When materials become critical : lessons from the 2010 rare earth crisis

Sprecher, B.

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Benjamin Sprecher

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PhD Thesis Leiden University, The Netherlands

sprecher@cml.leidenuniv.nl

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When materials become critical: lessons from the 2010 rare earth crisis

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Introduction – the Circular Economy and Critical Materials

This dissertation is the product of a research project that started as an extension of my internship at Van Gansewinkel Groep (VGG), the largest waste management company in the Benelux. At the time, Van Gansewinkel was re-assessing its role in waste processing. They expected material scarcity to necessitate a shift away from the traditional down-cycling towards the production of raw materials from waste. The then new concept of a “circular economy” was a conceptual framework behind this ambition. The research project with the working title ‘extraction of raw materials from waste streams and products’ had the broad industrial aim of making the circular economy-concept practical. In aid of this industrial aim, several scientific objectives were identified. In this introduction I will discuss the scientific and industrial context in which these where formulated, and introduce the research questions.

Under the banner of the “circular economy”, extraction of raw materials from waste has received significant attention in the past years. At its most basic level, a circular economy is an economic system in which ‘the value of products, materials and resources is maintained for as long as possible, and the generation of waste minimized.[1]

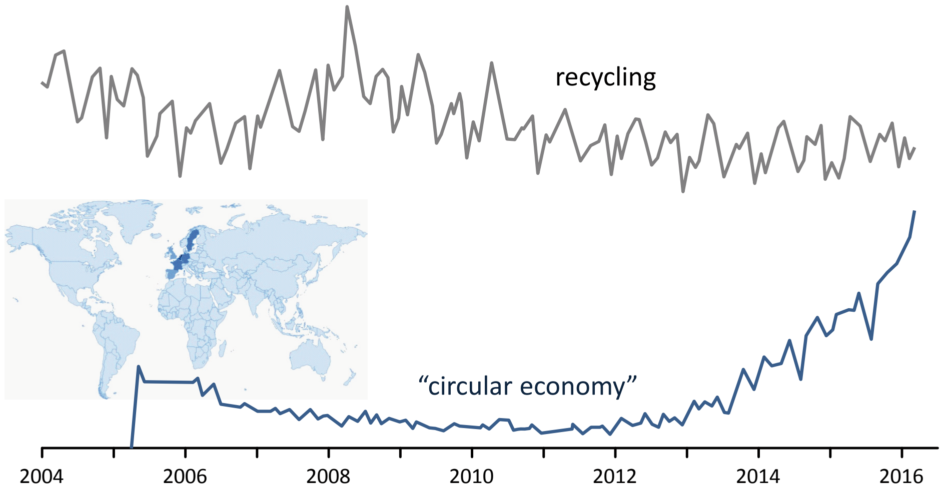

Figure 1. A Google Trends analysis of the interest in the topics ‘circular economy’ and ’recycling’. In absolute terms, circular economy was ca. 100-fold less popular than recycling. For ‘circular economy’ the regional distribution of interest in the term is shown, showing it to be a very European interest.

Figure 1 shows how popular interest in the topic 'Circular Economy' has been steadily growing over the past decade, in the wake of the related cradle-to-cradle design concept and the eponymous book of McDonough and Braungart (2002).[2] The general idea has roots going back at least to the 1960s[3] with major publications highlighting opportunities for Europe in the 1970s[4] and China in the 1990s.[5] The circular economy was formally accepted in 2002 by the Chinese government as a new development strategy that aims to alleviate the contradiction between rapid economic growth and the shortage of raw materials and energy.[5] However, the Google Trends search clearly indicates that popular interest is a rather regional, specifically European, affair. Japan is pursuing similar policy under banner of the older but similar concept 'reduce, reuse and recycle'.

1.1 Business Perspective on Challenges and Opportunities in the Circular Economy – the Case of Van Gansewinkel

The waste management perspective is best summarized by a series of reports by the International Solid Waste Association (ISWA). In these the ISWA points to three key drivers that advance sustainable resource management.[6]

Firstly, they highlight the crucial role of environmental legislation. For example, the main driver behind the reduction of landfilling was the EU Waste Framework Directive, which instructed member states to prevent organic waste from being landfilled. The new Circular Economy Package takes this legislation one step further and contains common EU targets for 2030, such as of minimum recycling of 65% of municipal waste and maximum 10% landfilling.[7]

Secondly, green taxation is an increasingly popular policy tool for supporting the marketability of secondary raw materials. For example, the Chinese 'Circular Economy Promotion Law' reduces or even eliminates VAT on products made from secondary materials. This type of green taxation has also been introduced in South Korea and Mexico. A side effect is that secondary materials from Europe are flowing towards these countries, reducing the scope for a circular economy within the EU.

Thirdly, the average price of commodities had risen twofold between 2000 and 2010. Although prices have dropped since, the fundamental driver for high commodity prices remains. ISWA notes that in order to meet rising living standards and projected population growth annual resource extraction would need to triple, from 45-60 billion tonnes in 2000 to 140 billion tonnes in 2050, and a further 40 billion tons of overburden or unused resources.[6]

- Although the majority of Van Gansewinkels' current business is driven by legislation that forces businesses and municipalities to achieve a certain level of waste management,[8] this research project was motivated by the third driver – increasing raw material prices. There were a number of questions to be answered:'Of all the materials that pass through the VGG system, which are most likely be part of a successful material loop?

- 'What is the optimal size (i.e. volume, geographically) and configuration of a material loop? For instance, should a material loop contain specific product take-back systems (resulting in a higher number of more consistent, high quality waste streams) or is it better to apply a more general collection system (with easier logistics but low quality, mixed waste streams).

- 'What is economically the optimal position for a waste management firm such as VGG to take in the value chain of a material loop? For example, VGG could choose to sell its scrap metals to a third party that refines it. Or purchase this third party (or its technology) so as to move up in the value chain, refine the scrap metals in-house and sell the purified metals directly to customers.'

Thus, the business objective of Van Gansewinkel in this scientific project was to identify a number of recycling opportunities along the following lines: 1) which material loops are relevant, 2) which are do-able for VGG, and 3) where is the money. Parallel to the scientific work, business plans would be formulated for each of these opportunities.

1.2 From Business Interest to Scientific Investigation – Neodymium Magnets as Case Study

In support of Van Gansewinkels' business objectives, the original project proposal defined several broad scientific goals:

- 'To gain insight in the system-level consequences of introduction of cyclical material flows;

- 'To create a methodology to determine what, of all current waste streams, are the most promising candidates for setting up a material loop;

- 'To explore possible configurations of the circular economy.'

The first scientific goal was to be the overall focus of this research project, while the latter two were not – or only peripherally – addressed.

In cooperation with Deloitte, a consultancy firm that was at the time analysing the VGG business model to optimize profitability, we determined that the scientific topic of "Criticality" would provide a good proxy for identifying relevant materials to develop collection and recycling business cases for. This assumed that a critical material would also have higher economic value. The next step towards an executable research program was the choice of a suitable case study.

Numerous studies have pointed to rare earth elements (REEs) as being critically scarce materials,[9,10] especially in the context of a transition towards a global low-carbon energy system.[11] There are several reasons for this. First and foremost, China currently wields a near-monopoly over rare earth production, with a global 86% market share and 50% of worldwide reserves.[12] This is due to years of China producing REEs under the costs of other producers, forcing them to shut down. In the past years China has tried to exploit this market power by implementing export quotas for rare earths, forcing companies to move the production of neodymium magnet containing products to

China in order to secure access. This would be more profitable for the Chinese economy overall than only exporting relatively low-value REE ore or alloys.[13]

The production of REEs is relatively difficult to scale up outside of China. Each REE bearing ore requires a unique extraction process tuned to the exact mineralogy of the REE bearing ore, making small mines prohibitively expensive. Most REE ores also contain radioactive thorium, which complicates the process and waste handling. And because of chemical particularities of REEs, it is not possible to extract neodymium without processing the majority of the other REEs found in the minerals. Furthermore, the REE bearing mineral itself is often a by-product of base metal (mainly iron) mining.[14]

The use of REEs has often been criticized for the environmental impacts related to the mining and purification processes, both in scientific reports[15] and in the media, where the use of REEs in sustainable energy technologies has given rise to newspaper articles with titles like 'clean energy's dirty little secret'.[16] These articles describe appalling conditions under which Chinese rare earths are produced. A quick search on the Internet will yield dozens of pictures of huge tracts of lands devastated by toxic wastewater, primitive metallurgical workshops and Chinese mine workers covered in radioactive mud. In fact, these detrimental environmental effects of REE production are the official reason why the Chinese government has clamped down on its domestic production, introducing export quotas and forcing many of the smaller production facilities to close. Inclusion of some type of environmental analysis therefore seems relevant to a research project on REEs.

Within the group of REEs, neodymium, which is used primarily for NdFeB magnets, was of most interest. Magnets made with this metal are attractive for application in wind turbines and electric vehicles because the use of a stronger magnet results in requiring less mechanical parts and mass for an equivalently performing generator or electric engine, compared to traditional iron and copper based electromagnets. As demand for sustainable technologies is projected to increase significantly, so is the demand for neodymium.[17] This reliance of sustainable technologies on NdFeB magnets, which are subject to the long-term resource constraints of REEs, means that these magnets are particularly attractive to investigate for recycling, even compared to other critical materials.[18]

Besides the assumed criticality on the basis of future demand, the NdFeB supply chain was the focal point of a 2010 trade disruption, when a sharp reduction of Chinese rare earth export quotas and a short-term boycott caused major upheaval amongst REE end-users.[19] Prices flew wildly out of control, in some cases increasing by an order of magnitude in the span of a few months, much to the profit of some and detriment of most.[20]

1.3 The criticality of Neodymium, and how to deal with such a material, would become the Material Criticality in the Scientific Literature

Before we turn to discussing the research questions, it is worthwhile to consider the methodologies employed to determine the status of an element as 'critical'. Graedel and Reck (2015) reviewed nine criticality studies (including their own).[21] Their overarching observation is that it will be almost impossible to devise a 'one true criticality assessment method'. Issues relevant to corporations will be different than to society, and differing levels of data availability may limit methodological choices. However, most criticality studies present their results on a two-dimensional matrix, where the first dimension is a measure of supply risk and the second dimension a measure of the vulnerability of a material to disruption caused by supply issues. Graedel et al. themselves added a third dimension in their 2012 criticality framework, assessing environmental impact of materials.[22]

The first dimension (supply risks) include 'potential physical interruptions in the supply chain (e.g., by war or natural disasters), market imbalances (e.g., by oligopoly market power or inability to expand supply in time), and governmental interventions (e.g., export bans or restrictions on mining for environmental considerations).'

Helbig et al. (2016) zoom in on the various indicators used to assess the second dimension (vulnerability to supply disruptions).[23] Reviewing 18 recent criticality studies, they find that vulnerability is composed of economic importance, strategic importance, and impact of supply disruption. They categorize the indicators found in the 18 studies into six categories: substitutability, product value, future demand, strategic importance, material value and spread of utilization.

Data quality also plays a significant role. Many criticality studies have based themselves on indicators such as crustal abundance, reserve base, economic reserves or extractable global resources. The data underlying such indicators is unfortunately often incomplete or unreliable. A good example can be seen when comparing the official uranium reserve figures published in 2005 and 2007. Between 2005 and 2007 the uranium reserves in Australia, Kazakhstan and South Africa more than doubled, while the Russian statistics bureau managed to find 1.770% more uranium.[24] Also of interest are spectacular reductions. For example, reported uranium reserves in Niger decreased by 88% from 2005 to 2007, for which there was no apparent basis in new research.[24] Such arbitrary reserve adjustments are typically politically or economically motivated. An upward adjustment of reserves can be motivated by the desire to attract foreign investments, while downward adjustment can be used to deter competing mining companies from entering the market. It has even been suggested that mining companies will under-report reserves so as to hide from national governments the true extent of their natural wealth.[24]

Beyond data considerations, Graedel and Reck (2015) surmise that environmental factors are often included in criticality assessments, but that their implementation is problematic and their inclusion in future criticality assessments is debatable.[21] They note that some materials can be limited in availability by environmental issues as much as by geological or geopolitical factors. This however does not seem to be the case for all critical materials, and therefore environmental considerations should be included on a case-by-case basis, rather than as part of a general framework. Furthermore, the evaluation of these environmental issues is challenging. The most common approach in literature has been to use life cycle inventory data, when available.

As pointers for future criticality studies, Helbig et al. (2016) stress that resource criticality is changes over time, and studies should therefore be periodically updated.[23] Graedel and Reck (2015) propose ten desirable aspects that studies of material criticality should take into account.[21]

The first six pertain to the scope of criticality studies:

1) Broad in terms of elements addressed, including both common elements and the increasingly used scarce elements.
2) Considers all factors that are generally important to criticality, including geology, culture, regulations, geopolitics, and other relevant topics.
3) Addresses the issue of substitutability or lack thereof.
4) Addresses the issue of companion metals.
5) Considers the degree to which recycling can affect virgin metal demand.
6) Addresses different using entities (e.g., corporations and countries) as target customers for the assessments.

The REE case study in this thesis will honour requirements 2-6, while, by its very nature, it is limited to the specific class of rare earth elements (requirement 1). The remaining four criteria describe how criticality studies attain and retain relevance:

7) Periodically updated.
8) Authoritative in nature, a stature achieved by such actions as scholarly peer review and/or governmental review.
9) Transparent. The methodology should be clear, and the data used for the evaluations should be described in detail and be made publicly available.
10) Addresses uncertainty, so that the reader has a sense for the rigor and confidence related to a particular criticality analysis.

We note that 8-10 are generally expected of scientific work and 7 is more relevant for broad criticality studies (1) than for a case study such as the present study.

One aspect that is mentioned by Graedel and Reck (2015) is that criticality is a dynamic attribute: ‘it will evolve over time as new technologies emerge and old ones die, as new ore deposits are opened and old ones exhausted, and as geopolitical situations wax and wane.’[21] However, in their list of desirable attributes they don’t take this to the logical conclusion, namely that studies should not study a single point in time (as almost all studies up until now have done), but should be either be dynamic (or at least include dynamic components) and therefore should study how material supply chains change over time and react to disturbances. This dynamic aspect of material criticality will be explored in the remainder of this dissertation.

1.4 Research Questions and a Guide to this Thesis

The environmental, economic and geopolitical factors described above together make for an interesting case-study: neodymium is an element with unique properties, making it both relevant to a sustainable society and relatively complicated to substitute. At the same time there are supply restrictions, and large environmental burdens associated with mining. Although recycling could help to alleviate scarcity of REEs, it is not immediately apparent that it would also carry a significantly lower environmental burden. REEs are notoriously difficult to process,[25] and, depending on the choice of recycling technology, many of the most energy intensive processing steps would have to be performed on recycled material as well. Nevertheless, the environmental damage caused by primary production of REEs had at the start of this research project not been a subject of more than cursory scientific investigation.[26,27]

All these elements create an interesting tension, one that can also be seen in other metals, so that the results of research on the NdFeB supply chain could also be of more general interest. Once the final decision was made to focus on NdFeB magnets, two initial research questions were formulated.

1. What are the material flows of neodymium for NdFeB, and how much can be made available for recycling?
2. What are the environmental burdens of NdFeB production, and how does recycling alleviate this burden?

This work directly led to the first two publications: “*Recycling potential of Neodymium: the case of computer hard disk drives*”, a Material Flow Analysis (MFA) paper that answers the very practical question of how much NdFeB is actually available for recycling, and “*Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets*”, a Life Cycle Assessment (LCA) study on the environmental benefits of recycling NdFeB compared with primary production, which are Chapters 2 and 3 of this dissertation.

Simultaneously, on the industrial valorisation side Van Gansewinkel was working on a business case for the recycling of NdFeB and began collecting NdFeB magnets from computer hard disk drives for a recycling pilot. At this point in time two unforeseen things happened: Van Gansewinkel was not able to find any partners willing to recycle NdFeB, and the price of REEs came crashing down, even though there was no meaningful increase in new primary production or recycling, and the Chinese export restrictions stayed in place.

Although we had – naively perhaps – expected that the market conditions surrounding neodymium were perfect for increasing recycling rates, in reality the system reacted in a different way.

Initially, the scientific aim of the research project was to gain insight in the system-level consequences of introducing cyclical material flows. This observation on the difficulty of getting even a small recycling pilot plant running showed that we needed to take a step back: before we could analyse the system-level consequences of introducing cyclical material flows, we should first understand the system level consequences of a supply chain disruption. Why did recycling not take off? And what did the system do instead to re-adjust itself after the significant 2010 supply chain disruption? From these deliberations followed a review of complex systems literature (Chapter 4), where I concluded that resilience would be the most suitable concept to answer a second set of research questions:

3. What type of mechanisms along the NdFeB supply chain provide resilience in response to supply constraints and disruptions?

4. Can we quantify the resilience mechanisms of the NdFeB supply chain, and identify which played the most significant role in the aftermath of the 2010 REE crisis?

This resulted in the second set of papers, the first, "*Framework for resilience in material supply chains, with a case study from the 2010 rare earth crisis*", introduced a theoretical framework on resilience in the NdFeB supply chain, and a second accompanying paper, "*Quantification of Resilience in the NdFeB Supply Chain"*, quantifying the resilience mechanisms described in the framework paper. These represent chapters 5 and 6 in this dissertation.

Finally, Chapter 7 offers a summary of the results and reflections of what these results mean in a broader context, as well as recommendations for future research.

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2

Recycling potential of neodymium: the case of computer hard disk drives

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2.1 Introduction

In this chapter we will explore the question of how much neodymium realistically is available for recycling. First we review the literature on production statistics of neodymium (Section 2.1.1) and its main applications and its potential for recycling (Section 2.1.2). This is followed by a short overview of the technical options for recycling (Section 2.1.3). From this review we conclude that recycling of computer hard disk drives (HDDs) is currently the most feasible pathway towards large-scale recycling of neodymium. In the Results section we present a dynamic model of the recycling potential of neodymium from HDDs. Compared to existing literature we add empirical data on collection rates, using historical HDD shipment figures and up-to-date forecasts for both desktop and enterprise markets in order to improve modeling accuracy. Finally, we will reflect on the potential of recycling to contribute to the neodymium market, and what could realistically be done to close the HDD neodymium material loop.

2.1.1 Statistics on Neodymium primary production and application

Unfortunately, literature sources are rather nebulous on the subject of neodymium production and usage statistics. Zepf[1] shows that almost all literature sources ultimately depend on a single source of information, the China Rare Earth Information Centre. Nevertheless, he estimates that the total neodymium production in 2007 was 21,141 tons. In that same year NdFeB magnet production was estimated to be around 70,000 tons, implying that 18,500 tons (88%), of total neodymium production was used for magnets. Figure 2 shows the breakdown of other neodymium applications.[1] Note that these numbers carry an uncertainty of roughly 40% when compared to different literature sources and market analysis reports.

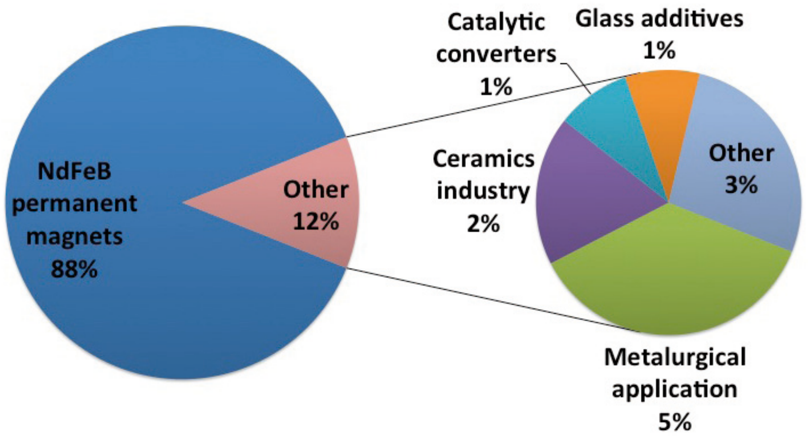

Figure 2 Neodymium use statistics.[1,2] Note that these figures contain significant uncertainty.

Within the application of neodymium in magnets, data quality is again of concern. HDDs are often cited as the biggest application (30% in 2008),[3,4] although Zepf[1] arrives at no more than 8% in 2010, a conclusion which is supported by our research presented later in this paper. Other NdFeB applications are noted in Table 1.

Table 1 NdFeB permanent magnet usage statistics.

Application	% range	Comment
Hard Disk Drive	8-35%	Most likely ~ 8%[1]
Wind turbines	0-15%	Most likely ~ 3.6%[1]
Automotive	15-25%	
Electrical motors	25%	Various industrial and consumer products
Optical	5%	
Acoustic	5%	
MRI	5%	
Others	0-37%	Calculated from the sum of other applications

The picture is complicated by reports from market analysis companies that during 2010-2012 NdFeB use fell by 50%, from 80 kton to 40 kton, reportedly because the rising price of rare earths caused many large consumers of NdFeB to switch to alternative technologies without permanent magnets.[5,6] Looking at 2012 – just after the height of the rare earth scarcity crisis – they peg the worldwide NdFeB production capacity somewhere between 80 kton and 120 kton, implying a large overproduction capacity.[6,7] This is corroborated by reports in the media that the main producer of neodymium halted production at its main facility for many months in the period 2011-2013.[8,9]

From a recycling point of view we can see that due to the small volume and varied and/or diffuse nature of the non-permanent magnet applications of neodymium, recycling from sources other than permanent magnets would not make a significant impact on the neodymium supply. In the next section we will review the literature on recycling potential of NdFeB magnets.

2.1.2 Recycling potential

Du and Graedel[3] estimate that in 2007 62,600 tons of neodymium and an additional 15.700 tons of praseodymium (Pr) were in stock in society. These in-use stock figures include magnets in many different applications, ranging from household appliances to wind turbines. Data quality issues aside (the authors write that these figures should only be seen as a first indication), these numbers are difficult to correlate directly to recycling because of the varying recycling potential of these different applications. Nevertheless Binnemans at al.[10] attempt to do so by extrapolating the in-stock values given in Du and Graedel[11] with estimated growth numbers for the various applications of permanent magnets. They use two scenarios for collection rates, 30% and 60%, and assume a recycling process efficiency rate of 55%. This results in a first, very rough, estimate of 3300 – 6600 tons of Nd+Pr recycling potential from magnets in the year 2020.

