Exploring the substitution potential of critical materials for the energy transition - A model-based analysis of substitution of Rare Earth Elements in NdFeB magnets in electric cars and wind turbines

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Exploring the substitution potential of critical materials for the energy transition – A model-based analysis of substitution of Rare Earth Elements in NdFeB Magnets in electric cars and wind turbines

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Executive summary

In light of transitioning towards a sustainable, low-carbon energy system, NdFeB (Neodymium-Iron-Boron) permanent magnets are set to play a crucial role. These magnets, currently the strongest available, are integral to the functioning of wind turbines, electric cars, and various digital appliances. Their superior performance is attributed to the inclusion of rare earth elements (REEs). NdFeB magnets contain four REEs: Neodymium and Praseodymium, categorized as Light Rare Earth Elements (LREEs), as well as Dysprosium and Terbium, classified as Heavy Rare Earth Elements (HREEs).

There is a general consensus among researchers that the amount of REEs available in the earth's crust suffices to meet the growing demand for NdFeB magnets by the energy transition. A potential bottleneck issue is therefore not the availability of REEs in the earth's crust, but the timely supply of REEs needed for NdFe B magnets under acceptable prices. China's dominance in NdFeB magnet production presents a substantial risk to the widespread adoption of wind energy and electric vehicles.

This study employs a model-based analysis to explore the potential of substituting REEs in NdFeB magnets within the NdFeB supply chain and clean energy technologies. To accomplish this, a combination of System Dynamics (SD) and Exploratory Modelling and Analysis (EMA) is employed to model the system and subject it to a wide range of scenarios. The assessment of the long-term demand and supply of materials supply chains is a complex and deeply uncertain issue. SD is tailored to model intricate systems with time delays, accumulation, internal feedback loops, and non-linear behaviours. To address the inherent uncertainty in the system, EMA is utilised to provide decision-making support under deep uncertainty through computational experiments.

The global supply system for NdFeB magnets primarily consists of several key elements, including the supply chain, demand, primary production, recycling, and the substitution of REEs. Primary REE production encompasses both legal and illegal activities, with a significant portion of HREEs being extracted through illegal means. The demand for NdFeB magnets and the REEs required for their production emanates from various industries, including electric vehicles, wind turbines, computer hardware, and other applications. To meet this demand, there are several potential methods for substituting REEs, including element-for-element, process-for-element, magnet-for-magnet, and component-for-component substitution. These substitution methods are influenced by factors such as the average periodic price of REEs, potential cost reductions in the case of process-for-element substitution, a substitution threshold for magnet-for-magnet substitution, and various considerations, including power density and technology readiness, for component-for-component substitution.

The study's findings indicate that the electric cars, wind turbines, and REEs in use will follow a similar pattern characterized by a significant level of uncertainty. In the most conservative scenario, there is a slight increase until 2050, while in the most optimistic scenario, there is exponential growth.

The most influential uncertainties affecting the quantity of electric cars and wind energy are driven by intrinsic demand stemming from the energy transition, product lifespan, and the production system's ability to adapt rapidly to changes in demand by scaling up or down. Differences in product lifespan are especially pronounced in the early stages of the simulation due to relatively low growth in intrinsic demand during that period. However, in the later phases of the simulation, intrinsic demand becomes the predominant influencing factor.

Both wind energy and electric cars demonstrate a positive relationship with the quantity of REEs in use. Nevertheless, scenarios exist where a relatively high number of wind energy systems and electric cars can be developed without an exceptionally high utilisation of REEs.

Substitution has the potential to temporarily alter demand or induce a permanent shift in the demand curve, depending on price levels and substitute product quality. Short-term demand for technologies and materials tends to remain continuous, with fluctuations in response to price changes. However, introducing new technology or changing production processes can lead to a permanent shift in the demand curve. Elevated prices incentivize firms to explore alternative technologies, leading to the development of superior products.

The study's findings suggest that both element-for-element and process-for-element substitution have the potential to induce both temporary and permanent shifts in demand. Magnet-for-magnet substitution is a more temporary solution, while component-for-component substitution often results in a more permanent change.

The development of alternative technologies that do not rely on NdFeB magnets has the potential to significantly impact the number of wind turbines and, particularly, electric cars without NdFeB magnets. Such advancements can lead to more permanent forms of substitution and contribute to increased adoption of these technologies. While currently available alternatives can also serve as substitutes for NdFeB-based cars, alternative technologies for electric vehicles that are still in development might have the potential to significantly reduce the number of electric cars utilizing NdFeB magnets.

In conclusion, this research suggests that substitution is unlikely to play a central role in securing a sufficient number of electric cars and wind turbines for several reasons:

1. The Earth's crust contains an ample supply of REEs, which should be sufficient for producing the necessary number of electric cars and wind turbines, at least until 2050.
2. Although REE production may lag behind demand, the process of substitution takes time and can only offer limited short-term flexibility. Moreover, short-term disruptions have a relatively minor impact on long-term supply.
3. Alternative technologies with reduced or no reliance on REEs do not significantly outperform their REE-intensive counterparts, thereby not leading to an increase in demand.

This is not to say that a substantial number of electric cars and wind turbines can only be produced with a large quantity of REEs. There are scenarios in which the utilisation of NdFeB and REEs remains relatively low, yet a considerable number of electric cars and wind turbines can still be manufactured.

While the importance of transitioning to a sustainable, low-carbon energy system is evident, the likelihood of a substantial number of electric cars and wind energy systems being in use by 2050 primarily hinges on demand for these technologies. Other factors such as technological advancements, price reductions of wind energy and electric vehicles, government policies, and incentives can also stimulate this demand.

Recommendations for future research include the use of this model for other critical metals. The extension of this model make it relatively easy to use this model to evaluate the substitution potential of critical metals in other technologies. Especially when metals are a vital component of an intermediate product that is used in the end-product, then the structure of this model would be directly applicable.

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List of abbreviations

ASM	Asynchronous motor
ASM with high RPM	Asynchronous motor with high revolution per minute
BEV	Battery Electric Vehicle
EMA	Exploratory Modelling & Analysis
ESDMA	Exploratory System Dynamics Modelling and Analysis
EV	Electric vehicle
HEV	Hybrid Electric Vehicle
HTS	High temperature superconductor
HREE	Heavy rare earth element
LREE	Light rare earth element
NdFeB	Neodymium-Iron-Boron
PHEV	Plug-in hybrid electric vehicle
REE	Rare earth element
REO	Rare earth oxide
SD	System Dynamics
SRM	Switch Reluctance motor
SSD	Sub-system diagram

1. Introduction

Neodymium-Iron-Boron permanent magnets (NdFeB) are indispensable for the energy transition (Gielen & Lyons, 2022). These magnets play a crucial role in converting mechanical to electric energy, enhancing the efficiency and performance of various appliances like consumer electronics, industrial motors and bonded magnets (Smith et al., 2022).

They also play an important role in clean energy technologies, specifically in wind turbines and electric cars (Guyonnet et al., 2015). The importance of NdFeB magnets in the green energy sector stems from their ability to facilitate lighter and more efficient designs (Klinger, 2018). In wind turbines, these magnets contribute to increased power generation efficiency, while in electric cars, they enhance motor performance and overall energy efficiency (Nakamura, 2018). As these technologies play pivotal roles in reducing carbon emissions and promoting sustainable energy practices, understanding and securing the supply chain of NdFeB magnets becomes critical for the broader goals of the energy transition.

NdFeB magnets outperform other magnets, because of the use of rare earth elements (REEs). REEs are a set of 17 elements that are found in the same deposits and are produced as co-products (Smith et al., 2022). Generally, REEs are divided into two groups, light and heavy rare earth elements (LREE and HREE, respectively), with HREEs generally being more scarce and also more expensive (Goodenough et al., 2018). NdFeB permanent magnets contain Neodymium and Praseodymium (both LREEs), as well as Dysprosium and/or Terbium (both HREEs) (München et al., 2021). A higher content of HREEs allows NdFeB magnets to operate at a higher temperature, which is desirable for technologies like wind turbines and electric cars (Smith et al., 2022).

Up until recently, the primary supply of REEs was dominated by China, a situation that has shown to be problematic (U.S. Geological Survey, 2013). Due to a geo-political issue, China implemented a stringent exportation policy, which resulted in a surge in the prices of products containing REEs (Zheng, 2019). The most poignant crisis happened in late 2010 when the prices of certain REEs increased by as much as two thousand percent (Klinger, 2018). Although prices fell quickly afterwards, concerns about the viability of technologies dependent on REEs remains (Eggert et al., 2016). This specific event created a strong awareness among policy makers and decision makers of the geopolitical situation and highlighted the dire political urgency to create a stable and sustainable supply chain.

After the 2010 REE crisis, the primary supply of REEs has become more diverse, but the production of NdFeB magnets has experienced the opposite effect. China is currently responsible for 60% of total annual amount of REE mined globally (U.S. Geological Survey, 2022). However, China’s dominance in the NdFeB supply chain increases at every downstream stage of production of NdFeB magnets, resulting in a 92% share of annual global magnet production (Smith et al., 2022).

A key question for decision makers on the energy transition is whether the supply of NdFeB magnets might hamper the supply of clean energy technologies like electric cars and wind turbines. The demand for NdFeB permanent magnets will likely grow tremendously due to an expected growth in demand for clean energy technology and further digitisation (Goodenough et al., 2018). In order to create a sustainable future, it is important to cope with a steady growing demand as well as sudden stark changes in demand. Therefore, it is vital to understand if there are certain policies that can be put into place to sustain development while facing (un)expected change.

Research regarding the material requirements and availability of REEs used in NdFeB magnets has been carried out quite extensively (Alonso et al., 2012; De Koning et al., 2018; Elshkaki & Graedel, 2013, 2014; Grandell et al., 2016; Habib & Wenzel, 2014; Hoenderdaal et al., 2013; Li et al., 2020; McLellan et al., 2016; Moss et al., 2013; Roelich et al., 2014; Speirs et al., 2013; Watari et al., 2019). There is a general consensus among researchers that the amount of REEs available in the earth's crust suffices to meet the growing demand of NdFeB magnets by the energy transition (Elshkaki & Graedel, 2014; Grandell et al., 2016; Hoenderdaal et al., 2013). A potential bottleneck issue is not the availability, but the timely supply of REEs needed for NdFeB magnets under acceptable prices (Hoenderdaal et al., 2013; Moss et al., 2013). The supply of REEs might not be able to keep up with the demand of the energy transition because of factors like long opening times of new mines and the monopolistic supply situation (Habib & Wenzel, 2014).

Potential material shortages could be alleviated by mitigation strategies like recycling and substitution (Moss et al., 2013). It has been found that the mitigating potential of recycling in the short term is rather low, mainly because of the long lifetime of key end-use products (Habib & Wenzel, 2014; Hoenderdaal et al., 2013). Research assessing material shortages of NdFeB magnets for energy technologies often exclude substitution (Habib & Wenzel, 2014; Hoenderdaal et al., 2013) or provide a qualitative assessment of the mitigating effect (Moss et al., 2013; Speirs et al., 2013).

NdFeB magnets are currently the strongest magnets on the market (Klinger, 2018). When other technologies are used to reduce or even eliminate the use of permanent magnets, cost-effectiveness will most likely be reduced under the current prices (Pavel, Lacal-Arántegui, et al., 2017). Nevertheless, other technologies are already available or are in the making to either reduce material usage or substitute the need for NdFeB magnets altogether (Pavel, Lacal-Arántegui, et al., 2017; Pavel, Thiel, et al., 2017). Substitution might be a viable mechanism to reduce the dependency on REEs in both the short and long term (Pavel, Lacal-Arántegui, et al., 2017; Pavel, Thiel, et al., 2017). For decision makers in the energy transition, it is valuable to understand how substitution of REEs can contribute to the supply of electric cars and wind energy.

Substitution can occur at various levels, involving direct substitution of one material for another, the reduction of material use by a different production technique of NdFeB magnets, using another type of magnet in the end product instead of an NdFeB magnet, or even employing entirely different components in the end product that do not require the use of a permanent magnet (Smith & Eggert, 2016). To comprehend substitution's mechanisms and its potential role in sustaining the development of electric cars and wind turbines, a comprehensive evaluation of individual substitution mechanisms is essential.

Several studies have investigated the potential of individual mechanisms for substituting REEs in NdFeB magnets. Smith and Eggert (2016) delved into the substitution of REEs in NdFeB magnets, focusing on the wind industry during the 2010 Rare Earth Crisis. They introduced a framework categorising responses of NdFeB magnet and wind turbine producers to REE price spikes during that crisis. In their subsequent paper, based on expert surveys, they identified the most effective responses during that period. Similarly, Pavel, Thiel, et al. (2017) and Pavel, Lacal-Arántegui, et al. (2017) assessed the substitution potential of individual mechanisms for REEs in NdFeB magnets for electric cars and wind turbines. Unlike the papers by Smith & Eggert, they not only evaluated the impact of substitution mechanisms during the Rare Earth Crisis but also assessed their potential in addressing changes in the short-term demand for REEs, electric cars and wind turbines. CRM InnoNet (2015) evaluated various substitution mechanisms using a roadmap, projecting developments in 2020, 2025, and 2030, considering the applications of NdFeB magnets not only for electric cars and wind turbines, but also for other applications.

While these studies contribute valuable insights into the short to medium term, the urgency of decision-making in the energy transition requires consideration of the long-term implications. With sustainability targets often set for 2050, understanding the role of substitution in this extended timeframe becomes crucial. Moreover, assessing long-term availability of supply and demand for material supply chains is a deeply complex and uncertain issue (Kwakkel & Pruyt, 2015). Therefore, even for experts in the field, it is virtually impossible to mentally simulate the development of the system and to understand what kind of role substitution might have in the future under varying circumstances.

In light of these complexities, constructing a model that integrates the dynamics of the REE supply system, general REE demand, and the increase in demand for electric cars and wind turbines, while also incorporating various substitution mechanisms, becomes imperative. To the best of the writer's knowledge, no study has comprehensively combined the evaluation of individual substitution mechanisms for REEs in NdFeB magnets within the REE supply system with simulations over a long-term timespan. This research aims to fill this gap by providing an integrated assessment of individual substitution mechanisms and their performance within the broader REE supply system.

A combination of system dynamics (SD) and exploratory modelling and analysis (EMA) is chosen as the modelling methodology, as this modelling methodology allows for incorporating the complexity and uncertainty of the system into the model and simulation of the model. SD is tailored to model complex systems with time delays, accumulation, internal feedback loops and non-linear behaviour (Forrester, 1995). Many of these characteristics inherent to SD can be found in material supply chains. Inventory accumulation is a common occurrence, stakeholders influence material flow through information sharing, and modifying production capacity involves inherent time delays (Rebs et al., 2019). In order to cope with the deeply uncertain nature of the system, EMA will be used to offer decision-making support under deep uncertainty (Bankes, 1993). A combination of SD and EMA has been used in recent years in modelling material supply chains (Auping, 2018; Bradley, 2021; van der Linden, 2020; van Essen, 2022).

This research investigates the potential impact of substituting rare earth elements on the long-term supply of wind energy and electric cars. The focus on electric cars and wind turbines is deliberate, given their role in the broader energy transition and the interdependence between these clean energy technologies and NdFeB magnets. Currently, a significant fraction of electric cars and wind turbines use NdFeB magnets. While their current demand forms only a small part of the demand for NdFeB magnets, it is expected that electric cars and wind turbines will increasingly make up a more dominant portion of the global NdFeB demand (Hoenderdaal et al., 2013).

To comprehensively assess the implications of REE substitution, the study explicitly incorporates complexity and uncertainty. The model systematically addresses both structural and parametric uncertainties, deliberately introducing variations in parameters through multiple model runs. This approach enables a nuanced exploration of potential future scenarios.

The material supply chain model used in this study was originally developed for the Copper supply system by Auping (2011) and was further adapted and expanded by van der Linden (2020) to explore the Cobalt supply system. The model by van der Linden (2020) will be adapted to fit the REE supply system and will then be extended to include various substitution mechanisms. The chosen time period is until 2050, seeing as many sustainability policies share this time span. The geographical scope of this research is global, due to the global nature of the material supply chain and the energy transition. This leads to the following research question:

How can substitution of Rare Earth Elements (REEs) contribute to the global supply of wind energy and electric cars until 2050?

The following sub questions are formulated:

1. What is the structure of the global NdFeB supply system and how does this relate to the supply and substitution of REE in NdFeB magnets in wind energy and electric cars?
2. How may the supply system of REEs, wind energy and electric cars develop until 2050 and what variables may be influential in this development?
3. What effect can substitution of REEs have on the dependency of electric cars and wind turbines on REEs?

The sub-questions are designed to explore and highlight different aspects of the main research question. Sub-question 1 aims to provide a better understanding of the system at hand. The important components and their interactions are captured into a model. Then, the model will be simulated and the results of these simulations are used to answer sub-questions 2 and 3. Sub-question 2 focuses on exploring the overall system behaviour, while Sub-question 3 looks specifically at how different substitution methods behave.

The remainder of this research is built up in the following manner: In chapter 2, the research methods are outlined, providing background information on the modelling methods, a more in-depth explanation of the research methods used per sub-question and the data collection. Chapter 3 provides a comprehensive overview of the model, explaining its components and relationships. Chapter 4 presents the results. In chapter 5, the research methods are discussed and the results are interpreted in the broader context . Chapter 6 offers a conclusion, summarizing key findings and their implications.

2. Research methods

This chapter discusses the research methods employed in this study. Because this study is a model-based analysis, firstly the problem at hand is discussed and the choice for the main modelling methods is motivated. Secondly, a more in-depth explanation will be provided of how, when and where the research methods are used in this study. Lastly, the data sources are discussed. In order to build a model of the kind used in this research, it is necessary to gather data from various different sources, of which the most important will be discussed in the last section of this chapter.

2.1. Motivation and explanation of research methods

Assessing long-term resource availability is a grand societal challenge that is characterized by dynamic complexity and deep uncertainty (Kwakkel & Pruyt, 2015). Therefore, a modelling method is used that can cope with the characteristics of these types of systems. Exploratory System Dynamics Modelling and Analysis (ESDMA) is used as the modelling and simulation method to cope with the dynamic complexity and deep uncertainty. A combination of these modelling methodologies has been used by other researchers that have conducted similar studies (Auping, 2018; Bradley, 2021; van der Linden, 2020; van Essen, 2022).

