a timeseries of neodymium inflows. For this, the net number of onshore and offshore wind turbines and their average capacity is obtained from BWE's annual publications (BWE, 2022). Historic market shares of turbine types are obtained from various sources, including studies published by the EU or research institutes (Alves Dias et al., 2020; Fachagentur Windenergie an Land, 2022; Fraunhofer IEE, 2019; IWR, 2023; JRC, 2022; Wehrmann, 2023; Wuppertal Institut, 2014). Current neodymium material intensities of NdFeB magnets reported in literature range between 27 and 31% (Cao et al., 2019; Rademaker et al., 2013; Shammugam et al., 2019; van Nielen et al., 2023; Wuppertal Institut, 2014) and so this thesis assumes it to be 30%. The average weight of each generator type is also obtained from previous studies. Although there are some deviations in reported weights (Cao et al., 2019; Glöser et al., 2016; Ortegon et al., 2013; Rademaker et al., 2013; van Nielen et al., 2023; Wuppertal Institut, 2014), this thesis follows the average weights assumed by Wuppertal Institut (2014). Historic and current recycling rates are obtained from research institutes or reports co-published by the EU (Alves Dias et al., 2020; UBA, 2019).

To compute neodymium inflows between 2023 and 2045, future wind power capacity targets are computed using the EEG targets (BMWK, 2023a). Future market shares of generator types are based on publicly available data from wind turbine manufacturers of already approved wind farms (IWR, 2023; Siemens Gamesa, n.d.). In cases where wind farm sites have not yet been tendered, projected market shares from peer-reviewed journals are used (Alves Dias et al., 2020). In line with the technological scope described above, NdFeB magnet material intensities and weights are assumed to remain constant throughout the entire period studied. Appendix A provides the source to each data point, as well as an overview of the data-related key assumptions described above.

To assess the data quality, the pedigree matrix is used (Ciroth et al., 2016). Although this approach was initially designed for uncertainty assessments in life-cycle assessments, it can also be used as a guidance to address data quality in MFAs (Fishman, 2023d). With this framework, indicator scores are provided across five criteria: reliability, completeness, temporal correlation, geographical correlation, and further technological correlation. Each criterion is scored on a scale of 1 – 5, with 1 reflecting a particularly high data quality. Although the specific criteria and their descriptions are not entirely applicable to MFAs, their definitions and requirements are nevertheless used as a basis to reflect on the overall data quality.

The reliability of the data is mixed. The dMFA in this thesis uses no primary sources and no verified data. Moreover, most of the assumptions are only based on qualified estimates reported in previous literature. Although the accuracy of these assumptions cannot be fully verified, it can be assumed that the peer-reviewed journals, official EU reports and data by the Bundesnetzagentur (German Federal Network Agency) nevertheless follow high reporting standards and reflect the most accurate data available.

In terms of its completeness, the data quality is limited. Although the required data points between 1989 and 2022 could be identified in the literature, the data sources are fragmented and may therefore include discrepancies between sources due to different underlying assumptions or specific research scopes. For the exploration of future developments and scenarios, the data is less complete, in that linear extrapolation and rough qualified estimates are used. Even though the goal of this thesis is not to predict, but rather to investigate what-if scenarios, the uncertainty and inaccuracies resulting from incomplete data nevertheless limit the quality of the scenario assumptions. Therefore, any assumptions are reported transparently.

With respect to the geographic and technological correlation, the quality of the data is reasonably high. Although in some cases EU data of wind turbine market shares or average NdFeB magnet weights were used instead of data specific to Germany, the impact on the overall reliability of the data is marginal. The reason for this is that the EUs domestic market is so intertwined, with only a limited number of wind turbine manufacturers operating in member states (Fernandez, 2023). Therefore, it is reasonable to assume that the technological specifications of turbines and NdFeB turbine magnets are comparable throughout the EU.

2.5 Sensitivity analysis

To ensure that the results of this analysis are robust, a sensitivity analysis is conducted (Appendix C, Figures 11 - 16). Testing the robustness allows to determine whether minor deviances or inaccuracies in the data lead to a significant distortion of the overall results. For this, the parameters of the survival curve (mean and standard deviation) are each changed by ±10%. Given the flow-driven nature of the model, a ±10% change in inflows is also analyzed. The sensitivity analysis is only conducted for the baseline scenario. The reason for this is that although changes in annual inflows and outflows translate into changes in the amount of secondary neodymium, it is reasonable to assume that the magnitude of the effect would be similar for the scenarios.

Given the large amount of individual data points in the baseline scenario (over 1000), no further sensitivity analyses on the raw data (number and average capacity of installed wind turbines, market shares of generator types and material intensities) used to calculate annual neodymium inflows are conducted. For the number of wind turbines and the average capacities installed between 1989 and 2022 this is unlikely to pose a significant issue, as this data is monitored by the Bundesnetzagentur and can hence be considered reliable and accurate. The data most likely to introduce inaccuracies are the past and future market shares of generator types, and the projected number and capacity of wind turbines and material intensities between 2023 and 2045. Even though, in particular, the market share of different generator types is likely to influence the inflow of neodymium, a more thorough, year-by-year sensitivity analysis is infeasible within the scope of this thesis.

Similarly, a sensitivity analysis of the linearly extrapolated CMU for the Commission's and Council's proposals and the recycling rate for the Parliament's proposal exceed the scope of this investigation. Given that Scenarios 1.1, 2.1 and 3.1 all assume constant levels from 2030 onwards and Scenarios 1.2, 2.2 and 3.2 assume a continuation of the linear trend between 2023 and 2030, the results can be seen as a wide range of possible intermediate paths. In other words, it is likely that the actual development of these rates will lie somewhere in between the two respective sub-scenarios; and so, investigating these sub-scenarios can be understood as the upper and lower boundary of a range of possible scenarios.

3 Results

To address the research objectives, the following section presents the baseline dMFA model and the three scenarios outlined above. To ensure that the obtained results are reasonable, they are compared to previous findings in the literature. Appendix D provides the python code used to generate the results.

3.1 Results baseline scenario

The baseline scenario provides answers to sub-questions (1) – (3). The historic development of neodymium inflows (sub-question 1) resembles the expansion pathway of wind energy in Germany described above (Table 1 and Figure 6). Figure 8 shows that, although the first onshore wind turbines were installed in 1989, first NdFeB magnet-based ones were only installed from 1995 onwards. Thereafter, neodymium inflows begin increasing more significantly from 2010 onwards, peak around 2017 and then decline rapidly. The level of neodymium inflows in 2022 of 92 tons is less than half the 2017 level of 229 tons. Although this decrease of inflows does not translate into a simultaneous decrease in stock, the stock between 2017 and 2022 only grows 47.5%, compared to the growth rate of almost 430% in the previous five-year period. The reason that stocks does not decrease promptly lies in the 20-year lifespan of wind turbines.

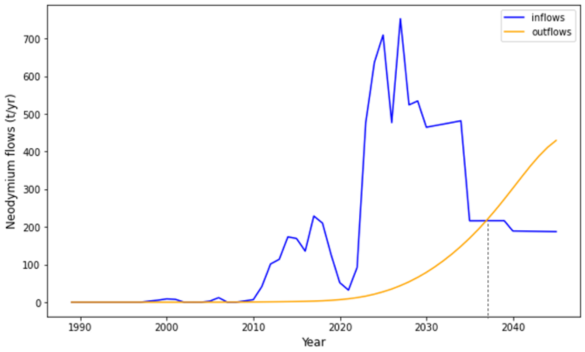
In terms of future demand for neodymium (sub-question 2), the projected inflows increase sharply between from 92 tons in 2022, to 662 tons in 2025, decline slightly in 2026 and then peak in 2027 at 700 tons. The decrease in inflows in 2026 can be explained by the fact that the already commissioned offshore wind farm projects in 2026 are not expected to use any neodymium-intensive PMSG-DD generators (Appendix A). From 2027 onward, the inflows decline to 482 tons in 2034. As Figure 8 visualizes, a sharp decline of inflows is expected between 2034 and 2035. This decline can be attributed to the fewer additions in wind power specified in the EEG (Table 1). In the period 2040 – 2045, the level of inflows remains almost constant, ranging between 173 and 189 tons. The reason for this is that the German government has not specified further onshore targets beyond 2040 and only an annual average addition of 3 GW offshore capacity.