Rademaker et al.[12] look at recycling potential from NdFeB magnets in more detail, but for a more limited set of applications. They provide a forecast for recycling potential from wind turbines, automotive and HDDs through 2030.

The very large quantity of magnets used in direct-drive wind turbines[13] would appear to be a prime target for recycling. However, because of the estimated 20-year lifetime of wind turbines these magnets will not be available for recycling in the foreseeable future. Rademaker et al.[12] estimate that it should be possible to recycle neodymium from wind turbines in small amounts from 2023 onwards. This could increase to 1 kton of Neodymium from wind turbines by 2030, which would notionally cover 10% of the neodymium demand for wind turbines at that time. However, these calculations are made using direct-drive wind turbine projections from before the rare earth scarcity crisis. It has been reported that large Chinese wind turbine producers have reduced their reliance on direct-drive wind turbines.[6] Therefore these figures could be a significant overestimation of the real future recycling potential in the projected time-span, However, lower demand from wind turbines also implies a lower neodymium demand, meaning that the potential for closing the neodymium loop might be less affected.

The same problems of recent NdFeB usage reduction exist with the estimations given for recycling from automotive applications. Additionally, while the total volume of NdFeB going towards the automotive industry is quite significant, this is not easily recyclable.

A car can contain between sixty and two hundred magnets in anything from seatbelts to the A/C system and different types of magnets are used for the same application depending on the car model.[14] Therefore, automotive is a very difficult sector to start recycling permanent magnets without large and sustained support from the car manufacturers themselves.

Besides the current applications of NdFeB magnets in the automotive industry, there is of course also the promise of large-scale electrical transportation. Zepf[1] estimates that in 2010 ~1% of total NdFeB production was used for hybrid and full electric cars. Although this figure is expected to increase, the large-scale use of NdFeB in electric cars is still an uncertain proposition. For example, the American Energy Department invested $22 million in research aimed at reducing rare earth use in this sector[15] and it has been reported that future models of the iconic Toyota Prius could be built without NdFeB magnets.[16]

Rademaker et al.[12] also provide a first look at the recycling potential of neodymium from HDDs used in PCs. They find that until 2025 HDDs remain the largest source of recycled neodymium. At its peak, in 2015, the HDD industry could source 64% of its NdFeB requirement (11% of total NdFeB demand) from EoL HDDs. This figure then steadily decreases to being able to supply 36% of HDD demand in 2030.

HDDs present a relatively easy path to recycling. Technically recycling is relatively easy, because the magnets are always found in the same place, and are often easily removable once the HDD is opened. The supply of magnetic material should be relatively stable over time because HDDs have been in production for decades and the amount of magnet per HDD has not decreased significantly in the recent past.[1] This leads us to conclude that realistically, HDDs are the only significant and consistent source of recyclable NdFeB at this moment.

We note that the magnets used in HDDs usually don't contain dysprosium, which is another critical rare earth element used to increase the operating temperature of NdFeB magnets. As such, it is used in applications such as electric motors and wind turbines. With respect to the analysis presented in this paper, dysprosium in NdFeB magnets can alter the economic viability of recycling, due to its high price relative to neodymium. Other considerations remain similar.

2.1.3 Short overview of recycling process technologies

In paragraph 2.3 we concluded that at this moment the recycling of HDDs presents the clearest route towards recycling neodymium. In this section we will briefly discuss the technical options most suited for HDD recycling. Unless indicated otherwise we base ourselves on the excellent in depth discussion of rare earth recycling found in Binnemans et al.[10]

The first challenge is to remove the magnet from the HDD. This can be done manually. However, the costs are relatively high as an average worker can only disassemble up to 12 HDDs per hour. Hitachi has presented a machine where up to 100 HDDs per hour shake, rattle and roll in a drum until they fall apart, allowing workers to manually remove the magnets.[10]

Another approach is to utilize the fact that the magnets are always found in the same corner, and use a shear to cut the section with the magnet from the HDD. Although the magnets will not be completely liberated, most of the volume of the HDD can be removed this way.[10]

After separating the magnets from the HDDs, there are three traditional processing routes that could be used for recycling: hydrometallurgical, pyrometallurgical and gas-phase extraction. The hydrometallurgical route is equivalent to the primary production process described in section 2.1. Although this process is well understood, it has the significant disadvantage of requiring the metallic neodymium in the magnet to be converted into a chloride, and then back into its metallic form. This necessitates large energy expenditure, chemical usage and causes significant wastewater production. Although gas-phase extraction, where the extraction process is done while the neodymium is vaporised, was developed to overcome some of the more problematic aspects of hydrometallurgy, it similarly converts metallic neodymium to a chloride.[10]

Pyrometallurgical routes are an interesting alternative. Most elegant would be direct melting, where the magnet is melted and directly reprocessed into NdFeB flakes, so it can be further used in the traditional NdFeB production process. Although the nickel coating of the HDD magnets is reported to initially not have any negative effects on magnet performance, repeated recycling would lead to a high nickel content, which not only would degrade magnetic performance but also constitute a waste of the nickel fraction. Various other pyrometallurgical routes are discussed in detail in Binnemans et al. All have in common that they require large amounts of energy for the melting of the material.

We see hydrogen decrepitation as the most promising process for HDD recycling.[10,17] The magnets are immersed in hydrogen gas, which causes them to disintegrate into small particles. Because the nickel coating does not react to hydrogen in the same manner, it can be removed through sieving. The powder can be directly reprocessed into new magnets because the particle size in the powder is almost equivalent to the particle size after jet-milling in primary magnet production. Recycling process efficiency rates of 95% have been reported.[10]

Additionally, hydrogen decrepitation works very well with the mechanical sectioning of HDDs, because the hydrogen will cause the magnetic material to turn to powder while not affecting the rest of the HDD. The powder can then be removed from the HDD case with rigorous shaking, with a reported 95% recovery rate. This eliminates the costly manual disassembly step.[10]

2.2 Method

In order to estimate the amount of neodymium available for recycling from HDDs, we constructed a dynamic model, using Vensim software (see supporting information for the model, its underlying datasets and additional information). The life cycle of HDDs was modelled with four main stages: production, in-society stock, End-of-Life (EoL) and recycling (see Figure 3).

2.2.1 Production

In the first stage of the model, the production of HDDs in a given year, we distinguish between two HDD formats: 2.5” HDDs containing relatively small NdFeB magnets, and 3.5” HDDs containing relatively large magnets. We also differentiate on the basis of application (see Figure 4). The time period 2000-2012 is based on historical production data while 2013-2017 is based on production forecasts by market analysis companies.

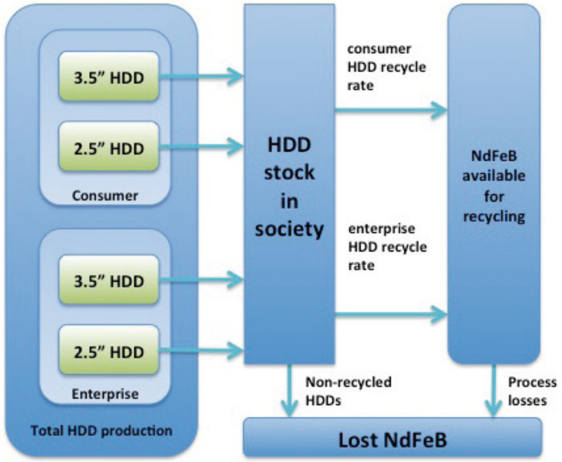

Figure 3 main model elements.

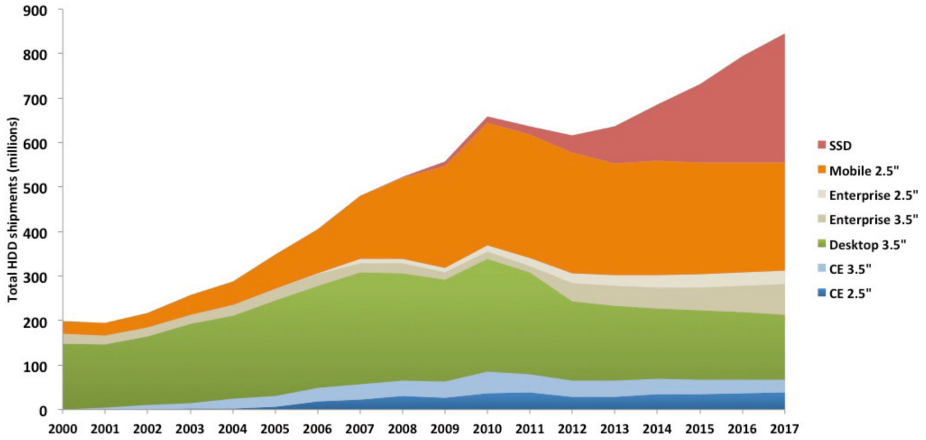

Figure 4 HDD production. Mobile 2.5" drives are used in laptops. Enterprise drives are used in servers or PCs in a business context. Desktop 3.5" are predominantly used in personal computers. Consumer electronics (CE), such as game consoles and digital video recorders, also frequently contain HDDs. For reference, we also include production statistics on solid-state drives (SSD) that do not contain magnets (see supporting information for data and references).

To arrive at the total amount of magnetic material used for HDD production in a given year, the HDD production figure is multiplied with the average NdFeB content of a HDD in that year. Zepf[1] has disassembled a large number of HDDs from the period 1990-2006 in order to measure the

change in NdFeB content of HDDs over time. For 2.5" HDDs there was no measured decrease and we assume 2.5 grams of NdFeB per unit. For 3.5" HDDs we assume that the average weight in 1990 was 17.87 grams, reducing each year by 0.35 grams. Additionally, we disassembled another 10 HDDs produced during 2007-2010. This allowed us to verify that there has been no significant departure from the trend line in more recent years.

2.2.2 In-society stock

The newly produced HDDs flow into the in-society stock, where they reside until the end of their lifespan. For consumer applications the Dutch WEEE collection agency reports an average lifetime of desktop PCs (with 3.5" HDDs) of ten years and six years for portables (2.5" HDDs).[18] In the absence of global data, we assume these numbers to be representative for the rest of the world. For enterprise applications we assumed a six-year lifetime for both 2.5" and 3.5" HDDs, based on information disclosures from large consumers of HDDs in an enterprise setting.[19,20]

2.2.3 End-of-Life

When the HDDs in the societal stock reach their EoL they can either be collected separately or discarded. This process is different for enterprise and consumer applications. In the Netherlands, personal computers and those consumer electronics most likely to contain HDDs are usually collected at municipal waste collection stations, their ultimate destination being general WEEE processing. On the other hand, HDDs used in enterprise applications are often collected and processed separately for reasons of secure data destruction.

In order to obtain empirically derived collection rates we set up a large-scale experiment at a WEEE-processing company, where three container lots with in total 27 tons of WEEE were sorted by means of hand picking. We found a potential 35% collection rate for HDDs from consumer applications. This experiment is discussed in detail in the supporting information. We assume that this 35% collection rate for consumer applications can be generally applied. We have not been able to conduct experiments for enterprise collection rates, because often they are already collected separately for secure destruction. Based on interviews with industry experts we assume a 90% collection rate.

2.2.4 Recycling

After collection the HDDs the magnets contained within them must still be recycled. In our model this process is represented by the recycling process efficiency coefficient. We assume that the recycling technology of choice is hydrogen decrepitation. In this process roughly 5% is lost when liberating the magnetic powder from the HDD encasing (see section 2.1.3); another 5% is lost due to the recycling process itself. We therefore assume the recycling process efficiency to be 90%.

Multiplying the number of HDDs that are EoL by the collection rate and the recycling process efficiency yields the total amount of NdFeB recyclable in a given year. We note here that the model runs until 2023 because data is available up to 2017, and the shortest HDD lifespan is assumed to be six years. Table 2 contains an overview of all the key assumptions in the model.

Table 2 key model assumption.

Assumption	Value	Source
NdFeB content of 2.5” HDDs	2.5 gram	[1]
NdFeB content of 3.5” HDDs	17.87-0.35*t gram (t=0@1990)	[1]
Lifetime of consumer HDDs	2.5” = 6 years 3.5” = 10 years	[18]
Lifetime of enterprise HDDs	Both sizes = 6 years	[19,20]
Collection efficiency consumer HDDs	35%	Experimental data
Collection efficiency enterprise HDDs	90%	Interviews with industry experts
Recycling process efficiency	90%	[10]
HDD production statistics	2000-2012 historical data, 2013-2017 forecasts	TRENDFOCUS INC.

2.2.5 Scenarios

In our baseline scenario the assumed collection rates and recycling process efficiency are relatively high. In order to test the influence of these assumptions in the model we constructed three alternative scenarios (Table 3).

In scenario A we explore what would happen if the collection rates were lower: 25% consumer collection rate (rather than 35%) and a 50% enterprise collection rate (instead of 90%). Note that reducing collection rates has the same effect as reducing recycling process efficiency would have.

The recent turmoil in the rare earth market could give HDD producers incentive to reduce their reliance on NdFeB magnets. Scenario B explores what would happen if the average NdFeB content of HDDs were reduced faster than suggested by the historical trend. We assume that the downward trend in HDD magnet content decreases twice as fast after 2012.

Finally, scenario C explores what would happen if both collection efficiency and NdFeB content were reduced.

The three scenarios are summarized in Table 3

Table 3 Scenario variations.

Scenario		Parameter
A	Lower collection efficiency	25% consumer recycling rate/50% enterprise recycling rate
B	Improved material efficiency in HDD	Doubling of downward trend in average NdFeB HDD content
C	Lower collection efficiency and improved material efficiency in HDD	Combination of A + B

2.3 Results: NdFeB magnet recycling potential from HDDs in the coming decade

The goal of this research was to ascertain the potential of neodymium recovery from computer hard disk drives (HDDs). In Figure 5 we present the results of our dynamic model, showing how the potential for recycling NdFeB magnets from HDDs changes over time. The results are divided into enterprise and consumer applications. For both applications we show the recycling potential from 2.5” and 3.5” HDDs.

Figure 2 also shows NdFeB demand for the production of HDDs, for all applications combined. Because of data constraints, this NdFeB-demand line ends in 2017. Since the shortest lifetime in our model is six years, the recycling potential forecasts ends in 2023.

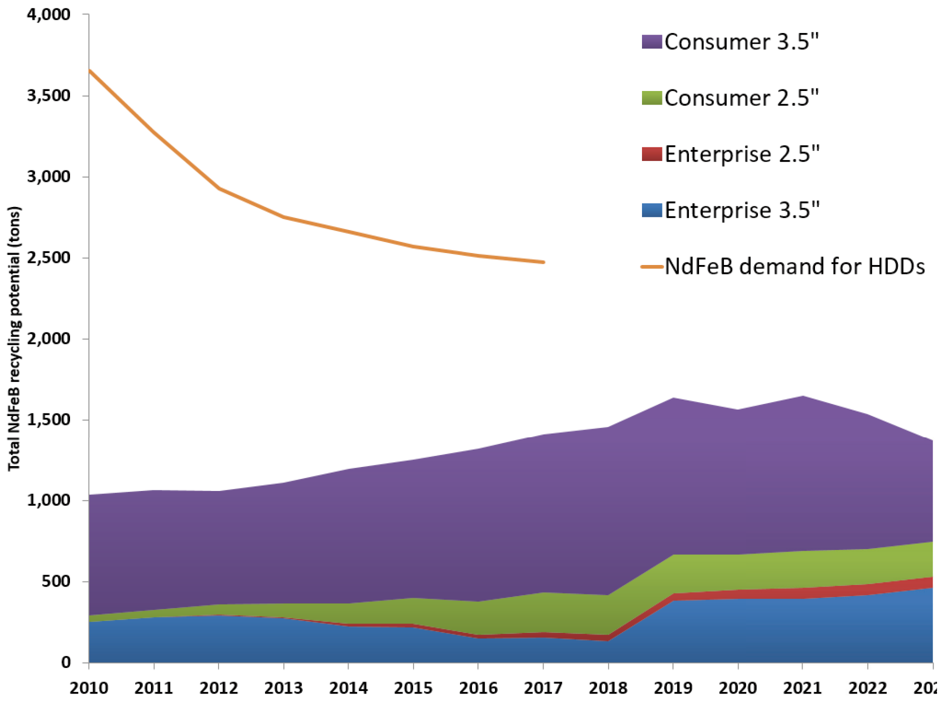

Figure 5 total NdFeB recycling potential (tons) from different HDD types/applications and NdFeB demand for the production of HDDs.

Our results indicate that in 2010, 28% of NdFeB demand for HDDs could have been provided by magnetic material from recycled HDDs. Because of decreasing NdFeB demand and increasing NdFeB available for recycling this increases to 57% in 2017. Based on the trend seen in Figure 5, it would be reasonable to assume that this number increase through 2023, after which the reducing quantity of NdFeB available for recycling will cause the loop-closing potential to decrease.

It is also of interest to put these results in the context of the wider Neodymium market. Our model shows that between 1.0 and 1.6 kton NdFeB can be recycled. Considering that the total NdFeB consumption is 2012 was roughly 40 kton and that this is projected to climb to 80 ktons in the near future,[6] our results imply that recycling from HDDs can supply in the NdFeB market with 1-3% of total demand.

In 2018 there is a sharp increase in NdFeB recycled from 3.5” enterprise HDDs. This is caused by the underlying dataset, where a methodological change in 2012 caused so-called ‘nearline HDDs’ (which are optimized for low-cost high storage capacity) to be added to the enterprise segment, at the expense of the 3.5” consumer segment.

The relatively sharp drop at the beginning of the NdFeB-demand line results from the chosen timespan, which coincides with major floods in Thailand. These caused a number of HDD factories to close, resulting in significantly lower HDD production. Subsequent reductions in HDD production results mostly from a shrinking market for 3.5” consumer HDDs, combined with a lower NdFeB content per 3.5” HDD.

Scenario analysis
In order to test the main assumptions in our model we constructed three scenarios. The results of these are shown in Figure 6. As expected, reducing the collection rate (scenario A and C) has a large impact on the results. On the other hand, varying the amount of magnetic material found in HDDs is less influential, although the effect would increase with time. Note that in scenario C lower collection rates also lessen the total impact of decreasing the NdFeB content of HDDs.

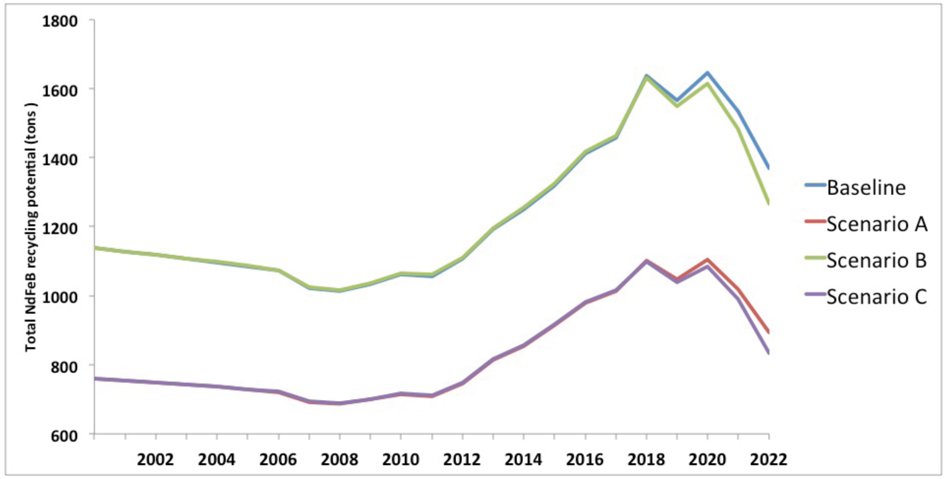

Figure 6 comparison of the baseline scenario with the three recycling scenarios described in Table 3.

2.4 Discussion

In this chapter we investigated the recycling potential of neodymium. Through literature analysis we concluded that of all current neodymium applications, NdFeB magnets are by far the most dominant. Furthermore, in most non-magnet applications neodymium is dispersed to such a degree that setting up a closed loop recycling system would be very difficult.

However, even when restricting ourselves to NdFeB magnets, we find that its usage is spread among an enormous range of applications. Wind energy and e-mobility are often seen as significant potential recycling sources because they contain a high volume of magnets. However, literature shows that because of long lifetimes and price sensitivity these magnets will probably not be available for recycling in large volumes in the next two decades.

As we can see from the tumultuous developments in the neodymium market in the past few years, making predictions on neodymium recycling two decades away is a too long time-horizon for forecasting. Therefore we believe that in the foreseeable future the only realistic source of recycled magnets is from computer hard disk drives (HDDs).

We looked in more detail at recycling from HDDs, using a combination of experimental data and dynamic modelling. Within the application of NdFeB magnets for HDDs the potential for loop closing is significant, up to 57% in 2017. However, compared to the total NdFeB production capacity, the recovery potential from HDDs is relatively small (in the 1-3% range).

In practice there are some obstacles to recycling NdFeB from HDDs.

First, the costs are currently prohibitive. The going rate for 1 kg of EoL magnets in Japan is 10-12€ (although the price can vary according to the dysprosium content, personal communication Toshiyuki Kanazawa, Kanazawa Shokai, 02-05-2014). Although this is an order of magnitude more than the recycling value of shredded HDDs (±1.2 €/kg, personal communication Ramon Bongers, Van Gansewinke Groep, 02-09-2013), the low weight of the magnet makes that the added value of recovery does not exceed the added processing costs. Likewise, although disassembly of HDDs yields a clean printed circuit board (PCB) fraction, containing a host of precious metals, the PCB is usually already mechanically sorted from shredded HDDs. Therefore this makes little difference to the final financial calculation.

Second, for enterprise applications we assumed that HDDs collected for secure destruction are available for recycling, since they are already collected separately. However in practice, contractual agreements sometimes stipulate that HDDs must be shredded immediately upon arrival at the waste management company. This makes it more difficult for companies to experiment with recycling. Finally, without high-temperature demagnetization, shipping and handling large volumes of NdFeB magnets can be difficult, because of their very high magnetic strength.

In the longer term there are a number of wild cards to consider. Although it is not forecasted that SSDs will significantly reduce the usage of HDDs, a technological breakthrough could cause the price of SSDs to drop significantly, which in turn would drive replacement of HDDs by SSDs. Manufacturers could also choose to drastically reduce the amount of NdFeB contained in HDDs, or change HDD design so that the magnets are less easily recycled. For instance, recently HDDs have become available that are filled with helium, in order to reduce friction with the spinning platters. These are welded shut to prevent the helium from escaping. Presumably this also makes it more difficult to recover the magnets (personal communication Thomas Coughlin, Coughlin Associates, 20 - 11- 2013).