2.1.1. System Dynamics

The SD methodology, developed by Forrester (1961) is a method for analysing complex systems over time. The key objectives of SD studies revolve around explaining the behaviour of the system and proposing alternatives to achieve desired system behaviour (Saysel & Barlas, 2001). This structure encompasses not just the physical components, but also includes policies and traditions, both tangible and intangible, that play a vital role in the system's decision-making processes (Roberts, 1978). Consequently, SD models can be categorized as causal-descriptive (white-box) models (Choi et al., 2016). The validity of SD models relies heavily on the "internal structure" of the model rather than just the "outputs," which is the primary focus of correlational (black-box) models (Barlas, 1996).

Feedback effects, accumulation, and delays are all essential characteristics of problems suitable for modelling using the SD methodology (Auping, 2018), and are all present in the REE supply system. Stocks within the system allow for the accumulation of critical states, such as production capacity or resources. The combination of stock and flows may add delays to the system. For example, it takes time to adjust production capacity to the desired level. Furthermore, feedback mechanisms often play a central role in the application of SD. For instance, there is a balancing feedback mechanism between the price of resources and their demand. When the demand for a resource increases, the price increases too. However, when the price increases, its demand is reduced, resulting in a balanced feedback mechanism.

The mental simulation of problems that are characterised by accumulation, delay and feedback is rendered virtually impossible (Sterman, 1994). Therefore, conceptual system models can be translated into numerical SD models to gain a deeper understanding of nonlinear behaviour over time within a defined system (Hatayama et al., 2007; Kleijn et al., 2000; Matsuno et al., 2012).

In essence, SD models can be understood as a collection of integral equations that are numerically solved (Auping, 2018). SD models fundamentally consist of four main components: stocks, flows, constants, and auxiliary variables. Figure 1 presents a small stock-flow structure from the model that incorporates all four elements. The stock *Wind capacity in use* increases through incoming flow *Production of wind capacity* and decreases through outgoing flow *Wind capacity to be destructed*. *Initial wind capacity in use* and *Average lifetime of wind turbines* are constants, meaning that their value does not change throughout the simulation of the model. *Annual newly installed wind capacity* is an auxiliary variable, which is a variable that does change throughout the simulation, in this case because it is modelled as an external input scenario.

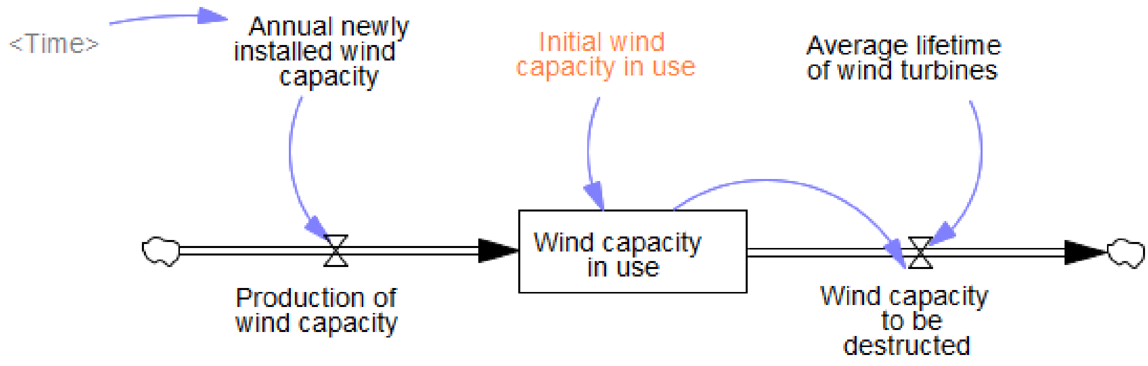

Figure 1: An example of a stock-flow structure from the model used in this research. The variable in orange denotes the initial value of the stock.

In this research SD is employed as the main modelling method, because of its ability to address the presence of dynamic complexity in these systems (Lane, 2010). Moreover, because of its stock-flow structure, SD is suitable to model material supply chains. It has therefore proven to be popular in modelling of the production and depletion of resources in general (Chi et al., 2009; Kwakkel & Pruyt, 2015; Meadows et al., 1972) and metals more specifically (Choi et al., 2016; Kifle et al., 2013; Sverdrup et al., 2019; Van Vuuren et al., 1999).

2.1.2. Exploratory Modelling and Analysis

In the realm of modelling research, there is a common practice among modelers to aim for a single, 'best' model by combining existing knowledge (Auping, 2018). As the famous saying goes, "All models are wrong, but some models are useful" (Box, 1979), most modelers will agree that there is not a single model that can be developed and used to perfectly resemble reality. However, when reflecting on deeply uncertain issues, one could argue that it is almost impossible to develop a single model that adequately represents the system (Bankes, 1993). That is why it is important to use a research methodology that is specifically designed for exploratory analysis by explicitly incorporating deep uncertainty into every step of the research process.

Exploratory Modelling and Analysis (EMA) is a research approach that is designed to explore deeply uncertain issues by conducting computational experiments (Bankes, 1993; Lempert, 2003). EMA involves exploring an ensemble of plausible quantitative simulation models, along with their associated uncertainties, through a large number of computational experiments (Bankes, 1993). Each individual model run serves as a computational experiment that shows how the world might behave if the assumptions about uncertainties in that particular model were to resemble reality. These computational experiments are carried out on a ensemble of models, systematically adjusting uncertain variables, resulting in a vast output space of data.

2.1.3. Exploratory System Dynamics Modelling and Analysis

Besides the aforementioned advantages of employing these research methods for the problem at hand, the combination of SD and EMA offers two more advantages. SD models typically have short simulation times, allowing modelers to conduct the high number of computational experiments that are required for EMA relatively quickly. Additionally, SD allows for a relatively easy incorporation of structural uncertainties into the model. These structural uncertainties can significantly alter the model's structure and can be seen as a way of creating a diverse ensemble of different models (Auping, 2018).

2.2. Implementation of research method

This section delves deeper into how the research methods are implemented in this research. The research methods are discussed per research question. Research question 1 is discussed in chapter *3 Model overview*, and research questions 2 and 3 are discussed in chapter *4 Results.*

1. What is the structure of the global NdFeB supply system and how does this relate to the supply and substitution of REE in NdFeB magnets in wind energy and electric cars?

To establish the system's structure, firstly a mental model of the system is created by conducting an extensive literature search, which is subsequently translated into a conceptual model. The process of model building is executed using Vensim software, a software designed to create SD models (System, 2010). This phase can be delineated into two distinct components: (1) the adaptation of the existing model to align with the REE supply system and (2) the extension of the model to incorporate substitution mechanisms.

The structure of the model is based on the Cobalt model by van der Linden (2020). Therefore, parts of the supply system of Cobalt that are relevant for the supply system of REEs are firstly adapted. The only novel element introduced to the model, considered an adaptation specific to the REE supply system, pertains to the incorporation of disturbances. The 2010 Rare Earth crisis has shown that disturbances in the REE supply system are plausible. As such, these disturbances are integrated into the model as a structural uncertainty.

In order to gain a more profound comprehension of substitution of REEs, the model is extended to include various substitution mechanisms.

2. What behaviour may the supply system of NdFeB magnets, wind energy and electric cars exhibit until 2050?

The primary objective is to encompass the entire spectrum of potential outcomes, thus the model is simulated using open exploration. This involves running a large number of experiments while sampling over the uncertainties (Kwakkel, 2017). The model is simulated using the EMA workbench package in Python (Kwakkel, 2017).

Within the scope of this research question, the focus is on the development and interaction of three performance metrics over time: the supply of electric cars, wind turbines and REE. We are interested in two things: analysing their behaviour over time, and finding out what the cause is of that behaviour.

The behaviour of these metrics over time is analysed by creating graphs that display the runs of these metrics over time. To facilitate the comparisons between the behaviour of REE supply and that of electric cars and wind turbines, the supply of the latter are characterised into low, medium and high quantities. Consequently, when illustrating the REE supply, these runs are grouped based on the supply levels of electric cars and wind turbines, revealing the interplay between REEs and these technologies.

To execute this clustering, firstly the distances are calculated using Complexity-Invariant Distance as the similarity metric (Batista et al., 2014). This similarity metric is chosen because of its application in other research on dynamically complex systems (Steinmann et al., 2020; van der Linden, 2020), and its implementation in the EMA workbench package. Subsequently, the runs are clustered using agglomerative clustering.

Then, in order to understand what the main causes are for the observed behaviour of these metrics, the variables responsible for the behaviour of the performance metrics are analysed. In order to so, a global sensitivity analysis is conducted. We are interested in the dynamics over time, so time series clustering is used (Kwakkel et al., 2013). Afterwards, a global sensitivity analysis is conducted using Extra Trees Feature Scoring. This method for sensitivity analysis is the preferred option, because of the significantly higher computational costs of alternative methods (Jaxa-Rozen & Kwakkel, 2018).

3. What effect can substitution of REEs have on the dependency of electric cars and wind turbines on REEs?

The research methods used for answering this sub-question are very similar to those used in sub-question 2. The behaviour of individual substitution mechanisms is of interest, and their behaviour will also be displayed in graphs over time. In some cases, structural uncertainties may play a significant role in the behaviour of the substitution mechanisms. Therefore, in these cases the runs are grouped on these structural uncertainties.

2.3. Data

During the model building phase a combination of qualitative and quantitative data sources were employed. Qualitative data was instrumental in delineating the structure of the NdFeB supply system, uncovering the intricate interplay between the supply system of REEs and the production of electric cars and wind turbines, and formulating the conceptual model.

Subsequently, when constructing the model itself, model variables were anchored in scientific literature whenever possible. This was drawn upon a diverse array of both qualitative and quantitative data sources. Given that the Cobalt model by van der Linden (2020) is used as a basis, those variables in the REE supply system that were analogous to those in the Cobalt supply system were left unchanged.

It is important to distinguish between data used for variables that remain constant and data used for variables that require input scenarios. A large share of the constant variables pertained to initial values of stocks. Among these, the most important were the initial values of metal stocks, primarily derived from Liu et al. (2022). When modelling the substitution dynamics among different types of cars and wind turbines, qualitative ordinal data was incorporated from Pavel, Lacal-Arántegui, et al. (2017) and Pavel, Thiel, et al. (2017). These sources employed a qualitative approach to assess the potential for NdFeB magnet substitution in electric cars and wind turbines. To model the intrinsic demand for applications beyond electric cars and wind turbines, annual growth rates from Hoenderdaal et al. (2013) were used.

In the case of modelling the intrinsic demand for electric cars and wind turbines, employed scenario-based data was used. The scenarios for electric cars' intrinsic demand used from van der Linden (2020) and BNEF (2019), while the demand scenarios for wind energy were derived from the Global Wind Energy Council (GWEC, 2016).

3. Model overview

This chapter outlines the conceptualisation and development of the model. The model presented here is a modified and extended version of other SD models focused on material supply systems (Auping, 2011; Bradley, 2021; van der Linden, 2020; van Essen, 2022). In particular, the model developed by van der Linden (2020) serves as the primary foundation for this research and shares the closest resemblance to the model utilised here.

Section 3.1 provides a conceptual overview of the model. In Section 3.2, the adaptations made to align the model with the REE supply system are described. Section 3.3 delves into the extension of the model to incorporate substitution mechanisms. The validity of the model is discussed in Section 3.4. Lastly, Section 3.5 presents the experimental setup employed in this study.

3.1. Conceptual overview

Figure 2 presents a conceptual overview of the system, illustrating the relationships between different sub-systems. To provide a high-level overview of these sub-systems and their interconnections, a Sub-System Diagram (SSD) is utilised, as it is well-suited for this purpose (Morecroft, 1982). The rectangles with rounded corners represent sub-systems. The red sub-systems were already present in the model by van der Linden (2020) and have been adapted to fit to the REE supply system, blue sub-systems are extensions to the model. The factors in italics denote external variables, those being disturbances and scenarios that influence demand.

In the work by van der Linden (2020), only the demand and production capacity of metals was implemented in the model. However, given the focus of this research on the interaction between REEs, wind turbines, and electric cars, sub-systems modelling the demand and production capacity of electric cars and wind turbines have also been included in this model. Additionally, three disturbances have been incorporated into the model to examine the effects of substitution on sudden changes in system behaviour.

The model by van der Linden (2020) comprises of four main sub-systems: price, primary production, demand and a supply chain (named stocks in figure 2). Price is a central factor in this model, either influencing or being influenced by all sub-models. Legal primary production is influenced by the price differently compared to illegal production. Illegal primary production can scale up and down much quicker, and is therefore directly dependent on the current metal prices. Changes in the legal primary production capacity of REEs take place with a delay and are influenced by changes in demand over a longer period of time. Metal demand is influenced by the metal price, the demand for electric cars and wind turbines, and the intrinsic demand for other products using NdFeB magnets that are modelled through exogenous scenarios.

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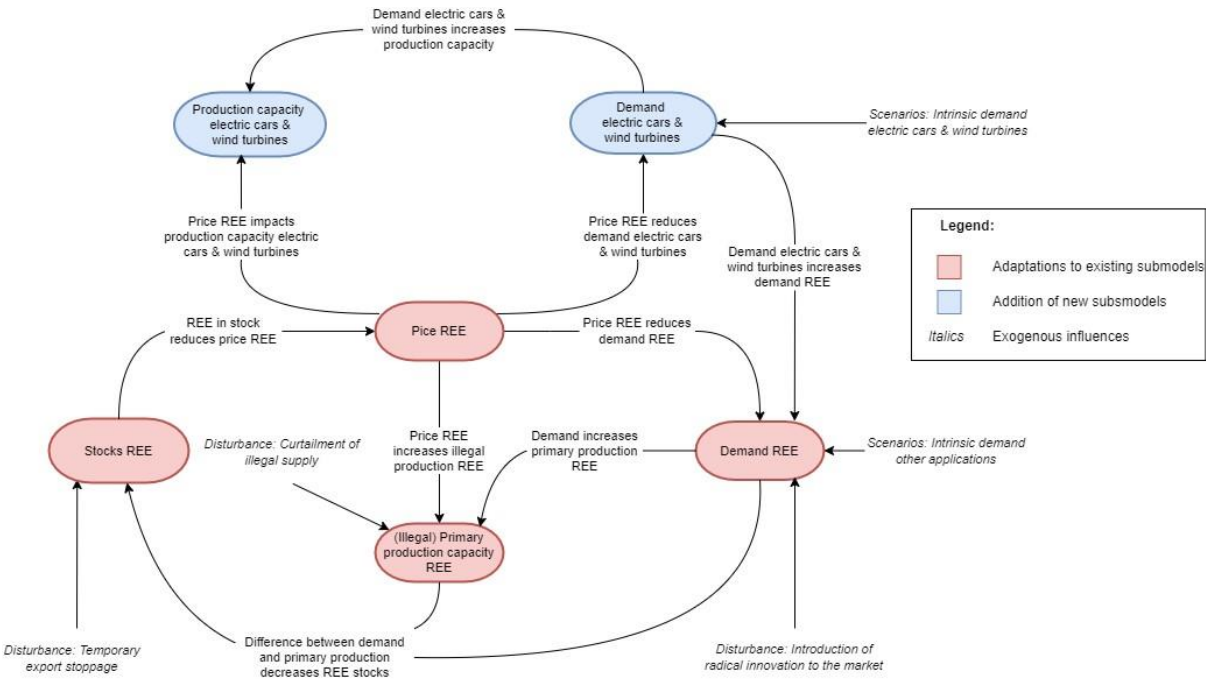

Figure 2: The sub-system diagram shows the interaction between individual sub-systems of the model. Rectangles with rounded corners represent sub-systems and factors in italics denote exogenous influences. The sub-systems in red were already present in the model by Van der Linden (2020), sub-systems in blue have been added to this model.

Production capacity of electric cars and wind turbines are influenced by REE prices, but not in the same way that the primary production capacity of REEs is. Demand for electric cars and wind turbines will lower when prices of REEs increase, resulting in an overall decrease of production capacity of electric cars and wind turbines. A large fraction of electric cars and wind turbines are currently manufactured with REEs, but alternatives exist that do not use REEs. Therefore, when REE prices increase, the production capacity of wind turbines and electric cars using REEs will decrease, but the production capacity of alternatives using less or no REE will increase.

Given that the research focuses on modelling the dynamics of REE substitution in electric cars and wind turbines, other factors typically deemed influential in the REE supply system are modelled as exogenous influences rather than being incorporate in the model endogenously. For instance, there is no geographical disaggregation, meaning distinctions based on geographical location are not made for factors such as inventory and raw material prices. However, recognizing the significance of some of these factors in the REE supply system, they are included as exogenous variables. For instance, even though strategic behaviour by China is not modelled endogenously, it is accounted for as an exogenous influence in the *Temporary Export Stoppage* disturbance.

3.2. Model overview: Adaptation to the REE supply system

The structure of production capacity, demand and supply of REEs remains largely unchanged from the work by van der Linden (2020), and therefore will not be extensively elaborated upon. However, REEs are mined from different minerals, so the choice of aggregation level regarding mineral types will be discussed. Furthermore, aspects related to illegal mining capacity, demand and price that are specific to REEs will be discussed.

3.2.1. Mineral types

REEs are found in over 100 different types of minerals, but only bastnaesite, monazite, loparite and ion-adsorbed clays have been successfully processed (Eggert et al., 2016). The three largest REE deposits, Bayan Obo and Maoniuping in China, and Mountain Pass in the USA, mainly mine bastnaesite (Eggert et al., 2016). Bastnaesite, monazite, and loparite are naturally enriched in LREE and have relatively low levels of HREE (Eggert et al., 2016).

On the other hand, ion-adsorption clays are notably enriched in HREE (Li & Yang, 2016; Voncken, 2016). These clays serve as the primary source of HREE globally (Kynicky et al., 2012). Due to their easy extraction process, illegal mining activities are predominantly focused on ion-adsorption clays (Nguyen & Imholte, 2016; Zhou et al., 2017).

In this study, the deposit types are categorized into two main groups: (1) Minerals and (2) Ion-adsorption clays. Limited research has been conducted beyond China regarding the processing of REE minerals between 1980 and 2010 (Marx et al., 2018). Consequently, there is a scarcity of information regarding the economic viability differences among various deposit types. Due to the lack of information concerning the economic viability of different mineral deposit types, and to simplify the modelling process, mining of other minerals outside of ion-adsorption clays will not be differentiated.

3.2.2. Illegal mining capacity

The majority of illegal mining takes place in two provinces of Southern China, where ion-adsorption clay is found (Nguyen & Imholte, 2016). Approximately 20% of China's total production is estimated to come from illegal mining operations (Zhou et al., 2017), accounting for approximately 60% of the total mined HREEs (Nguyen & Imholte, 2016). The ion-adsorption clay deposits are the cheapest and most accessible source of HREE worldwide (Packey & Kingsnorth, 2016). Therefore, in this research only illegal mining of ion-adsorption clay is included in the model.