With respect to outflows (sub-question 3), three main insights are derived. First, given the relatively long lifespans of wind turbines, inflows occurring between 2010 and 2020 only generate significant volumes of outflows in the second half of the 2020s. From then on, outflows continue rising steadily from until the end of the modelled period. Second, outflows exceed inflows for the first time in 2037. During the rapid expansion of wind energy anticipated between 2023 and 2030, inflows are lower than outflows. While inflows are 458 tons in 2023, 700 tons in 2034 and 481 tons in 2034, outflows are at 16, 43 and 146 tons, respectively. The fact that outflows surpass inflows in 2035, however, can be explained by the simultaneous sudden drop in inflows. Third, the level of stock continues to grow steadily until it reaches 7198 tons in 2036 and then slowly declines to 6015 tons in 2045 (Figure 9). The declining stock from 2036 on is a combination of two effects: the growth of outflows and the sudden decline of inflows.

The results obtained in the baseline scenario correspond to previous research on this topic. In their study on the raw metal needs for Germany’s wind power expansion, Shammugam et al. (2019) report a neodymium demand of 240 tons in 2018, 500 tons in 2030 and 1000 tons in 2045. The results of this thesis yield inflows of 210 tons in 2018, 513 tons in 2030 and 187 tons in 2045. While the results for 2018 and 2030 are very similar, a large deviance can be observed for 2045. One likely explanation for this is the additional wind capacity installed on an annual basis. Even though the cumulative capacity in 2050 assumed by Shammugam et al. (2019) is comparable to the current German capacity targets, the years of installation and the development of turbine type market shares differ. However, in terms of the outflows, the results of this study are in line with previous literature. As projected by multiple previous studies, significant amounts of outflows are only to be expected after 2025 (Glöser et al., 2016; Rademaker et al., 2013; van Nielen et al., 2023). Glöser et al. (2016), for instance, expect neodymium outflows from wind turbines in Germany to be below 10 tons in 2023 and close to 40 tons in 2023. Although similar in terms of overall magnitude, these projections are lower than the outflows of 16 and 80 tons in 2023 and 2030, respectively, obtained in this study. One explanation for this deviance may by the lower historic share of permanent magnet-based turbines assumed by Glöser et al. (2016).

Figure 17

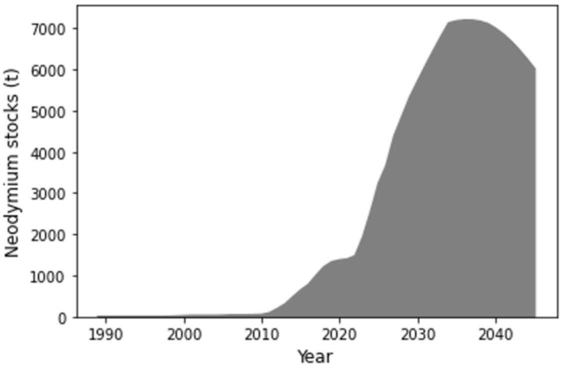
Baseline scenario inflows and outflows



Note. The dashed line indicates the year 2037, when outflows exceed inflows for the first time. The sudden drop in inflows in 2035 reflects the sharp decline in annual expansion targets pursued as part of the EEG.

Figure 18

Baseline scenario stocks



Note. The stocks show the amount of neodymium in wind turbines per year. The stock reaches its peak in 2036 and declines thereafter.

3.2 Results scenario 1: European Commission’s proposal

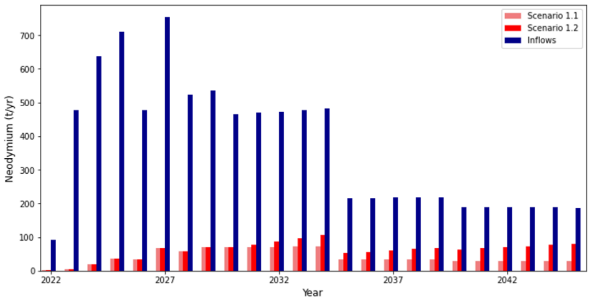
In Scenario 1, the Commission’s proposal of a 15% CMU rate in 2030 is explored. The model reveals that the Commission’s target of a 15% CMU rate translates into approximately 70 tons of secondary neodymium in 2030 (Figure 19). Using the extrapolated CMU rates, a total of 329 tons of primary neodymium would be generated between 2023 and 2030. Between 2030 and 2045, Scenarios 1.1 and 1.2 would generate further 529 and 1037 tons of secondary neodymium, respectively. Over the entire period between 2023 and 2045, Scenario 1.1 could hence replace 858 tons and Scenario 1.2 could replace 1366 tons of primary neodymium inflows.

To determine if generating sufficient secondary neodymium to meet the Commission’s CMU rate target is realistic, secondary neodymium is compared to available outflows. Figure 20 shows that the amount secondary neodymium is larger than available outflows are between 2023 and 2029. For instance, outflows are expected to be 28 tons in 2025, while required secondary neodymium is 35 tons. This trend reverses after 2030, with outflows increasingly exceeding secondary neodymium. By 2035, outflows are approximately three times larger in 2035 than required secondary neodymium in both scenarios. By 2045, outflows are up to ten times larger in Scenario 1.1 and almost five times larger in Scenario 1.2.

As described previously, another way to visualize whether the CMU targets can be achieved is by looking at the recycling rates of outflows. To this end, Figure 21 visualizes the recycling rates of outflows. Similar to what Figure 20 reveals, the Commission’s CMU targets are not achievable between 2025 and 2030, given that recycling rates of above 100% would need to be realized. In 2030, the necessary recycling rate drops to approximately 88%. After 2030, the rates continue decreasing with Scenario 1.1 reaching 19% and Scenario 1.2 reaching 31% in 2035. The significant decrease in recycling rates can be explained by the simultaneous drop in inflows. Because the Commission’s targets are consumption-based, the annual CMU is dependent on expected inflows. When inflows drop as they do in 2035, while outflows available for recycling remain constant, less secondary neodymium will be required. Of course, in theory more secondary neodymium could be generated, however, given the definition of the recycling rate and the Commission’s targets, the amount of secondary neodymium generated decreases.

Figure 19

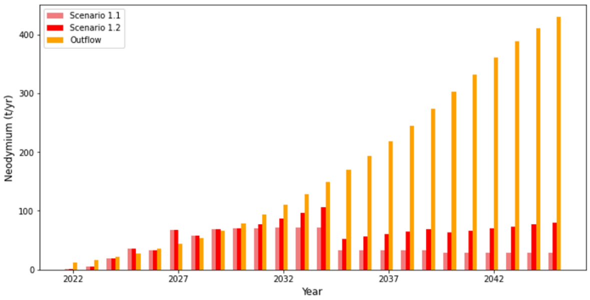
Scenario 1: Neodymium inflow and secondary neodymium



Note. The figure compares neodymium inflow to secondary neodymium in Scenarios 1.1 and 1.2, respectively. Between 2023 and 2030, secondary neodymium is equal. In 2030, 70 tons of secondary neodymium is generated.