We suggest that it could be possible to design a HDD so that a true closed loop should be possible. Considering that the aluminium casing and the placing of the magnet is almost identical in every HDD we imagine it should be possible to standardise these two components and use a simple standardised method to remove the other components from the casing.

Moving beyond the subject of how much NdFeB we can recycle, we would like to address the question of what problems recycling would alleviate. The discussion is often framed in terms of security of supply: for western countries it is not desirable to be dependent on China for virtually the entire supply of rare earths. Since most of the basic processing facilities that are needed to produce neodymium magnets are to be found in either China or Japan, measures to reduce dependence should focus not only on the recovery of NdFeB from waste, but also on the production facilities to reprocess the EoL magnets into new material.

In terms of resource scarcity, we think that in the near future, recycling neodymium will be able to contribute very little because of the distributed nature of the applications. The fact that the whereabouts of a critical metal such as neodymium can only be traced for such a small fraction of the total use, leading to a diminutive recycling potential, should give pause for thought. We suggest that if neodymium is to be used sustainably, a concerted effort must be made to categorize the applications in which it is possible to create a closed-loop and only use Neodymium for these applications. The potential of recycling can be increased significantly if neodymium can traced from mine to material, product and finally to waste. Therefore we are now working on combining global input output data with data on product composition in order to increase our knowledge on the whereabouts of different elements (http://fp7desire.eu/).

Finally, as other authors have done before us,[1] we would like to highlight data quality issues. During our literature research we found many inconsistencies and data of uncertain origin. We have tried to provide a quantitative model on the basis of the available data, but given the degree of cross-referencing in the current literature, more accurate results require new sources of primary data.

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Supporting Information Available

A description of the collection experiments and a short analysis of the environmental benefits of HDD recycling, the input and output of the dynamic model and the dynamic model itself. This material is available free of charge via the Internet at http:// pubs.acs.org/.

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3

Life cycle inventory of the production of rare earths and the subsequent production of NdFeB rare earth permanent magnets

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3.1 Introduction

In the past years the environmental damage caused by the production of rare earth elements (REEs) has received substantial media coverage. The use of REEs in sustainable energy technologies such as wind turbines and electric vehicles has given rise to newspaper articles with titles like 'clean energy's dirty little secret'.[1] These articles describe the appalling conditions under which rare earths are produced. Indeed, a quick search on the Internet will yield dozens of pictures of huge tracts of lands devastated by toxic wastewater, primitive metallurgical workshops and Chinese mine workers covered in radioactive mud.

These detrimental environmental effects of REE production are the official reason why the Chinese government has clamped down on its domestic production, introducing export quotas and forcing many of the smaller production facilities to close. Because China currently wields a near-monopoly over rare earth production (50% of worldwide mineral reserves and 86% market share),[2] this caused great upset in the rare earth market.[3] Numerous studies have pointed to REEs as being critically scarce materials,[4,5] especially in the context of a transition towards a global low-carbon energy system.[6] Recent publications have also focused on how global trade flows of REEs influence scarcity[7] and the possibility of recovering REEs from the bottom ash of municipal solid waste incinerators.[8]

The difficulties encountered in scaling up REE production outside of China, combined with the sharp increase in demand of technologies depending on these rare earth elements and increasingly tighter Chinese export restrictions led to a short-lived scarcity crisis in 2011, where, in the timespan of a few months, the price of certain REEs jumped more than tenfold. During this period numerous industrial and academic initiatives to recycle REEs were announced.[9-12]

Although recycling could help to alleviate scarcity of REEs,[13] it is not immediately apparent that it would also carry a significantly lower environmental burden. REEs are notoriously difficult to process,[14] and, depending on the choice of recycling technology, many of the most energy intensive processing steps would have to be performed on recycled material as well. Nevertheless, the environmental damage caused by primary production of REEs has not been a subject of more than cursory scientific investigation.[15,16] To our knowledge, the environmental impact of REE recycling is not discussed in scientific literature.

In our research we set out to quantify the environmental impact of producing 1 kg of neodymium magnets using virgin material, compared with producing 1 kg of neodymium magnets from recycled material. Magnets are the single largest application of rare earths, taking up 21% of the total rare earth production by volume and generating 37% of the total value of the rare earth market.[17] Although there are two types of rare earth permanent magnets (neodymium-iron-boron and samarium-cobalt), neodymium magnets are more powerful, resulting in the fact that samarium cobalt magnets play only a minor role in the market.[18]

3.2 Method

We used life cycle assessment (LCA) methodology to compare the environmental impact of producing 1 kg of neodymium (NdFeB) permanent magnets in China with 1 kg of equivalent magnets from recycled sources. We assumed these to be used for voice coil motors, as found in computer hard drives (HDDs), and weigh 10-20 grams.[19] The foreground processes covered the entire production chain of NdFeB magnets, from mining to the production of the magnets, but not the incorporation of these magnets into the final products. Capital goods were assumed to be of negligible impact, and therefore not included in the foreground processes.

We created the Life-Cycle Inventory (LCI) using CMLCA software, version 5.2 (www.cmlca.eu), combined with the ecoinvent 2.2 database (www.ecoinvent.ch) for the background processes. The impact assessment was done according to Guinée.[20]

The foreground processes are based on literature sources and interviews with experts.

One of the difficulties encountered in constructing a representative LCA is data availability. Many recent English language publications are based on process descriptions that are over twenty years old.[14,21] Although more recent techniques used for the production of rare earth elements are well described in Chinese literature, associated emissions and environmental damage are usually only referred to in anecdotal manner. Furthermore, there is significant uncertainty surrounding the state of technology in Chinese REE processes. In order to deal with these sources of uncertainty we constructed three scenarios. The baseline scenario is what we think is a realistic representation of the current state of the industry. When literature descriptions are open for interpretation we lean towards more advanced processing technologies, because of the strides China has made recently in consolidating the industry and closing old processing facilities.[22] Of the two alternative scenarios, high-tech represents the best available technology case while low-tech represents the more polluting processing technologies, the main differentiation being efficiency and emission controls.

The exact composition of NdFeB magnets varies by application. Elements such as dysprosium and holmium are added when the magnet is required to operate in a high temperature environment. Usually a mixture of neodymium (Nd) and praseodymium (Pr) is used as an alloying agent, instead of pure neodymium. Because Nd and Pr differ only one atomic number an extra solvent extraction step is needed to separate them. Therefore, in all but the most high-end application neodymium and praseodymium are not separated. However, because this has little influence on the production processes described here, as praseodymium will for all intents and purposes have the same properties as neodymium, we will refer to NdPr alloy as Nd. NdFeB magnets used in HDDs generally do not contain dysprosium, because HDDs are not designed to operate in high-temperature environments. Dysprosium use is not considered in our study.

Finally, it is important to note that during the different processing steps the chemical form of rare earth changes considerably. For instance, the mineral form bastnäsite is $RECO_3F$. During the sulphuric acid leaching step this is transformed to $RE_2(SO_4)_3$ and then to $RECl_3$. However, for sake of clarity we often refer to all of these different forms of rare earths as rare earth *oxides* (REO). This is also how these steps are referred to in the literature.

3.3 Life cycle inventory

In this section we discuss the life cycle inventory (LCI) in detail. Each subsection discusses one process of the LCA. Section 3.3.1 describes the conventional method of rare earths in China from mineral sources. Section 3.3.2 describes the production process used to transform neodymium oxide into an NdFeB magnet. Finally, section 3.3.3 describes two alternative recycling processes that could be used. Detailed information on the LCI, assumptions and allocation choices can be found in the supporting information.

3.3.1 Chinese rare earth production route

In this section we describe the processes used for the production of rare earth oxides (REO), based on the ore composition as found in the Bayan-Obo mine in Inner-Mongolia, China.

Ore removal from mine

Du and Greadel[23] estimate that two-thirds of the total Chinese REO production originates from the Bayan-Obo mine, making it the world's single largest source of REE's. Ore is recovered from the open pit mine using conventional surface mining techniques such as drilling and blasting. The mine contains 750 million tons of ore at 4.1% REO.[24]

Historically Bayan Obo was mined primarily for its iron contents. Rare earths were discarded with the tailings. With REO prices increasing and the Fe content of the ore decreasing this situation has changed. Even though the iron content of Bayan Obo ore is currently only at 30-35%, it is still being commercially recovered.[25]

Beneficiation of REO containing ore

The ore is transported 150 km from the Bayan-Obo mine to the city of Baotou, for further processing.[25] After transportation the rare earth containing minerals, mainly bastnäsite and monazite, are separated from the iron ore and other less valuable minerals. The ore also contains 0.04% ThO_2, which exposes workers to radioactive dust.[25]

First the ore is crushed and grinded to the required particle size, where 90% of the particles are smaller than 74 micrometre. This causes the grains of various minerals to be separated from each other. Magnetic separation is used to remove the iron bearing minerals, while other minerals are removed using a combination of froth flotation and table separation.[18] Table separation utilizes the difference in specific gravity of the various minerals. Froth floatation is a somewhat more complicated process where various chemicals are added to a mixture of finely grinded ore and water. Air is bubbled through the mixture. Certain minerals will attach to the bubbles and float to the surface. The resulting froth is then mechanically removed.

Several chemicals are needed for an efficient floatation process. Frothers are used to produce froth with the required properties, such as being strong enough to support the weight of the minerals, but not so strong as to be detrimental to further processing. Typically alcohols, pine oil or low molecular weight polypropylene glycols are used. Collector chemicals such as fatty acids give certain minerals hydrophobic properties and cause the mineral particle to be more likely to stick to an air bubble. Depressant chemicals such as sodium silicate have the reverse function. Using depressants and collectors in unison makes it possible to separate minerals that would normally both end up in the froth layer. There are many other factors of relevance, such as pH or particle size. The particle should be small enough for the bubble to be able to lift, but not so small as to not stick to the bubble at all.[26] Schüler et al.[18] estimate REO recovery rates of 40% for private and 60% for state-owned enterprises. We assume an average 50% REO recovery rate.

The end result of the beneficiation process is a concentrate containing 61% rare earth bearing minerals, consisting of 50 wt% bastnäsite and 20 wt% monazite with the balance consisting of other minerals, such as iron oxide and carbonates.[27]

Acid roasting

In the acid roasting process we model the production of 1 kg $RE_2(SO_4)_3$ from the 61% REO concentrate produced in the previous process.[27]

Bastnäsite ($RECO_3F$) is a carbonate that can be decomposed to REO and REOF, using high temperature oxidative roasting. Monazite ($REPO_4$) is a highly stable phosphate mineral structure that requires roasting with addition of strong acid or alkali agents. The goal of acid roasting is to remove the fluoride and carbonate so that only water-soluble rare earth sulphate remains, which is leached out of the ore in a later process.

Before the actual acid roasting the concentrate is first dried in a rotary kiln at 400 – 500 °C to less than 0.2% moisture. The subsequent acid roasting is done in a roasting kiln at 150 – 320 °C. The kilns are usually heated with heavy oil, kerosene, gas or coal.[27]

The roasted ore consists of spherical loose balls in 5 – 50mm in diameter. These will easily disperse into water forming slurry, which is important for the subsequent leaching step. More than 90wt% of the mineral particle size of the concentrate is less than 47_m in size.[27]

Other compounds such as ThO_2, CaO (CaF_2), Fe_2O_3 and BaO also consume acid, and HF will react with SiO_2 to generate SiF_4 in the off-gas.

Leaching

After acid roasting the ore will contain $RE_2(SO_4)_3$. This is mixed with cold water in a 1:9 solid/liquid ratio and stirred for four hours, during which the REO will dissolve in the water. Dissolution of $RE_2(SO_4)_3$ is an exothermic reaction. The solubility decreases with increasing temperature. For instance, at 20 °C, the average solubility is 86 g REO/l, while at 40 °C this decreases to 45 g REO/l.[27]

At this point the leachate will still contain impurities such as Fe, Th and P. MgO or $CaCO_3$ is added to adjust the pH of the leachate to 3.5-4.5 (literature does not state the pH before adjustment).[27] This causes the impurities to precipitate in the form of non-soluble hydroxides, phosphates, sulphates, silicates or complex salts.

After settling for 12 hours impurity levels are lower than 0.05 g/l for Fe and P, and lower than 0.01 g/l for Th. The leaching solution will contain $RE_2(SO_4)_3$ and H_2SO_4. At this point a molar excess of caustic soda (NaOH) is added, causing the REO to precipitate in the form of double salts. These precipitates are then washed and dried.[27]

In the final step of the leaching process a molar excess of HCl is added. This converts the salts into $RECl_3$, which can be used as input for the following solvent extraction process.

Solvent extraction

After obtaining a relatively pure 92% $RECl_3$ concentrate from leaching, the individual rare earths must be separated from each other. This is done using a process known as solvent extraction, which exploits the fact that different rare earths differ slightly in their basicity.

The leachate, containing ± 1 mol/l $RECl_3$, is mixed with an organic solvent. Different solvents can be used, such as P204, P507 and P350. Literature indicates that P204 – short for $(C_8H_{17})_2PO_2H$ – is currently most widely used for separating the light/middle weight REE's. By varying the pH, an individual REE can be selectively extracted from the leachate. This must be done in order of atomic weight, from light to heavy. Other parameters like HCl concentration and organic composition will also play important role in the REE separation. A small amount of kerosene is added to prevent emulsification of the two liquids.[27]

Because the difference in basicity between the $RECl_3$'s is minute, the process is repeated at least twelve times for each REE, with higher purities requiring more solvent extraction steps. At this point the separated $RECl_3$ solutions will still contain impurities such as iron and thorium. 0.8 mol/l HCl is added, causing the impurities to precipitate. This washing step is repeated eight times.

Subsequently an inorganic salt (e.g. ammonium bicarbonate) is added. The inorganic salt causes the rare earths to precipitate from the solvent in the form of $RE_2(C_2O_4)_3$ or $RE_2(CO_3)_3$. Finally, the precipitate is heated, causing the formation of rare earth oxides with a purity of up to 99.99%.[18]

3.3.2 NdFeB production route

In the following paragraphs we describe the most widely used industrial processes for making NdFeB permanent magnets, starting with the Nd oxide resulting from the Chinese primary production route described in the previous section.

Nd-oxide molten salt electrolysis

The most common industrial process for the production of metallic neodymium involves dissolving Nd_2O_3 into fluoride based molten salt (e.g. NdF_3-LiF), and electrolysing to produce pure liquid Nd metal. The process is similar to the Hall-Héroult process, used for aluminium production.

NdFeB alloying and strip casting

After obtaining metallic Nd an alloy of NdFeB must be made. In the past this was done using traditional casting methods. However, during this type of casting a small amount of iron is formed in between the NdFeB crystals. This so-called free iron is detrimental to the magnetic properties of the magnet and should be prevented. Additionally, iron is softer than NdFeB alloy, leading to problems later in the milling process. However, free iron is only formed at temperatures somewhat below the liquefying temperature of NdFeB alloy. Cooling the alloy very rapidly from a molten to a solid state can prevent the formation of free iron. For this reason, the most common casting process in industry is strip casting.

In strip casting a mixture of Nd, Fe and B is molten in an induction furnace. This is then poured over a fast spinning copper wheel. The copper wheel is water cooled, leading to cooling rates of 40.000 C°/s. As soon as the alloy hits the copper it solidifies and flies off the wheel, breaking up in flakes of a few mm thick and several cm long in the process. Not only do these flakes contain very low levels of free iron, they are also much easier to process than the solid slab of NdFeB alloy produced by traditional casting methods.

Casting the material increases the oxygen content of the alloy from a few hundred ppm to 2000-4000 ppm. Oxygen has a negative impact on the magnetic properties of the final magnet.

Hydrogen decrepitation

The structure of the strip casted NdFeB flakes consists of NdFeB crystals, forming 100-300 nm-sized grains. The space between the NdFeB grains is known as the grain boundary and is filled with metallic Nd.

When the flakes are exposed to hydrogen the Nd-rich grain boundaries form a hydride, which expands in volume. This causes the alloy to fall apart in a fine powder, where the particle size is equal to the size of the NdFeB grains. The NdFeB particles themselves form an interstitial hydride, where the hydrogen molecules don't actually react with the NdFeB but rather sit in the empty space in the crystal structure. This causes the NdFeB particles to crack, further reducing the average particle size. Together these reactions greatly reduce the amount of energy needed in the following jet milling process to reduce the particle size to the desired 5-7 micrometre range.

Sometimes the powder is then immediately de-gassed by heating it to 600 C, under a vacuum. This causes the particle volume to return to its normal size, which is better for the subsequent pressing process. However, this adds extra costs to the process and makes the material more hazardous to handle, because very fine non-hydride NdFeB powder is pyrophoric. If the material is not de-gassed the hydrogen is released in a later stage, during the sintering of the material.

Jet milling

The NdFeB flakes are milled into 5-7 micron particles using a process known as jet milling, or fluid energy milling. In this process the particles are fed into a cylindrical grinding chamber using compressed gas. Inside the chamber, the compressed gas forms a vortex in which the NdFeB flakes are grinded into ever-smaller sizes. Centrifugal forces cause the bigger particles to move to the outside of the vortex, while the smaller particles move to the centre. A strategically placed outlet removes particles at the desired particle size.

Aligning and pressing

The NdFeB particles need to be pressed before they can be sintered together. Additionally, the particles have a magnetic axis. The better the alignment of the particles when they are pressed, the better the final magnet will be resistant to demagnetisation.

The hydrogenated NdFeB particles are soft magnetic, meaning that they will magnetise under a magnetic field but will lose its magnetic properties as soon as the field is removed. This feature is used for alignment. The NdFeB powder is poured into a mould. The particles are then aligned using a short 4-8 tesla magnetic pulse.

There are two methods for pressing the powder: die setting, where the powder is put in a mould and pressed from the sides, or isostatic pressing, where the powder is put in a rubber mould in a vat with oil. The oil causes the powder to be evenly pressed everywhere. Die setting is cheaper and faster, but the alignment of the NdFeB particles is slightly changed because of the mechanical pressure. With isostatic pressing the alignment remains perfect. Both methods are used commercially.

Vacuum sintering

The blocks of aligned and compressed NdFeB particles are vacuum-sintered at pressures of 2-10 mbar. The temperature (1000 C°) is chosen so that the neodymium-rich phase between the NdFeB particles will liquefy, while the particles themselves remain solid. During sintering the material reaches its final density and all remaining hydrogen is removed.

Grinding and slicing

The sintered block of NdFeB alloy is sliced into rough shape and then grinded and polished into its final form, most commonly using the centreless grinding method. Grinding losses are highly dependent on the final shape of the magnet. For instance, if we assume that our reference flow of 1 kg NdFeB magnet would be a solid block there would be no losses at all at this stage. We will use an average loss rate for voice-coil motors, as used in hard disk drives (HDDs). Losses are estimated to be around 30-40% in China. Production in western countries is more efficient, with loss rates of 15-20%.[28]

The material lost during grinding and slicing can be recovered and re-used for production of magnets, albeit usually at a somewhat lower quality level.

Electroplating

NdFeB magnets are very susceptible to damage in a moist environment, because the Nd-rich phase in the grain boundaries of the NdFeB particles catalyse formation of hydrogen from water. The hydrogen then forms a hydride with the Nd-rich phase, which, similarly to the hydrogen decrepitation process, causes the magnet to disintegrate. For instance, if an uncoated NdFeB magnet would be used in a sea based wind turbine it would be destroyed in a matter of weeks. In these very demanding environments the magnets are laser welded into stainless steel canisters. Most magnets are used in less demanding environments, allowing coating with a nickel or nickel-copper-nickel layer. For our LCA we assume a nickel coating applied via electroplating, both because of data availability and because this is the most common coating for NdFeB magnets. Based on experiments we report that HDD neodymium magnets contain on average 10wt% nickel from their nickel coating.

Pulse magnetising and testing

After coating the NdFeB magnets are subjected to a strong (4-8 Tesla) magnetic field in order to magnetise them. Finally, magnets go through quality control. Depending on how strict the final requirements of the customers are up to 5% can be rejected. Before the dramatic price increases of rare earths these magnets would be discarded. Now they are recycled. Because only a small percentage is rejected and these magnets are recycled we neglect the rejecting of magnets in our LCA. Energy consumption of magnetization is likewise negligible.

3.3.3 Recycling processes

In this section we describe life cycle inventories of two proposed recycling routes. In the first route, NdFeB magnets are manually recovered from HDDs and recycled using a novel hydrogen decrepitating process, described in Binnemans et al.[19] In the second route HDDs are shredded, after which magnetic material is recovered and reprocessed into neodymium.

Recycling using manual dismantling

EoL HDDs can be found in general electronic scrap. Electronic scrap in the Netherlands is usually collected by municipalities, and then sold as container lots to waste management companies, who recycle it. Electronic scrap must be depolluted before further processing in order to remove toxic components such as batteries and printer cartridges. The scrap is spread over a conveyor belt and a team of workers manually removes hazardous components. HDDs are often readily accessible on the conveyor belt. Every 700 kg electronic scrap yields on average one HDD.[28] Since the electronic scrap must be depolluted anyway, this step incurs negligible marginal environmental costs.

The collected HDDs are manually dismantled and the magnets removed. This step is assumed not to have any environmental impact, because it only involves manual labour. We assume each HDD yields on average 15 grams of magnet.[28]

The NdFeB magnets are then put in a container with hydrogen gas. The hydrogen seeps into the grain boundaries, forcing them to expand, resulting in the disintegration of the magnet. This process is equivalent to hydrogen decrepitation during the virgin production process, except that the particle size of the product is much finer, because the powder from the recycled magnet has already been jet milled. Some additional milling is still necessary, but this can be done using a low energy milling process, saving energy compared to the jet milling process used during virgin production. Before milling the powder is sieved to remove the nickel coating. After milling the process steps are equivalent to primary magnet production.

Manual dismantling also benefits the recycling of the other components of the HDD – primarily printed circuit board and aluminium – since these are now less contaminated and could in theory be worth more, although this is currently not the case in the Netherlands.