The growth of illegal mining depends on the minimum price of REEs for which illegal miners are willing to work and the potential for growth of illegal mining, as is shown in figure 3. A maximum illegal mining capacity is assumed of twice the illegal mining capacity of 2007, to avoid illegal mining becoming too exposed (Nguyen & Imholte, 2016). Moreover, illegal production is also capped at 40% of total primary production.

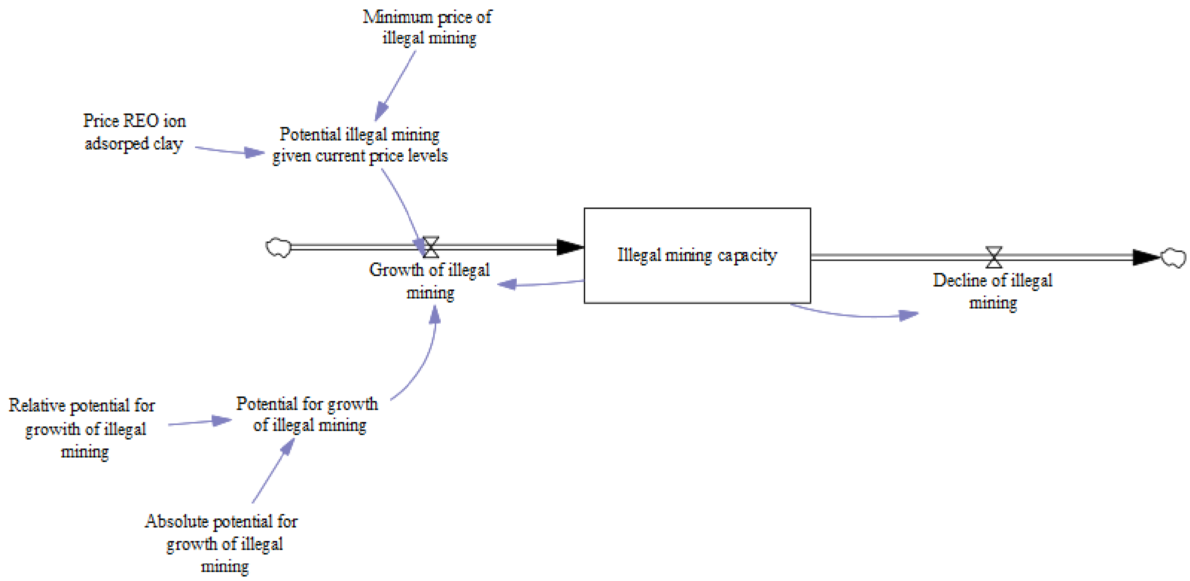

Figure 3: The model overview of illegal mining capacity

3.2.3. Demand

Two approaches can be used to model demand: bottom-up and top-down. When anticipating significant changes and advancements in demand, a bottom-up approach is preferable to capture the complexity. On the other hand, top-down modelling can be based on GDP developments and/or annual growth rates (Auping, 2011; van der Linden, 2020).

NdFeB permanent magnets are used in electric cars, electric trucks, electric buses, wind turbines, computer hardware appliances, industrial motors, acoustic appliances and others (Hoenderdaal et al., 2013). The focus of this research is on modelling electric cars and wind turbines, so demand for these applications and alternatives for it will be modelled in more detail. For all other applications, including electric trucks and electric buses, demand will be modelled top-down, in a more simplified manner by multiplying last year's demand with annual growth rates from Hoenderdaal et al. (2013).

The intrinsic demand for electric cars and wind turbines is modelled through scenarios. For both applications, differences are made between which types of technologies are used. For wind turbines a distinction is made between on- and offshore, for electric cars a distinction is made between Battery electric vehicles (BEV), Plug-in hybrid electric vehicles (PHEV) and Hybrid electric vehicles (HEV). The two scenarios for electric cars, business-as-usual and energy transition, are developed by Bradley (2021). The energy transition scenario is based on BNEF (2019) and van der Linden (2020) and the business-as-usual scenario is based on the Reference Technology Scenario by Abergel et al. (2017). The wind energy scenarios are developed by the Global Wind Energy Council (GWEC, 2016). They have four scenarios with an increasing order of wind capacity: New Policies scenario, 450 scenario, Moderate scenario, and Advanced scenario.

3.2.4. Price

The pricing of REEs is influenced by several variables, with some contributing to a relatively stable portion of the price, while others introduce fluctuations. The stable part of the REE price is determined by factors such as marginal cost, profit margin, and the individual REE content per rare earth oxide

(REO). On the other hand, price fluctuations are influenced by factors such as stock levels, demand elasticity, and the disparity between production and demand, as is shown in figure 4.

The marginal costs of REEs encompass expenses related to mining, concentration, separation, and transportation (Sykes, 2013). Subsequently, the combined sum of these factors is multiplied by resource tax and value-added tax (VAT) (Nguyen & Imholte, 2016; WTO, 2014). In contrast to many other metals, mining costs constitute only a small fraction of the overall production cost of REEs. This is primarily due to the significant costs associated with concentrating the REO and separating them into individual REEs, which account for more than 90% of the production costs (Sykes, 2013).

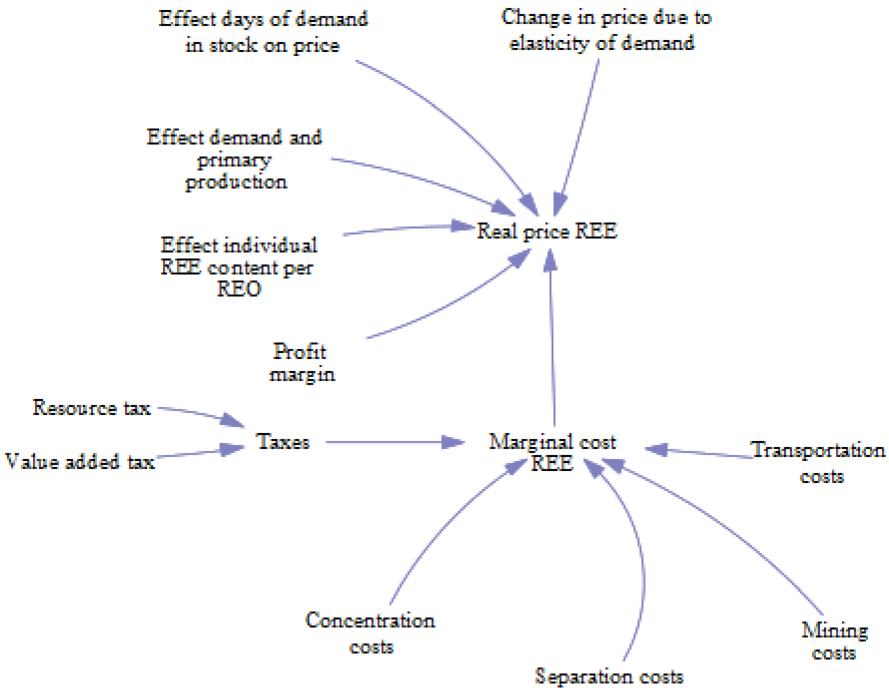

Figure 4: Computation of price in the model

3.2.5. Disturbances

The 2010 Rare Earth crisis has showcased that the REE supply system can be subject to major disturbances, and seeing as the model is simulated until 2050, the occurrence of another disturbance is deemed plausible.

While it is impossible to include every potential disturbance, a deliberate selection of disturbances is made that exert varying impacts on the system. Three types of disturbances are included in this research: one affecting the demand side and two affecting the supply side. Furthermore, a distinction is made between short-term disturbances and permanent changes to the system, and the timing of each disturbance's entry into the system varies. The entry into the system of disturbances takes place between 2025 and 2030, because this leaves enough time to analyse the effect over time.

Demand side disturbance

Radical innovation. The growth of consumer electronics has played a significant role in driving the demand for NdFeB permanent magnets over the past 25 years (Shaw & Constantinides, 2012).

However, the introduction of a radically new product utilising NdFeB magnets with widespread market adoption has the potential to create a disruptive shift in demand. To capture this rapid and significant demand disturbance, the model incorporates the arrival of a new type of digital product set to enter the market in 2025. By 2030, this product is expected to reach demand levels comparable to all other products using NdFeB besides electric cars and wind turbines.

Supply side disturbances

NdFeB magnets commonly utilise a combination of both LREEs and HREEs (Smith et al., 2022). While the majority of LREEs are sourced legally, a significant portion of HREEs is derived from illegal mining activities (Packey & Kingsnorth, 2016). Consequently, the model includes one focussed on the production of LREEs and another that affects HREE production more heavily. Riddle et al. (2021) modelled supply disruptions in the global REE market. Two of the disturbances in their study will be used in this research:

Temporary export stoppage. The first supply disturbance is a temporary one-year export stoppage of NdFeB magnets from China in 2030, resulting from an international trade conflict. The 2010 Rare Earth Crisis serves as a reminder of how seemingly unrelated geopolitical disputes can significantly impact the supply of REEs. Currently, China holds a dominant market share of approximately 90% in NdFeB magnet production (Smith et al., 2022). In this study, it is assumed that China's market share will decrease to 80% by 2030. The underlying assumption is that, like the global trend in reduction of China's dominance in REE production, the rest of the world will, for geopolitical reasons, aim to reduce China's predominant position in NdFeB production. Despite this intention, given China's extensive experience in this sector, the study settles on an 80% market share. The disturbance is modelled by reducing the production of end-use magnets by 80%, reflecting the disruption caused by the export stoppage during that period.

Permanent curtailment of illegal production. The second supply disturbance is an 80% curtailment of illegal mining. This disturbance will be implemented from 2027 without an end date. The ion-adsorption clay deposits form a large source of HREE, so modelling this disturbance will offer more insight into the dependence on HREE dominant suppliers.

3.3. Model overview: Extension of substitution methods

In this section the extension of the model of substitution mechanisms is described. It commences by providing an overview of the various substitution mechanisms relevant for REE in electric cars and wind turbines. Subsequently, the individual substitution mechanisms will be covered in more detail, along with their implementation into the model.

3.3.1. Overview of types of substitution

In related research, it is commonly acknowledged that multiple forms of substitution exist, but many studies tend to narrow their focus to a single form of substitution (Elshkaki & Graedel, 2013; Graedel et al., 2015).On the other hand, some research makes a distinction between direct material substitution, where one element is replaced with another, and technological substitution, where components are redesigned to reduce or even eliminate the need for these materials (Sprecher et al., 2015). However, substitution can take place in many different forms (Pavel, Lacal-Arántegui, et al., 2017), but is often defined differently (Smith & Eggert, 2018). This underscores the importance of establishing a clear terminology framework for this research.

In this research, the overview of substitution types presented by Smith and Eggert (2016) is used as a basis, because it provides a very detailed overview of different types of substitution. Tilton (1984) and Schlabach (1984) conducted research on substitution of tin and came up with a comprehensive examination, comprising of five forms of substitution. Building upon their work, Smith and Eggert (2016) adapted these forms of substitution to be applicable to the substitution of REEs in NdFeB magnets in the wind industry. This overview is further adapted to the scope of this research and expanded to fit the scope of this research and to provide a more comprehensive overview. The forms of substitution are listed in table 1 below.

Table 1: Different forms of substitution of REEs in NdFeB magnets, based on Schlabach (1984), Tilton (1984) and Smith and Eggert (2016).

Forms of substitution	**Definition**	**Example**	**Implemented in the model**
Element-for-element	Substitute one element for another without fundamentally changing the properties of the magnets	Substitute Dysprosium for Terbium	Yes
Process-for-element	Decrease the use of one or more elements by using an alternative manufacturing method to create a magnet with comparable characteristics	Use grain boundary modification instead of powder metallurgy to produce an NdFeB magnet of the same grade	Yes
Grade-for-grade	The ability to substitute for a magnet with a different grade	Use a magnet that is less resistant to temperature	No
Magnet-for-magnet	Employ a different sort of magnet	Employ a SmCo magnet instead of an NdFeB magnet	Yes
Component-for-component	Employ a different component in the end-product	Switch from a wind turbine with a direct-drive generator to generator with a gearbox	Yes
System-for-system	The ability to switch to another system	Switch from wind to solar energy	No

This overview differs from Smith and Eggert (2016) in two aspects. Firstly, we introduce “Component-for-component” substitution as a distinct form, also referred to as technological substitution (Sprecher et al., 2015) and component substitution (Pavel, Lacal-Arántegui, et al., 2017). In Smith and Eggert (2016) definition, “System-for-system” substitution encompasses both the ability to switch to a different component in the end-product as well as the ability to switch to another system altogether. However, for the sake of clarity and comprehensiveness, we separate this form of substitution into “Component-for-component” and “System-for-system” substitution.

Secondly, the substitution type “Process-for-element” in this research is labelled “Technology-for-element” in Smith and Eggert (2016). In Smith and Eggert (2018), this substitution type was renamed to “Process-for-element”, possibly due to its similarity in name to “Technological substitution” in other research (Sprecher et al., 2015). In this research, the term “Process-for-element” is also preferred, to prevent any confusion.

In figure 5 the forms of substitution are presented in a schematic way. This figure serves a dual purpose: it provides context by illustrating where individual forms of substitution occur in the production process, and it offers a detailed overview of the individual substitute products for each form of substitution. For instance, under "Magnet-for-magnet substitution", there four different types of permanent magnets are listed, three of which are substitute products for NdFeB magnets. In sections 3.3.2-3.3.5, the individual forms of substitution and the substitute products are discussed in more detail. Therefore, readers can now use this figure to gain an initial understanding of where each form of substitution occurs, and it may also serve as a helpful reference later on, providing a visual perspective on the various substitute products associated with each form of substitution included in this model.

On the right side of the figure, the functionality of the products using NdFeB magnets is depicted in the orange cells, those being sustainable transportation for electric cars and sustainable energy generation for wind energy. Given the focus of this research on electric cars and wind turbines, the functions of other products that use NdFeB magnets, like acoustic appliances, are not further dissected. The further to the left, the smaller the product that is being substituted, ending in the substitution of single REEs. The top of the figure shows the stages at which various types of substitution occur. Not all substitution types are included in this research; those that that are included are shown in green, while those excluded are shown in blue.

Due to a lack of data and information, "Grade-for-grade" substitution is not included in this research. Although many wind turbine manufacturers used "Grade-for-grade" substitution during the 2010 Rare Earth crisis, there is a rich variety of different grades of NdFeB on the market, and predicting what grades are actually used under different scenarios is nearly impossible (Smith & Eggert, 2018). Moreover, "Process-for-element" and "Grade-for-grade" substitution are similar in the sense that both types substitute part of the REE content, the differences being that grade-for-grade substitution results in a decrease in functionality and is executed by end-users of magnets, whereas process-for-element does not lead to a reduced functionality and is done by magnet producers. Therefore, incorporating at least one form of substitution that changes the amount of REE in NdFeB magnets is deemed sufficient.

"System-for-system" substitution is also not included in this research, because it is deemed to be outside of the scope of this research. This research specifically focuses on how substitution of REEs can be beneficial for the implementation of electric cars and wind turbines, so substituting wind turbines and electric cars as a whole is deemed to be outside of the scope of this research. Moreover, other research with a similar research scope also did not include this type of substitution within their research (Pavel, Lacal-Arántegui, et al., 2017; Pavel, Thiel, et al., 2017; Smith & Eggert, 2016).

Therefore, this model incorporates four types of substitution: element-for-element, process-for-element, magnet-for-magnet, and component-for-component. The first two substitution methods can be carried out by magnet producers, while the latter can be implemented by producers who utilise magnets in their products. Magnet producers engage in agreements with end-users regarding product functionality and content, thus magnet content does not constantly fluctuate with current prices. Therefore, average medium periodic price levels are utilised in substitution.

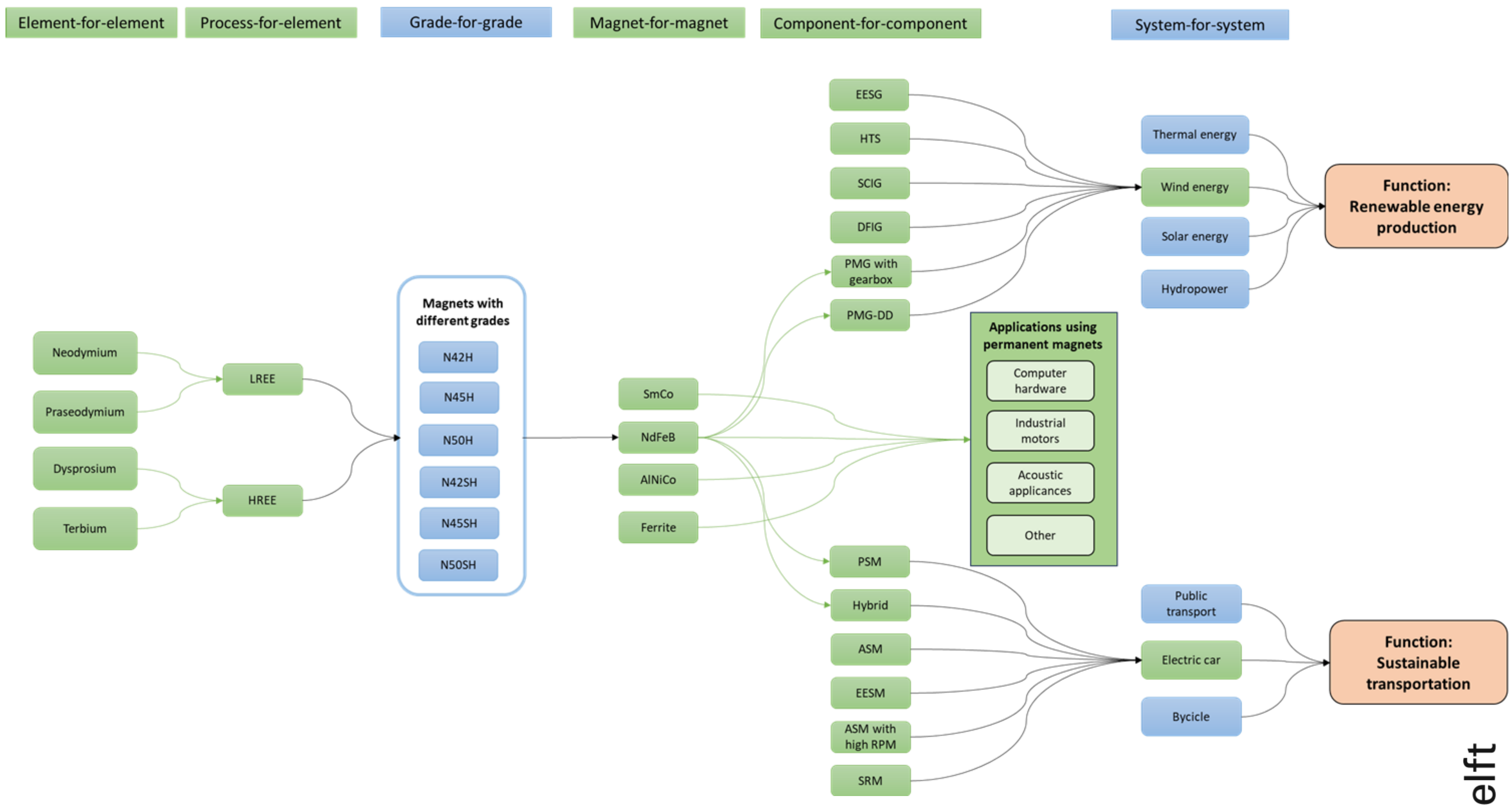

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Figure 5: Schematic overview of the dimensions of substitution. This overview is adapted from Smith and Eggert (2016). The top of the figure shows the different forms of substitution. The forms of substitution in green are included in this research, the cells in blue are excluded in this research.