Figure 20

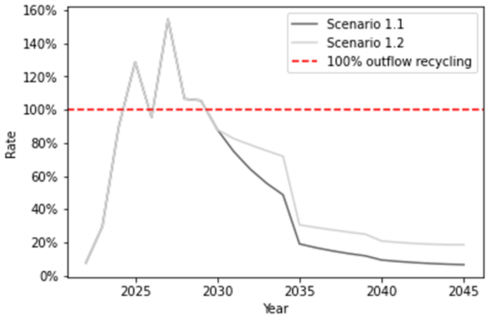
Scenario 1: Neodymium outflow and required neodymium



Note. The figure compares the amount of secondary neodymium generated in accordance with the Commission’s targets with expected outflows. 2030 is the first year in which expected outflows exceed secondary neodymium

Figure 21

Scenario 1: Recycling rates



Note. The figure shows the recycling rates that would need to be realized, for the Commission’s targets to be met. The recycling rates of above 100% between 2025 and 2030 imply that required secondary neodymium exceeds outflows. After 2030, the recycling rates drop to 19 and 21% for Scenario 1.1 and 1.2, respectively.

3.3 Results scenario 2: European Council’s proposal

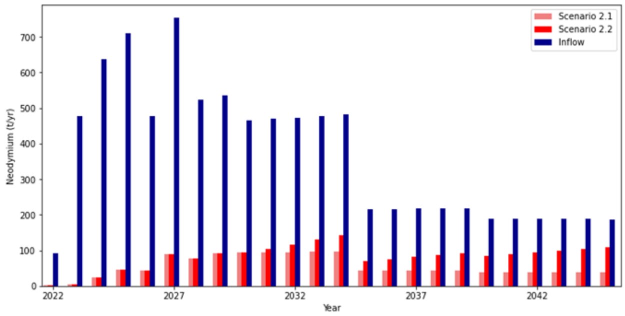
Scenario 2 is very similar to Scenario 1, the only difference being that the Council’s proposal of a 20% CMU rate target is more ambitious than the Commission’s 15% target discussed previously. Following the Council’s CMU target, 93 tons of secondary neodymium need to be generated in 2030, and a total of 469 tons secondary neodymium between 2023 and 2030 (Figure 22). After 2030, Scenario 2.1 would need to generate 467 tons and Scenario 2.2 1189 tons of secondary neodymium.

Comparing secondary neodymium to outflows (Figure 23), reveals similar patterns as in Scenario 1. Until 2031, the amount of secondary neodymium required to achieve the 20% CMU rate target is lower than available outflows. For instance, in 2030, 93 tons of secondary neodymium are needed, while only 79 tons of outflows are available. Outflows exceed secondary neodymium for the first time in 2032 under Scenario 2.2 and in 2034 under Scenario 2.1. By 2045, outflows are more than eight times as large as secondary neodymium in Scenario 2.1 and almost four times as large in Scenario 2.2. Overall, the gap between secondary neodymium and outflows is smaller than in Scenarios 1.1 and 1.2, respectively, but nevertheless significant.

Compared to Scenario 1, the recycling rates in Scenario 2 are consistently higher. The reason for this is that a greater demand for secondary neodymium with unchanged inflows and outflows necessarily translates into a higher necessary recycling rate. Figure 23 shows that recycling rates of above 100% between 2024 and 2030/2033 are necessary to meet the Council’s CMU rate target. Similar as discussed for Scenario 1, the sudden drop in inflows in 2035 translates into a decrease in the necessary secondary neodymium which, in turn, leads to a lower required recycling rate in 2035; namely, 25% for Scenario 2.1 and 41% for Scenario 2.2.

Figure 22

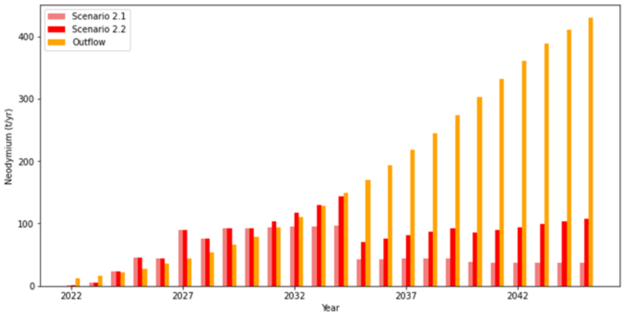
Scenario 2: Neodymium inflow and secondary neodymium



Note. The figure compares neodymium inflow to secondary neodymium in Scenarios 2.1 and 2.2, respectively. Between 2023 and 2030, secondary neodymium is equal. In 2030, 93 tons of secondary neodymium is generated.

Figure 23

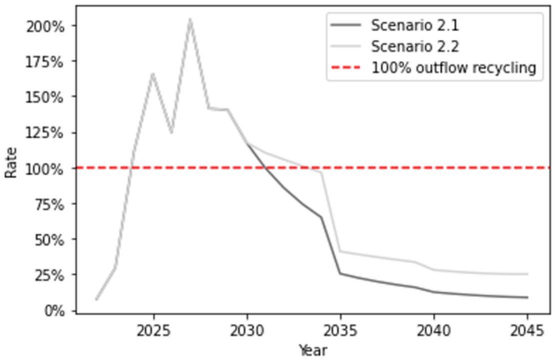
Scenario 2: Neodymium outflow and secondary neodymium



Note. The figure compares neodymium outflow to secondary neodymium in Scenarios 2.1 and 2.2, respectively. Between 2023 and 2030, secondary neodymium is equal. Outflows exceed secondary neodymium for the first time in 2032 in Scenario 2.1 and in 2034 in Scenario 2.2.

Figure 24

Scenario 2: Recycling rates



Note. The figure shows the recycling rates that would need to be realized, for the Council’s targets to be met. The recycling rates of above 100% between 2024 and 2030/2024 imply that required secondary neodymium exceeds outflows. In 2035, recycling rates drop to 25 and 41% for Scenario 2.1 and 2.2, respectively.

3.4 Results scenario 3: European Parliament’s proposal

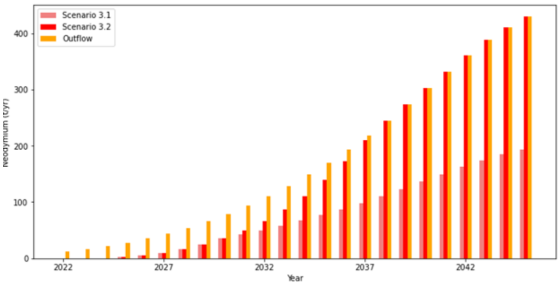
In contrast to Scenarios 1 and 2, the Parliament’s proposal sets recycling targets and no consumption-based CMU rate targets. Figure 25 compares outflows with secondary neodymium generated assuming recycling rates set in Scenarios 3.1 and 3.2 are met. Because the recycling rate reaches 100% in 2037 in Scenario 3.2, the amount of secondary neodymium generated is capped at the amount equivalent to inflows. The reason for this is the strict closed-loop recycling assumption according to which any secondary neodymium above that need to satisfy inflows is not needed (see Appendix E for more elaboration). Secondary neodymium in Scenario 3.2 is therefore equal to inflows from 2038 onwards.