Recycling using shredded HDDs

An alternative to manual dismantling is using shredders to liberate all the individual components of the HDD. However, this method results in the destruction of the magnet, not only leading to low recovery rates, but also oxidising the material and introducing many contaminants. This results in the necessity of many more processing steps, because the neodymium needs to be leached out of the HDD fragments.

After shredding the neodymium must be leached out of the material and then be reprocessed in almost the same manner that virgin material is processed. Several experiments were undertaken to determine the optimal leaching conditions. 99% of Nd can be recovered from the scrap if a molar excess of sulphuric acid is used. The mixture must be agitated to achieve optimal contact between the scrap and the acid. The Nd is leached relatively quickly, and after eight hours the highest leaching rate is achieved. Temperature has no influence on the leaching rate.[29]

3.4 Results

In this section we present our LCA results. We also report our findings of the environmental impact of the rare earth oxides (REO) production process, since this process is generic for many rare earths and may be of use. Because of the large uncertainties surrounding the primary production process we constructed three scenarios to explore the consequences of different levels of technology.

Section 3.4.1 presents our results on the REO production, 3.4.2 presents the results with respect to the NdFeB magnet production and finally section 3.4.3 contains a contribution and sensitivity analysis.

3.4.1 Production of rare earth oxides

In our LCA we modelled the production of REO with a process that is commercially used for the production of neodymium, cerium, lanthanum, praseodium, europium, gadolinium and samarium. Therefore our cradle-to-gate results for the production of 1 kg REO (99% purity) could be of use outside the context of NdFeB production. These are presented in Table 4. See supporting materials for more information.

Table 4 Characterised results (according to CML2001 impact assessment method) for 1 kg REO.

Name	1 kg REO, High-tech scenario	1 kg REO, baseline scenario	1 kg REO, Low-tech scenario	Unit
eutrophication potential	0.12	0.15	0.18	kg NOx-Eq
acidification potential	0.14	0.17	0.22	kg SO2-Eq
photochemical oxidation (summer smog)	5.3-E03	6.5-E03	85-E03	kg ethylene-Eq
climate change	12	14	16	kg CO2-Eq
Ionizing radiation	3.9E-08	4.1E-08	4.4E-08	DALYs
freshwater aquatic ecotoxicity	2.7	3.0	3.5	kg 1,4-DCB-Eq
stratospheric ozone depletion	2.5E-06	2.7E-06	3.0E-06	kg CFC-11-Eq
human toxicity	36	140	320	kg 1,4-DCB-Eq

3.4.2 NdFeB magnet production

In Table 5 we compare the environmental impact of our baseline scenario for the production of NdFeB magnets from virgin material with two recycling processes of NdFeB magnets found in HDDs.

Compared to the primary production process, recycling via hand picking scores significantly better with respect to most impact categories. This is caused mainly by lower energy use. Additionally, human toxicity is significantly lower, because this recycling process does not include the most polluting processing steps associated with virgin production. The same is true for the recycling of magnets via shredding. Although this recycling process is much more involved compared to recycling via hand picking, the processes related to mining and beneficiation are still avoided, resulting in lower environmental impacts.

Table 5 Characterised results (according to CML2001 impact assessment method) for NdFeB production.

Name	Primary NdFeB magnet, baseline	Recycled NdFeB magnet via hand picking	Recycled NdFeB magnet via shredding	Unit
eutrophication potential	1.9-E01	7.7-E03	3.2-E02	kg NOx-Eq
acidification potential	0.44	0.027	0.20	kg SO2-Eq
photochemical oxidation (summer smog)	1.7-E02	1.1-E03	8.0-E03	kg ethylene-Eq
climate change	27	3.3	10	kg CO2-Eq
Ionizing radiation	5.1E-08	2.0E-08	8.1E-08	DALYs
freshwater aquatic ecotoxicity	14	5.3	11	kg 1,4-DCB-Eq
stratospheric ozone depletion	2.6E-06	9.3E-08	1.0-E06	kg CFC-11-Eq
human toxicity	150	3.6	28	kg 1,4-DCB-Eq

The normalised results (presented in the supporting materials) indicate that for the primary production process the human toxicity component is by far the most relevant environmental impact. Both recycling processes also count human toxicity and freshwater aquatic ecotoxicity as their main impacts, but much less overwhelmingly so.

Figure 7-A shows the amount of neodymium lost along the primary processing chain. The largest losses occur during beneficiation, where 50% of the rare earth containing mineral is lost to tailings. Further losses amount to a total of 64% of the total input of neodymium in the production chain for neodymium magnets is lost. Note that losses during the grinding and slicing of NdFeB blocks are highly dependent on the final size and shape of the magnet, in this case voice coil assemblies used in HDDs.

Figure 7-B shows the neodymium losses along the production chain of the shredded recycling process. We would like to highlight that >90% of the magnetic material is lost during the shredding process.

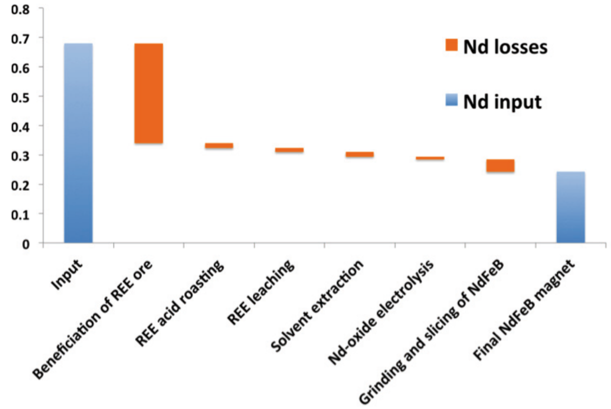

Figure 7-A Neodymium losses along the primary production chain in kg.

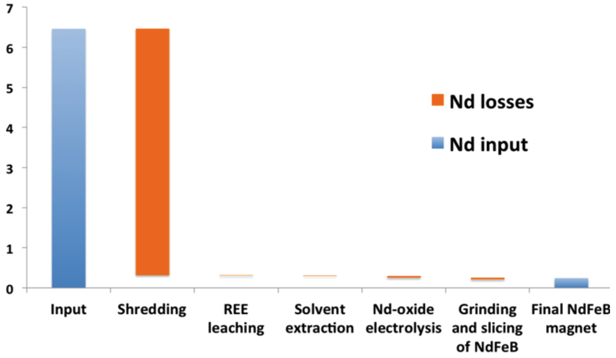

Figure 7-B Neodymium losses along the shredded recycling chain in kg.

3.4.3 Contribution and sensitivity analysis

This paragraph looks in more detail at our results of our LCA modelling. First we will look at scenario's covering different assumptions for the primary production process. Then we will highlight the biggest contributions to the LCA results.

Scenarios

Because of the large uncertainties surrounding the processes used for the production of Neodymium, we constructed three scenarios: a baseline scenario that represents the current state of the industry, a high-tech scenario that assumes best available technology and finally a low-tech scenario. The main differences between the scenarios are efficiencies of various processes along the production chain and differing emission controls. Table 6 shows our scenario results.

Table 6 results of LCA, different scenarios.

Name	[A1] High-tech, primary, NdFeB magnet	[A2] baseline, primary, NdFeB magnet	[A3] Low-tech, primary, NdFeB magnet	Unit
eutrophication potential	0.14	0.19	0.30	kg NOx-Eq
acidification potential	0.37	0.44	0.66	kg SO2-Eq
photochemical oxidation (summer smog)	1.4-E02	1.7-E02	2.6-E02	kg ethylene-Eq
climate change	21	27	41	kg CO2-Eq
ionizing radiation	4.1E-08	5.1E-08	7.2E-08	DALYs
freshwater aquatic ecotoxicity	13	14	20	kg 1,4-DCB-Eq
stratospheric ozone depletion	2.0E-06	2.6E-06	3.9E-06	kg CFC-11-Eq
human toxicity	42	150	470	kg 1,4-DCB-Eq
cumulative energy demand	260	330	490	MJ-Eq
Ore use (4.1% REO)	28	43	76	kg

Compared to baseline, the high-tech scenario requires 22% less energy and 35% less ore. This is reflected in most of the indicators, which are reduced in roughly the same amount. For the freshwater aquatic ecotoxicity indicator the difference is only 7%. This indicator is dominated by nickel use in the coating of the magnets. The high-tech and baseline scenario both use the same coating process, explaining the small difference. Human toxicity is reduced by 72%, due to the modelling of more robust emission controls.

The same trend is observed with the low-tech scenario, which requires 32% more energy and 77% more ore per kg of NdFeB compared to baseline. Most indicators also increase in this range. The exception is human toxicity, which increases by 68%, again caused by modelling the relative lack of emission controls.

Contributions

Regarding human toxicity, in the baseline scenario 81% is caused by emissions of hydrogen fluoride (HF), with the balance consisting of various smaller emissions of heavy metals. 93% of HF is emitted during acid roasting. The low-tech scenario shows the same structure, albeit with higher absolute numbers. In the high-tech scenario, only 52% of human toxicity is due to HF emission, with the balance relating mostly to heavy metal emissions. Of the shredded recycling process, 43% is related to HF emissions during solvent extraction. 36% is related to the emissions of heavy metals related to nickel electroplating, and the remainder to various smaller emissions.

Global Warming Potential (GWP) of all alternatives is almost exclusively due to energy use. In the baseline scenario, 48% of total GWP is due to electricity use of the foreground processes. 17% is attributed to the burning of diesel in electric generators in the mining process. The remainder is due to energy consumption elsewhere in the system. Similarly, eutrophication is mostly due to energy use, although this indicator is dominated (52%) by the emissions of nitrogen oxides of the diesel electric generating sets used during mining.

Acidification, photochemical oxidation, freshwater ecotoxicity and stratospheric ozone depletion all show a similar pattern in that ± 40% is due to the use of nickel in the electroplating process, and the remainder to various small emissions related to energy production. All alternatives show a similar structure, varying with the difference in energy use.

Finally, for the recycling via shredding scenario, we also explored the influence of using the British energy mix instead of the Chinese energy mix. This caused GWP, acidification and photochemical oxidation to increase by roughly half. Eutrophication potential doubled, while freshwater aquatic ecotoxicity, stratospheric ozone depletion and human toxicity hardly changed.

3.5 Discussion

In this chapter we investigated the environmental impact of the primary production process of 1 kg of NdFeB rare earth permanent magnet, and compared this with two alternative recycling processes.

Primary production process
For a technically advanced primary production process of NdFeB, most of the impacts are related to energy use. The outcome of our model is correspondingly sensitive to energy related emissions. Technically less advanced production processes also incur a large human toxicity penalty.

The issue of radioactive waste connected to rare earth production is important. Unfortunately a combination of uncertain data and a lack of appropriate characterisation factors means that the ionising radiation results should only be seen as a first attempt to quantify radioactive impacts during primary production.

Our scenarios from the sensitivity analysis highlight the importance of emission controls and process efficiency. They show a doubling of GWP emissions from the high-tech to the low-tech scenario, while the Human Toxicity indicator increases by an order of magnitude. Please note that the Human Toxicity indicator is very sensitive to hydrogen fluoride emissions during the acid roasting of REE containing ore. Although we are confident of the literature used to obtain our emission data, the characterisation factors associated with hydrogen fluoride are quite uncertain.[30]

We also want to highlight that in our baseline scenario 64% of the total neodymium input is lost along the production chain. 50% of the total loss occurs during the beneficiation process of REE containing ore, meaning that not only neodymium but also all other REEs contained in the ore are lost as well. An improvement to the recovery rate in this process has the potential to significantly reduce supply side constraint. Indeed, Peiró and Méndez[14] report that recovery rate is expected to rise to 75% by 2016.

Recycling process
We looked at two recycling processes. The first recycling process involves collecting HDDs from end-of-life computers, removing by hand the NdFeB magnets contained in HDDs and recycling these using a novel recycling process.[19]

Because this manual recycling process allows the recycled material to be utilised very late in the NdFeB magnet production process, it is very benign, using 88% less energy and scoring 98% lower on Human Toxicity than the baseline primary production process. The largest contribution to the environmental impact of this recycling process is from applying the nickel coating to the final magnet. However, this very positive result also reflects a lack of data on emissions related to this – for the time being – hypothetical recycling process.

The second recycling process involves collecting HDDs from end-of-life computers and shredding these, thereby completely destroying the HDD. Because the most polluting production steps can still be avoided, this less efficient manner of recycling still uses 58% less energy and scores 81% lower on the Human Toxicity indicator, compared to baseline primary production.

These results show that for recycling the choice of recycling method is of significant influence on the environmental impact. However, the most important difference between the two recycling processes is not adequately reflected in the environmental indicators: recycling through shredding results in a very significant (>90%) loss of NdFeB. Because the discussion on the use of rare earths is framed in terms of scarcity more than environmental damage, this is a serious issue not address through LCA.

We conclude that the value of recycling of neodymium is highly dependent on the method of recycling. Although from an environmental point of view recycling always be an improvement over primary production, the large losses of material incurred while shredding the material puts serious doubts on the usefulness of this type of recycling as a solution for scarcity. Furthermore, our LCA also shows that technological progress can make a significant difference in the environmental impact of producing neodymium magnets from primary sources.

Supporting Information Available
This information is available free of charge via the Internet at http://pubs.acs.org/ .

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4

Theoretical background of the resilience framework

In this chapter an overview of theoretical concepts is presented that will be used in the next two chapters to describe and assess the resilience of the NdFeB supply system. It is anticipated that this case study will have wider relevance for critical material supply chains. The first section discusses the social sciences concepts used to understand how the individual actors in the NdFeB supply chain behave and interact with each other. The following section introduces the concept of complex adaptive systems as the general theoretical background for understanding what kind of system the NdFeB supply chain is, from which resilience follows as the theoretical framework to analyze the problems surrounding the NdFeB supply chain.

4.1 Social Sciences theoretical background

This section follows Boons and is mostly based on his book *Creating ecological value*,[1] combined with some elements presented in his paper *Dynamics of industrial symbiosis*.[2] The work of Boons deals with how individual firms shape their ecological strategies to deal with emerging environmental problems, and how these firms interact to shape the dynamics at the system level. There were two main reasons for using the work of Boons. Firstly, Boons uses the company as the basic unit of analysis and explicitly places this company in a larger context, and specifically investigating the interaction between companies in a network. Secondly, Boons includes intangibles such as knowledge and legitimacy, which is an important aspect to the success of circular economy projects, yet not often addressed in industrial ecology literature.

In accordance with *Creating Ecological Value,* the socio-technical system can be looked at from three levels of analysis:

- The *production-consumption system*. Society has certain needs, which the production-consumption system meets by converting materials into services (e.g. the need for energy can be met by the producers of wind turbines or PV panels).

- The NdFeB *supply chain*. The collection of actors that cooperate to provide the NdFeB required by the production system to provide its services (e.g. direct-drive wind turbines).

- The *individual company.* The basic unit of analysis in this framework.

4.1.1 The production consumption system

When viewed from the production-consumption system level, change is often framed in evolutionary terms, both by Boons and in industrial ecology literature.[3] After Boons,[1] the main evolutionary mechanisms through which companies adapt to changing conditions are:

Coercion: an organization is forced to adopt a certain concept or routine by another organization that holds power over it, such as the government issuing a rule. Coercion is very evidently in play when looking at the 2010 Chinese export blockade and all its repercussions, for example multinationals moving the factories of NdFeB containing products to China because the price of NdFeB is significantly lower in China because of export restrictions and taxation (see also the discussion of research question 4, conclusion section in Chapter 7).

Imitation: organizations may adopt routines and concepts they see in similar organizations.

Private interest governance: a group of organizations may choose to collectively adopt a concept or routine voluntarily, because of the threat of legislation if they remain inactive. For example, the current standardized format for describing the different qualities of scrap metal are too coarse for high-level recycling. The International Solid Waste Association (ISWA) is currently in the process of identifying new material quality standards more befitting a circular economy.

Demonstration projects: actors may initiate experiments with new concepts and routines, and actively spread the results of these under a label like 'best practice' to accelerate its diffusion. For example, VGG actively pursued C2C projects with interested other companies. Even though many were not instantly profitable, they were pursued in the hope of demonstrating the viability of the concept.

Training and professionalization: individuals may learn about new concepts and routines through education, and subsequently start to apply these in their work environment.

Choi suggest that allied companies in a complex supply network should try to improve their cooperation through common work norms, procedures and shared language.[4] This notion of creating a shared language can go a long way in alleviating coordination problems and can be done through training programs and workshops. For example, after VGG came into contact with C2C it sent hundreds of its personnel, including the upper management, to Hamburg for C2C training by EPEA. The effect of this was an increased willingness in the company to work with C2C.

Altering boundary conditions: actions to stimulate actors within resource networks to self-organize. For example, the main driver for this research project is perceived future resource scarcity and sustainability. In that sense one might argue that the looming resource and energy crisis form an altering boundary condition that stimulate actors to self-organize.

In Chapter 5 we will identify mechanisms that were triggered in the NdFeB supply chain in response to the 2010 REE supply disruption. The above set of principles can usefully be seen as the evolutionary mechanisms that underlie the ability of the NdFeB supply chain to react to such supply disturbances.

4.1.2 Supply chains and resource networks

The NdFeB supply chain (or any supply chain for that matter) requires a large number of disparate inputs in order to operate. This makes a complete supply chain quite complicated to analyze from a network point of view. Therefore, Boons proposes to use resource networks as the unit of analysis. These networks are a subset of the overall supply chain network that only deal with a single type of resource. These are not only physical resources, but also with intangibles such as knowledge and social resources such as legitimacy. Boons distinguishes between four types of resource networks: economic/material exchange, knowledge, rules, and collective perceptions & societal demands.

Boons hypothesizes that the creation of closed-loop material systems is aided by a high level of institutional capacity, which is defined as "an array of practices in which stakeholders, selected to represent different interests, come together for face-to-face, long-term dialogue to address a policy issue of common concern".[2]

Using the concept of resource networks (that deal with different types of resource, both physical flows and intangibles such as information) allows us to separate the discussion on physical flows and intangibles. The work in this dissertation is mostly based on the physical part of the supply chain. The work on intangibles is reflected in the MSc thesis *Information exchange and collaboration in recycling supply chains: Lessons from the paper and plastic recycling industry* (Valstar 2013).

4.1.3 Companies

As discussed in the introduction of this chapter, the research results in this dissertation are mostly on the level of the overall NdFeB supply chain. In order to give a complete theoretical framework, this paragraph will briefly discuss the types of environmental strategies that companies commonly follow with regards to adapting their behavior to a changing environmental context. Boons distinguishes companies according to their overall strategy in reacting to environmental challenges. These three basic 'strategic perspectives' are:

- Stable; which more or less equates to conservative; companies want to keep the status quo. Their environmental strategy can for instance be obtaining illegally smuggled material if regular supply becomes unavailable. Examples from outside the field of material criticality include resisting environmental regulations or only applying end-of-pipe pollution reduction measures.

- Dynamic; these companies tend to go with the flow. They could for instance try to weather material crises by relying on stockpiles or substituting critical materials.

- Transformative; companies that really try to transform the system. For example, invest in vertical integration to ensure a steady supply of raw materials, or focus on product-service systems so that the materials used by these companies remain in their ownership.

In order to following a general strategy, a company needs a collectively shared perception of the ecological impacts created by the company, and the possibilities for dealing with this impact. For example, the 2008 annual report of VGG states that:

> 'Cradle-to-Cradle is leading for our approach to waste management. This philosophy is based on possibilities instead of "guilt management". It also is our drive for giving sustainability a place in our daily routine. Our knowledge of waste is valuable for our partners. With them we can play a role in the design phase of their products, so that a profitable solution is possible.'

At VGG, resource scarcity plays a much larger role than global warming or biodiversity. This is due to the fact that resource scarcity very directly affects the day-to-day business of the company, in the form of rising prices they receive for recycled materials. In this sense, VGG's embrace of resource scarcity as a key driver for its sustainability commitment is logical as it presents an opportunity rather than a threat. Other aspects such as the impacts from emissions are dealt with in a more conservative fashion, with factories adding end-of-pipe technologies to reach emissions levels required by legislation. In this sense VGG is a transformative company on its primary business domain (resources), while having a stable strategy to deal with environmental concerns outside its immediate area of interest.

Boons uses the concept of routines to describe how companies actually implement their environmental strategies. Routines are procedures that have proved their usefulness. They represent knowledge that is somehow embedded in the organization's structure, culture or processes. These routines are used by a company to attain the goals set in its general strategic orientation. Boons distinguishes three dimensions of organizational routines:

- Operative routines; the knowledge and organizational abilities for getting the actual work done.
- Coordinative routines; the knowledge and organizational abilities for coordinating activities with other companies, for instance partnerships with suppliers or competitors.
- Formative routines; the knowledge and organizational abilities to shape the context in which operative routines are taking place. These routines are intended to influence the wider system surrounding the company so that the activities of the company are considered legitimate. For example, marketing to influence public opinion or lobbying to influence legislators.

An interesting point related to coordinative routines is that the recycling industry works with certain specifications, for instance the EU scrap specifications.[5] These are very general. For VGG to become a provider of raw materials, the recycled material will need to comply with much tighter specifications, comparable to that provided by primary production. During discussions at VGG it was often mentioned that better sorting and processing to achieve these high quality specs is not profitable since no-one is willing to pay extra for pure materials. This is probably a chicken-egg problem, but nevertheless it is clear that for a circular economy the quality of recycled material must improve drastically.

4.2 Complex Adaptive Systems theoretical background

In this section the basic theoretical concepts behind complex adaptive systems (CAS) will be reviewed, providing a further theoretical basis for the following two chapters. We start with a short description of the main characteristics of complex systems, and then conclude that resilience is a suitable concept through which to apply the insights gained from complex systems theory to the problems faced by complex supply chains such as that of NdFeB.

According to Dijkema & Basson, complex systems 'are characterized by diversity, multiple interactions both within and between layers, feedback loops, and emergence'.[3] Waldrop more formally defines complex adaptive systems as:

> 'A dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a CAS tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents.'[6]

Competition and cooperation among agents is also indirectly referred to in the social sciences section, which describes change on the system level in evolutionary terms (section 4.1.1). In this sense the social sciences section provides an interpretation of the complex NdFeB supply chain system.