3.3.2. Element-for-element

Element-for-element substitution is the ability of a magnet producer to substitute one element for another (Smith & Eggert, 2016). The ability to quickly implement element-for-element substitution is limited, because it changes the magnet's properties (Smith & Eggert, 2018). However, the distribution of individual elements can be tweaked depending on the price levels of the individual elements over a longer period of time. A NdFeB magnet consists of ±30% Neodymium and/or Praseodymium and 1-8% Dysprosium and/or Terbium (Pavel, Thiel, et al., 2017). NdFeB magnets can function with Neodymium as the only LREE, or with a 4:1 ratio of Neodymium:Praseodymium (Pavel, Thiel, et al., 2017). Dysprosium is fully interchangeable with Terbium, but Terbium is not considered to be a convenient substitute due to its steep price (Smith & Eggert, 2018).

As depicted in figure 6, element-for-element substitution affects the material composition of the magnet, in the model referred to as the *Allocation of relative content per element in NdFeB magnet*. In other words, this factor determines what fraction of substitutable LREE is allocated to Neodymium and Praseodymium, and what fraction of HREE is allocated to Terbium and Dysprosium.

The medium periodic prices of LREEs and HREEs are compared between elements that are substitutable of one another. For every element this results in a fraction that is between 0 and 1. If the prices of interchangeable elements is equal, this value will be 0.5. The higher the fraction, the more of this element will be allocated to the magnet. A lookup function in the shape of an S-function is used to allocate the relative content per element, and uses the aforementioned fraction as input.

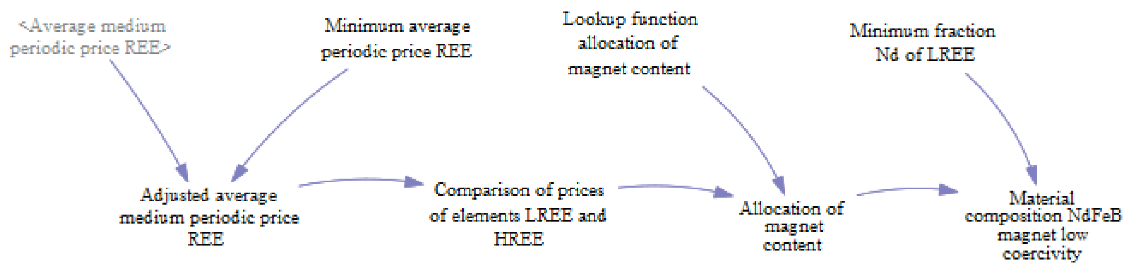

Figure 6: The implementation of element-for-element substitution in the model.

3.3.3. Process-for-element

Process-for-element substitution is concerned with in- or decreasing the content of LREE and HREE in NdFeB magnets (Smith & Eggert, 2016). This is depicted in figure 7 in the variable *LREE and HREE content NdFeB magnet low* coercivity. The REE content can vary, but NdFeB magnets must contain a certain minimum REE content. Current studies indicate that the amount of Neodymium and Praseodymium required to create NdFeB magnets with comparable properties may decrease in the near term (Pavel, Thiel, et al., 2017). The LREE content might decrease to 20% by 2030 (Lacal-Arántegui, 2015). Additionally, wind turbines have been modified to accommodate the use of NdFeB magnets containing only 1% of HREE (Smith & Eggert, 2018).

The REE content thus consists of a minimum content and an additional substitutable part. NdFeB magnets can be manufactured using a lower quantity of REEs, but this leads to additional production costs. As can be found in figure 7, in *Comparison costs high and low LREE and HREE content* the material costs of a maximum REE content are compared with the material costs of the minimum REE content plus the additional associated production costs. A lookup function is then used that takes the outcome of this variable and uses that as an input to allocate the current substitutable REE content.

In cases where elevated prices persist over a prolonged period, producers are motivated to develop more efficient processes, which may result in more sustainable reductions in production costs. In turn, this can lead to a more permanent shift in the quantity of REEs utilised in NdFeB magnets.

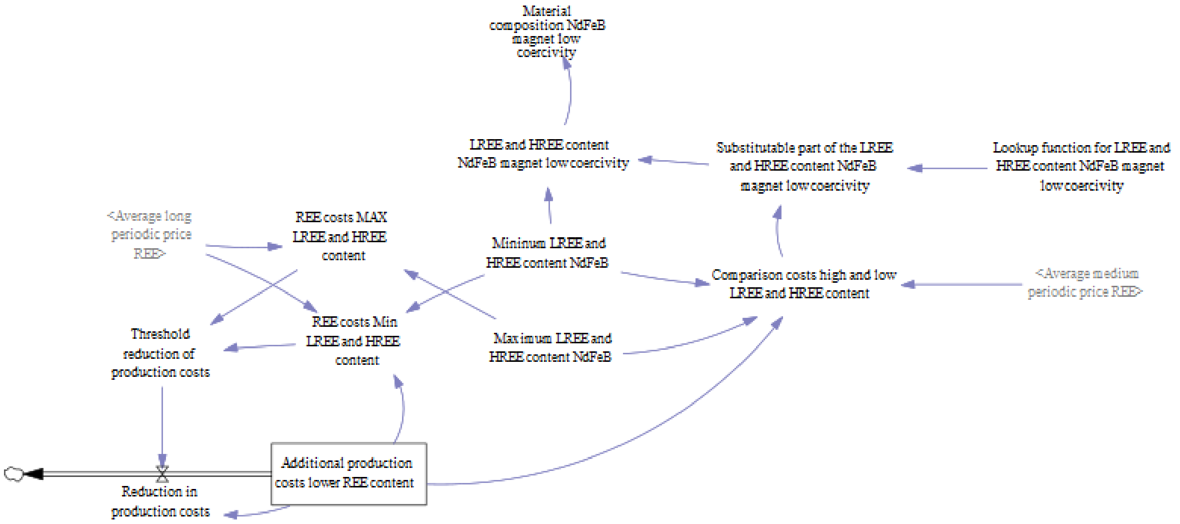

Figure 7: The implementation of process-for-element substitution in the model.

3.3.4. Magnet-for-magnet substitution

Magnet-for-magnet substitution pertains to the ability of producers of end-products to substitute NdFeB magnets for other type magnets (Smith & Eggert, 2016). The viability of magnet-for-magnet substitution depends heavily on its application. There are three other major permanent magnet types on the market; ferrite, aluminium-nickel-cobalt and samarium-cobalt (Eggert et al., 2016; Widmer et al., 2015). These substitutes have a lower energy-efficiency and often demagnetise at higher temperatures (Brumme, 2014; Widmer et al., 2015), making them unsuitable for products like wind turbines and electric cars (Pavel, Thiel, et al., 2017; Smith & Eggert, 2018). They can be used in other low-value applications when price levels of NdFeB are significantly elevated over a long period of time (ERECON, 2015).

As depicted in figure 8, magnet-for-magnet substitution is driven by a relation between the price of NdFeB magnets and a substitution threshold. Because alternative magnets are not used in wind turbines and electric cars, the prices and functionalities of alternative magnets is left out of the scope of this research. The substitution threshold is the product of the initial price of NdFeB magnets and a substitution factor that is higher than 1. When the average medium periodic prices of NdFeB magnets are elevated higher than the substitution threshold, substitution starts taking place. A similar structure is also put in place for applications that require a magnet with a higher coercivity. The substitution threshold for these applications is higher.

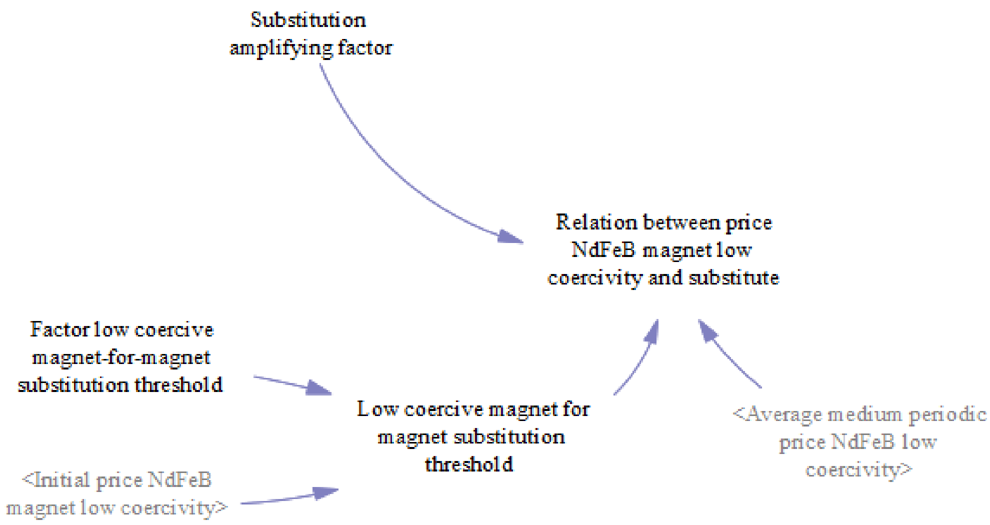

Figure 8: The drivers behind magnet-for-magnet substitution as implemented in the model.

3.3.5. Component-for-component substitution

Component-for-component substitution, as implemented in this research, refers to the ability of wind turbines and electric cars producers to switch to components that require a reduced amount of NdFeB or no NdFeB at all. Therefore, the supply of electric cars and wind turbines is disaggregated into various components. The supply of electric cars and wind turbines, as modelled in this research, depends on the production capacity, the demand, the availability of REEs (the amount in stock versus the demand) and the priority factor, as is shown in figure 9. First, the structure of the production capacity and supply will be explained. Subsequently, the function of the priority factor will be elucidated. Lastly, the different types of components in this research will be explained.

Structure of the production capacity and supply

The structure of the production capacity and supply is similar for electric cars and wind turbines. The structure is depicted in figure 9, where the term *energy technology* is employed to encompass both electric cars and wind turbines. The supply of wind turbines is disaggregated in on- and offshore wind, and for electric cars the supply is disaggregated in Battery electric vehicles (BEV), Plug-in hybrid electric vehicles (PHEV) and Hybrid electric vehicles (HEV). The supply of energy technologies is influenced by several factors, including demand, production capacity, a priority factor, and the availability of REEs. Energy technologies can be manufactured with various types of components, with some incorporating NdFeB magnets and others not. The priority factor determines the allocation of production quantities for each type of energy technology with a certain component.

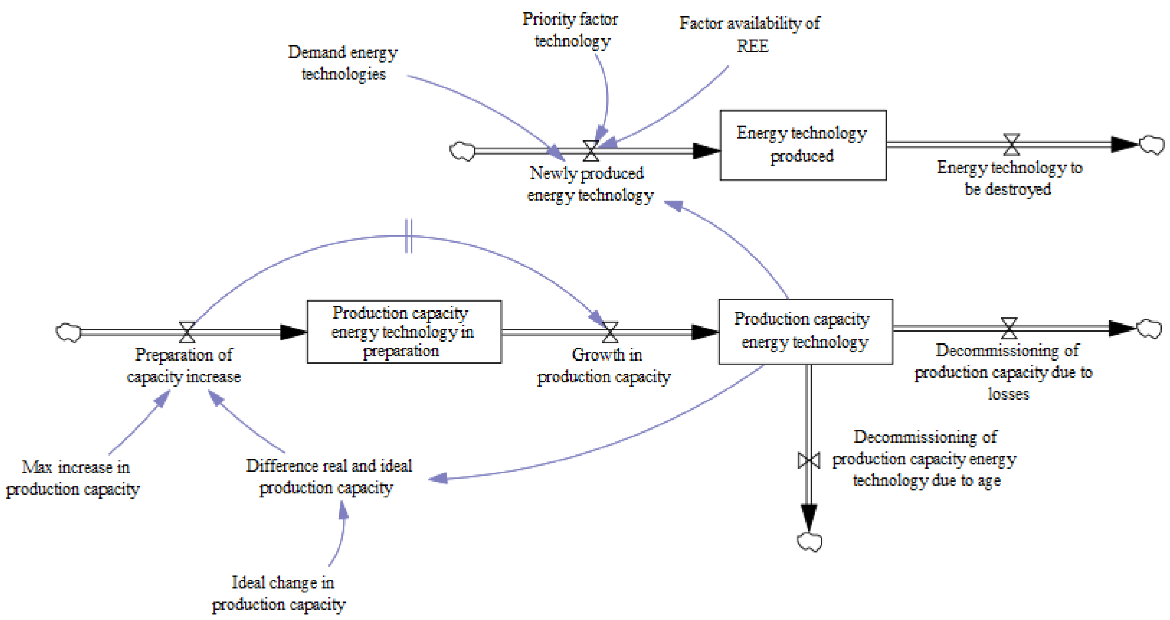

Figure 9: The supply structure of wind turbines and electric cars

Production capacity is lost due to age and also when there is a surplus of production capacity compared to demand. When there is a deficit, new production capacity can be realized under a procurement delay. The size and composition of production capacity is constantly monitored and evaluated against the ideal production capacity. The ideal production capacity is the ideal distribution of production capacity of different types of turbines and cars under current REE prices.

Therefore, when price levels change, the composition and size of production capacity must change in order to start producing optimally under current prices. However, there is a limit to how fast production capacity can scale up, which is modelled using the *Max increase in production capacity* variable. Scaling up and down between different types of cars or turbines can be achieved at a much faster pace.

Priority score

The decision to adopt substitutions is guided by the priority score, which reflects the desirability of selecting a specific component under current conditions. The priority score is influenced by various factors which differ slightly for electric cars and wind turbines, but share some similarities. These factors encompass technology readiness, as not all technologies are initially in full-scale production, and a factor representing economies of scale, which models the increasing dominance of a particular component when it remains preferable over an extended period. Cost considerations are also taken into account as an essential factor in the priority score calculation.

For electric cars a power density factor is also included. Metrics for assessing the performance of a motor for electric cars are: *construction space*, *power density*, *weight*, *production costs*, *cooling*, *reliability* and *noise* (Pavel, Thiel, et al., 2017). Seeing as performance per motor type is similar on *construction space*, *weight*, *cooling*, *noise*, *reliability* and *power density* (Pavel, Thiel, et al., 2017), in this study these factors are combined into a single factor *Power density*. For components that are still under development, the Technology readiness variable is zero at the beginning of the runtime and can grow to one in runs where the structural uncertainty allows it and if there are no suitable alternative components available. Figure 10 shows the variables that influence the priority factor for electric cars.

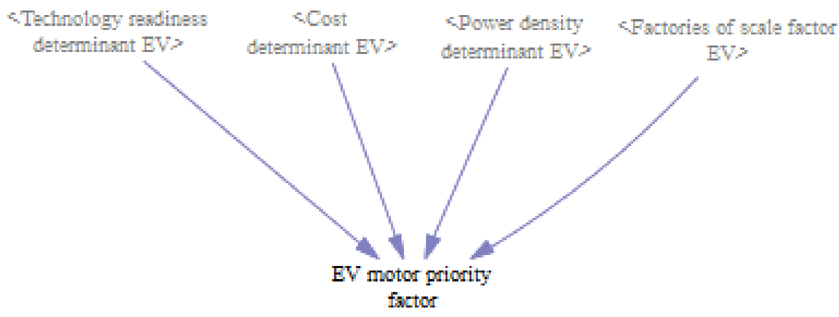

Figure 10: The factors influencing component-for-component substitution for electric cars.

In addition to the factors mentioned earlier, the priority score for wind turbines incorporates several other considerations, as can be seen in figure 11. One such factor is the nameplate capacity, which reflects the expected growth of wind turbines over time, as the efficiency of the technology is influenced by the turbine's size (Wiser & Bolinger, 2019). Furthermore, factors such as maintenance requirements, generator efficiency, and weight are crucial considerations in the selection of a specific generator type for wind turbines (Pavel, Lacal-Arántegui, et al., 2017).

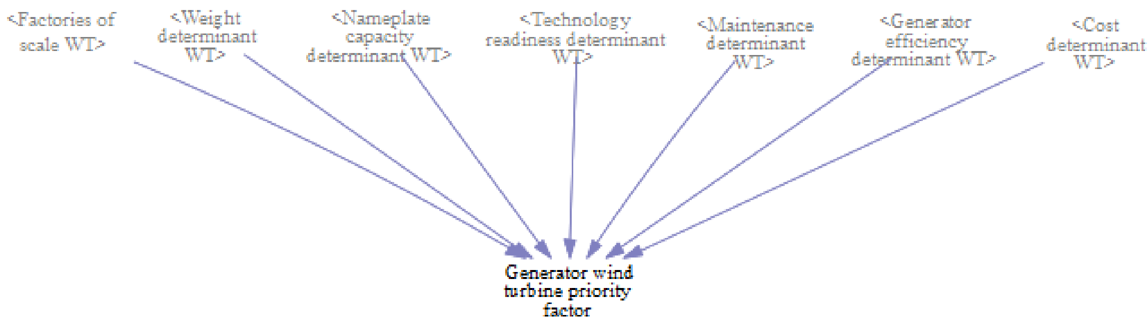

Figure 11: The factors influencing component-for-component substitution for wind turbines.