In Figure 26, inflows are compared with secondary neodymium. The amount of secondary neodymium is small compared to secondary neodymium between 2023 and 2030. In absolute terms, only a total of 95 tons of secondary neodymium are generated under the Parliament’s proposal between 2023 and 2030. These 95 tons have the potential to replace just 2% of primary neodymium. However, between 2030 and 2045, Scenario 3.1 could generate an additional 1037 tons, thereby avoiding 23% of primary neodymium. Scenario 3.2 could generate a total of 2151 tons between 2030 and 2045, thereby avoiding 47% of primary neodymium. The fact that inflows drop abruptly in 2035 implies that from 2038 onwards, Scenario 3.1 is able to satisfy more than 50% of inflows and Scenario 3.2 produces more neodymium than needed. Taken together, Scenario 3.1 would generate 1331 tons of secondary neodymium between 2023 and 2045, thereby supplying 13% of inflows. Scenario 3.2 could produce 2245 tons of secondary neodymium between 2023 and 2045, lowering demand by 24%. The low amounts of secondary neodymium generated between 2023 and 2045 can be explained by the Parliament’s focus on recycling rates. Given that outflows are low, the corresponding amount of secondary neodymium is also low. This trend reverses as soon as outflows begin increasing more significantly.

Another way to visualize the results allowing for greater comparability with Scenarios 1 and 2, is the CMU rate. Figure 27 shows that in 2030, the CMU rate is approximately 8% for both scenarios. In Scenario 3.1, the CMU rate rises to 35% in 2035 and reaches 100% in 2045. For Scenario 3.2, the CMU rate is 64% in 2035 and reaches 100% in 2038.

Figure 25

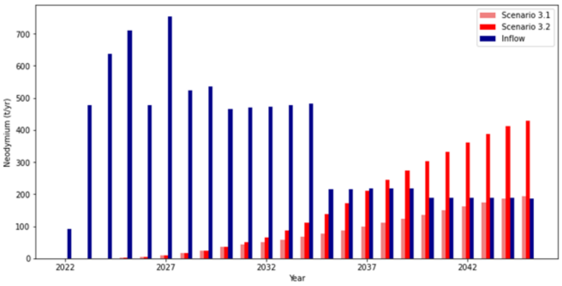
Scenario 3: Neodymium outflow and secondary neodymium



Note. The figure compares neodymium outflow to secondary neodymium in Scenarios 3.1 and 3.2, respectively. Until 2037, secondary neodymium is smaller than outflows. From 2037 onwards, Scenario 3.2 generates as much secondary neodymium as equal to outflows.

Figure 26

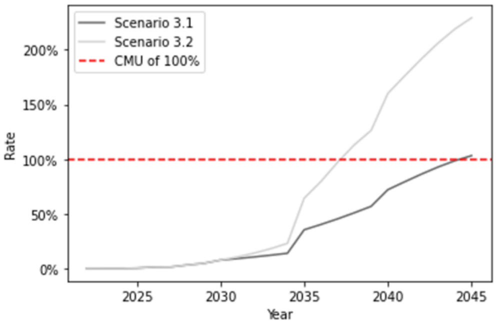
Scenario 3: Neodymium inflow and secondary neodymium



Note. The figure compares neodymium inflow to secondary neodymium in Scenarios 3.1 and 3.2, respectively. Between 2023 and 2030, secondary neodymium is equal for both scenarios. In 2038, secondary neodymium exceeds inflows for the first time for Scenario 3.2.

Figure 27

Scenario 3: Circular Material Use rate



Note. The figure shows the CMU rates that would need to be realized, for the Parliament’s targets to be met. Scenario 3.1 reaches a CMU of 100% in 2038, Scenario 3.2 reaches this in 2045.

3.5 Comparison of key results across scenarios

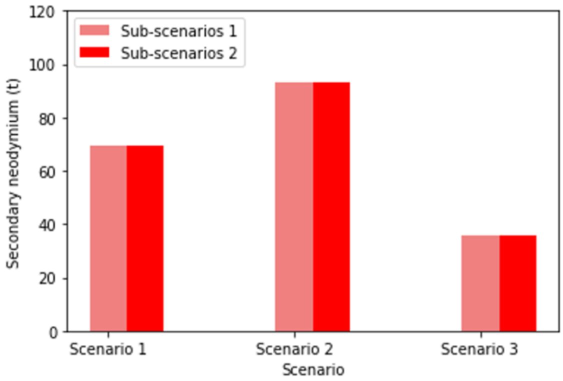
To answer the fourth sub-question on how the scenarios compare in terms of secondary neodymium generated, the previous results are combined. The comparison distinguishes between the amount of secondary neodymium generated, the point in time by which this is generated and whether achieving this target is realistic in the short run (by 2030) and long run (until 2045). With respect to the amount generated in 2030, the results reveal that Scenario 2 generates the most and Scenario 3 generates the least amount of secondary neodymium (Figure 28). The results for 2030 imply that the Council's proposal can contribute most to meeting supply more sustainably and the Parliament's approach least.

However, when considering the entire period of this dMFA, a different pattern emerges. While Scenario 3 generates the least secondary neodymium in 2030, this trend reverses in the mid-2030s. Around 2035, the Parliament's approach begins to generate more secondary neodymium than the Commission's and Council's proposals do. In fact, considering the entire period between 2023 and 2045, Scenario 3.1 generates more secondary neodymium than Scenarios 1.1 and 2.1 do, and Scenario 3.2 generates more than Scenarios 1.2 and 2.2 (Figure 29). This trend reversal is due to the different approaches and the underlying inflow and outflow dynamics. More specifically, because the Commission's and Council's targets are inflow-dependent and the Parliament's target is outflow-dependent, the amount of secondary neodymium generated is significantly affected by the underlying flow dynamics. The expected rise in neodymium inflow and the simultaneous slow increase of outflows over the next decade therefore lead to larger amounts of secondary neodymium needing to be generated earlier on under the Commission's and Council's targets, while the amount of secondary neodymium needing to be generated under der Parliament's proposal shifts to a later point in time.

The target increases explored in the second sub-scenarios (1.2, 2.2 and 3.2) generate more secondary neodymium than the targets remaining constant at their 2030 levels (1.1, 2.1, 3.1). While this observation may appear obvious and insignificant, it is nevertheless a crucial insight. Although different approaches and with that different amounts of secondary neodymium are generated over time, the results show that continued increases in the targets not only have an influence, but in fact a significant one. Figure 29 visualizes that the second sub-scenarios generate approximately one third more secondary neodymium in the long-run. Expressed in relative terms, Scenarios 3.1 and 3.2 generate at least 10 percentage points more secondary neodymium than Scenario 1.1 and 1.2 over the entire period considered (Figure 30). Accounting for the insufficient amounts of outflows (see Appendix E), Scenarios 1.1 and 1.2 can satisfy 11 and 17% of inflows with secondary materials and Scenarios 3.1 and 3.2 can satisfy 21 and 28%, respectively. This difference can also be observed in Figure 31, where the CMU rates are initially higher for Scenarios 1 and 2, the rates for both Scenarios 3.1 and 3.2 exceed these from the mid-2030s onwards. Similar to before, the steep increase of CMU rates in 2035 for Scenarios 3.1 and 3.2 can be explained by the sudden drop in inflows. Although the proposed CMRA targets in Scenario 3 are not tied to the CMU rate, lower inflows nevertheless imply that higher CMU rates are realized.

Figure 28

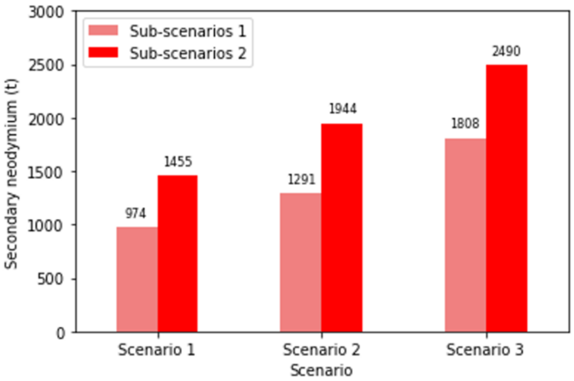
Secondary neodymium generated in 2030



Note. Secondary neodymium is equal across sub-scenarios in 2030, given that proposed targets are set for 2030.