Examples of complex adaptive systems range from schools of fish to ecosystems to the human brain. Recently complexity theory has increasingly been used to understand the functioning of our society. For instance, an essay in Foreign Affairs argued that the collapse of empires throughout history should be seen as a function of the fact that empires are complex adaptive systems, which fail when they can't resolve inevitable issues with resource constraints.[7] A commentary in *Nature* lamented that our current economic system is badly mismanaged because monetary policies are based on statistical models that are inherently incapable of adequately describing the more extreme, non-linear, behavior of the global economy, caused by the fact that the economic system exhibits behavioral traits of complex systems.[8] *Science* reported how complex systems-based modelling was able to predict the eruption of ethnic violence in India and former Yugoslavia based on a characteristic group size of people that prefer similar neighbors.[9] Nissim Taleb wrote a popular science book on the consequences for our personal lives of erroneously interpreting a complex system as a linear system.[10] And finally, complexity theory is also fundamental to industrial ecology where sustainability is seen as an emergent property of our society.[3,11]

The journal of Industrial Ecology has dedicated two special issues to the topic (April 2009, Volume

13, Issue 2, and April 2015, Volume 19, Issue 2). This growing interest in complexity from the industrial ecology community is because complexity theory and related methods '… can help us determine how these systems shape both the relation and the mutual impact between us humans and the planet. It provides information to underpin policy and strategy for sustainable development',[12] and adds a very useful dynamic aspect to the traditional toolbox of LCA and MFA.[13]

The remainder of this section contains a discussion of relevant attributes and aspects of complex systems. Concepts such as emergence and feedback loops are core concepts in the resilience framework presented in Chapter 5, while it will become apparent that path dependence plays an important role in substitution options, because having more substitution options implies that your product development is not as dependent on the previous path it has taken.

4.2.1 Emergence

In industrial ecology literature (un)sustainability has been defined as emergent behavior of our social system.[13] A definition of emergence is 'the arising of novel and coherent structures, patterns and properties during the process of self-organization in complex systems',[14] resulting from many agents interacting with each other according to relatively simplistic rules (also known as fundamental rules). A classic example of emergent behavior is that of schools of fish:

> '[The emergent behavior is] based on fundamental behavioral rules such as attraction, parallel-orientation, and repulsion. Multiple individuals following the same rules interact with each other and thus realize school movements. When the school advances, unstable movements by the front individuals cause a change in the moving direction of the individuals that follow that individual. The transmission of the change in moving direction of the front individuals to rear individuals depends on how the individuals react to the motion of their neighbors. When the individuals react mainly to the motion of their front neighbors, the change in direction of the front individuals is transmitted quickly to the rear individuals, resulting in sharp turns by the school. In contrast, when the individuals react mainly to the motion of their side neighbors, the change in direction of the front individuals is slowly, if at all, transmitted to the rear individuals, resulting in only gradual turns by the school.'[15]

A unique feature of human society as a complex adaptive system in comparison to schools of fish is the fact that humans are not only adaptive but also reflective. That is, humans reflect upon society and this thinking informs human action, through which we manipulate the fundamental rules of society in order to obtain the desired behavior (but also unintended consequences). Rotmans & Loorbach distinguish 'three different types of emergence: discovery, mechanistic emergence, and reflective emergence. In systems exhibiting the latter type of emergence, the observers are among the objects of the system and have some reflective capacity, which enables them to observe the emergence they produce.'[16]

When applying this distinction to the NdFeB supply chain, one might theorize that the emergent resilience responses to the 2010 REE crisis are a form of mechanistic emergence; the actors in the supply chain did not reflect on the crisis but reacted more or less blindly, for example substituting a materials after it has become prohibitively expensive. On the other hand, when actors now decide to redesign their products to facilitate future substitution, this is an act under the umbrella of reflective emergence. With respect to the conclusions drawn from this research project, the entire dissertation can be framed as an exercise in reflective emergence.

4.2.2 Feedback loops

An important feature of complex systems is that they react non-linearly to input. This behavior is caused by feedback loops and can be explained by looking at the fundamental rules of a system. If you change something that goes against the fundamental rules, its effect will be damped because the fundamental rules are applied a huge number of times by all of the agents in the system. This is the negative feedback loop. On the other hand, if something happens that is amplified by the fundamental rules, or even a change in the fundamental rules themselves, it will propagate very fast throughout the entire system, also known as a positive feedback loop. This extreme change (relative to the input) will then interact with other parts of the system that could again involve positive feedback loops, leading to completely unpredictable but potentially very extreme changes.

According to literature, changing the fundamental rules in a complex system seems a matter of applying the goldilocks principle: not too much but also not too little. Rotmans & Loorbach write that "immediate radical change would lead to maximal resistance from the deep structure, which cannot adjust to a too fast, radical change. Abrupt forcing of the system would disrupt the system and would create a backlash in the system because of its resilience. Incremental change allows the system to adjust to the new circumstances and to build up new structures that align to the new configuration."[16] On the other hand Choi notes that the tendency of a complex system to maintain its stable and prevalent configuration works against incremental changes that go against the accepted practices. Therefore a meaningful change has more chance of lasting.[4]

In summary, the literature suggests that the most effective way of changing the emergent behavior exhibited by complex adaptive systems is by creating novel positive feedback loops.

4.2.3 Complexity and complicatedness

Complexity is not the same as complicatedness. Although they can be difficult to differentiate, distinguishing between the two is important because, according to Allan & Tainter, increasing the complexity of a system could solve problems while increasing complicatedness actually worsens these problems.[17] An example: suppose we have an ecosystem with only herbivores, which leads to overgrazing. Adding another species increases the number of elements in the system. The system becomes either more complex or more complicated. Conversely, adding a herbivore would make the system more complicated while not solving the problem of overgrazing. Adding a carnivore on the other hand would add a completely new layer of organization to the ecosystem, thus increasing complexity.

An example more closely related to the subject of resource constraints: in ancient Roman times copper could be mined in the hills around Rome at 20% ore concentration. Today we still mine copper ore, but at much lower concentrations, and at much remoter locations. Even though theoretically enough resources remain, the law of diminishing returns dictates that the costs of extracting these resources are increasing. As found in Chapter 6, one of the most forceful system responses to the 2010 REE crisis was to open new mines. However, this method of dealing with problematic resource extraction by increasing resource extraction amounts to replication of structure, and thus increasing complicatedness.

The most obvious way to increase complexity is by adding a different type of species to the REE ecosystem: recyclers. Although a single small recycler won't have much of an impact on the system level, once recycling incurs lower costs than mining, a positive feedback loop can be established with the potential to reorganize the supply chain.[17] The fact that this positive feedback loop was not established in the REE sector is discussed in Chapter 7.

4.2.4 Path dependence

The evolution of complex adaptive systems is inevitably path dependent and often irreversible, leading to lock-in. This is a problem because complex adaptive systems are fundamentally unpredictable (e.g. when fossil fuels started to be used climate change was not a big concern). Having expensive, fixed technological pathways that operate in unpredictable systems is undesirable.

Take for example our transport system: if one could re-design the world from the ground up, maybe cars could be replaced with a radically different and more efficient transport system. However, the huge investments in roads, technologies, vehicles, etc. mean the sunk costs and vested interest are simply too large to abandon the system.

4.2.5 Complex Adaptive Systems and resilience

Complex adaptive systems are unpredictable and difficult to manage. They are not only unpredictable, but even their unpredictability is unpredictable, meaning that one cannot even make an uncertainty estimate. The chances of these kind of extreme events are low, but as a system becomes more complex and interconnected the odds of an extreme event becomes ever greater. The 2010 REE crisis is a good example, which was initially caused by a completely unrelated diplomatic incident between Japan and China.

It is very difficult to plan for this kind of uncertainty.[1] Fortunately, complexity theory also suggests a coping strategy in the form of resilience, which has been argued to be in itself an emergent behavior of complex systems.[18]

Although a massive amount of scientific literature is available on resilience, the starting point of the resilience work presented in this dissertation was Wardekker et al.,[19] who formulated a number of resilience strategies:

- Homeostasis: multiple feedback loops counteract disturbances and stabilize the system.
- Omnivory: vulnerability is reduced by diversification of resources and means.
- High flux: a fast rate of movement of resources through the system ensures fast mobilization of these resources to cope with perturbations.
- Flatness: the hierarchical levels relative to the base should not be top-heavy. Overly hierarchical systems with no local formal competence to act are too inflexible and too slow to cope with surprise through rapidly implementing non-standard highly local responses.
- Buffering: essential capacities are over-dimensioned such that critical thresholds in capacities are less likely to be crossed.
- Redundancy: overlapping functions; if one fails, others can take over.

Interestingly, flatness is the opposite of increasing complexity, as discussed in the preceding section. According to Allan & Tainter increasing complexity of a system has the potential to solve problems, but also increases the risk of system collapse when not enough resources are available to support that level of complexity.[17] Therefore it makes sense that there is a point at which a system becomes overly complex, reducing the resilience of that system.

Meerow & Newell published a review of resilience and industrial ecology, showing that there is limited but growing interest in the topic.[20] Topics of research were eco-industrial parks, urban ecology, the built environment, recycling, and energy, water, food, economic, and agricultural systems. They also performed a network analysis, finding that the five most clusters research topics of resilience in IE were: (1) topically diverse; (2) risk and resilience in technical systems; (3) IE and resilience; (4) urban systems; and (5) agricultural systems. Meerow & Newell then conclude that 'given the emerging importance of the resilience concept and its relevance for sustainability issues, industrial ecology should expand research efforts in this area,' which is exactly what this dissertation aims to do.

A further review of literature specifically relevant to resilience in material supply chains can be found in Chapters 5 and 6.

4.3 References

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5

Framework for resilience in material supply chains, with a case study from the rare earth 2010 crisis

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5.1 Introduction

The 2010 REE crisis provoked a multitude of reactions across the entire NdFeB supply chain, ranging from dozens of junior mining companies claiming imminent rare earth production to end users reducing their reliance on neodymium magnets, or even substituting NdFeB completely.[1,2] The sum of these events resulted in prices falling significantly, if not actually reaching pre-2010 levels. Although the REE sector has many idiosyncrasies, when looked at from afar this type of boom-bust dynamics can often be observed when small raw material supply chains are integrated as supplier into a major industry.[3]

As the dust of the 2010 REE crisis was settling numerous reports and scientific publications investigated the rare earth sector, sometimes with diametrically opposed conclusions. For instance, Gholz writes that "the largely successful market response" offers the lesson that "policymakers should not succumb to pressure to act too quickly or too expansively in the face of raw material threats."[4] On the other hand, Tukker concludes that "Western governments ignored market failures" resulting in the fact that the Western world was "entirely outmaneuvered by an economy that was guided."[5]

More cautious analyses are made by Machacek and Fold, who focused on the efforts of Molycorp, Lynas and Great Western Minerals group to build a Western primary REE supply chain.[6] They give a good historical overview of events and conclude that the bottleneck for the establishment of alternative REE supply chains is at the chemical separation phase, because this technically challenging process is both expensive to build and operate. Golev et al. contribute a broader overview of several non-Chinese supply chains, discussing their opportunities and constraints in increasing primary production while also noting that there is industrial interest in recycling.[7]

Both Rademakers[8] and Sprecher[9] investigated the recycling opportunities for NdFeB, showing that recycling of magnets will most likely have limited effect on global supply. Seo and Morimoto compared recycling and substitution strategies from a Japanese perspective and concluded that substitution makes more sense because most of the Japanese REE demand is subsequently exported and not available for recycling to the Japanese industry.[10]

From this body of literature it is clear that the REE supply chain is a complex and intricately interlinked system. However, previous work has for the most part only analyzed small parts of the system in relative isolation. We are not aware of any work that takes a broader systems perspective and uses a rigorous theoretical framework to analyse the resilience of the NdFeB system as a whole. This perspective allows the analysis of different aspects in a wider system context, whilst also investigating interactions between different parts of the supply chain. We feel this is especially relevant because it provides an interesting case study for more generally applicable insight into the ways supply chains of critical materials can respond to resource constraints and disruptions.

Based on an extensive literature review and interviews with actors ranging from large players such as Siemens and Hitachi Metals to individual entrepreneurs and government agencies, we developed a framework that aims to improve our understanding of how material supply chains respond to supply constraints and disruptions. We were guided by two research questions:

1) What type of mechanisms along the NdFeB supply chain provide resilience in response to supply constraints and disruptions?
2) What system perspective based policy recommendations can be made to improve the capacity of the NdFeB system to deal with future constraints and disruptions?

In our research, we used resilience theory as a framework to interpret the information we gathered from the interviews. Resilience can be defined as the capacity of a system to tolerate disruptions while retaining its structure and function.[11] Further below we develop a framework for the interrelated and complementary mechanisms that provide resilience in material supply chain, when these are confronted with resource constraints and disruptions.

In the remainder of this work we use ‘disruption’ to refer to quick, short-term supply disturbances and ‘constraint’ to refer to slower, long-term disturbances.

The resilience of systems has long been a subject of research, and is a recognized feature of many types of systems ranging from ecological to socio-technological.[12,13] We hope to advance resilience research by developing a novel and concrete framework that defines and clarifies resilience in material supply chains. Novel, because we are not aware of any research on the combination of resilience theory and resource constraints. Concrete, because we made extensive use of knowledge of the physical flows in the NdFeB supply chain. Our framework conceptualizes the dynamics of the NdFeB system in terms of resilience, and shows how and where distinct resilience concepts apply in the various stages of the NdFeB supply chain.

5.2 Method

Using a semi-structured interview format we first interviewed actors from across the NdFeB supply chain, as well as governmental and academic experts. 15 interviews were conducted in total. Seven interviewees were from Japan, seven from the EU and one from the US.

We then used the input from the interviews to build a qualitative representation of the NdFeB supply chain, using the system dynamics methodology introduced by J. Forrester.[14] As far as possible we used the same terminology as commonly used in material flow analysis.[15] This allowed us to map the socio-economical drivers on the physical flows in the supply chain, and visually represent at what places in the physical supply chain different mechanisms contribute to resilience.

NdFeB magnets often contain other rare earths in addition to neodymium, most notably praseodymium and dysprosium. For the sake of readability we will address these collectively by using the terms NdFeB and neodymium, except when relevant (in section 5.4.3).

Our results are based on information provided by the interviews, except where references to specific sources are given. The developed framework is our own work, that served to interpret the provided content in view of resilience theory. The full list of interviewees and the semi-structured interview questionnaire can be found in the supporting materials.

5.3 Resilience and the NdFeB supply chain

In section 5.3.1 we define supply chain resilience. Section 5.3.2 introduces rapidity, resistance and flexibility as the three system traits that together give rise to supply chain resilience. In section 5.4 we discuss the concrete mechanisms found in the rare earth supply chain that underpin rapidity, resistance and flexibility.

5.3.1 Definition and features of supply chain resilience

A more resilient system has properties that allow it to show limited consequences from disruptions and fast recovery times.[16] In the context of material supply chains we define resilience as *the capacity to supply enough of a given material to satisfy the demands of society, and to provide suitable alternatives if insufficient supply is available*. In practice this means that both the supply and demand of NdFeB will need to have a certain elasticity, which allows the system to absorb supply or demand disruptions without significant price fluctuations.

Although the literature mentions reduction of failure probabilities as playing an important role in enhancing resilience,[13,17-21] we stress that in the context of this framework we see resilience as the sum of several generic system dynamics, observable in material supply chains. These dynamics together enhance the overall response of the system to any kind of disruption, whether foreseen or unforeseen.

Our work could suggest that resilience is always good thing. However, whether this is true depends both on the boundaries of the system under investigation and the timescale under analysis.[11] It is worthwhile to note that the flip side of resilience is lock-in. Thus, short-term desirability for resilience can come in conflict with long-term desire for system change.

For example, the energy system could become more resilient, if more unconventional fossil sources were put into production. In the short term and from a local perspective the improved stability of energy infrastructure (energy security) is a positive. For instance, the increased production of light tight oil in the US has weakened the OPEC monopoly. However, if one enlarges the system boundaries to include the long-term perspective of society as a whole, the benefits of these huge investments in fossil energy and related infrastructures are less clear, because the lock-in created by these investments makes it more difficult to move away from using fossil fuels, thereby making our society less resilient against climate change. Here we note that the ecological literature offers a way out of lock-ins through adaptive capacity on a longer time scale (provided by a purging of nonfunctional system traits and innovation introducing new functional system traits), as it provides novelty to the functioning of supply chains. However, this mechanism was not mentioned by any of the experts interviewed.

5.3.2 Resistance, rapidity and flexibility: the cornerstones of resilience

In this section we introduce the concepts of resistance, rapidity and flexibility,[17,22] and use these to discuss how our case study relates to the larger socio-economical system it is embedded in.[23] But first we need to define our system boundaries clearly. We conceptualize our system as having three levels:

- Society; which has certain needs, such as transportation or energy.
- The production system; the system that meets the needs of society and is responsible for converting materials into services. For example, the need for sustainable energy can be met by the producers of wind turbines.
- The NdFeB supply chain; the system that provides the materials required by the production system to provide wind turbines to society.

We conceptualize the resilience of a system as depending on factors that either allow it to directly maintain function under disturbance, to rapidly recover from a disruption, or to switch between alternative systems that can provide the same service. More formally these are defined as:

- Resistance; the system maintains it function, i.e. it is able to tolerate various types of disturbances without experiencing unacceptable loss of function.
- Rapidity; the system is able to rapidly recover so that it meets its goals again within a short period following the disturbance.
- Flexibility; the system is capable of meeting supply needs under a disturbance by switching between different (alternative) subsystems.

The supply chain resilience framework is a clear example of industrial ecology, as all of the three resilience-contributing factors above have direct counterparts in ecology: ‘resistance’ is used to describe how ecological systems remain ‘essentially unchanged’ under disturbance; ‘rapidity’ is often defined in terms of ‘return times to equilibrium’ or in terms of the closely related resilience measure ‘1/return time’, and ‘flexibility’ is used as such to refer to how consumers in ecological food webs switch between alternative resource types.[13,18-21]

Let us consider the previous example of energy: given the fact that society will need to switch to a sustainable source of energy to avert catastrophic climate change, it is desirable to have a resilient sustainable energy sector capable of meeting the rapidly increasing demands of society. Wind turbines are one of the main options for producing sustainable energy. Modern wind turbines can use either geared or direct drive technology. The latter utilises a large amount of NdFeB magnets, while the former requires specialty metal alloys for the gearboxes. Direct drive wind turbines are expected to increase in market share because they allow for higher efficiency and lower maintenance costs.[24-26]

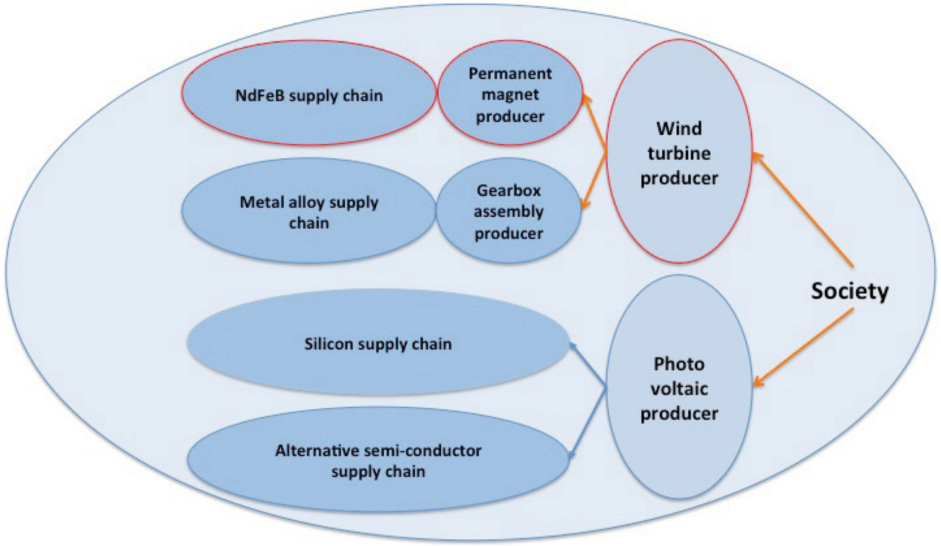

Figure 8 Resistance and rapidity depend on the strength of the system against disturbances. In this case the NdFeB supply chain, highlighted in red. Flexibility is the ability to switch between subsystems, and can occur on all levels of the overall system, highlighted in orange. Examples of alternative energy related supply chains are outlined in blue.

We would consider the wind turbine industry resilient if it is capable of providing sufficient wind turbines to fulfil the needs of society, even in the face of exponentially increasing demand and potential constraints and/or disruptions.

The resilience of the wind turbine system depends on the ability of the NdFeB system to provide a sufficient quantity of magnets to fulfil the demand for direct drive wind turbines (resistance) in the face of disruptions and/or constraints, and, if the NdFeB supply chain fails, on the speed with which the supply chain can recover (rapidity), or on the ability of the system to switch from producing direct drive to geared wind turbines (flexibility).

Figure 8 shows how resilience of the sustainable energy system depends on the resistance and rapidity of the actors within each level of the larger socio-economic system, as well as on flexibility between these levels. If demand for sustainable energy grows so fast that both the direct drive and the gearbox supply chains are not capable of keeping up with demand, society has the choice to use an alternative source of sustainable energy. For example photovoltaic energy, which will invariably have its own supply chain challenges.

A real-world example is Siemens, whose current generation of wind turbines is of the direct-drive type. It has invested in take-off agreements with the rare earth industry to ensure access to neodymium.[22] However, it also has geared wind turbine designs, ensuring that it can switch between alternative supply chains if this becomes necessary. Competing wind turbine producer Enercon has invested in direct-drive technology that functions without NdFeB magnets, using a synchronous generator and an electrical rotor instead.[25]

5.4 Mechanisms of resilience in the NdFeB supply chain

In the previous section we discussed at an abstract level how resistance, rapidity and flexibility contribute to resilience in material supply chains. In this section we use system dynamics to discuss which concrete resilience mechanisms we identified in the NdFeB supply chain.

As a reference point, Figure 9 shows the physical supply chain in the visual language of mass flow analysis. A more detailed description of the supply chain can be found in Sprecher et al. (2014).[27]

5.4.1 Diversity of supply

The Chinese export quotas were especially problematic because at that point in time China controlled 96% of the world REE production. Within China, two-thirds of rare earth oxides production originates from the Bayan Obo mine in Inner-Mongolia.[24] Clearly, such a narrow supply base is not robust. Therefore we introduce 'diversity of supply' as the first feature of a resilient material supply chain (note that this feature is closely linked to the concept of redundancy in resilience literature,[28] and to switching capacity. In this case not between alternative supply chains, but alternative providers of the same raw material).