Overview of component types

Producers of both wind turbines and electric cars have the choice between six components, including one that fully relies on NdFeB magnets, one with a reduced amount of NdFeB, and four that are entirely free of NdFeB magnets. Table 1 provides an overview of these technologies, which shows the intensity of the usage of NdFeB magnets in these technologies and whether these technologies are already on the market or are still in research and development.

Table 2: This table provides an overview of the components used in modelling component-for-component substitution of electric cars and wind turbines in this research. For every type of component the usage of NdFeB is scored as being high, medium or not present, which is shown in the table as red, orange and green. Additionally, the market status is provided, which indicates if the component is on the market at the beginning of the runtime of the model.

Electric cars		**Wind turbines**	
Motor type	**NdFeB usage & Market status**	**Generator type**	**NdFeB usage & Market status**
PSM	Market	PMG-DD	Market
Hybrid	Market	PMG with gearbox	Market
ASM	Market	SCIG	Market
EESM	Market	EESG	Market
ASM with high RPM	R&D	DFIG	Market
SRM	R&D	HTS	R&D

■ High usage of NdFeB ■ Medium usage of NdFeB ■ No usage of NdFeB

For electric cars, generally the following types of motors are used: permanent synchronous motor (PSM), Hybrid, Asynchronous motor (ASM), Externally excited synchronous motors (EESM), Switched reluctance motors (SRM) and Asynchronous motor with high RPM (ASM high) (Månberger & Stenqvist, 2018; Pavel, Thiel, et al., 2017). Currently, the majority of electric cars use permanent magnets, either relying fully on NdFeB (PSM) or having a reduced amount of NdFeB (Hybrid) (Frieske et al., 2019). Permanent magnets allow a reduction in weight and volume, and operation at a higher efficiency at partial load. The use of permanent magnets is therefore especially beneficial for PHEV and HEV cars, because their electric engines are smaller and used to complement a conventional combustion engine (Månberger & Stenqvist, 2018). PM-free motor designs exist in the form of ASM and EESM (Månberger & Stenqvist, 2018). SRM and ASM high are motor prototypes showing potential for a high market penetration, but they are still in the R&D phase (Pavel, Thiel, et al., 2017).

For wind turbines, a mix of turbine designs is required to offer optimal performance under varying conditions. Generally, a distinction is made between the following turbine designs: Squirrel-cage induction generator (SCIG), doubly-fed induction generator (DFIG), Electrically-excited synchronous generator (EESG), Permanent magnet direct-drive (PMG-DD), permanent magnet with gearbox (PMG geared) and High-temperature superconductors (Barteková, 2016; Goudarzi & Zhu, 2012; Pavel, Lacal-Arántegui, et al., 2017). Most of these wind turbine types can be suitable for onshore turbines, but for offshore turbines it is essential to reduce maintenance costs and any downtime of production (Hart et al., 2014). Moreover, because offshore turbines are already much larger than their onshore counterparts, and because this difference is only expected to grow, the weight of the turbine must be minimised (Pavel, Lacal-Arántegui, et al., 2017). PMG-DD have a direct-drive drivetrain, thereby eliminating the use of a gearbox and significantly reducing maintenance costs and downtime of production, making them very suitable for offshore turbines. High-temperature superconductors show high potential for the development of turbines over 10 MW (Pavel, Lacal-Arántegui, et al., 2017). Therefore, HTS also shows great promise for offshore turbines, but only for very large that might be built in the near future.

Not all six technologies have reached technological maturity, and their market entry is uncertain. Therefore, they have been included as structural uncertainties, meaning that in some runs they are assumed to enter the market, while in others they are not. Specifically, for wind energy, the High-

Technology Superconductors technology, and for electric cars, the Asynchronous motors with high RPM and Switch reluctance motors are still under development (Pavel, Lacal-Arántegui, et al., 2017; Pavel, Thiel, et al., 2017).

3.4. Verification & validation

Verification and validation are essential processes for testing and enhancing the confidence in the usefulness of models. Verification focuses on confirming that the model is correctly coded and simulated, while validation aims to ensure that the model is suitable for its intended purpose (Sterman, 2002).

3.4.1. Verification

Multiple model verification tests as described by Senge and Forrester (1980) were conducted to ensure that the model is coded correctly. Debugging was conducted throughout the development stages, allowing for immediate testing of model adjustments to ensure that new elements produced the expected behaviour and were correctly coded. Additionally, indications provided by the modelling software like unit errors were considered to address any potential issues. Tests were conducted to determine the appropriate numeric integration and step size. To further enhance the verification process, the model was subjected to extensive testing under conditions of significant parametric and structural uncertainty, which helped to uncover and rectify any remaining coding flaws. In particular, extreme conditions tests in the form of disturbances were conducted to test if the model would still run under extreme conditions. This test enhances the confidence in the usefulness of a model by forcing the system to operate outside of expected regions of behaviour (Senge & Forrester, 1980).

3.4.2. Structural validation

Direct structure tests are used to evaluate if the model is based on accepted theories and that important variables are in the model (Senge & Forrester, 1980). To ensure a realistic representation of the REE supply system, the structure of the model is mainly based on scientific literature. For instance, the supply chain is almost similar to the structure of the supply chain Sprecher et al. (2015).

The purpose of this model is to analyse the specific issue at hand, and as a result, it provides varying levels of detail in modelling different aspects of the REE supply system. The primary production and demand for REEs are modelled with a relatively high level of detail. Additionally, due to the research's strong focus on the substitution of REEs in NdFeB magnets, electric cars, and wind turbines, the decision-making processes related to different types of electric cars and wind turbines are extensively modelled.

Conversely, other aspects, such as recycling and geopolitical influences, are addressed more broadly. Elements of the REE supply system that have received substantial attention, like the environmental pollution associated with primary REE production (Chen et al., 2005; Weng et al., 2013), have been deemed out of the scope of this research and have been deliberately omitted from the model.

Given the research's primary emphasis on substitution, certain factors that may not directly impact substitution, such as environmental pollution, are considered acceptable to be excluded from the model. Furthermore, this research asserts that the model adequately incorporates the dynamic complexity and uncertainty inherent in the REE supply system, providing a sound basis for assessing the potential and behaviour of REE substitution in NdFeB magnets.

3.4.3. Behavioural validation

Furthermore, to validate the behaviour of the model the model was subject to behavioural validation, where model outcomes are compared with future projections of other modelling attempts in the scientific literature. The runtime of the model starts in 2000 and runs until 2050. In order to assess if the dynamics occurring in the model outcomes are in anyway similar to real-world dynamics, it is deemed favourable if the model outcomes are in a similar range compared to projections made by related research, but it does not have to portray the exact same behaviour.

For comparison with related research, the demand for Neodymium is chosen as an indicator. Neodymium is the metal that is used most often in NdFeB magnets. Moreover, the demand for Neodymium is also leading in the development of new mining capacity. Projections of future demand for Neodymium has been done quite extensively in the scientific literature, so there is much comparison available.

As can be seen in figure 12, most of the projections from other research lie roughly in the same distribution as the runs from this research. However, generally, the outcomes from this research seem to be a bit lower than that of other research. This can most likely be attributed to the focus of substitution in this research, which may result into more demand being substituted. Given that the projections of Neodymium demand for this research fall within in a similar range as the projections or related research, this is deemed good enough for the purposes of this research.

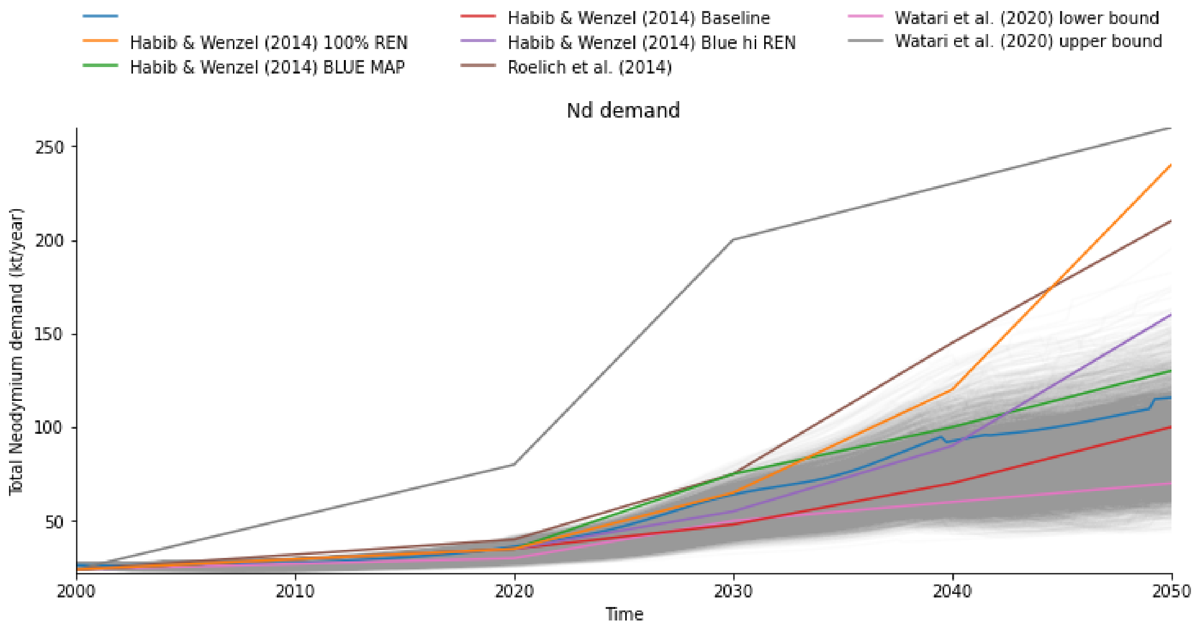

Figure 12: Comparison of the projections of future Neodymium demand from this research and related scientific research.

3.4.4. Fitness for purpose

The suitability of this model depends on the specific problem it is intended to address. Given its significant complexity and inherent uncertainty, this model is not appropriate for making precise predictions regarding future behaviour. Nevertheless, it can serve a valuable purpose in analysing dynamic and uncertain interactions within the system.

While this model lacks in-depth detail in certain areas of the REE supply system, it may not be well-suited for delivering a comprehensive analysis of the entire system. However, it is considered well-suited for its intended purpose due to its alignment with the REE supply system and its dedicated focus on the topic of substitution.

3.5. Experimental setup

The model is implemented in Vensim (version DSS 9.4.0), a software tailored for SD modelling, and parametrised for the NdFeB supply system. The model is simulated for 50 years between 2000 and 2050 with a time step of 0.0078125 years using the Euler integration method. The simulation runs until 2050, because many sustainability policies share this time span.

The model is simulated using the EMA workbench (version 2.1.1) in Python (version 3.9). In order to reduce computational complexity and to enhance interpretability of results, a selection of uncertainties is made that contain an uncertainty range. A total of 29 uncertainties are included of which 22 are parametric uncertainties and 7 are structural and/or scenario uncertainties. The uncertainty ranges of variables are displayed in table 3.

In order to still provide an uncertainty range to a larger number of variables, instead of individually varying each input for different demand growth rates, a single uncertainty factor is introduced that influences the collective of variables simultaneously. Latin hypercube sampling with uniform distribution is used to vary the input parameters. The model was simulated a total of 5,000 times. The model and the Python code can be found as online supplementary material on https://github.com/JonasBesselink/Thesis.

Table 3: Table of uncertainties

Variable name	Unit	Min	Max	Reference
Fraction extra production costs for a lower magnet content	Dollar/kg	0.2	0.5	Assumption[2]
Decay factor	Dimensionless	0.01	0.05	Assumption[2]
Uncertainty factor disassembly rate NdFeB	Dimensionless	0.7	1.3	Schulze and Buchert (2016)
Uncertainty factor marginal cost	Dimensionless (Dollar/kg)[1]	0.5	2	Sykes (2013)
Uncertainty factor demand growth rate	Dimensionless (1/Year)[1]	0.7	1.3	Hoenderdaal et al. (2013)
Uncertainty factor lifetime	Dimensionless (Year)[1]	0.7	1.3	Horvath (2006); Schulze and Buchert (2016)
Uncertainty factor weight NdFeB in application	Dimensionless (kg)[1]	0.7	1.3	Hart et al. (2014); Polinder et al. (2006); Watari et al. (2019)
Low coercive magnet-for-magnet substitution threshold	Dimensionless	1.5	3	Assumption
High coercive magnet-for-magnet substitution threshold	Dimensionless	2	4	Assumption
Uncertainty factor share offshore wind	Dimensionless	0.7	1.3	Assumption based on GWEC (2022)
Price elasticity short term	Dimensionless	0.02	0.08	van der Linden (2020)
Price elasticity long term	Dimensionless	0.1	0.2	van der Linden (2020)
Maximum increase production capacity	1/Year	0.1	0.2	van der Linden (2020)
Maximum decrease production capacity	1/Year	0.01	0.05	van der Linden (2020)
Proposed mine lifetime	Year	20	30	van der Linden (2020)
Smelter and refiner usage investment cap	Dimensionless	0.6	0.9	van der Linden (2020)
Minimum stock transit time	Year	0.05	0.3	van der Linden (2020)
Uncertainty factor change in production capacity	Dimensionless	0.7	1.3	Assumption[2]
Minimum price of illegal mining	Dollar/kg	1	4	Assumption based on price
Substitution amplifying factor	Dimensionless	0.7	1.3	van der Linden (2020)
Long term substitution strength	Dimensionless	0.05	0.2	van der Linden (2020)
Short term substitution strength	Dimensionless	0.1	0.3	van der Linden (2020)
Switch SSP	Dimensionless	1, 2, 3, 4 [3]		IIASA (2018)
Switch energy price growth scenario	Dimensionless	1, 2, 3 [3]		Auping et al. (2016)

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Switch technology readiness HTS	Dimensionless	0, 1 [3]	Pavel, Lacal-Arántegui, et al. (2017)
Switch technology readiness SRM	Dimensionless	0, 1 [3]	Pavel, Thiel, et al. (2017)
Switch technology readiness ASM high	Dimensionless	0, 1 [3]	Pavel, Thiel, et al. (2017)
Switch annual newly installed wind capacity	Dimensionless	1, 2, 3, 4 [3]	GWEC (2022)
Switch vehicle scenario	Dimensionless	0, 1 [3]	BNEF (2019)
Switch disturbance	Dimensionless	0,1,2,3[3]	Riddle et al. (2021)

[1] To reduce computational complexity, uncertainty factors are employed to simultaneously vary input parameters for multiple variables. The range of uncertainty is determined by the modeller, and the values of the variables being varied are obtained from various sources, as indicated in the referenced table. The units specified in brackets correspond to the units to which the uncertainty factors are applied.
[2] These assumptions are based on analysis conducted by the modeler.
[3] These are categorical variables, meaning they are assigned one of the following numbers.

4. Results

In this chapter, the behaviour of the model is analysed, and the impact of substitution on the future implementation of wind energy and electric cars is examined. First, the supply of electric cars, wind turbines and REEs over time is analysed, as well as what variables are the most influential on the development. Next, the effect of individual substitution mechanisms on the supply of electric cars and wind turbines is analysed. Overall, this chapter provides a comprehensive analysis of the model's behaviour and investigates the implications of substitution on the future implementation of wind energy and electric cars.

4.1. Development of the supply system

In order to assess the development of electric cars, wind turbines and REEs over time, the runs are clustered into low, medium, and high ranges, as depicted in figures 13, 15, 17 and 18. On the right side of the figures, a density plot is portrayed which shows the density of the clusters at the end of the run time.

The total electric cars in use, depicted in figure 13, shows exponential behaviour over time, with a wide range of possible outcomes. It shows a large gap in the middle, which can most likely be attributed to the differences in intrinsic demand scenarios. The demand for electric cars is influenced by the REE price levels and the intrinsic demand scenarios. The difference between certain scenarios of intrinsic demand is most likely so large between 2020 and 2045 that differences in price levels do not cause a more distributed demand.

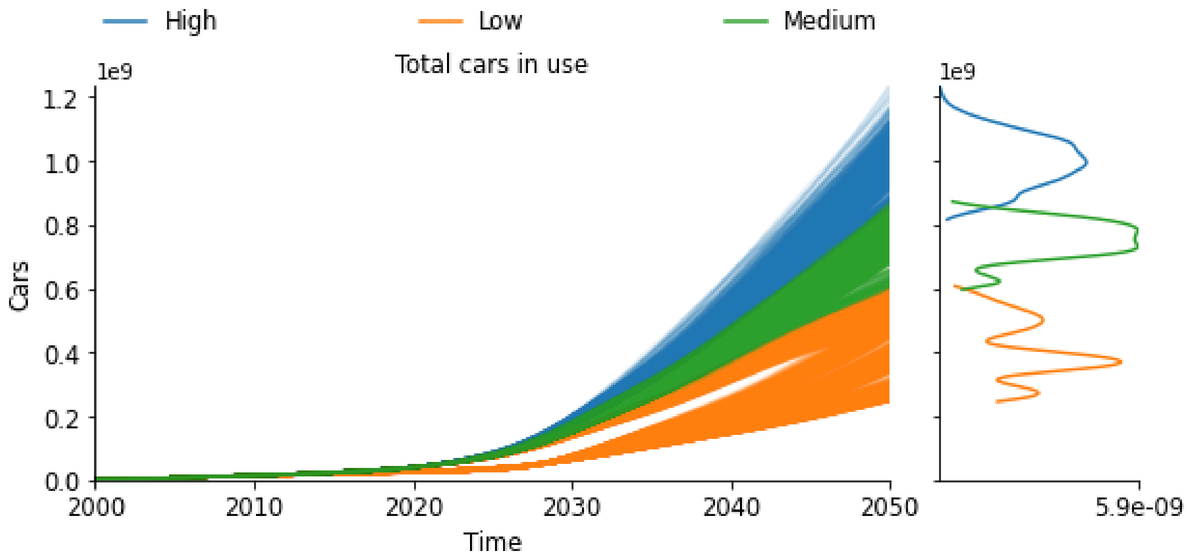

Figure 13: Total electric cars in use clustered.

To identify the key drivers impacting the supply of electric cars and wind turbines, an Extra Trees feature scoring analysis is performed. This analysis evaluates the influence of variables on the outcomes within two-year increments. The scoring assigns higher values to variables that have a greater impact on the outcomes during specific time periods.

Figure 14 illustrates that regarding electric cars, the most influential variables are associated with the scenarios of intrinsic demand and the lifetime of electric cars. In the initial 15 years of the simulation, the scenarios of intrinsic demand for electric cars exhibit relatively low levels. However, after this period, the demand significantly increases. Consequently, the relative impact of losing electric cars due to their aging was more pronounced in the beginning due to a relatively low growth in intrinsic demand during the early years. However, after the growth of intrinsic demand becomes so strong that the losses due to cars reaching the end of their lifetime become less pronounced.