Figure 29

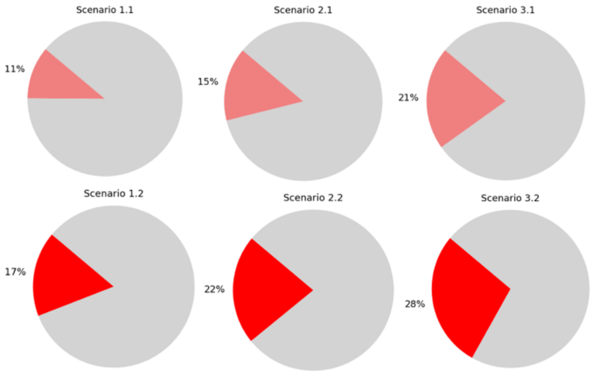
Secondary neodymium generated between 2023 and 2045



Note. The values presented reflect the cap described in Appendix E.

Figure 30

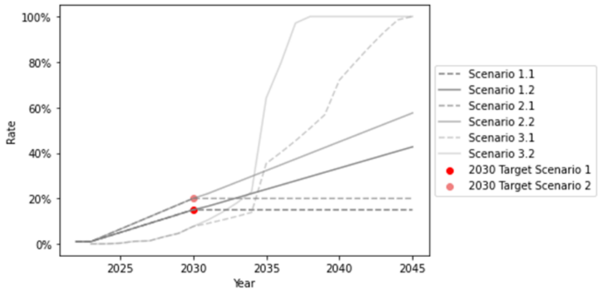
Inflows satisfied from secondary neodymium between 2023 and 2045



Note. The shares reflect the cap described in Appendix E.

Figure 31

CMU rates across scenarios between 2023 and 2045



Note. CMU rates of Scenarios 1 and 2 are extrapolated based on 2030 target. CMU rates for Scenario 3 shows share of inflows that would be satisfied according to the defined recycling target.

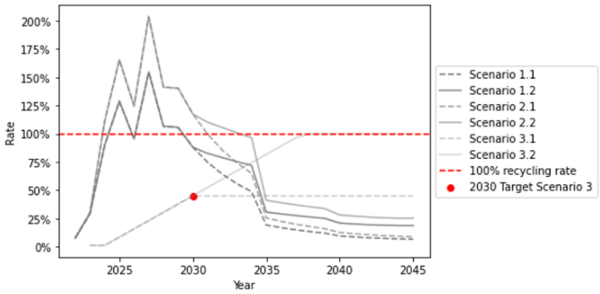
In addition to comparing the amount of secondary neodymium generated under the proposals, an equally important dimension to consider is whether the achievement of the defined targets is realistic. Although the focus of this thesis is not to evaluate the technological or economic feasibility, the modelling outcomes nevertheless provide insights on the achievability based on underlying material flow dynamics. Based on the results discussed previously and on the strict closed-loop recycling assumption used in this thesis, achieving the 2030-targets explored in Scenarios 1 and 2 is not possible. The reason that these short-term targets cannot be met lies in the insufficient amount of outflows available for recycling. This insufficiency translates into impossible recycling rates of above 100% (Figure 31). In contrast, because the Parliament's targets are relative to outflows, recycling rates do not exceed 100%.

Even though the targets specified in the proposals are defined for 2030, the dMFA is used to also address the long-term perspective. As Figure 32 shows, the necessary recycling rates for Scenarios 1 and 2 decrease to below 100% in the early 2030s and drop abruptly in 2035. Although the recycling rates necessary to achieve the CMU rates remain ambitious between 2030 and 2035, their achievement is possible from a material flow perspective. With respect to the Parliament's proposal, their definition based on outflows implies that outflow material shortage cannot prevent the target's achievement.

The comparison of the scenarios suggests that the main challenge of meeting neodymium demand more sustainably is not a long-run but rather a short-run issue. From the perspective of material flow dynamics, the scaling of wind energy over the next decade requires so much neodymium, that satisfying even this demand through secondary neodymium as anticipated by the Commission and Council is not realistic. In contrast, the Parliament's approach of setting targets for specific recycling rates is realistic by 2030. In fact, the Parliament's targets would yield a CMU rate of approximately 7% in 2030, compared to the Commission's and Council's targets of 15 and 20%, respectively.

Figure 32

Recycling rates across scenarios between 2023 and 2045



Note. Recycling rates of Scenarios 1 and 2 show share of outflows that would need to be recycled to satisfy defined CMU targets. Scenario 3 is extrapolated recycling rate based on 2030 target.

4 Discussion

The objective of this research has been to compare the implications of the CRMA proposals made by the European Commission, Council and Parliament. More specifically, the research question addressed in this thesis is how their CRMA proposals compare in terms of their potential for meeting CRM demand more sustainably through secondary materials. Given the currently dynamic nature of the legislative process, no research could be identified that compares the implications of the individual proposals. To fill this research gap, a case study on closed-loop recycling of neodymium from NdFeB magnets from and for wind turbines in Germany was conducted. The dMFA and explorative scenarios reveal that by 2030, neither the Commission's nor the Council's proposed targets are achievable. Although the Commission's and Council's targets are most ambitious in the amount of secondary neodymium required by 2030, the lack of available outflows prevents the targets from being achievable. Beyond 2035, however, the Commission's and Council's targets become more realistic due to the simultaneous decreasing of inflows decreasing and increasing of outflows.

Despite this long-term potential of the Commission's and Council's targets, the Parliament's approach nevertheless appears to have the greatest potential in satisfying demand more sustainably overall. Not only can the recycling rate targets set by the Parliament be achieved from a material flow perspective, but they also have the largest potential to satisfy demand most sustainably. In other words, based on the scenarios developed and investigated in this thesis for the period between 2023 and 2045, the Parliament's proposal would yield the largest amount of secondary neodymium, thereby replacing the most amount of primary materials. This avoidance of primary material can therefore be considered to be meeting supply most sustainably.

In addition to the insights related to the main research question, another more general finding is derived. The results obtained in this study confirm what multiple studies on various CRM applications described in the literature review have already found: demand for CRMs such as neodymium is expected to increase over the next decade, while outflows only begin increasing significantly after 2030. The implication that follows from this imbalance is that meeting demand more sustainably is a short-term, rather than a long-term issue. While this does not imply that achieving a more sustainable supply and mitigating supply risks will not be a challenge in the future, the material flow dynamics suggest that the issue is particularly relevant in the next decade. Not only are the outflows limited, but because many technologies are currently still being designed and developed, it is important to consider the implications as early as possible. Arguably, the main challenge therefore lies in developing solutions for slowing the inflow of primary materials during the next decade.

It is important to realize that the slowing of primary material inflows does not imply that the scaling of wind energy or other net-zero technologies as such should be slowed down or even postponed. The urgency associated with the decarbonization of the current economic system finds wide consensus. Rather, the notion is to explore and implement approaches that reduce the demand for specifically primary materials. These approaches include the previously described other R-strategies such as material reduction or substitution (i.e. using fewer or other critical raw materials), or product-life extensions including large-scale repair and reuse of magnets. At the same time, remanufacturing and recycling capacities should be increased so that the growing amount of outflows can be further processed to avoid downcycling or waste. Even though empirical data on the wider potential of these product-life extension methods is limited, the material flow dynamics of this thesis indicate that considerable potential for replacing the inflow of primary materials with secondary materials.

Although the general interpretation of the results is in line with results of other studies described in the literature review, the methodological limitations of thesis, as well as its narrowly-defined scope of this research (see Section 4.2 below).