In terms of system dynamics, having high diversity reduces the impact of a given disruption of the supply of REE ore to the rest of the supply chain. Figure 10 shows how we integrate diversity of supply into the NdFeB supply chain, which we conceptualize as the sum of primary production, post-consumer recycling and smuggling. Note that diversity of primary supply is only useful if the subsequent actors in the supply chain – in this case the REE refineries – have the technical and organizational capacity to switch timely between suppliers.

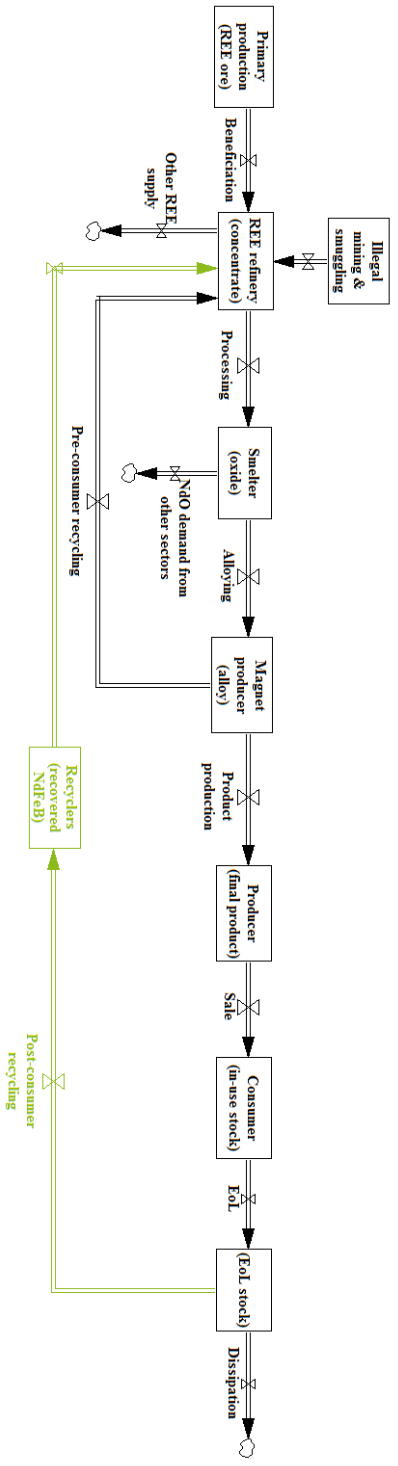

Figure 9 The NdFeB supply chain. Each box represents a stock of neodymium, while the form in which the neodymium is in that part of the supply chain is indicated between brackets. The arrows between the stocks represent physical flows of material, and are named according to the process used to transform the neodymium to its next form. Green indicates stocks and flows that do not currently happen on a relevant scale ('post-consumer recycling').

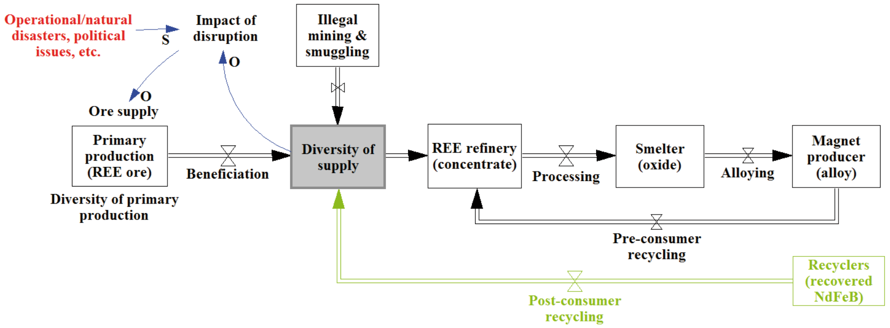

Figure 10 Diversity of supply: red indicates a system disruption or constraint. The blue arrows represent how the elements in the system influence each other: the arrowheads indicate the direction of the influence, the S or O next to the arrowhead indicate whether the connected parameters change in the Same or Opposite direction.

Primary production

The most obvious way to increase diversity is to have more mines, and to build mines in different countries. However, as Chinese attempts to buy REE mines in Australia and Greenland show, one should also pay attention to ownership issues, not just location.

Recycling

We distinguish between two types of recycling: pre- and post-consumer recycling.
In Figure 10 the green arrow represents the (at the moment of writing) mostly hypothetical option of recycling post-consumer waste magnets. Because of quality concerns, post-consumer recycling would in all probability lead back to the REE refinery stage, where the rare earths are extracted via acid leaching.[27]

Post-consumer recycling increases the diversity of supply because it can complement primary production. In contrast, pre-production recycling (the black arrow in Figure 10) of material lost during manufacture of the magnets (e.g. grinding losses) should be seen as a measure to increase production efficiency, which does not affect diversity of production.

Illegal mining & Smuggling

Besides the legal export of Chinese REEs, illegal sources can also provide a significant supply of raw material, estimated at one point to add 40% to official Chinese production.[29] This illegal material is either used in China or exported in the form of ore concentrates or oxides. The option of acquiring illegally exported material can reduce the impact of a supply disruption, but we note that smuggling and illegal mining go hand in hand with enormous social and environmental problems.[30] To simplify the figure we assumed all smuggling was in the form of concentrates. In India, illegal export of REE bearing monazite ore has also been reported in the press, albeit at a smaller scale.[31]

Other options

Finally, we would be remiss not to mention more exotic options such as deep-sea mining,[32] which, despite being challenging for technical, regulatory and environmental reasons, have significant disruptive potential because of the enormous amount of metals they could release into the market. Because interviewees indicated this is most likely still decades away we did not include it in our formal framework (interview Dr. Jiro Yamatomi).

5.4.2 Feedback loops through price mechanism

There are a number of feedback loops throughout the NdFeB supply chain. Here we will discuss the main feedback loop: the supply/demand price mechanism, shown in Figure 11.

Although in reality each actor in the supply chain has an associated supply and demand, we simplify this by representing supply as ‘ore supply’ at ‘primary production’. This simplification still captures the essential system dynamics because, based on interviews, we infer that supply side constraints mostly exist at the beginning of the supply chain.

Increasing ‘material demand’ leads to a higher ‘neodymium price’ and vice-versa, while a high price will depress demand. Similarly, less availability of ‘ore supply’ causes an increase at ‘Neodymium price’. This in turn will lead to ‘investments in new primary production’, which, after a significant time delay, increases the ore supply.

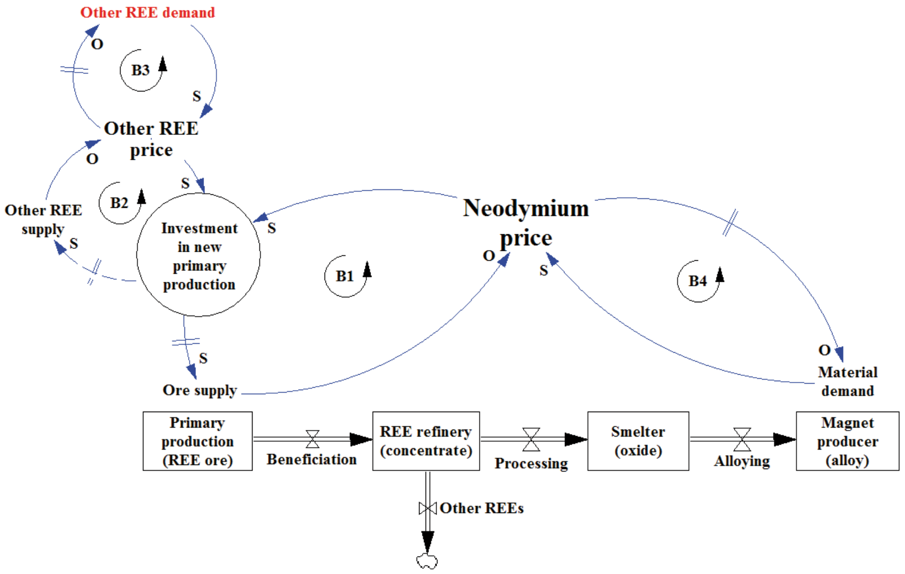

Figure 11 The supply/demand mechanism: feedback loops are represented with a circular arrow. The number is used to identify the feedback loop for further discussion. Feedback loops are identified by their number (B1), where the B indicates that this is a balancing feedback loop. The double dashed blue arrows indicate that there is a delay in the influence.

Because it is not possible to process a single REE without processing the majority of the associated REEs,[33] the primary production feedback-loop is complicated by the demand for other REEs. These are part of an identical feedback loop that also influences the decision to invest in new primary production. Although an important feature of many minor metals, the issue of co-mining is vital in rare earth economics. This means that increasing production of one high-demand REE will lead to overproduction of the associated REEs.

'Other REE demand' is coloured red, to indicate that it falls outside the system boundaries of this model. Note that in the full system dynamics picture (Figure 14), neodymium price also drives other factors such as investments in recycling. However, for clarity's sake we only describe the main feedback loop here. There are numerous other feedback loops discussed in the remainder of this work.

5.4.3 Material substitution and improved material properties

On the material demand side, a number of options are discussed in the material efficiency literature, such as increasing the lifetime of products, increase the use intensity of products (e.g. through products service systems) and the re-use of components.[34]

The NdFeB supply showed a more limited response with respect to reducing material demand. Interviewees identified two mechanisms that actors used to change their neodymium consumption.

Substitution

Substitution is the well-known switching mechanism whereby one material is substituted for a different material. There are many levels where substitution can occur, ranging from using a lower grade of the same material to outright substitution of the entire technological system dependent on that material (e.g. replace wind energy with PV). Based on our interviews we highlight the two most common types of substitution:

- Material substitution: the case where the requirement of using magnets remains in the final product design, but this requirement is fulfilled with a different material (e.g. replacing NdFeB magnets with samarium-cobalt magnets).

- Technological substitution: where a product is redesigned to operate without any magnets at all (e.g. replacing a direct drive with a geared wind turbine).

Changing material properties

Improvement of the properties of materials with the goal of reducing material usage represents a less drastic but more often realized measure (e.g. using grain boundary diffusion technology to allow magnets with lower levels of dysprosium to have equivalent high temperature operational specification).[10]

The distinction between substitution and material properties is relevant because they are different types of actions taken by different actors. As shown in Figure 12, substitution is done at the level of product design and relates to flexibility, while improving the material properties is done at the level of the magnet producers and relates to resistance.

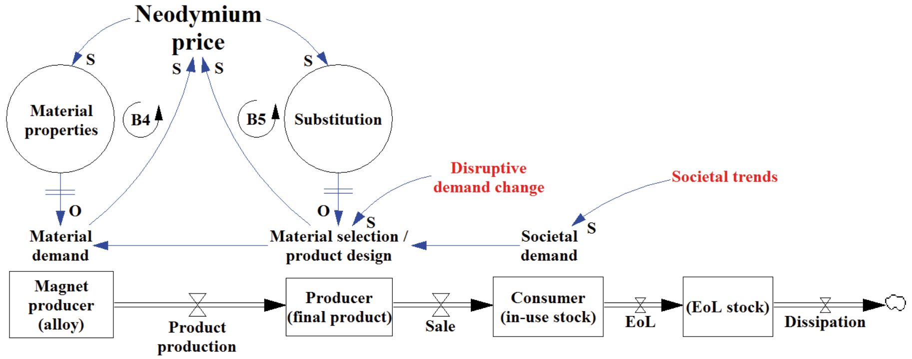

Figure 12 material properties and substitution: these have the same function (creating balancing feedback loop with price) but are implemented by different actors.

Figure 12 also shows how demand changes are incorporated into the model. Societal trends, such as increased demand for sustainable energy or smartphones, may change over time, leading to demand changes. At a lower system level, component changes may also lead to changes in demand (such as replacing LCD with OLED screens).

There are also two balancing feedback loops: substitution and improved material properties both reduce the demand for neodymium and/or dysprosium. This causes the price of NdFeB to go down, which in turn will lessen the need for further substitution or property improvement. Conversely, a low REE price can also lead to inefficient material use and cheaper production techniques that yield lesser material properties.

5.4.4 Stockpiling

Stockpiling can improve the resistance of the system, because a stockpile can absorb sudden price and/or supply fluctuations. However, stockpiling can also have a detrimental effect. During the 2010 REE crisis some Japanese companies forced their suppliers to increase their stockpile of raw materials to up to two years, at the very moment the prices were highest and the materials were hardest to obtain. This drove the price of neodymium and dysprosium up significantly (interview Hitachi Metals).

Because there are many different grades of NdFeB magnets, each with slightly differing alloying element ratios, it is difficult for magnet producers to keep significant stockpiles (interview Arnold Magnetics). Stockpiles are usually kept in the form of REE oxides, by the companies producing alloys.

Stockpiles also exist at country level. For example, the 2013 bi-annual US Strategic and Critical

Materials report recommended to stockpile $120 million in heavy rare earths,[35] and the Japanese independent administrative institution JOGMEC holds a 42 day stockpile for nine metals (Ni, Mn, Cr, Mo, W, Co, V, In, and Ga, but not REEs). Japanese companies are obliged by law to hold an 18 day stockpile.[36]

Finally, stockpiling can also be employed by speculators who aim to benefit from price volatility.

In our resilience framework we represent the stockpiling dynamic by adding a physical stockpile at the level of the REE smelter and a 'perceived short-term threat of supply disruption' parameter. Speculation played a (limited) role in driving up prices during the 2010 crisis[37] and is represented here at the same level as emergency stockpiling. Representing both the positive and negative effects of stockpiling, there are two competing feedback loops governing this mechanic:

- Reinforcing feedback loop: a supply disruption and/or a sharp increase in price increases the 'perceived short-term threat of supply disruption', which leads to emergency stockpiling by manufacturers and speculation. This drives up the material demand, which in turn increases price. A strong price increase in itself will fuel the perceived threat of supply disruption, leading to more emergency stockpiling.
- Balancing feedback loop: physical stockpiles act to reduce 'perceived short- term threat of supply disruption'. Increasing this stockpile through emergency stockpiling will reduce the perceived threat of supply disruption, causing a reduction in the need for emergency stockpiling.

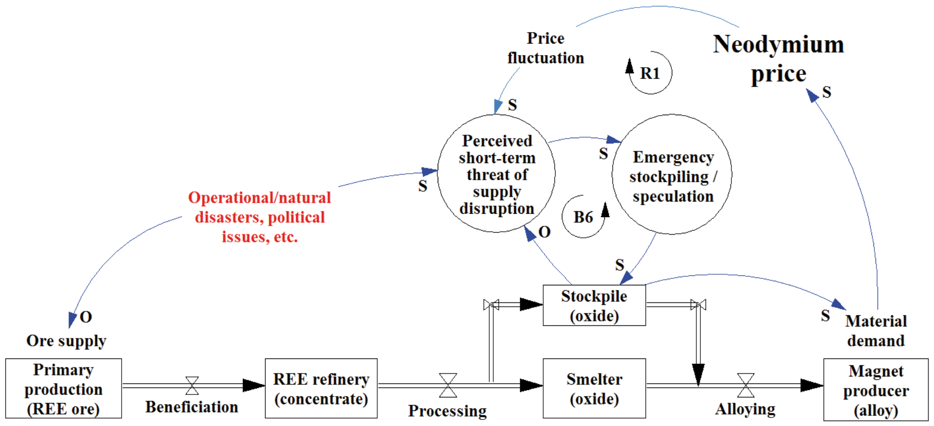

Figure 13 Stockpiling mechanic: in this figure we introduce the parameter 'perceived short-term threat of supply disruption'. This type of parameter is distinct from others in the model, because it shows how beliefs of actors in the system influence behaviour. It also features a reinforcing feedback loop (R1).

5.5 NdFeB supply chain system dynamics

In this section we look at the NdFeB supply chain from a complete systems perspective. First we discuss the different types of system constraints and disruptions, then the various system level interventions that could be implemented to improve resilience. Finally we combine the resilience mechanisms into a single system dynamics representation of the NdFeB system that shows how the various elements interact with each other.

5.5.1 Types of system constraints and disruptions

On an abstract level there are two types of system disturbances: those that affect supply and those that affect demand. These disturbances can range from fast to slow. As shown in Table 7, a sudden disruption of supply could be the result of natural disasters, such as the 2011 flooding in Thailand, or political issues such as the Chinese rare earth embargo of 2010. In the long-term, supply constraints could be caused by ore depletion or policies like export quotas and taxes.

A sudden increase in supply can come from governments releasing stockpiles. This happened for instance with tungsten in 1995: a sharp increase in price led to China, Kazakhstan and Russia releasing their inventories, which caused an oversupply situation.[3,9] A more long-term oversupply situation can currently be observed in the cerium market, a REE that is co-produced with neodymium. The increased demand for neodymium resulted in a cerium glut, severely depressing prices (interview Nissan).

Table 7 Types of system disturbances.

	Supply	Demand
Fast	Natural disaster, political issues	Disruptive demand change
Slow	Protective measures, ore depletion	Societal, technological trends

On the demand side relatively slow constraints come from societal and technological trends, such as increasing electrification and use of sustainable energy. Fast demand increases usually stem from either an exploding demand for a new type of product (e.g. smartphones), or from component changes in existing products (e.g. new generation of wind turbines switching from geared to NdFeB containing direct drive technology).

5.5.2 Options to improve supply chain resilience

Since the 2010 crisis several alternatives to Chinese primary REE production have come online, indicating that this is a mechanism that the NdFeB supply chain naturally resorts to in order to solve constraints. In this section we describe various other policy options to improve the resilience of the NdFeB supply chain.

Reduce red tape to improve system response times
Although laws and regulations often exist for a good reason (e.g. ensuring that the social and environmental consequences of new economic activities are well understood) they can also act as an impediment to system change. The long lead-time in obtaining permits is a frequently mentioned example of red tape leading to delay in building new primary production. On the recycling side an example of regulatory issues are the European waste laws. These can obstruct recycling because once a material is labelled as a waste it is difficult to use it as an end product again.

Companies and governments should work together to reduce the impact of regulations on the time needed to implement solutions, for instance through doing some of the work already in advance. For example, the German Rohstoffallianz provides its members with options to bundle interests from a value chain perspective and optimizing the supply planning horizon, for instance by drafting templates for framework take-off agreements (interview Rohstoffallianz).

Implement a mineral tax
One of the challenges with implementing a recycling scheme is that the prices of raw materials are often too low to warrant recycling. The production costs of primary production are lower than the collection and processing costs of recycling. Because of the supply/demand feedback loop, primary production will outcompete recycling. This is of course assuming sufficient reserves for increasing primary production, which for REEs certainly is the case. The same effect can be seen at the product design level with regard to efficient use of materials.

The principal reason for a mineral taxation scheme levied at primary production is to re-distribute the profit made from exploitation of non-renewable resources.[38] However, if a mineral tax were to be implemented on a significant (if not global) level, a secondary effect would that the increased costs of primary production can prevent the supply/demand feedback loop from steering the NdFeB system away from more sustainable material use, especially if some of the tax revenue would be used to support recycling.

Support R&D to expand use of excess REEs
A low consumption of other REEs can prevent investment in primary production. This is also known as market inelasticity, where an increase in demand does not translate automatically to an increase in supply. In order to solve this balance problem one could stimulate the demand for other REEs through focused R&D to find new applications.

For example, there is a trend to alloy magnesium with REEs to improve the creep resistance of magnesium alloys.[39] Creep resistant magnesium alloys are used for drive train applications in the automotive industry for purposes of weight-saving.[40]

Promote design for recycling
Products using NdFeB magnets are currently designed in such a way that separating the magnets is very difficult.[9] This is reflected in the fact that even when the price of neodymium increased dramatically, post-consumer recycling did not take off in any meaningful way. Even if recycling of some applications with large volumes of magnets would become feasible (e.g. wind turbines, electric vehicles), this still leaves the many applications of smaller magnets – weighing no more than a few grams – where recycling would be uneconomical under almost any circumstance. This also applies for the many other critical elements that are used in very low concentrations.
Implementing design for recycling principles and having waste regulations that are not mass based targets, but regulate which materials need to be recycled would in all probability improve this situation (interview Dr. Allan Walton).

Increase stockpiling
Stockpiles offer the possibility to completely negate the impact of any temporary supply disruption, albeit at significant capital costs. Especially for neodymium (and rare earths in general) there is a case to be made for stockpiling, because their costs are but a fraction of the overall value of the products they are contained in, meaning that a stockpile could acts as a relatively cheap insurance policy.[5]

However, as described in section 4.4, it does not make sense for end-users to stockpile neodymium, but rather the alloy producers, for whom the cost of neodymium is a very significant barrier to stockpiling. Although there is some ad-hoc stockpiling based on individual agreements between end-users and magnet producers (interview Arnold Magnetics), we suggest a common stockpile would be an efficient way to solve this problem. This stockpile can come with a pre-arranged protocol on how to divide its contents in case of an emergency. This would help to prevent actors from driving up the price by chasing the same stockpile, as happened in 2010.

5.5.3 Complete system dynamics of the NdFeB system.

In Figure 14 we combine the previously introduced system elements into a complete overview, which shows how and where the various resilience mechanisms interact with the physical stocks and flows of the NdFeB system. The green elements show the options to improve resilience, while the red elements show the various types of disturbances. Both disturbances and mechanisms to deal with disturbances are distributed across the entire system.

Having all of the various elements of resilience together in one figure illustrates that every part of the supply chain is somehow involved. Insofar that, especially in the aftermath of the 2010 REE crisis, the individual actors have relatively little information on the behaviour of other actors in the system, we consider resilience to be an emergent system property.

Compared to the individual resilience mechanisms there are also some minor additions. In order to recycling to ‘Neodymium price’ we add the ‘investment in recycling infrastructure’ parameter that mirrors the ‘investment in new primary production’ parameter.