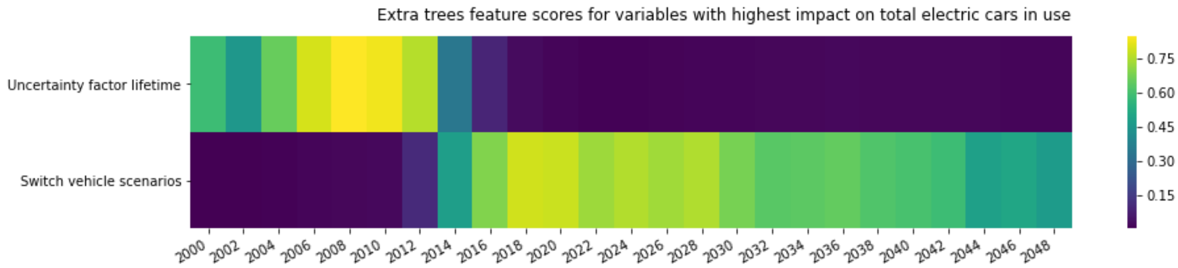

Figure 14: Extra trees feature scoring for influential variables on electric cars in use.

For wind capacity, the behaviour portrayed in figure 15 is similar compared to electric cars with a smaller distribution until 2030 and then the differences in scenarios of intrinsic demand really show. In all runs in the low cluster and part of the runs in the medium cluster, they show that after 2030 the total wind capacity does not continue to increase and in some cases might even decrease. The root of the cause of this behaviour is most likely formed by there not being enough REE available to produce new turbines. The production capacity there is geared towards producing wind turbines using NdFeB magnets, and when there is little REE available, then few new turbines can be produced and the total wind capacity in use might even decrease due to already installed wind turbines being decommissioned.

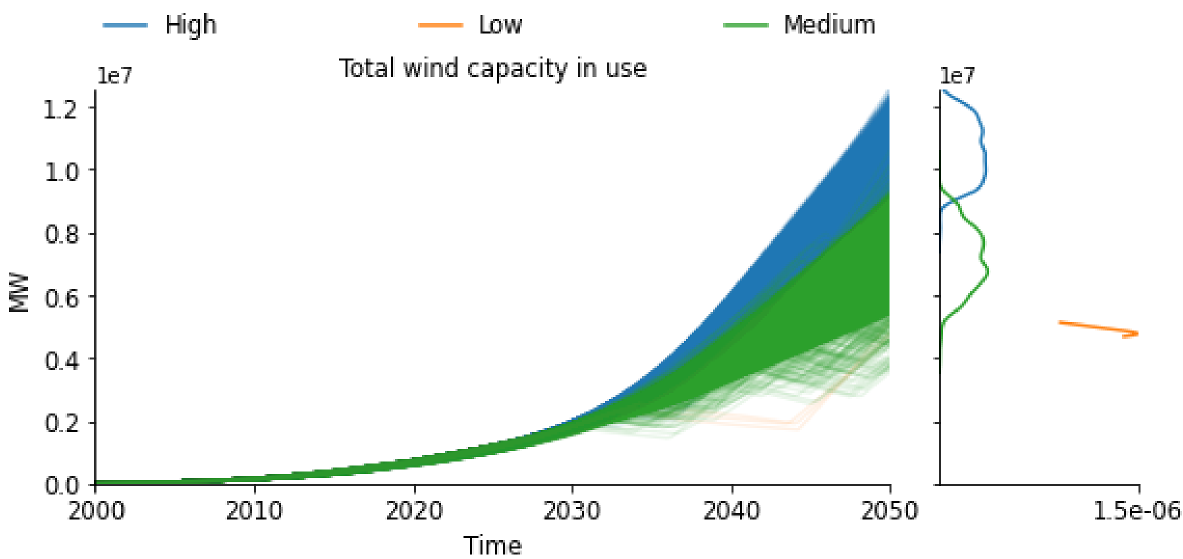

Figure 15: Total wind capacity in use clustered.

Similarly, wind capacity in use is also influenced by the lifetime of wind turbines, scenarios of intrinsic demand, and an additional factor - the ability to adjust production levels. Manufacturers face limitations on how quickly they can scale up production. Changes in price levels of REEs over time can impact the financial viability of producing new wind capacity, particularly turbines with NdFeB magnets. As a result, producers may consider adjusting production levels of specific turbine types in response to market conditions. This introduces an element of uncertainty related to changes in production capacity, which proves to be an influential factor in shaping the dynamics of wind capacity in use.

The effect of the uncertainty factor change in production capacity is relatively low past 2030, even though figure 16 shows that past 2030 there are runs at the bottom of the distribution showing the behaviour that there is little or no growth in wind capacity. This is most likely because the majority of the runs do not require changing of the composition of production capacity and the strong effect of the growth in scenarios of intrinsic demand. Being able to quickly scale up production capacity of other turbine types would most likely be very beneficial for the runs that show that they do not grow for a certain amount of time past 2030, but this is only a relatively small fraction of runs.

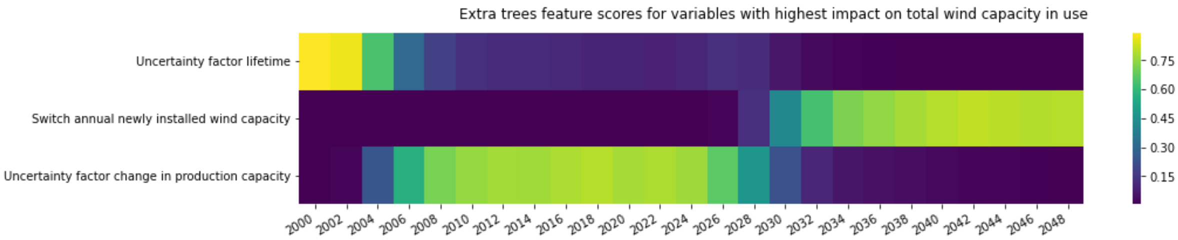

Figure 16: Extra trees feature scoring for influential variables on wind capacity in use.

In order to analyse the dependency of wind capacity and electric cars on REEs, the clusters of runs with low, medium and high wind capacity and electric cars are compared to the REE demand. Neodymium is selected for analysis as the REE of choice due to its predominant presence in NdFeB magnets and its role as a driver in primary REE production.

Over time, the demand for Neodymium exhibits a significant increase. As anticipated, figures 17 and 18 demonstrate a positive relationship between Neodymium demand and the implementation of electric cars and wind turbines. The low cluster of wind capacity in use is a small sample size, so little information can be distracted from that cluster. However, the kernel distributions of the medium and high cluster of wind capacity on the side of figure 17**Error! Reference source not found.** show a large difference, indicating that when more wind capacity is built, this will most likely result in a higher demand for Neodymium.

The kernel densities of the clusters of electric cars in figure 18 show slightly different behaviour. The majority of the runs in every cluster end up on the average outcome of the demand for Neodymium, suggesting the potential for large-scale production of electric cars without or with reduced reliance on NdFeB magnets. Because the kernel distributions of clusters of wind capacity overlap, there is also a potential of achieving high levels of wind capacity with limited Neodymium that is being used. These findings imply the feasibility of exploring alternative strategies that minimise the dependency on REEs, specifically NdFeB magnets, while still achieving substantial electric cars and wind turbine production levels.

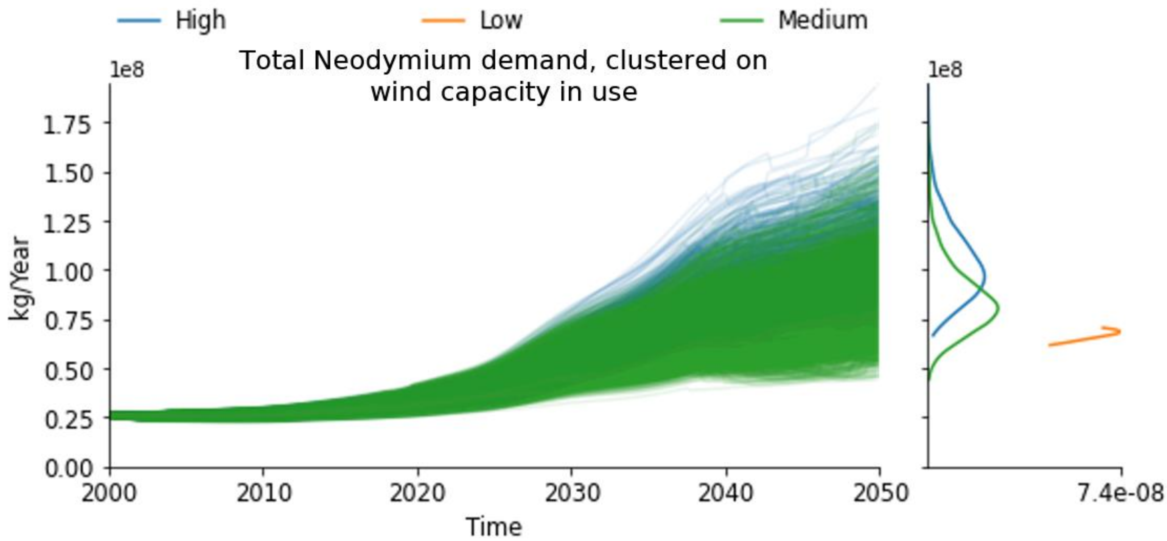

Figure 17: Neodymium demand, clustered on wind capacity in use.

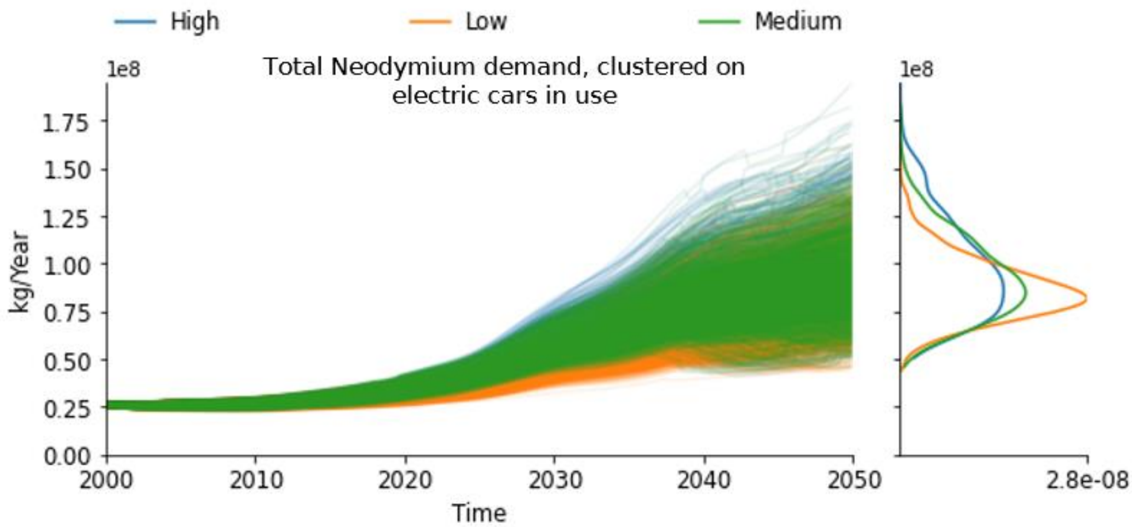

Figure 18: Neodymium demand clustered on electric cars in use.

4.2. Effect of substitution mechanisms

The subsequent analysis focuses on assessing the impact of individual substitution mechanisms. The analysis aims to provide insights into the specific substitution mechanisms and their implications for the supply dynamics of electric cars and wind turbines.

4.2.1. Element-for-element substitution

Element-for-element substitution in NdFeB magnets is the substitution of one LREE for another. The same goes for HREE. Generally, the majority of the LREE is Neodymium, with part of that Neodymium that can be substituted for Praseodymium. Terbium and Dysprosium can both be used as the HREE component used to increase coercivity. However, usually only Dysprosium is used seeing as Terbium is generally more expensive. Element-for-element substitution is generally considered to be a minor form of substitution for REEs used in NdFeB magnets (Graedel et al., 2015).

Figure 19 illustrates the variation in the fraction of Neodymium over time. Seeing as magnet producers make different types of magnets with a different distribution of metal content, the figures displaying REE content are more of an average fraction of REE in NdFeB magnets rather than specific magnet contents. In all scenarios, Neodymium accounts for at least 80% of the LREE content, as the minimum requirement is a 4:1 Neodymium : Praseodymium ratio (Pavel, Thiel, et al., 2017).

After a slight initial increase in all runs, the fraction of Neodymium stabilizes between 0.9 and 0.95. The demand for Praseodymium initially outstrips the supply, quickly reducing the amount of Praseodymium in stock. Then, when demand for Praseodymium reduces and production for Praseodymium increases, demand and supply balance out leading to an equilibrium. The prices of Neodymium and Praseodymium lie very close together. When demand for LREEs increases, demand for both these elements increases simultaneously and production increases simultaneously as well, resulting in the equilibrium. This trend demonstrates a clear example of a long-lasting change in demand.

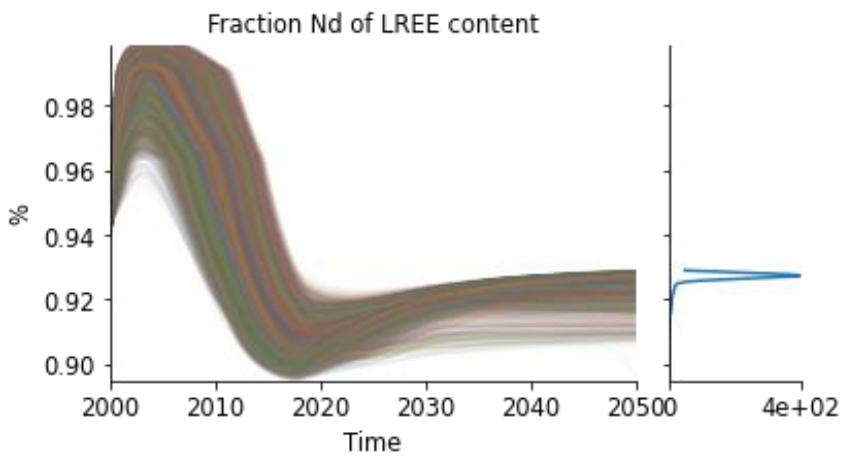

Figure 19: Fraction of Neodymium of LREE content.

Figure 20, showcasing element-for-element substitution of HREE, depicts that in all scenarios the fraction of Dysprosium is higher than that of Terbium over the entire runtime. Substituting Dysprosium for Terbium is primarily a short-term solution, as Terbium typically has higher price levels compared to Dysprosium (Smith & Eggert, 2018). Most of the runs displays two very short-lived peaks: one around 2010 and another peaking between 2025 and 2040.

When demand for Dysprosium outstrips its supply, then the demand for Terbium increases, resulting in an increased fraction of Terbium in the HREE content of NdFeB magnets. However, due to the scarcity of Terbium in the ground, production levels are very low, quickly resulting in demand outstripping supply. The prices of Terbium rise as well making it an inconvenient substitute for Dysprosium, resulting in a return to the prior fraction of Dysprosium in HREE.

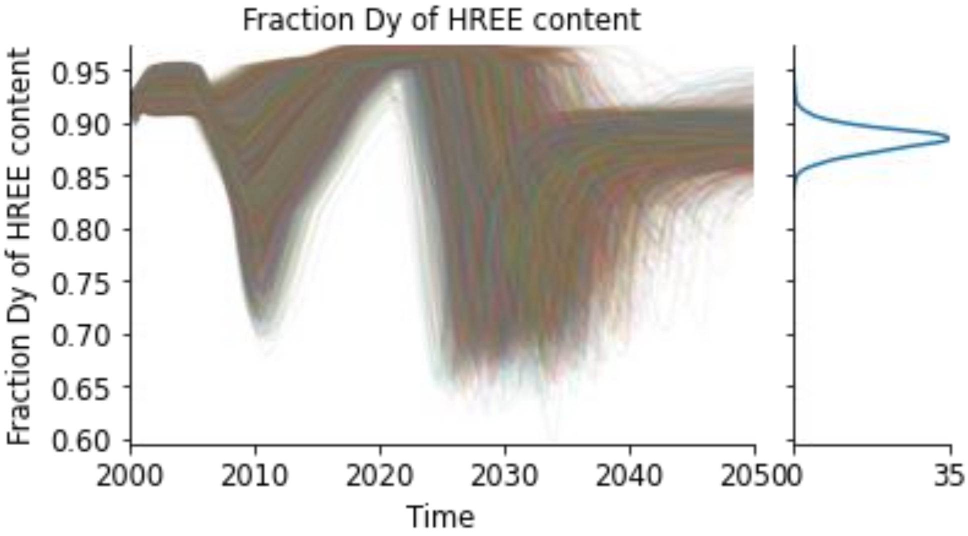

Figure 20: Fraction of Dysprosium of HREE content.

4.2.2. Process-for-element

Process-for-element substitution is a mechanism for both short-term shock absorption and long-term adjustments in demand. NdFeB magnets with lower REE content, while maintaining similar functionality, are generally more expensive to produce. Therefore, in the short term, part of the price shock can be absorbed by process-for-element substitution. However, it is assumed that production costs for magnets with lower REE content decrease when REE prices remain elevated for a considerable period of time. This trend was observed during the 2010 Rare Earth Crisis (Smith & Eggert, 2016). Consequently, there is a potential for a lasting reduction in REE content in NdFeB magnets. Only when REE prices significantly decline would it become feasible to consider increasing REE content once again. The dynamics of process-for-element substitution depend on the prevailing REE price levels and the associated production costs.

Process-for-element substitution is modelled separately for LREE and HREE content. The LREE content generally makes up around 30% of the magnet's weight. Magnets have been produced with a LREE content of only 25%, and it is expected that magnets will be produced with only 20% LREE content (Lacal-Arántegui, 2015). Depending on the user case of the magnet, the HREE content can be anywhere between HREE free and a HREE content of 8% (Pavel, Thiel, et al., 2017). A difference is made between low and high coercivity magnets in the model, where high coercivity magnets have a HREE content of 0.02 higher than low coercive magnets, so the low coercivity NdFeB magnets are modelled as to have a maximum HREE content of 0.06. It is modelled in such a way that the LREE and REE content decreases when average medium periodic prices increase, and vice versa. The LREE content has a maximum of 0.3 and a minimum of 0.2, and the HREE content has maximum of 0.06 and a minimum of 0.01.