4.1 Policy recommendations

Although the case study conducted in this thesis is based on Germany and only has a narrowly-defined scope, the dynamics and implications observed in relation to the CRMA proposals are of relevance not only for policy-makers in Germany, but also of great relevance for EU policy-makers. More specifically, the German policy-makers need to be aware of the dynamics related to CRMs in general, and because the CRMA will need to be translated and enacted in national law, understanding its implications is crucial. For EU policy-makers, case studies like these enable them to identify which of their proposals are realistic, effective and have the largest potential to contribute to the overarching Green Deal. The following section therefore provides policy recommendations targeted at both the EU-level, as well as that of individual member states.

Generally speaking, the CRMA has been welcomed by many member states and industry representatives, suggesting that the specification of targets is important. Arguably, without them and their ultimately binding nature, it would be less likely for the European economy to decrease its dependency on foreign suppliers and to achieve the closely connected NZIA and climate goals. Nevertheless, given the status-quo of recycling rates across the EU and the underlying supply-demand dynamics CRMs such as neodymium, policy makers must be aware that all of the currently proposed targets are very ambitious and, in part, unrealistic in the short-term. If the EU decides to agree on the consumption-based targets proposed by the Commission and Council, the EU and the individual member states should prepare for the case of non-achievement and clearly define what is to happen in this case. For instance, the question must be answered of whether certain applications may nevertheless be realized, even if not sufficient secondary CRMs are available to comply with the CRMA targets. Similarly, the question must be addressed of whether certain industrial applications are awarded priority over others in case of secondary material supply shortages or whether a free market will allocate them.

In addition to these open questions, policy makers are advised to set targets for the years beyond 2030. Increasing both CMU and recycling rate targets beyond 2030-levels may not only translates into additional secondary neodymium being generated over the entire time period, but it would likely also have beneficial effects for the industry. For instance, clear targets until 2045 would enable firms to make long-term investment decisions, thereby contributing to the establishment of an industry for CRM recycling. Even though recycling rates may grow organically once a market and supply chain for secondary CRMs is established by 2030, 2030 is only seven years away. Given that other strategies such as the Green Deal's climate neutrality goal by 2050 includes long-term targets, developing a more long-term roadmap for policy makers and industry to adapt to would have far-reaching benefits.

In addition to these legislative dimensions, policy makers are advised to provide financial support to promote and facilitate the rapid expansion of domestic recycling and other approaches reducing dependency on primary materials. For instance, favorable credit terms could be established, funding to pilot projects could be granted and subsidies for commercial-sized facilities could be provided. While calls for financial support are always quickly raised in times of transformations, the undeniable importance of CRMs for a range of applications and sectors implies that sufficient funding should not be an obstacle. Ensuring not only that demand is met more sustainably, but also that it is subject to less supply risks and the thereby the economy less vulnerable as a whole, is likely to also avoid high economic costs in the future. Lastly, to develop the necessary supply chains, support could be provided that brings together, aligns and enables knowledge exchange between the relevant stakeholders. This support could include round table formats and networking opportunities, both within member states and across borders.

4.2 Limitations

The limitations of this research are divided into two parts. In the first part, the main data and methodological related shortcomings are addressed. In the second part, more general aspects related to the research scope are reflected upon.

4.2.1 Data and methodological limitations

As discussed along the framework (Ciroth et al., 2016) above, the raw data quality is limited for three main reasons. First, data on past market shares of wind turbine generator types in Germany is fragmented. One reason for this is that because the absolute number of wind turbines is relatively small, it is difficult to obtain disaggregated data for just Germany over an extended time period. As documented in Appendix A, many sources only contain data for a few years at a time and so different sources with varying assumptions and approaches are compiled to compute the inflow data over the entire time period studied. Despite these likely inconsistencies, the inflows calculated in this baseline model are reasonably consistent with previous literature. Moreover, the sensitivity analysis shows that ±10% deviances in annual inflows do not significantly impact the general trends observed. Taken together, this suggests that despite the data shortcomings, the results can nevertheless be used to draw cautious conclusions about the case study investigated.

The second limitation relates to the uncertainty of future developments. Although the goal of this investigation is not to create a precise projection, creating reasonably realistic exploratory scenarios is nevertheless important. In the context of this case study, this implies that assumptions related to future inflows (including the actual annual capacity installations in Germany, average turbine capacity, market share of generator types and neodymium content), as well as assumptions related to the pathways to reach the defined targets and beyond should reflect a possible future. While the individual modelling choices are explained and justified above, it is important to realize that the respective sub-scenarios need to be understood as the upper and lower bounds of a range of potential pathways. Because it is unlikely that the recycling rates will follow the precise linear trends extrapolated in the model, the results merely reflect possible scenarios. Understanding and acknowledging that these scenarios reflect a range of possible future pathways nevertheless allows to derive insights.

The third limitation of the data is closely connected to the previously discussed uncertainty of future developments and relates to future inflows in this dMFA model. Unlike most dMFAs, the inflows beyond 2023 do not exhibit a smooth curve. The reason for this is that the baseline scenario uses the annual expansion targets by the German federal government. Unlike most dMFAs, in which relatively smooth increases or decreases between years are observed, the German targets change very abruptly and even somewhat arbitrarily between years. While it is questionable whether the actual expansion will follow the patterns described in the EEG, these values are nevertheless used to ensure transparency and to provide the most accurate representation of current targets.

4.2.2 Research scope limitations

In addition to some of the methodological limitations, two main shortcomings of this research in relation to its research objective and main research question are identified. The first limitation relates to the temporal scope of this research and its dynamic and fast-moving context. Although very recent proposals from the Commission, Council and Parliament are used, the final agreement on the CRMA targets may be different to the targets explored in this research. Despite this, the scenarios provide a range within which a compromise is likely and so valuable insights can be derived, nonetheless. The second limitation relates to the narrow technological scope of closed-loop recycling. Because recycling is not the most sustainable and therefore desirable strategy from a circular economy perspective and a closed-loop recycling system is not necessarily representative of (future) neodymium processing, the recently proposed CRMA targets nevertheless provide a strong rationale to investigate this strategy.

5 Conclusion

In this thesis, the CRMA proposals made by the European Commission, Council and Parliament are compared in terms of their potential to satisfy CRM demand more sustainably. Based on this case study on neodymium from NdFeB magnets in wind turbines in Germany, the results suggest that the Parliament's approach has the largest potential to increase the sustainability of neodymium supply. Not only does its recycling rate target for end-of-life streams ensure that sufficient end-of-life streams are available for recycling, but it also generates more secondary neodymium than the Commission's and Council's proposals would until 2045. Despite the Parliament's proposal being realistic from a material flow perspective, the analysis also reveals current recycling rates need to increase significantly to be able to process and generate these material amounts. The findings provide a novel perspective to both policy-makers and academics, given that no research has yet compared the proposals in such depth.

Interpretations and policy implications based on these results, however, need to be treated with caution. In particular the limited data quality, the uncertainty involving some of the assumptions, the definition of scenarios, and the narrow technological and geographic scope, imply that interpretations may not necessarily be fully representative of a wider context or applicable to other technologies and CRMs. Mindful of this, one key insight from this research is that a more sustainable satisfaction of demand is not primarily a long-term, but rather a short-term problem. This is due to the underlying material flow dynamics over the next decade, where CRM demand is expected to increase at an unprecedented scale, while many applications only slowly begin reaching their end-of-life. As a result, increased focus needs to be placed on approaches aimed at decreasing the annual demand of primary materials. Despite the still limited empirical evidence, such approaches could include smarter material use and substitution or product-life extensions, such as repair, reuse, and remanufacturing.