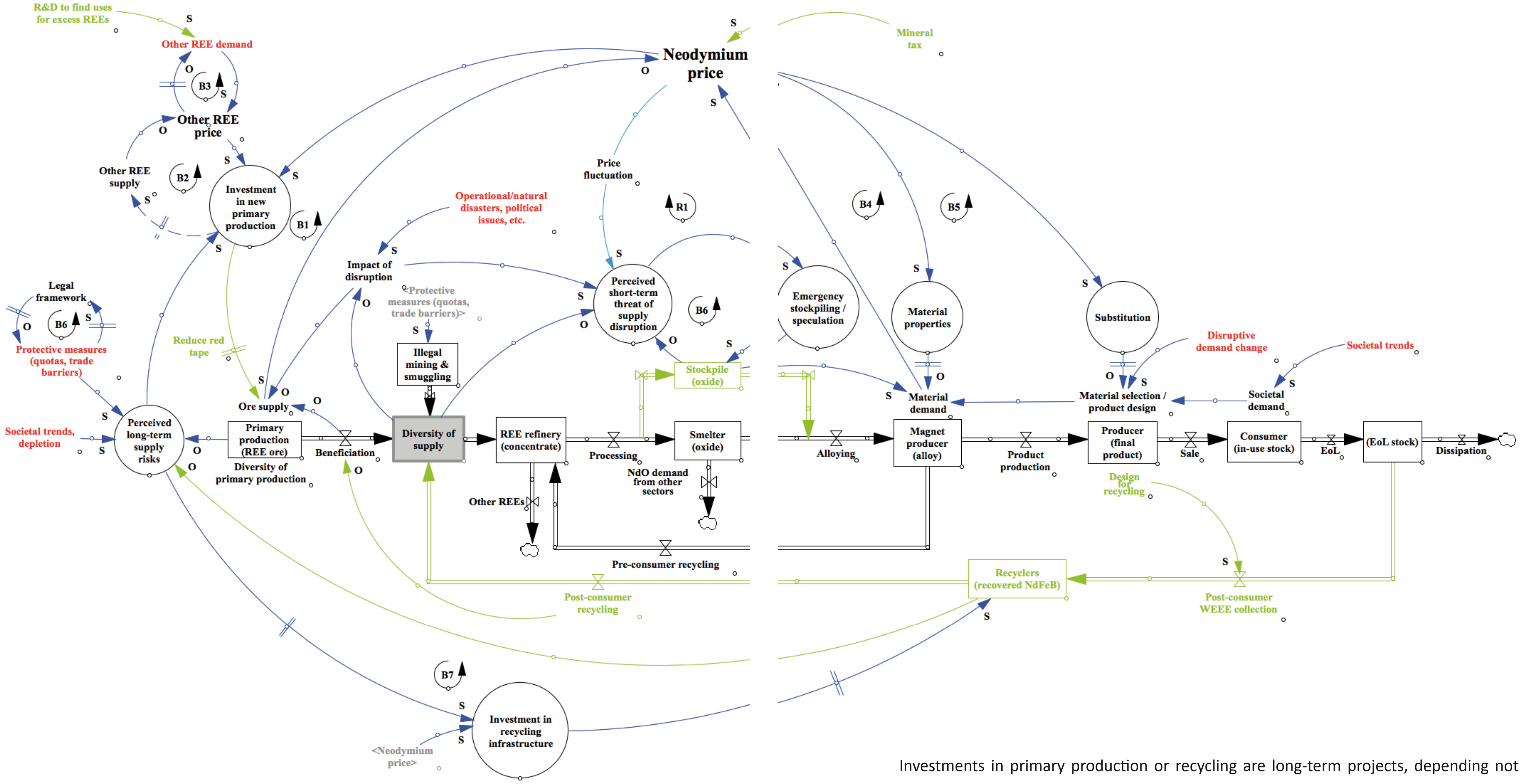

Figure 14 System dynamics of the NdFeB supply chain: this figure combines the resilience mechanisms from the previous section and adds some elements, as discussed in the text.

Investments in primary production or recycling are long-term projects, depending not only on the spot price of rare earths but also on the expected long-term demand. We model this by making long-term investments dependent on the ‘perceived long-term supply risks’ parameter, which accounts for slow trends such as depletion of existing mines, societal trends, technological developments and protective measures. One might expect that long-term supply risk is something that influences material selection choice at the product design stage, but according to our interviews this is not the case, and materials are selected solely on their economic and physical properties (interview Chatham House).

Finally, there is a minor feedback loop connected to ‘perceived long-term supply risks’ that covers the legal responses to protective measures by states, mainly in the form of WTO lawsuits.

5.6 Discussion

In this paper we provide a framework that defines and clarifies supply chain resilience. We demonstrated the use of this framework by analyzing the multiple responses of the neodymium magnet (NdFeB) supply chain to the 2010 Chinese export restrictions. As a consequence of these restrictions, the price of neodymium increased by a factor of 10, only to return to almost normal levels in the following months, despite the fact that the restrictions were not lifted (export quota have been lifted since 1 January 2015, but export licensing may substitute its restrictive effect).[41] These events indicate that the NdFeB supply chain was not very resistant to the disruption, but it recovered with remarkable rapidity.

Compared to previous literature discussing REE supply chains, our framework allows a more nuanced and complete analysis of how supply chains of critical materials respond to disturbances. Besides contributing to the understanding of NdFeB supply chain system dynamics, we also believe the framework to be of more generic relevance to those interested in material criticality and the resilience of material supply chains.

Through literature review and extensive interviews with actors across the NdFeB supply chain we have shown that resilience in the NdFeB supply chain is comprised of resistance (the ability to tolerate disturbances without unacceptable loss of function), rapidity (the ability to rapidly recover from a disruption), and flexibility (the ability to switch between alternative subsystems). We found that the following concrete mechanisms are primarily responsible for this resilience. On the supply side:

- Diversity of supply; more variety in sources of raw material potentially reduces the impact of a disruption or constraint on the remainder of the supply chain.
- Stockpiling; acts as a buffer that lessens the impact of temporary supply disruptions.

On the demand side:

- Improving the material properties; magnet producers have responded to supply constraints by improving the properties of NdFeB, greatly reducing the required amount of dysprosium for high temperature resistant magnets.
- Substitution; some producers substituted NdFeB magnets with other magnets, while others switched to a completely different technology that did not rely on permanent magnets.

The main stabilizing/destabilizing forces in the system are the feedback loops, of which the economic feedback loop (i.e. price mechanism) is the most important. Figure 14 gives an overview of how all the feedback loops and mechanisms are connected to the supply chain. Not all responses to the 2010 REE crisis contributed positively to system resilience. We note the two most explicitly negative responses. The first is panic buying by Japanese companies, who tried to increase their stockpile only after the Chinese export quotas came in full force. This contributed greatly to the price increases. The second is illegal mining and smuggling of Chinese rare earths (estimated at 40% of the official production).[29] Although smuggling increases the diversity of supply and thus increases the resilience of the sector, illegal mining has devastating environmental and social effects.[30]

In the past several years the diversity of primary production has improved significantly, with several new primary production sources of REE becoming operational.[6] However, increasing the diversity is only one, potentially limited and exclusively supply-side focused lever that can be pulled in order to improve the capacity of the NdFeB supply chain to deal with future constraints and disruptions. We proposed five additional system interventions:

- Reduce red tape for faster system response times (i.e. legislation related to mining permits, recycling)
- Implement a mineral tax to promote more sustainable use of raw materials
- Support R&D to expanded use of REEs that are co-mined in excess
- Promote design for recycling
- Increase stockpiling to effective levels

Improving the rapidity of the system can be achieved by improving the robustness of production facilities against natural/operational disasters. This did not come up in any of the interviews, probably due to the fact that we did not succeed in interviewing actors related to the first stages of the supply chain, predominantly located in China.

In the introduction we discussed how Gholz argued that the NdFeB case study shows a “largely successful market response”[4] while Tukker wrote that it shows how “western governments ignored market failures”.[5] Out of the above five system interventions – based on suggestions from actors in the NdFeB supply chain – only ‘reduce red tape’ is in favor of further improving the free market response, while the other four relate to intervening in the free market. From this we tend to agree with Tukker, that our case study indeed contains a certain amount of market failure.

Finally, we would be remiss not to discuss our framework in relation to the various critical materials methodologies that have recently been proposed. Most notably by Graedel et al., who present a very thorough analysis of how to measure and rank the criticality of metals, applied to REEs by Nassar et al.[42,43]

Although there are dissimilarities in timeframe and system boundaries, their dimensions ‘supply risk’ and ‘vulnerability to supply disruptions’ strongly overlap with our supply and demand side resilience mechanisms. However, there are significant conceptual differences. Our work is focused on the dynamic aspects of the supply chain; how it changes over time in response to disturbances, while the Graedel et al. framework essentially generates a static snap-shot of criticality. The latter acknowledges but does not take into account the fact that non-linearity plays an important role in complex systems; this framework incorporates non-linearity through the explicit use of feedback loops.

Furthermore, Graedel et al. consider environmental implications to be a dimension of criticality. It is an unfortunate fact that our interviewees indicated environmental considerations to be of little importance to their decision making process, and therefore is not explicitly included in our resilience framework.

Despite the differences there is a clear overlap between our framework and the frameworks proposed in the critical materials literature. The question is then: how do resilience and criticality relate to each other? We would go so far as to argue that one can define the criticality of a material in terms of how resilient its supply chain is.

Further development of supply chain resilience theory could greatly benefit from a body of mathematical work in theoretical ecology, that provides in-depth analysis of the causes and consequences of resistance, rapidity-like measures of recovery speed and flexibility, in complex ecosystems and food webs.[13,18-21]

It would be very interesting to see this framework applied to other supply chains than that of NdFeB magnets. We hope this paper will enable other researchers to look at leverage points, bottlenecks, and to develop policy options that take into account the full system surrounding the supply chains of critical materials.

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6

Quantification of resilience in the NdFeB supply chain

Benjamin Sprecher, Ichiro Daigo, Matthijs Vos, Rene Kleijn, Shinsuke Murakami, and Gert Jan Kramer (submitted)

6.1 Introduction

Sustainability as envisioned by industrial ecology entails a move of industry away from stand-alone, once-through operation to an interconnected, complex web of interlocking industries that minimize waste and maximize re-use.[1] However, this increased complexity can make parts of the system more susceptible to unexpected risks because disruptions in one part can have unexpected and major effects elsewhere. These effects will be compounded by the wider changes brought on by globalization and climate change. The 'cost of interdependence' that may be associated with an increased interconnectedness of industries needs to be properly addressed. Therefore, resilience – the ability of a system to resist or rebound from a disruption – is essential for designing truly sustainable systems based on industrial ecology principles.[2]

In the previous chapter we developed a qualitative framework for resilience in material supply chains. We used the 2010 REE crisis as a case study to investigate resilience in the supply chain of NdFeB rare earth magnets, an exceedingly powerful type of permanent magnet that is invaluable for a quick transition to a sustainable energy sysem.[3] China, the world's largest producer of rare earth metals (REEs), had long since harbored the wish to use its dominant position in the primary production of REEs to force companies to move more of their production chains to China. This would be more profitable for the country than only exporting relatively low-value REE ore or alloys.[4] Against this backdrop, China unexpectedly blocked the export of REEs after an unrelated diplomatic incident with Japan involving the Senkaku/Diaoyu islands. This caused major disruptions in the supply chains of electrical vehicles, wind turbines, and many other industries. These industries had until then never considered themselves at risk to incidents such as the Senkaku/Diaoyu island dispute.

In this paper we present a quantitative analysis of supply-chain resilience. We do this by identifying a set of indicators that allows us to assess the degree of resilience of the NdFeB supply chain, and to assess the relative importance of different resilience mechanisms described previously.

Literature on the empirical assessment of resilience in the socio-technosphere is rare.[5] One approach is to estimate the economic production of a system in its alternative ecological states, which is then used to calculate the benefit of having resilience against switching from a high value state to a lower value state. This was done by Walker et al. for water levels in Australian farmland.[6] Another method, focused on quantifying resilience in the context of earthquakes, is to look at how often structural performance thresholds are exceeded (e.g. the chance that an earthquake will exceed the structural thresholds of a building). A team of social scientists, engineers and economists then jointly determine the subsequent effects of exceeding the thresholds and the speed with which the previous state can be attained again.[7]

Resilience can also be quantified by looking at existing, static indicators and investigating how these indicators would change in response to disruptions. This was for instance done by Milman et al.[8] In the context of urban water systems, they developed a Water Provision Resilience indicator, which is based on an existing indicator for the percentage of the population with access to safe water. The new resilience indicator improved on the previous static indicator by adding a dynamic aspect to it: the odds of maintaining or improving the current level and quality of access to water over the next 50 years, despite disruptions, such as a strong population increase.

As Meerow and Newell write, 'quantifying some resilience characteristics would help us expand our knowledge of the relationship between resilience and sustainability, which needs to be more clearly articulated theoretically, empirically, and practically.'[2] In the present study we aim to contribute to this ongoing discourse by providing empirical observations on the supply chain resilience of NdFeB, a material deemed to be essential for a sustainable future.

6.2 Methodology

Our framework for resilience in material supply chains proposes four primary mechanisms.[3] On the supply side, 1) diversity of supply (e.g. primary production in different countries, recycling) is a crucial mechanism to prevent disruptions, while 2) stockpiling of materials can buffer against the impact of temporary supply disruptions. On the demand side, NdFeB producers have the option of 3) improving the properties of NdFeB magnets to reduce material demand, especially with respect to dysprosium content. Finally, 4) substitution can play a significant role in dampening the effects of a supply disruption, either by swapping NdFeB magnets for other types of magnets or by (temporarily) switching to a different technology that does not rely on permanent magnets. As can be seen in Figure 15, each of these four mechanisms are connected to specific actors in the NdFeB supply chain. The mechanisms also influence each other via the neodymium price feedback loop.

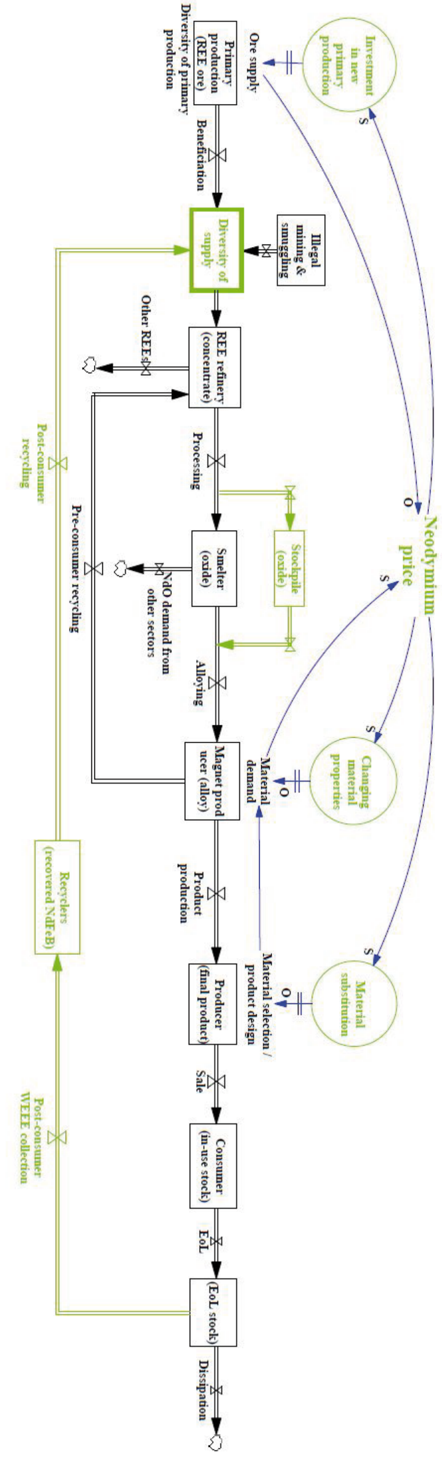

Figure 15 The conceptual model of the NdFeB supply chain (black) and the associated resilience mechanisms (green) as developed in our previous paper.[3] The blue arrows indicate the direction of influence: S = same, O = opposing.

Through internet based research and discussions with experts we identified a number of actors for each position in the supply chain. The actors – 40 in total – were chosen both because they were key players in the supply chain and because of data availability. For all these actors we identified the type of actions they undertook and how these actions developed over time. We supplemented these specific actor centered data with general production statistics obtained directly from industry sources, and through interviews with sixteen experts from across the NdFeB supply chain (see SI for more information).

6.3 Results

The effect of the four resilience mechanism depends on the following parameters: 1) the time-lag between the disruption and the moment that a measure actually starts to become implemented and thus starts to have an effect (this would include both the reaction time until for example the decision is made that a new mine needs to be opened and the time required for that new mine to come online). Only after that time-lag a quantifiable effect on the system can start to take place. 2) The speed with which the mechanism can influence the system (i.e. the speed with which a producer can scale up a change in production from its initial reaction to its desired final amount). And 3) the maximum magnitude of a mechanism's effect (e.g. the maximum amount of neodymium obtained through recycling). In the following paragraphs we will discuss these parameters for each mechanism.

6.3.1 Feedback loops through the price mechanism

The price spike of NdFeB magnets in the latter half of 2010 (Figure 16) incited actors across the supply chain to change their behavior. This illustrates how the price mechanism forms the overarching feedback loop through which the supply and demand of Neodymium influence each other.

A functional supply/demand feedback loop requires the existence of a transparent market. As an indicator of the existence of such a market we suggest comparing the volume of material traded on the spot market (i.e. where trade is public and delivery is close to immediate) compared to the total market volume. Although the Chinese government has attempted to establish a spot market, the majority of REEs are still not traded in a transparent manner.[9] An indicator along the line of 'ratio of material traded on open market and total market volume' would be interesting. However, it proved to be impossible to obtain the necessary data. Furthermore, a much wider comparison with other materials would be necessary to determine at which ratio a supply/demand feedback loop would become functional.

Not only transparency of the market itself is of importance, but also the transparency of companies along the supply chain. A lack of financial transparency (e.g. publication of annual reports) will hinder access to fresh capital from outside sources if companies need to expand due to a sudden increase in demand (interview Chatham House).

6.3.2 Diversity of supply

Having various sources of raw material can reduce the impact of a supply disruption on the remainder of the supply chain. In the resilience framework we distinguish between primary production, recycling, and illegal mining and smuggling as sources of diversity of supply.[3] While diversity of supply can be seen as a unified mechanism from a resilience point of view, there are marked differences between the actual realization of recycling and mining infrastructures. We therefore analyze these sources separately, while we will not consider the sources illegal mining and smuggling due to lack of data.

As a high-level indicator of diversity of supply, we use the Herfindahl-Hirschman index (HHI), which is equivalent to Simpson's diversity index (D) as used in ecology:[10] the market shares of relevant companies are squared and summed, providing a score between 0 and 10,000. An HHI of 10,000 would indicate that one single producer governs the entire market. In contrast, low HHI values indicate that market shares are evenly distributed among a great diversity of producers. An HHI above 2,500 is considered to be highly concentrated, indicating high market power of larger producers.[11] Calculating the HHI for each step in the supply chain allows one to assess which step is most critical from a diversity of supply point of view.

Figure 16 shows the HHI for both primary REE ore production and NdFeB production. There are some limitations to the data: the primary production HHI is based on overall REE production data per country.[12] For our analysis we assume this to be proportional to primary production of metallic neodymium.[13] The NdFeB HHI is based on production in Japan, China, and the aggregated production of the rest of the world. This simplification does not influence the results, since the production in the rest of the world is negligible. For NdFeB production we include a forecast over the period 2015-20.[14]

With respect to primary production, we found that in the years before the crisis there was an extreme market concentration (indicated by a HHI value slightly above 9,400), with the sum of all producers in China holding an estimated 98% market share. In the years following the 2010 crisis the HHI index dropped to values of around 7,400. This is analyzed in more detail in the following section.

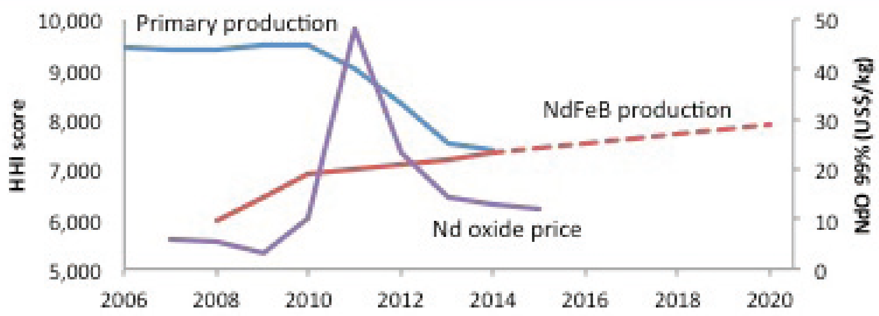

Figure 16 Herfindahl-Hirchman Index of REE primary production and NdFeB magnet production showing the extreme concentration of REE production in China prior to the 2008 crisis and its subsequent redress. The dotted line for market concentration of NdFeB production is based on industry forecasts for the 2014-20 period.[14] The purple line gives the price of neodymium in its oxide form.[15]

Although the 2010 crisis led to a noticeable increase in the diversity of primary REE ore production, the opposite is the case for the production of NdFeB: diversity declined at a steady pace and is estimated to keep doing so in the foreseeable future. When looking at the data underlying the HHI calculations we see that this is caused by an increasing market share of Chinese producers, while the share of producers from other countries (mostly Japan) remains constant.

So far we assumed that strong national policies of Japan and especially China imply that the sum of companies within each of these countries can, for HHI purposes, be analyzed as single actors. To verify this assumption, we analyzed the per company HHI for NdFeB production (comparable data for primary production was not available). We found that globally the biggest company (Beijing Zhong Ke San Huan High-Tech Co., Ltd.) had a 13.500 tons production capacity at an estimated 65% utilization rate, giving it a 12% worldwide market share, while all the other companies had market shares of 6% or smaller.[14] This results in an HHI index of ~300, indicating that on a company level there is no market concentration. An important implication of this result is that market disruptions can probably be attributed to decisions made at the level of national policy, rather than by decisions made by a few dominant producing companies.

6.3.3 New primary production

Our research indicates that the most publicized response to the 2010 REE crisis was to build new mines. Dozens of junior mining companies (i.e. companies that focus solely on exploration) were hopeful to be the first to supply jittery western and Japanese REE consumers with non-Chinese supply, as did a number of pre-crisis rare earth projects (e.g. Molycorp, Lynas). Their cumulative efforts can be seen in Figure 17, which clearly reflects the 2010 crisis, both in the reduced Chinese output (from a high point of 130,000 tons in 2010 to 95,000 tons in 2014) and the subsequent increase in non-Chinese production (from 3,500 tons pre-2010 to 16,000 tons in 2014). The figure shows that the time-lag between the crisis and the increase in non-Chinese production was less than one year. This quick ramp up of production is due to existing mining projects. We find that the time-lag between announcing the intention of starting to mine REEs and actual production is 4 to 13 years.