Figure 21 shows the varying LREE content of NdFeB magnets over time. The runs exhibit significant variation, with most runs ending up with a LREE content above 26% of total weight of the NdFeB magnet. The runs show a similar pattern, increasing until 2010, then having a short decline for approximately 5 years. Afterwards, it either settles around a certain level or it fluctuates. This also most likely has to do with the difference in primary production and demand, leading to a surplus of Neodymium initially. Then, when the stock of Neodymium becomes lower, the prices go up and it becomes more logical to use a lower fraction of Neodymium. Because the Neodymium price is then high for a more or less extended period of time, the additional production costs also lower, eventually to settle around a certain price level. Then, the prices of Neodymium seem to remain relatively stable over time showing some fluctuation, but no strong swings anymore.

The runs start off on a spectrum between 0.26 and 0.29, which can results eventually due to the uncertainty in the model to end up between 0.25 and 0.3 at the end of the runtime. This variety can for the most part be attributed to an uncertainty factor of the additional production costs.

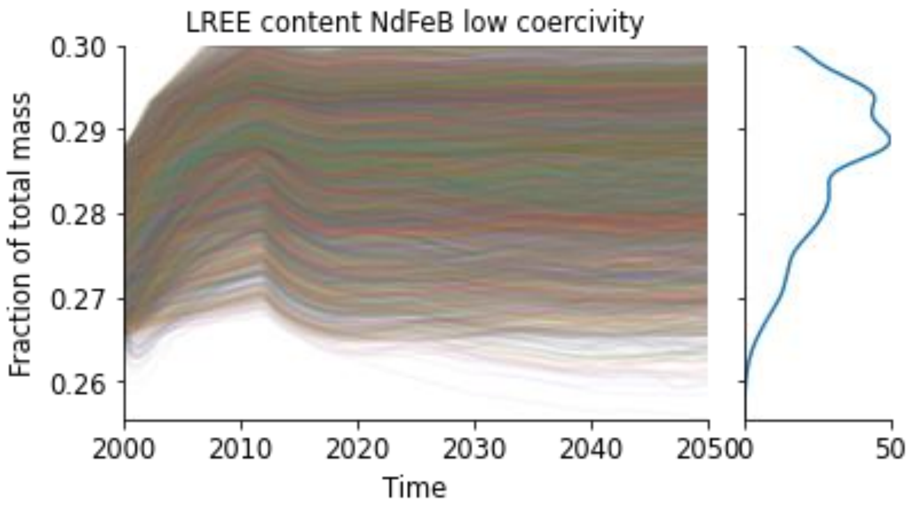

Figure 21: LREE content of low coercivity NdFeB magnet.

On the other hand, the HREE content in figure 22 demonstrates both temporary and more lasting effects of substitution. There is a downward trend between 2000 and 2010, which quickly reverts back to original content levels. However, around 2025, a noticeable reduction in production costs occurs, leading to a permanent decrease in the fraction of HREE over time. This indicates the potential for sustained substitution and a shift towards lower HREE content in the NdFeB magnets produced.

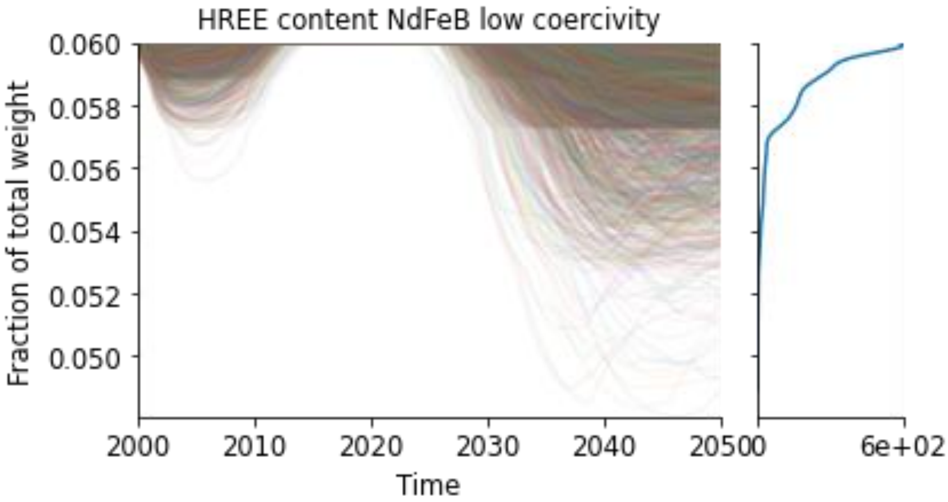

Figure 22: HREE content of low coercivity NdFeB magnet.

4.2.3. Magnet-for-magnet substitution

Magnet-for-magnet substitution is generally considered viable only for applications that do not necessitate magnets with high power density and coercivity (Pavel, Thiel, et al., 2017). Therefore, for electric cars and wind turbines, magnet-for-magnet substitution is not a feasible strategy, and the study does not include magnet-for-magnet substitution specifically for these applications.

Nevertheless, if the demand for REEs in other applications can be substituted, it may help alleviate potential material shortages of REEs for electric cars and wind turbines. This would result in a larger quantity of REEs available for use in electric cars and wind turbines, supporting their production and deployment.

In figure 23, the total amount of REE that is substituted by magnet-for-magnet substitution is compared to the demand for REEs. The peak in the density plot on the right of the figure shows that the majority of the runs end up with a very low fraction of demand being substituted by magnet-for-magnet substitution. The runs that do not make up part of the peak in the density plot exhibit a different pattern, though some display more pronounced behaviour than others. The figure displays two distinct peaks: one around 2010 and another later, peaking around 2050. These peaks likely stem from the dynamics between REE demand and the capacity for mining and refining. Initially, there may be a shortfall in primary production capacity relative to demand, leading to higher prices and increased magnet-for-magnet substitution. Subsequently, primary production capacity expands, resulting in lower prices and reduced magnet-for-magnet substitution. This cycle repeats, contributing to the observed peaks in the figure. The level of magnet-for-magnet substitution declines close to zero after the first peak, indicating that material demand for NdFeB magnets can be substituted temporarily by magnet-for-magnet substitution, but it does not lead to a permanent change in demand.

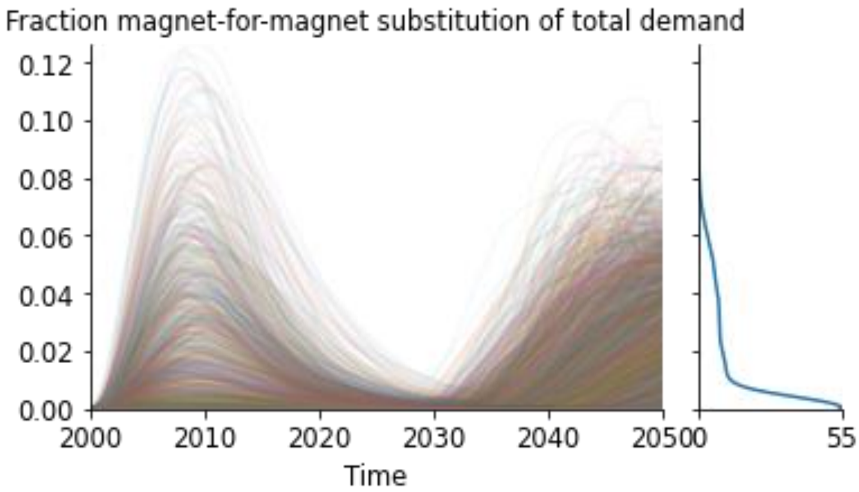

Figure 23: Fraction magnet-for-magnet substitution of total demand.

4.2.4. Component-for-component substitution

Component-for-component substitution in this research refers to the construction of electric cars and wind turbines using a reduced amount or no NdFeB magnets at all. It is therefore depicted as the fraction of electric cars and wind turbines with NdFeB magnets. The lower this fraction becomes, the more component-for-component substitution takes place.

For each application, six potential turbines or cars were modelled, including one that fully relies on NdFeB magnets, one with a reduced amount of NdFeB, and four that are entirely free of NdFeB magnets. Specifically, for wind energy, the High-Technology Superconductors, and for electric cars, the Asynchronous motors with high RPM and Switch reluctance motors are still under development (Pavel, Lacal-Arántegui, et al., 2017; Pavel, Thiel, et al., 2017). However, not all six technologies have reached technological maturity, and their market entry is uncertain. Therefore, they have been included as structural uncertainties.

Wind turbine component-for-component substitution

Figure 24 shows the development over time of the fraction of wind capacity in use with NdFeB magnets, showing a fairly continuous trend of de-substitution throughout the entire runtime. Around 2000 approximately 10% of the wind turbines use NdFeB magnets, whereas in the end 80-100% of the turbines employ NdFeB magnets. Wind turbines were originally manufactured without the use of NdFeB magnets and relied on gearboxes. However, as turbines increase in size, gearboxes become less suitable for larger wind turbines (Wiser et al., 2016). The growth in the size of wind turbines trend is also included in the model and favours the priority factor of wind turbines with NdFeB magnets and HTS.

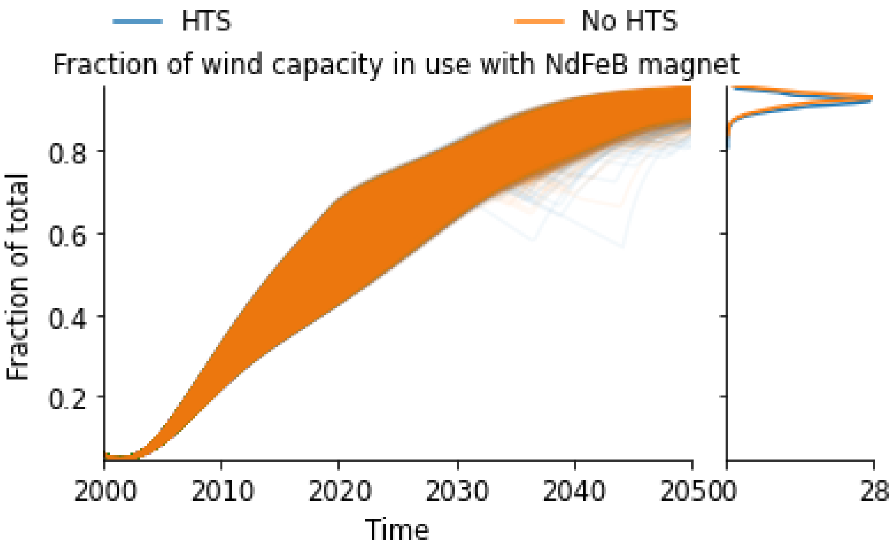

Figure 24: Fraction of installed wind capacity with NdFeB magnets, clustered on technology readiness of High-Technology Superconductors.

A few runs show a sudden drop in the fraction of installed wind capacity with NdFeB magnets after 2030. The same behaviour can be found in figure 15, in which the wind capacity in use over time is depicted. This most likely has to do with there being little REE available to produce turbines with NdFeB magnets. However, this substitution seems to be of a more temporary nature, seeing as, after an initial drop, the runs grow quite steeply and end up in the 80-100% range.

When looking at the density plot on the right part of figure 24, the cluster with a high supply of wind energy also has a relatively high fraction of wind turbines in use with NdFeB magnets.

Electric car component-for-component substitution

Figure 25 illustrates the fraction of cars in use with NdFeB magnets, clustered on structural uncertainties of alternative NdFeB-free motor types under development. It shows that, for a significant portion of the runs, there is a large fraction of cars equipped with NdFeB magnets and little component-for-component substitution takes place throughout the entire duration of the runtime. When component-for-component substitution of electric cars occurs, it tends to result in a long-term shift in demand. Substituted demand does not revert to its original levels.

However, around 2030, component-for-component substitution starts taking place for a notable amount of runs, resulting in runs where the fraction of electric cars with NdFeB magnets decrease to as low as 20%. This can be attributed mainly to two things: (1) the fraction that battery electric vehicles (BEV) makes up from the total amount of electric cars grows over time and (2) alternative motor types may come onto the market.

Whether component-for-component substitution takes place depends on the proportion of BEV cars to the total amount of electric cars. For BEV cars, various types of motors can be used. However, in PHEV and HEV cars the electric motor is used to complement an internal combustion engine, thereby severely limiting the volume and weight of the electric motor. Motors operating with permanent magnets are therefore more suitable for PHEV and HEV cars. The development of the fraction that BEV makes up from the total amount of electric cars heavily depends on the demand scenario. In some scenarios, BEV is very dominant, resulting in a much lower fraction of cars in use with NdFeB magnet.

The runs in the clusters with ASM high rpm and/or SRM reaching the market show a notable increase in component-for-component substitution. Although the density plot on the right side of figure 25 shows that the majority of the runs will still end up with motor employing NdFeB magnets being the most dominant motor type, the peak is much lower. Moreover, the fraction of cars in use with NdFeB magnets can drop to as low as 20%. This is significantly lower than minimum of approximately 50% in the runs where ASM high rpm and SRM do not reach the market.

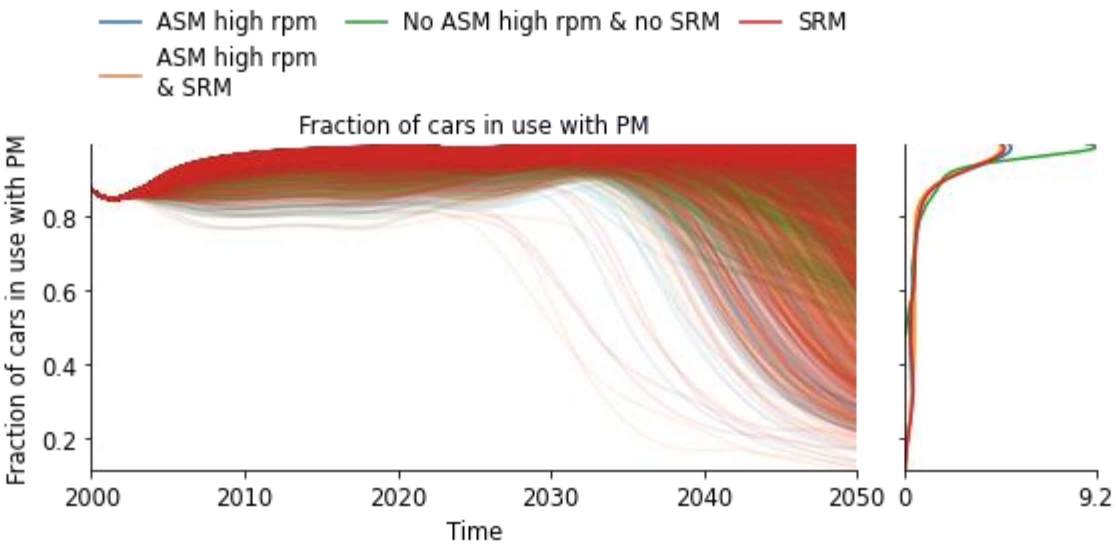

Figure 25: Fraction of cars in use with PM, clustered on technology readiness of motor types.

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5. Discussion

In this chapter, the research methods, model and results are discussed, and a broader perspective on the concept of substitution is provided. Section 5.1 provides and interpretation of the results regarding the development of the supply system of REEs, electric cars and wind turbines. In section 5.2 the results regarding the substitution mechanisms are discussed. In section 5.3 the advantages and disadvantages of substitution in sustainable development are discussed. Section 5.4 discusses the limitations of this research, and recommendations are made for future research.

5.1. Interpretation of the development of the supply system

The findings of this research contribute to the existing scientific literature by addressing a research gap in the understanding of substitution mechanisms for REEs in NdFeB magnets, specifically within the context of electric cars and wind turbines. The initial research gap emphasized the need for a comprehensive model-based evaluation of individual substitution mechanisms to sustain the development of these clean energy technologies.

One notable contribution lies in the elucidation of the relationship between the production quantities of electric cars, wind turbines, and the corresponding REE consumption. The prevailing pattern from the runs is a positive correlation between the utilisation of electric cars, wind turbines, and the demand for REEs. However, it is noteworthy that a substantial subset of runs exhibits a weaker connection between REE usage and the deployment of these technologies. In these cases, a relatively low amount of REEs is employed, while still having a high number of electric cars and wind turbines in use. This suggests that while the majority of runs maintain a relatively REE-intensive production approach, there exists the potential to achieve comparable quantities of electric cars and wind turbines with reduced REE intensity.

Incorporating insights from the extra trees feature scoring analysis, the foremost influence on the adoption of wind turbines and electric cars appears to be the intrinsic demand for these technologies, a driving factor for the final demand for these technologies that is modelled using scenarios. While the uncertainty range of substitution-related input variables were considerable, their influence on the model outcomes concerning the implementation of wind turbines and electric cars by 2050 remained relatively modest. This could be attributed to two primary factors: firstly, short-term substitutions tend to have limited influence on long-term implications; and secondly, there is a lack of substitutions that significantly outperform their REE-intensive counterparts.

Over the 50-year simulation period, temporary disruptions or delays in REE production are plausible and may cause short-term disruptions in the supply of electric cars and wind turbines, but are predicted to exert a relatively small impact on the supply of these technologies over the full runtime of the model. It is essential to note that in this research the assumption is made that there are temporary short-term disturbances in primary production, but that there are no permanent stops in primary production. There is a substantial amount of REE in the ground, which should be able to facilitate the energy transition, at least until 2050 (Elshkaki & Graedel, 2014; Grandell et al., 2016; Hoenderdaal et al., 2013). None of the model runs indicate reaching a critical level where the accessible and cost-effective extraction of REEs is depleted, which would otherwise lead to strongly elevated prices. Moreover, primary production of REE has been diversifying over the years (Smith et al., 2022), which will most likely contribute to a smaller risk of disturbances in supply. Consequently, while more effective substitution might mitigate the shock of a supply disturbance, this effect is relatively minute in comparison to the influence of the scenarios of intrinsic demand over the entire runtime of the model. When comparing the influence of one scenario of intrinsic demand to another, there will be a difference throughout the entire runtime of the model, resulting in a much larger long-term influence compared to the effect substitution has on mitigating short-term disturbances.

The subset of runs with a high number wind turbines and electric cars and relatively low REE in use indicates, that there is certainly long-term substitution. However, these substitutes are most likely not significantly better or more cost-effective than technologies that are currently in use. Therefore, long-term substitution does not result in an increased level of demand for electric cars and wind turbines, but distributes existing demand over multiple technologies, resulting in an overall reduction of REE in use.