While the proposed CRMA is not perfect and certainly falls short of addressing many important levers from a circular economy perspective, it is nevertheless an important policy-making step. The analysis has shown that not only the proposed recycling targets are very ambitious, but also that substantial primary mining will be necessary to satisfy CRM demand in the foreseeable future. To meet the EU's various goals, ranging from the expansion of low-carbon technologies to transitioning to a circular economy and developing more autonomous supply chains, the proposed approach of focusing on domestic mining, processing, and recycling is therefore paramount. Ultimately, the question of whether the EU can meet its net-zero targets will also partly depend on whether the CRMA and the closely-connected NZIA targets are met. Only if access to the necessary primary and secondary materials and technologies is maintained, without doing so at the expense of the environment, society, or the economy, can the transition to a net-zero economy succeed. Whether the targets proposed by the CRMA are too ambitious or not ambitious enough hence depends on the perspective. While more far-reaching and comprehensive circular economy strategies and goals should have been considered in the proposal, the targets for specifically recycling are in fact very ambitious.

6 Recommendations for future research

Both the methodological- and scope-related limitations of this research should be addressed in future research. With respect to the data and methodological limitations discussed above, more comprehensive data quantifying precise neodymium use over time needs to become available. This lack in data quality and data completeness is not only an issue in this thesis, but similar shortcomings are likely to persist in other research contexts too. To overcome this, manufacturers could be asked to provide information on the amount of CRMs in their products. To avoid any proprietary information becomes publicly available, this data could be anonymized and made accessible for research purposes only.

To improve the scenarios developed in this research, further research could explore additional pathways of the recycling and CMU rates, as well as of future wind expansion. For instance, non-linear extrapolation could be used to determine the annual recycling and CMU rates until and beyond 2030.

Although the gap between available end-of-life streams and neodymium demand is so large that non-linear rates are unlikely to change the general patterns observed in this thesis fundamentally by 2030, the exploration of different rates could nevertheless yield more nuanced insights. Similarly, other wind energy expansion pathways could be considered that do not follow the EEG targets as strictly. For this, a smoother curve could be developed so that the annual differences in additional capacity follow less arbitrary and arguably more realistic patterns. Moreover, given the uncertainty of whether wind energy expansion targets will actually drop as significantly in 2035 as currently anticipated by the EEG, other scenarios exploring a not as steep decrease or even exploring a continued increase could be valuable.

With respect to the more general limitations related to the research objective and scope, three main recommendations are made. First, depending on the final compromise the Commission, Council and Parliament find related to the recycling targets, a similar investigation could be conducted investigating the final targets and the extent to which these could contribute to meeting demand more sustainably. Second, further research should investigate the impact of other R-strategies on the material flow dynamics in more depth. This includes changes to product design, but also the influence of product-life-extensions on annual inflow and outflow rates. Given the still limited empiric research on produce-life-extensions, implies that their contribution to CRM supply being met more sustainably is mainly of theoretical nature. Quantifying these potential contributions would not only deepen the understanding of a circular economy from a scientific perspective but could also pinpoint specific levers for either EU or member-state policy-makers to facilitate a circular economy in practice.

Lastly, instead of conducting a dMFA for a single application only, multiple applications using the same CRM could be considered. This would allow to loosen the strict closed-loop recycling assumption and could allow to analyze the interplay between different applications. More specifically, such an investigation could investigate how other applications possibly reaching their end-of-life earlier can contribute to satisfying CRM demand of applications experiencing a rapid scaling. In other words, relaxing the closed-loop assumption could generate more pronounced economy- and supply chain-wide insights.

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Appendix A: Raw data and sources

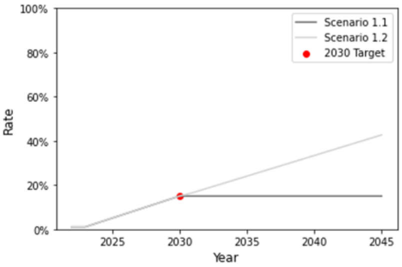
The raw inflow data and its corresponding sources, the survival curve matrix and cohort survival matrix, the baseline scenario timeseries data and the data to be read by the code are provided in a supplementary Excel file named *Appendix A_Hennings_Clara.*

Appendix B: Extrapolated CMU and recycling rates

Figures 8 – 10 visualize the extrapolated CMU and recycling rates. As described in the Methodology above, the Commission’s and the Council’s proposals with certain CMU rate targets for 2030 require the CMU rates to be extrapolated, while the Parliament’s approach of setting a recycling target on waste streams in 2030 requires recycling rates to be extrapolated. Sub-scenarios 1.1, 2.1 and 3.1 assume the respective rates to remain at their 2030 target once this is reached. Sub-scenarios 1.2, 2.2 and 3.2 on the other hand assume the growth trends between 2023 and 2030 to be extrapolated beyond 2030. In Scenario 3.2, the recycling rate reaches 100% in 2037 and remains at this level thereafter.

Figure 8

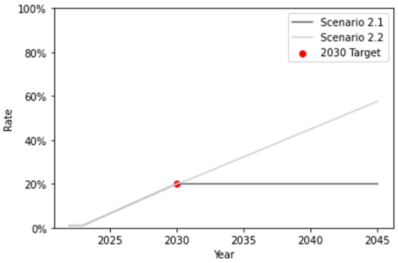
Scenario 1: Circular Material Use rate



Note. CMU rates are equal between 2023 and 2030. The CMU reaches 43% in 2045 in Scenario 1.2.

Figure 9

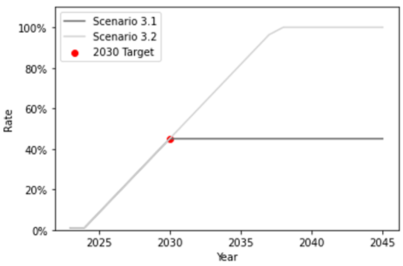
Scenario 2: Circular Material Use rate



Note. CMU rates are equal between 2023 and 2030. The CMU reaches 58% in 2045 in Scenario 2.2.

Figure 10

Scenario 3: Recycling rates



Note. Recycling rates are equal between 2023 and 2030. The recycling rate reaches 100% in 2037 in Scenario 3.2.

Appendix C: Sensitivity analysis

Figures 11 – 16 visualize the sensitivity analysis performed for the standard deviation (shape) and mean (scale) of the survival curve and for the inflows. Overall, the model is not particularly sensitive to changes of ±10%. Changes in the standard deviation on outflows and stocks are neglectable. Changes to the mean have a greater influence on outflows and stocks. However, even though the outflows surpass the inflows at a slightly earlier or later point in time and the decline in stocks takes place either more or less rapidly, the overall effect of a ±10% change in mean does not change the general behavior of the model. With respect to the inflows, the sensitivity analysis reveals a proportional effect on outflows and stock over the entire time period studied. It is important to note that the sensitivity analysis only traces the effects that an increase in overall inflows has. Even though a sensitivity analysis of individual data points could provide more detailed insights into how sensitive the model is to its basic assumptions such as the share of a certain type of generator type, this in-depth analysis lies outside the scope of this research.