While substitution might not substantially alter the number of deployed electric cars and wind turbines on the long term, its role should not be dismissed entirely. Every form of substitution that is researched in this study has shown potential to substitute part of the REEs used in electric cars and wind turbines. Exploring the potential effects of substitution remains valuable as it can offer insights into alleviating material supply chain challenges. Moreover, it is very helpful to understand what substitutes might become more dominant and what type of influence one can expect from a specific substitution mechanism. It is important to distinguish between substitution in the form of temporary shock absorption and technologies that can lead to a permanent shift in demand.

Generally viewed, substitution can cause a temporary or a permanent shift in the demand curve, depending on the price levels and the quality of the substitute product. Demand for technologies and/or materials is generally regarded as continuous, especially in a short time frame. When price levels rise, demand is reduced and/or substituted. Then, when price levels return to the original price levels, demand also reverts to its original state (Smith & Eggert, 2018).

Introducing new technology and/or changing production processes, however, can permanently shift the demand curve (Smith & Eggert, 2018). When price levels are elevated, firms are incentivised to conduct research on alternative technologies, which could result in the development of superior products. Then, when price levels of the original product decline, the substitute product may still be the better choice. These differences between temporary and permanent substitution are also clearly visible in the different substitution mechanisms of REEs in electric cars and wind turbines.

5.2. Interpretation of the behaviour of individual substitution mechanisms

Element-for-element substitution of LREE has the potential to induce both temporary and permanent shifts in demand. In the case of Praseodymium and Neodymium, Praseodymium can serve as a partial substitute for Neodymium in the short and long term due to their relatively similar prices. On the other hand, element-for-element substitution of HREE only shows some potential for short-term substitution, but very limited potential for long-term substitution. Terbium can fully replace Dysprosium, but given the low concentration in which Terbium is found, and therefore the significantly higher price of Terbium, this substitution is not considered preferable in the long term (Pavel, Thiel, et al., 2017; Smith & Eggert, 2018).

In the context of process-for-element substitution, the LREE content in NdFeB magnets can fluctuate slightly, but individual runs do not show great variability throughout the run. Individual runs show little variability in LREE content throughout the run. There is quite a significant variability between runs, but this can be attributed to the uncertainty factor of production costs which primarily influences the starting conditions of the LREE content, but holds limited influence over the behaviour throughout the rest of the run. HREE process-for-element substitution does demonstrate more significant variability, with the potential for both short-term as well as long-term substitution. Primary production is mainly driven by the demand for Neodymium (Ganguli & Cook, 2018). Therefore, there is little need for substitution of the LREE content, because when the price of Neodymium rises, primary production is also increased. Depending on the HREE content of the mined minerals however, HREE production might lag behind demand. This could result in having prolonged increases in HREE prices, and HREE being substituted more permanently.

Magnet-for-magnet substitution appears to provide a relatively temporary solution, capable of substituting a portion of the overall demand. Consequently, unless a significant breakthrough occurs, introducing a strong competitor to NdFeB magnets, magnet-for-magnet substitution cannot be deemed a viable mechanism, particularly when it comes to electric cars and wind turbines.

Component-for-component substitution seems to occur in a more permanent manner. The lack of short-term substitution can most likely be attributed to the amount of time required to scale up production capacity for a different type of generator or motor and the economies of scale that are introduced when switching between production of different types of components.

In the case of offshore wind turbines, component-for-component substitution could prove to be important, particularly as turbines continue to grow taller in the future (Wiser et al., 2016). Unless new technologies like High-Temperature Superconductors emerge, there will be no viable alternative to tall offshore wind turbines utilising NdFeB magnets. Consequently, the dependence on NdFeB magnets makes offshore wind turbines highly susceptible to fluctuations in the supply of REEs. Regarding electric cars, alternative technologies already exist that are fairly competitive with NdFeB motors. Two promising technologies are currently under development that might outperform NdFeB motors in the future.

At the end of the runtime, a larger share of electric cars has adopted NdFeB-free components compared to wind turbines. This can be attributed to the versatility of NdFeB-free alternative motor types like Switch-Reluctance Motors and Asynchronous Motors with high revolutions per minute, which can be employed in all types of electric cars (BEV, PHEV, and HEV) (Pavel, Thiel, et al., 2017). In contrast, High-Technology Superconductors turbines are economically feasible only for very large offshore wind turbines. Additionally, the lifespan of cars is considerably shorter than that of wind turbines. All technologies that are introduced later in the runtime are introduced around the same time, approximately in 2030. Therefore, all cars in use in 2050 will have been built past 2030, but that is not the case for all wind turbines.

5.3. The role of substitution in sustainable development

It is incredibly complex to determine how one can use substitution to the best of its abilities, especially when looking over a longer period of time. Even when a single goal is set, such as maximising the amount of wind turbines or electric cars in use in 2050, creating the most efficient types of short-term substitution may not always be the most effective mechanism for long-term development.

Short-term substitution can provide a way of increasing resilience. Generally viewed, substitution can cause a temporary or a permanent shift in the demand curve, depending on the price levels and the quality of the substitute product. Demand for technologies and/or materials is generally regarded as continuous, especially in a short time frame. When price levels rise, demand is reduced and/or substituted. Then, when price levels return to the original price levels, demand also reverts to its original state (Smith & Eggert, 2018).

Resilience, however, is not per se desirable in all situations. Resilience is an attribute of a system, and whether it is beneficial depends on the scope of the system and the time scale under analysis (Sprecher et al., 2015). Resilience can be desirable for sustaining development in the direction that the system is already headed (Elmqvist et al., 2019). However, substituting REEs or NdFeB magnets with suboptimal alternatives may not only lead to a suboptimal situation compared to using NdFeB magnets but could also hinder the necessary shock to the system. Such shocks could potentially incentivise the development of more economically viable and sustainable long-term substitution mechanisms (Folke, 2016).

For instance, magnet-for-magnet substitution has shown that it can mitigate shocks to the system by substituting part of the demand. However, other types of magnets are considered to be suboptimal alternatives to NdFeB magnets (Klinger, 2018). When price levels are elevated for a longer period of time, firms and researchers may be incentivised to conduct research on alternative magnets, which could result in the development of superior products (Smith & Eggert, 2018). Therefore, while temporary substitutions can offer short-term benefits, it is important to consider their potential impact on the overall trajectory of innovation and the pursuit of more effective and enduring solutions.

5.4. Limitations & recommendations

While this study has yielded valuable insights into the substitution of REEs in wind turbines and electric cars, it is important to recognize that the research does carry certain limitations. This section aims to delve into these limitations and subsequently offer recommendations for addressing and mitigating them. Furthermore, this section will propose suggestions for the broader advancement of this research and the potential application of the knowledge gained from this study in alternative domains. The limitations and recommendations can be mainly divided into four topics: modelling of primary REE production, modelling of substitution, model-based optimisation and application of this model in similar fields.

5.4.1. Modelling REE primary production

When constructing material supply system models, it is important to model the primary production a realistic manner. While this research primarily centres on the evaluation of substitution effects, constructing a well-grounded model of primary production is important for evaluating the potential of substitution. The primary production of REEs is a really complex process, which has only really received extensive global attention over the last 15 years (Marx et al., 2018). Currently extracted from four types of minerals, REEs exist in over 100 mineral variations, and their extraction continues to undergo exploration (Eggert et al., 2016).

In this study, owing to data limitations, a decision was made to differentiate between mining two REE sources: general minerals and ion-adsorption clays. Both sources have a distinct content and distribution of REEs. In future research, the incorporation of a more disaggregated perspective on REE sources could yield dynamic insights not fully captured here. While the current model attempts to emulate the complex behaviours emerging from multiple REE sources through parametric and structural uncertainty ranges, introducing a higher number of sources might introduce unique behaviours not captured in the current model.

Furthermore, geographical and geopolitical considerations are important in primary REE production. Although China predominates in mining, recent years have witnessed a diversification of mining locations globally, altering China's stronghold on supply. However, production of NdFeB magnets is still mainly located in China (Smith et al., 2022). In this study, a modest attempt is made to incorporate geo-political considerations by introducing a disturbance representing a hypothetical scenario where China's primary REE production share experiences a temporary disruption. Nevertheless, the evaluation of REE substitution within NdFeB magnets could benefit from a more detailed modelling of geo-political influences.

5.4.2. Modelling of substitution

For a complete evaluation of substitution potential, it can be important for decision-makers to also understand the demand for its substitutes. Decision-makers who have the responsibility to implement substitution mechanisms have to consider supply risks not only of NdFeB magnets, but also the supply risks of its substitutes. In this study, two approaches are used to model a substitution mechanism: (1) the product of interest is compared to the substitute products resulting in a certain distribution of demand over the available products, and (2) the price of the product of interest is compared to a certain substitution threshold, and when this threshold is passed, substitution occurs. Most of the substitution mechanisms follow this first approach, only magnet-for-magnet substitution is modelled using the second approach. Magnet-for-magnet substitution, as implemented in this study, solely models NdFeB magnet demand, which is substituted for other magnets when the NdFeB price surpasses a certain threshold. Consequently, losses in NdFeB magnet demand due to substitution correspond to increased demand for alternative magnets. However, the demand for alternative magnets is not explicitly modelled, leaving decision-makers uninformed about which alternative magnet proves to be most dominant.

In future research, the model could be extended to also model magnet-for-magnet substitution using an approach similar to that of component-for-component substitution with a priority score. This approach would allow for the comparison of different types of magnets, taking into account both the magnet's price and its properties. In the current model, magnet-for-magnet substitution was not incorporated in this way due to the lack of available information on the prices and properties of alternative magnets in a realistic manner. However, consulting experts in this field might provide insights to more realistically include this aspect in the model.

Another valuable expansion to this research could involve the integration of system-for-system substitution. This variant of substitution entails replacing entire end-products with alternative products that serve the same function – for example, substituting electric cars and wind turbines for public transport and solar panels, respectively. While this study does account for demand fluctuations in electric cars and wind turbines due to REE price changes and technological advancements, it does not explicitly encompass system-for-system substitution. This omission overlooks potentially insightful dynamics, as system-for-system substitution can be instigated not only by price fluctuations and technological progress within wind turbines and electric cars, but also by developments among their substitutes. For instance, a technological breakthrough solar panels could suddenly alter the demand for wind turbines. While the model integrates intrinsic demand scenarios for electric cars and wind turbines to capture demand changes over time, system-for-system substitution could introduce dynamics currently absent from the model. Moreover, incorporating this form of substitution could offer a more comprehensive overview of substitution types, and improve the understanding of interactions between different substitution types.

5.4.3. Model-based optimisation

In this study, simulation of the model was done using open exploration. A set of variables was provided with an uncertainty range, and the model was simulated a large number of times with the input values for these variables being varied systematically. This simulation method allows for exploration on what could potentially happen in the future and is most helpful for a general exploration of the interactions within the system (Bankes, 1993).

An alternative simulation method involves employing model-based optimisation, also known as directed search. This approach entails optimising over uncertainties or policy levers. Due to time constraints, this study refrained from employing model-based optimisation. Nonetheless, conducting model-based optimisation could potentially yield insights and results.

When optimising over uncertainties, one can evaluate how uncertainties map into the outcome space. For instance, model-based optimisations can be employed to assess which specific combinations of uncertainties yield either best-or worst-case scenarios. Depending on the scope of the decision-maker and the interest at hand, certain objectives can be formed over which can be optimised. An intriguing pursuit could involve determining what uncertainties can lead to worst-case scenarios in the implementation of electric cars and wind turbines. Another topic that could be interesting to research is under what circumstances the most substitution takes place.

Optimisation could also target policy levers by optimising the policy lever space in order to lead to desirable outcomes. For instance, one could evaluate the effect of certain policies that could vary the time of implementation of a substitution mechanism. Time is an important dimension to substitution (Sprecher et al., 2015). Existing solutions are implemented much more quickly than solutions that are still under development (Smith & Eggert, 2018). Solutions that are under development may either experience a longer delay or may not be implemented at all depending on the duration of the raised price levels. There are already certain variables in the current model that have an uncertainty range in determining the time of implementation. For instance, the speed of scaling up and down of production capacity of wind turbines and electric cars has been varied and studied in this research. It could be interesting to include these variables as policies that certain decision makers can tweak. Especially when there are certain costs related to these policies, then trade-offs can be made with these policies.

These two types of model-based optimisation can also be combined. First worst-case scenarios can be developed with uncertainty-based optimisation. Subsequent policy-based optimisation could unveil strategies preventing or mitigating these scenarios.

5.4.4. Application in similar fields

The model developed by van der Linden (2020) for Cobalt served as the foundation for our study, and was then modified and extended for this research's context. The extension of this model make it relatively easy to use this model to evaluate the substitution potential of critical metals in other technologies. Especially when metals are a vital component of an intermediate product that is used in the end-product, then the structure of this model would be directly applicable. An example of this would be the use of Cobalt in batteries in electric cars. While van der Linden (2020) already incorporated substitution in Cobalt's context, this research's model structure could offer a more detailed understanding of substitution potential in this scenario.

6. Conclusion

In this study the substitution potential of REEs in NdFeB magnets in electric cars and wind turbines until 2050 is explored using an exploratory system dynamics modelling approach. In this chapter the research questions will be answered which will ultimately tie into answering the main research question, and therefore draw the main conclusions of this research. In order to do so, the structure of the global NdFeB supply system and its interaction with the supply and substitution of REEs in NdFeB magnets in wind turbines and electric cars is mapped. Potential behaviour and development of the global NdFeB supply system, electric cars and wind energy is explored in a material supply chain model. In addition, the effect of individual substitution mechanisms have been examined.

SQ1: What is the structure of the global NdFeB supply system and how does this relate to the supply and substitution of REE in NdFeB magnets in wind energy and electric cars?

The global supply system for NdFeB magnets primarily revolves around several key elements: the supply chain, demand, primary production, recycling, and the substitution of REEs. Primary REE production encompasses both legal and illegal activities, with these elements typically extracted from a variety of minerals. Most of these minerals contain a significant proportion of light rare earth elements (LREEs) and a smaller portion of heavy rare earth elements (HREEs), while a few, such as ion-adsorption clays, have a relatively higher HREE content. Illegal mining activities are particularly prevalent in ion-adsorption clays.

The demand for NdFeB magnets and the REEs required for their production originates from various industries, including electric vehicles, wind turbines, computer hardware, and other applications. To meet this demand, there are several potential methods for substituting REEs, four of which are detailed in this research: element-for-element, process-for-element, magnet-for-magnet, and component-for-component substitution.

These substitution methods are influenced by factors such as the average periodic price of REEs, potential cost reductions in the case of process-for-element substitution, a substitution threshold for magnet-for-magnet substitution, and various considerations, including power density and technology readiness, for component-for-component substitution.

SQ 2: What behaviour may the supply system of NdFeB magnets, electric cars and wind energy exhibit until 2050?

The amount of electric cars, wind turbines, and REEs in use exhibits a similar pattern characterised by a significant level of uncertainty. In the most conservative scenario, the amount shows a slight increase until 2050, while in the most optimistic scenario, the amount experiences exponential growth.

The most influential uncertainties on the amount of electric cars and wind energy are the intrinsic demand driven by the energy transition, the product's lifespan, and the production's ability to quickly adapt to changes in demand by scaling up or down. Differences in the product’s lifespan were especially pronounced in the beginning of the simulation due to a relatively low growth in intrinsic demand during that period. Consequently, the amount of products in use experienced a relatively slow growths as the as more went out of service. However, in the later phase in the simulation, the intrinsic demand takes over and then remains the most influential uncertainty.

Both wind energy and electric cars exhibit a positive relation with the quantity of REEs in use. Nevertheless, there are also scenarios where a relatively high number of wind energy systems and electric cars can be developed without an exceptionally high utilization of REEs.

SQ 3: What effect can substitution of REEs have on the dependency of electric cars and wind turbines on REEs?

Substitution can temporarily alter demand or cause a permanent shift in the demand curve, depending on price levels and substitute product quality. In the short term, demand for technologies and materials tends to be continuous, with fluctuations in response to price changes. When prices rise, demand decreases or switches to substitutes. As prices return to their original levels, demand reverts to its initial state.

However, introducing new technology or changing production processes can permanently shift the demand curve. Elevated prices incentivize firms to research alternative technologies, leading to the development of superior products. Even when prices of the original product decline, the substitute product may remain the preferred choice due to its advantages.

Both element-for-element and process-for-element substitution have the potential to induce both temporary and permanent shifts in demand, magnet-for-magnet substitution is a more temporary solution, whereas component-for-component substitution often results in a more permanent change.

The development of alternative technologies that do not rely on NdFeB magnets could impact the number of wind turbines built in the future. This development could be even more influential in the production of electric cars. Such advancements can lead to more permanent forms of substitution and contribute to increased adoption of these technologies. While currently available alternatives can also serve as substitutes for NdFeB-based cars, alternative technologies for electric cars that are still in progress might have the potential to really reduce the amount of electric cars with NdFeB magnets.

General conclusion

While it may seem evident, the likelihood of a substantial number of electric cars and wind energy systems being in use by 2050 primarily hinges on the demand for these technologies, which can be spurred by factors like technological advancement and price reductions of wind energy and electric cars itself and of its competitors, government policies and incentives. Substitution, however, is unlikely to play a key role in securing sufficient electric cars and wind turbines. This is due to a number of reasons:

1. The earth's crust contains sufficient REE, which should be adequate for producing the necessary number of electric cars and wind turbines, at least until 2050.
2. Even though the production of REEs might lag behind demand, it takes time for substitution to take place, so it can only provide relatively little short-term shock absorption. Moreover, short-term shocks have a relatively small impact on the long-term supply.
3. Alternatives with a reduced or eliminated use of REEs do not significantly outperform its REE intensive counterpart, therefore not leading to an increase in demand.

That is not to say that we will only be able to build a lot of electric cars and wind turbines with a lot of REEs. There are scenarios in which the utilisation of NdFeB and REEs remains relatively low, yet still a considerable amount of electric cars and wind turbines can be manufactured.

Moreover, while substitution might not substantially alter the number of deployed electric cars and wind turbines on the long term, its role should not be dismissed entirely. Every form of substitution that is researched in this study has shown potential to substitute part of the REEs used in electric cars and wind turbines. Exploring the potential effects of substitution remains valuable as it can offer insights into alleviating material supply chain challenges. Moreover, it is very helpful to understand what substitutes might become more dominant and what type of influence one can expect from a specific substitution mechanism. It is important to distinguish between substitution in the form of temporary shock absorption and technologies that can lead to a permanent shift in demand.

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