Figure 11

Sensitivity analysis baseline scenario standard deviation flows (shape)

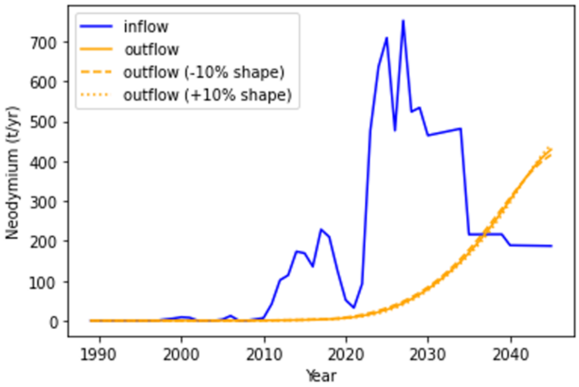


Figure 12

Sensitivity analysis baseline scenario standard deviation stocks (shape)

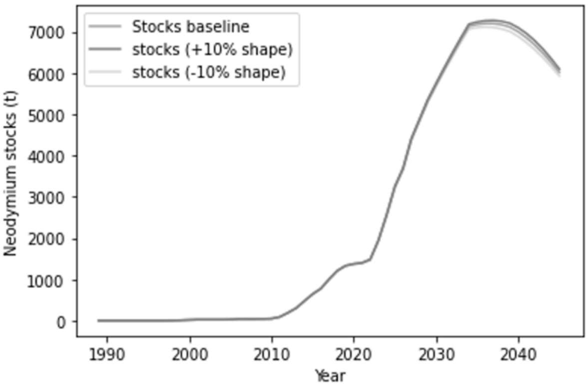


Figure 13

Sensitivity analysis baseline scenario mean flows (scale)

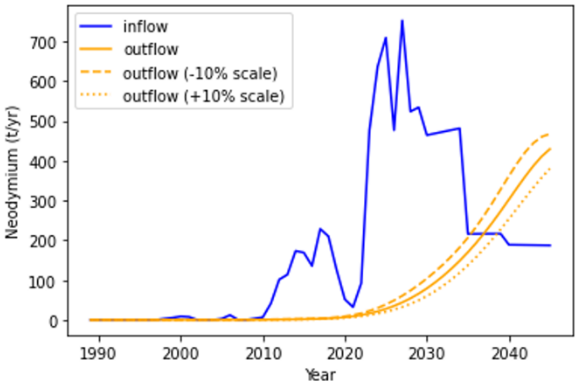


Figure 14

Sensitivity analysis baseline scenario mean stocks (scale)

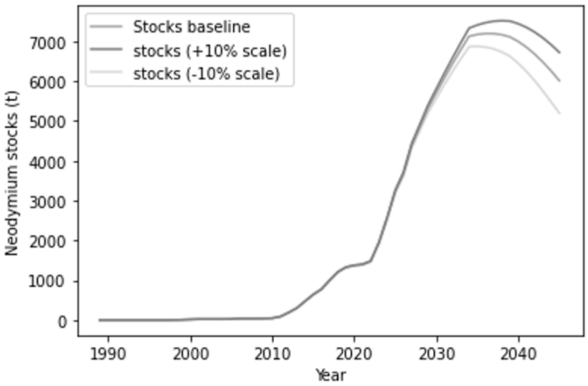


Figure 15

Sensitivity analysis baseline scenario inflows flows

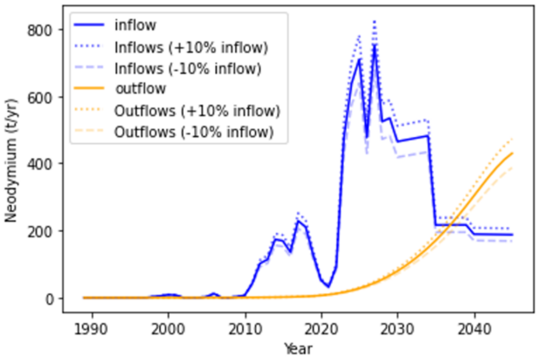
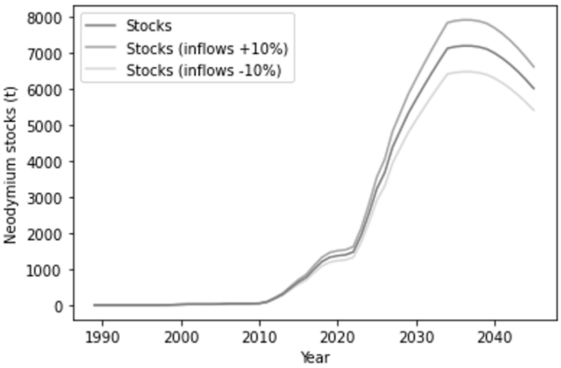


Figure 16

Sensitivity analysis baseline scenario inflows stocks



Appendix D: Modelling code

For transparency purposes, the full code used to model is provided in a supplementary file named *Appendix D_Hennings_Clara.py* and on Github:

https://github.com/clarahen97/MasterThesis.git

The code is set so that it reads the raw data in sheet “code_input” provided in Appendix A.

The code was programmed in Python, version 3.10.0 64-bit.

Appendix E: Results uncapped

As described above, achieving the targeted amount of secondary neodymium to satisfy inflows as proposed by the Commission and Council by 2030 is unattainable because outflows are insufficient. Hence, the amounts of secondary neodymium presented above are capped at the maximum outflows available. In other words, the shares of inflows that can be satisfied through secondary neodymium above reflect those percentages actually possible when capped at outflows. For completeness purposes, Figures 33 – 35 provide the amount of secondary neodymium that would need to be generated according to the targets. The difference between the secondary material amount required under the Commission's and Council's proposals in Scenarios 1 and 2 and those actually available are marginal, with 13 tons difference for Scenario 2.2, 24 tons difference for scenarios 1.1 and 1.2, and 125 tons for scenario 2.1.

With respect to the Parliament's proposal, the results indicate that the amount of secondary neodymium generated exceeds the volume required for permanent magnets in wind turbines. Due to the assumption of a closed-loop system, the amount of secondary neodymium generated is hence capped at the amount equivalent to inflows for the years it would otherwise exceed them in the results above. For the purpose of completeness, the values for Scenarios 3.1 and 3.2 in Figures 33 – 35 present the values if secondary neodymium would not exceed inflows.

Figure 33

Secondary neodymium between 2023 and 2045, not capped

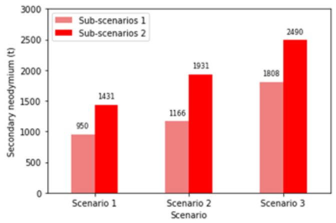


Figure 34

Inflows satisfied from secondary neodymium between 2023 and 2045, not capped

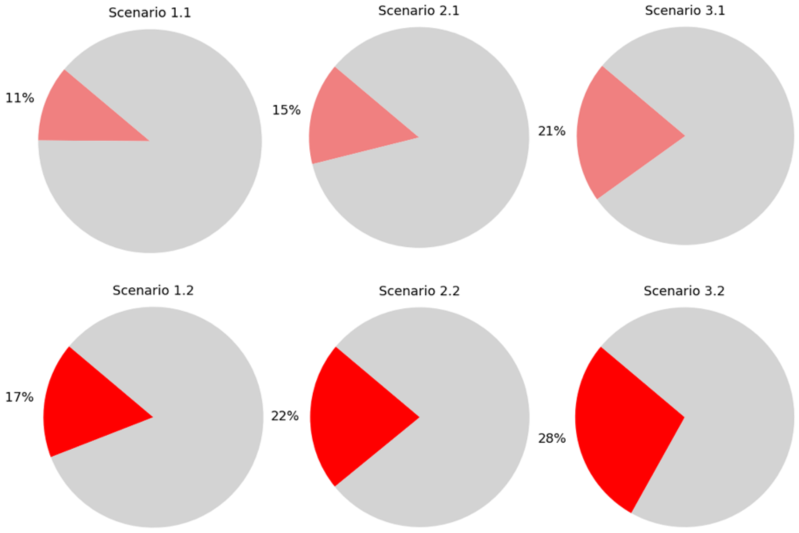


Figure 35

Secondary neodymium generated in 2030, not capped