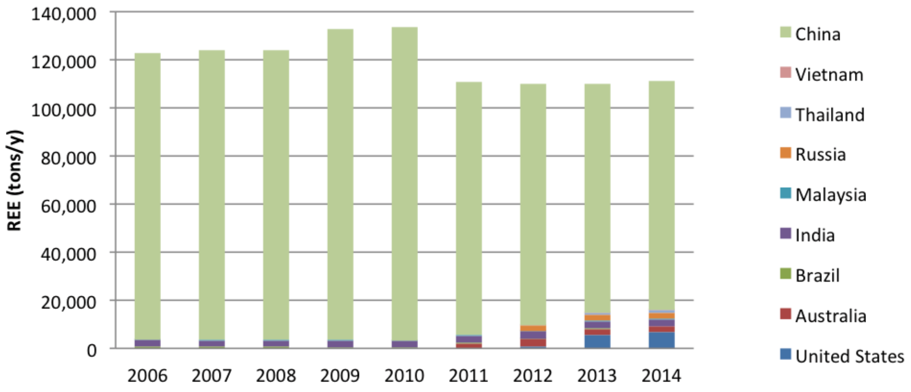

Figure 17 Primary production or REEs over time, per country.

Although the reduction of REE prices has seemingly caused most truly new REE mining projects to be put on hold, it is still plausible that new production capacity will come online somewhere in the coming decade. As it stands, the actual impact of non-Chinese REE production seems to be limited, with the maximum year-over-year increase of REE production outside China being ~5000 tons (~4% of total production volume) for 2012-13. However, since these 5000 tons are still significant compared to the ~20.000 tons shortfall, it seems that the rate of increase in production will decrease rather than increase in the near future. This also bears out in the fact that the 2013-14 increase is smaller than the increase for 2012-13.

6.3.4 Recycling

We distinguish between two types of recycling: pre-consumer recycling of material lost during magnet manufacturing (e.g. through grinding losses and defective products), and post-consumer recycling of NdFeB from End-of-Life equipment and products.

Pre-consumer recycling

Before the 2010 crisis, pre-consumer waste was not recycled because of economic feasibility issues, although at least one trading company stockpiled the potentially recyclable material (see stockpiling section). Pre-consumer recycling is currently done via two processing routes (interview Hitachi):

1. Melting and strip casting, which can be done either at the magnet manufacturer or its supplier. For this processing route the material must be of good quality (i.e. low oxidation). This is usually the case for batches with production defects, such as cracks or insufficient magnetic strength. Only 1-2% of total production is recycled in this way.

2. Acid leaching, where the alloy elements are separated in their oxide forms. This route is used for all grinding losses, which, depending on factors such as final shape of the magnet and quality of grinding equipment, accounts for 10-20% of total production.

Post-consumer recycling

Even before the 2010 price spike there was academic interest in the recycling of post-consumer NdFeB (interview Allan Walton). The crisis sparked a flurry of activity, with press releases announcing the imminent start-up of at least seven recycling factories throughout 2011-2013. However, the actual availability of recycled NdFeB remains negligible, indicating that either there is currently no commercial scale recycling, or that recycled material is sold in take-off agreements, is used internally, or does not reach the market for other reasons.

Economically viable post-consumer recycling is complicated to achieve for three main reasons: first, the inherent ease of oxidation of NdFeB makes it desirable to seal the magnets to stabilize them, which makes it more difficult to recover the magnets during the End-of-Life phase. Second, the amount of NdFeB is usually too small to warrant any kind of manual labor to liberate the magnet. Third, the many different grades of NdFeB (with differing chemical compositions) make it difficult to achieve high quality level recycling, unless the source of the material is known exactly.

Although many lab-scale options for recycling NdFeB have been reported,[16] realistically one has to either take the material back to the REE refinery stage and extract the REEs via acid leaching, or use magnet-to-magnet recycling technologies.[13] The latter has the downside that the recycled material needs to be very uniform if a high grade of NdFeB is to be produced, and therefore has limited potential compared to the total amount of NdFeB that can potentially be recycled.[17]

Quantification

Based on interviews, we find that the time required to go from start-up to small-scale recycling of HDDs (40 t/y) is 5 to 8 years. It can then take another 2 to 10 years to increase that production by an order of magnitude, because of difficulties associated with collecting enough HDDs (interview Allan Walton).

Figure 18 shows the upper and lower boundary of recycling, assuming that the first steps towards the recycling of NdFeB from HDDs were made in 2007. The upper boundary is based on previously estimated maximum recoverable NdFeB volumes. This maximum NdFeB production from recycled material is dependent on the lifetime of products containing NdFeB, the total production at the beginning of the lifetime of those products, and the collection rate.[17]

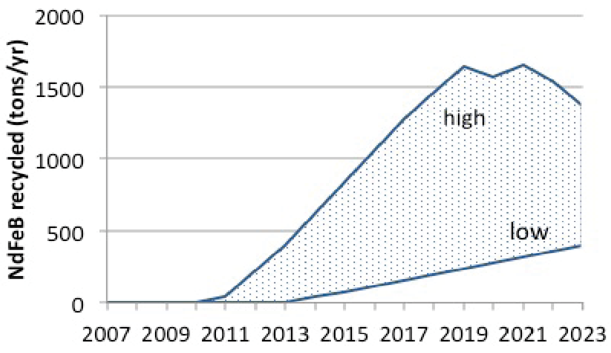

Figure 18 Quantification of the potential for NdFeB recycling. High and low refers to upper and lower boudary scenarios.

Although it is very difficult to obtain real numbers, we observe that the recycling of NdFeB seems to follow the lower bound of our estimates.

6.3.5 Stockpiling

Stockpiles act as a buffer that can lessen the impact of temporary supply disruptions. In the case of the NdFeB supply chain, stockpiling is only practical for smelters, who can stockpile the rare earths in their oxide form and use that to produce whatever specific grade of NdFeB is in demand. For actors further along the supply chain the variety of NdFeB grades means that stockpiling all of these is not feasible (interview Arnold magnetics).

Timely stockpiling seems like a straightforward insurance against supply chain disruptions, especially in the cases of rare earths, in which the cost of the material is usually very small compared to the value of the final product. However, because the stockpile can only be held by smelters, capital investment requirements will influence the decision making process, because smelters are several steps removed from the final producer and the cost of a stockpile is relatively large for them because producing REE alloys is their core business.

Furthermore, the act of stockpiling itself can also increase demand, thereby driving up prices. For example, Japanese car manufacturers were caught off guard by the impact of the Chinese export blockade on their manufacturing capability and started building a dysprosium stockpile at the height of the crisis. One of the largest REE traders, Santoku (Japan), had relatively large stocks of grinding waste because it had an oral agreement with its customers to recycle that material. However, it had not been economically viable to do so before the crisis, so they had stored the material, which amounted to a years' worth of stock. During the height of the crisis, their customers demanded that Santoku would stock 2 years of supply, forcing them to buy a years' worth of material at the highest cost. Later, when the cost of the material went down again, they could not recuperate this high price from their customers. Overall, this caused a loss of billions of yen for smaller players and tens of billions of yen for larger players in this part of the REE supply chain (interview Biko Chemical Company).

Quantification

Measuring stockpiling requires different parameters than those defined at the beginning of this section. As a global indicator we suggest the ratio of total neodymium oxide storage to worldwide NdFeB demand. This yields the number of months the supply chain could sustain itself while the supply is disrupted. In other sectors that have mandatory stockpiles (e.g. certain types of metals, oil) this figure is usually set at 1 to 3 months.

The complicating factor in determining the optimal size of a stockpile is that the choice of which supply disruptions to target and how long these are expected to take is subjective and relies on past experience. By its very nature this cannot take into account as yet unknown types of future disruptions, i.e. ones that have not occurred before, or that will occur too many steps removed in the system to be foreseeable.

Although the indicator for stockpiling is relatively straightforward, quantification of the current stockpile is not. There seems to be a very large disparity across industries as well as cultures. Before the crisis, German companies had five weeks' worth of NdFeB in storage, while Japanese companies had several months of supply. This reflects a difference in cultural aversion to risk, which also is a necessary perspective for understanding why some Japanese companies reacted to the Chinese embargo by increasing their stockpile to two years, while a more typical reaction of European producers was to either use lower grade magnets or stop production completely. Other factors, such as differences in the market positioning of final products, may also have played a role. At the time of writing, Japanese car companies hold a stockpile of 6-12 months (interview Nissan), whereas European companies still have a stockpile of only 2-5 weeks (interview Rohstoffallianz).

6.3.6 Changing material properties

Magnet producers have responded to supply constraints by improving the properties of NdFeB, greatly reducing the required amount of dysprosium for high temperature resistant magnets. For instance, using grain boundary diffusion allows for a more precise deposition of dysprosium in the NdFeB microstructure for increased functionality. This technology was available relatively quickly because the necessary basic research had already been performed in earlier R&D, the aim of which was to increase the maximum temperature resistance of NdFeB magnets. Although at that time the increased production costs associated with grain boundary diffusion proved to be prohibitive, the extreme increase in dysprosium price turned it into a viable proposition (interview Hitachi).

The basic R&D for grain boundary diffusion took 2 to 3 years. The subsequent scaling up of such a technology from small scale to volume production can take 6 to 24 months. As with material substitution, one also needs to take into account product life cycles: once the novel material becomes available it can take from several months to 5 years before it is actually incorporated into the final products. At the time of writing, a reduction of up to 50% of dysprosium content has been achieved (interviews Hitachi, Arnold magnetics).

6.3.7 Material substitution

The producers of the final goods that use NdFeB can substitute on many levels, ranging from using a lower grade of the same material to outright substitution of the entire technological system dependent on that material (e.g. replacing wind energy with photovoltaic energy). In our previous paper (Sprecher 2015)[3] we highlighted the two most common types of substitution:

- Material substitution: the requirement of using magnets remains in the final product design, but this requirement is met with a different material (e.g. replacing NdFeB magnets with samarium-cobalt magnets).
- Technological substitution: a product is redesigned to operate without any magnets at all (e.g. replacing a direct drive with a geared wind turbine).

On the basis of our most recent research, we add another type of substitution:

- Grade optimization: a high performance magnet is substituted by a low performance magnet with a lower REE content. This can be done almost instantly. Our impression is that Japanese manufacturers tried to obtain their material at any cost, while European manufacturers sometimes opted for temporarily using much lower grades of NdFeB, accepting that their products would not perform as advertised, although for obvious reasons this is a sensitive topic.

The variety of substitution possibilities makes it challenging to arrive at a comprehensive quantitative indicator. Nasser et al. (2015) solved this by first collecting data on a range of indicators (substitute performance, substitute availability, co-mined fraction, environmental impact ratio and net import reliance ratio), then giving these a weight, and finally calculating an overall substitutability score.[6,18] This is an appropriate approach for comparing the substitutability of various elements for the purpose of ranking them on criticality, but it does not yield the dynamics of substitution that we are looking for in this work.

Time-delay of implementing substitution can be quite significant, owing to the fact that it usually requires a product redesign. Substitution will usually occur at the end of a product life-cycle, although this can be expedited in the case of acute disruptions. The delay is highly dependent on the sector. Interviewees indicated that, assuming no significant R&D is necessary, components of consumer products can be substituted within several months. Strict regulations cause the automotive industry to take a year, and the extremely risk-averse aerospace and defense sectors can take up to five years.

One major global NdFeB supplier reported that overall, ±10% of their customers substituted NdFeB for samarium-cobalt (SmCo) magnets and were not aware of any other types of substitution amongst their customer base. Roughly 20% of their customers preferred to switch to lower grade NdFeB magnets. This is probably an underestimation of the true extent of grade optimization. Since grade optimization may negatively affect performance and/or lifetime of the final product, there is almost no publishable data available on the topic, making it difficult to estimate the actual impact of grade optimization on total NdFeB demand.

Several audio equipment manufacturers and factory automation manufacturers reported that they almost completely substituted NdFeB magnets with non-REE magnets about 2 years after the 2010 crisis.

Siemens reported in 2014 that they were working on producing wind turbines with dysprosium-free NdFeB magnets ‘in a few years’ time’.[19] One patent described a method to replace dysprosium containing NdFeB magnets with dysprosium-free NdFeB magnets that are twice as large.[20] This shows how substitution can have very different goals and effects for individual applications.

Another interesting side-effect of substitution is that it may disrupt other markets; the drastic price increase of NdFeB caused a knock-on price increase of ~10% for samarium cobalt magnets (interview Arnold Magnetics).

In summary we roughly estimate that the compound effect of substitution was to reduce demand for NdFeB by 10% of total demand per year. If one is willing to implement systemic substitution, the maximum magnitude will in theory be 100%. However, interviewees indicated that for the overall market, maximum magnitude will be between 20-50%.

6.4 Discussion

Rare earth elements (REE) including specifically Neodymium are often considered to be among the more critical materials.[21,22] Therefore, how the REE supply chain responds to disruptions is important for the assessment of criticality. In this work we quantitatively assessed how the NdFeB supply chain responded to the disruption in supply caused by the 2010 REE crisis. The results are summarized in Table 8.

The most salient finding is that substitution was both the fastest and largest system response. Although it should be noted that substitution possibilities are highly dependent on the specific application, we found that some producers opted for using samarium-cobalt magnets, while others temporarily used lower grade NdFeB magnets. A more thorough substitution type requiring product redesigns followed a year or two after the disruption.

Secondly, non-Chinese primary production also responded within a year. It was, however, much slower to ramp up than substitution. Since truly new primary production capacity can take 4 to 13 years to come online, this quick uptick in primary production can be attributed to increased co-production of REEs in existing mines for other metals that had no commercial incentive to do so until the REE price increase

Third, use of dysprosium as an alloying element was reduced significantly, both by substituting dysprosium-rich NdFeB alloys for other alloys and by changing the production method of temperature-resistant NdFeB magnets.

Fourth, recycling is of note primarily because of its trivial impact on the market, due to well-documented problems with collecting and processing NdFeB magnets from waste electrical and electronic equipment WEEE.[17]

Finally, stockpiles were available at the beginning of the disruption. However, in the perception of NdFeB consumers, these stockpiles were not large enough to cover the time needed to implement measures such as substitution. This caused some actors to acquire more material at any cost, driving the price of REEs significantly higher than otherwise would have happened. Thus, rather than cushioning the supply disruption by releasing material from the stockpile, additional stockpiling actually worsened the disruption into a crisis. Interviewees indicated that the current level of stockpiling is 6 to 12 months for Japanese car companies, while European companies generally have a 2 to 5 week stockpile.

Combined effects of multiple resilience mechanisms

Figure 19 shows how the resilience mechanisms add up compared to the disruption of primary production. The resilience mechanisms were able to compensate for the disruption in less than two years. We highlight two interesting dynamics: between 2010 and 2012 the resilience mechanisms were not able to compensate for the drop in production, which could indicate that actors were drawing on stockpiles, or even stopped production altogether. After 2012, the resilience mechanisms overshot the gap in primary production, which can be interpreted as compensation for the demand growth that would have occurred post-2010 if there had been no disruption.

With respect to data quality, we believe the present description to be an accurate description of how the sector as a whole responded to the 2010 disruption. However, given the opaque nature of the REE sector and the wide diversity between actors, it would be very challenging to go beyond the level of detail presented. The response speeds listed in Table 8 reflect the annual change in the years immediately following the disruption. Since the REE price was elevated for a limited time only, this case study does not show what the average response speed would be in case of a more permanent disruption.

Table 8 A summary of resilience mechanism parameters. Time-lag denotes the lag between the 2010 REE crisis and the first observable response, with the range indicating the time it took various actors to implement a given mechanism. Response speed is expressed as the annual percentage with which the market substitutes, compared to the total market volume at the beginning of the crisis (we used a percentage indicator because interviewees were more comfortable giving percentages than absolute numbers). Maximum magnitude indicates the maximum effect a resilience mechanism can eventually reach.

Mechanism	Time-lag	Response speed	Maximum magnitude
Diversity: new primary production	1 – 13 years	4% of total market/y	Determined by reserves base
Diversity: recycling	5-8 years	< 1% of total market/y	Limited by production and recycle rate
Substitution	Months – 5 years	10% of total market/Y	20-50% of total market
Changing material properties	2-3 years R&D + months-5 years implementation	15% reduction/Y	50% of dysprosium content
Stockpiling	Instantaneous	High	Limited by the size of the stockpile

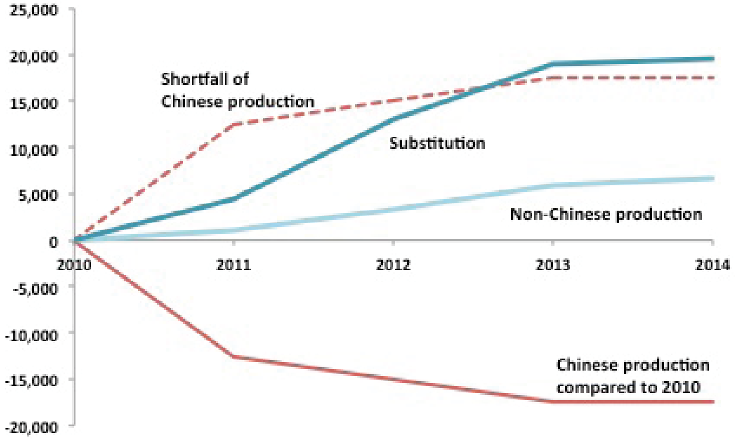

Figure 19 Chinese REE production shortfall and the combined effect of the compensating resilience mechanisms.

So has the system become more diversified and resilient as a result of the crisis? We believe this to be the case. After 2010, full compensation for the disruption took around two years. The overall disruption was caused as much by maladaptive system response (actors engaging in emergency stockpiling behavior) as by the initial disruption itself.

While it is arguable to what extent a two-year response time can be seen as resilient, there is every indication that a new disruption will be dealt with more quickly, because a lot of the groundwork for the resilience mechanisms has already been done. However, for the system to be truly resilient, the current stockpiles should be large enough to provide resilience until the other mechanisms can take over. What this means exactly is highly dependent on the type of actor and product, but our interviewees indicated that one should generally aim for a 3-9 month stockpile. Given the time lags in Table 8 (mostly at the scale of years), increased stockpiling might be advisable.

Finally, it seems that production of NdFeB has increasingly concentrated in China. Figure 14 shows that market concentration is now higher for NdFeB production than for primary production. This is not likely to be a problem from a supply chain disruption point of view, because sufficient technical capacity to produce NdFeB outside China exists. This statistic however shows that the Chinese goal of leveraging its market dominance in REE production to force production further in the value chain to China is successful.

Future research

Further application of the resilience framework to other metals is necessary to see to what extent the results presented in this work are reproducible in other supply chains. Additionally, some resilience mechanisms might take longer than the period under investigation in this work. Therefore, it seems desirable that in the future, the case study will be revisited. A further development of indicators could involve a derivative kind of indicator, (i.e. the rate of increase of a problem divided by the response rate).[23] This dynamic aspect of systems is relevant because comparing the rate of change of the resilience mechanisms with the speed with which a system can be disrupted gives insight into the overall resilience of the system.[24]

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Supporting information

The supporting Information is available free of charge on the ACS publications website.

- Interview list
- Cover letter
- Semi-structured interview format

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7

Discussion

In the preceding chapters we have considered a number of aspects of neodymium supply and recycling. This scientific enquiry was done in the context of the 2010 REE crisis. Neodymium is a generally recognized critical material with a relevant application in the form of NdFeB magnets, whose unique strength makes it a key component for sustainable energy technologies (direct-drive wind turbines and motors for electric vehicles) as well as in consumer goods (e.g. hard disk drives).[1,2] Additionally, material resource constraints are generally seen as important aspect of sustainability.[3] Therefore, the NdFeB supply chain makes for an interesting industrial ecology case study. Furthermore, the criticality of REE present an appropriate case study of what ‘criticality’ is, because for current demand there is more than enough REE bearing ore available across the globe. This implies that any near-future supply constraints are not the consequence of inherent problems with resource availability, but rather of a (mal)functioning of the supply chain. Finally, as a practical consideration, the NdFeB supply chain makes for a case that is quite ‘small’, i.e. one with a limited number of actors, and also compact in time, allowing us to track the process from initial disruption to re-equilibration of the system, even while the crisis is relatively recent.

This dissertation aimed to answers four main research questions:

1. What are the material flows of neodymium for NdFeB, and how much can be made available for recycling?
2. What are the environmental burdens of NdFeB production, and how does recycling alleviate this burden?
3. What type of mechanisms along the NdFeB supply chain provide resilience in response to supply constraints and disruptions?
4. Can we quantify the resilience mechanisms of the NdFeB supply chain, and identify which played the most significant role in the aftermath of the 2010 REE crisis?

First, in sections 7.1 through 7.4, we answer each research question separately. In section 7.5 we draw conclusions with respect to the overall NdFeB supply chain and in section 7.6 we discuss resilience from the perspective of each type of actor along the supply chain. In section we 7.7 discuss the merit of the resilience framework in comparison with other criticality-focused frameworks. We end with an outlook for future research (7.8).

7.1 The material flows of neodymium and their availability for recycling

The vast majority of neodymium is used for NdFeB magnets (88%, see Figure 2). We found that for most non-magnet applications neodymium is dispersed to such a degree that setting up a closed loop recycling system would be very difficult. However, even when restricting ourselves to NdFeB magnets, we find that its usage is spread among an enormous range of applications (see Table 1). Wind energy and e-mobility are often seen as significant potential recycling sources because they contain a large quantity of NdFeB magnets. However, literature shows that because of long lifetimes these magnets will probably not be available for recycling in large volumes in the next two decades.

Our results indicate that for the foreseeable future, the only available source of recyclable NdFeB is from computer hard disk drives (HDDs). We find that within the application of NdFeB magnets for HDDs the potential for loop closing is significant, up to 57% in 2017 (see Figure 5). However, the recovery potential from HDDs compared to the total NdFeB production capacity is relatively small (in the 1-3% range). Moreover, we found there to be severe barriers to NdFeB recycling, such as prohibitive costs, collection rates and uncertainty about future use of NdFeB for computer storage. These were discussed in more detail in Chapter 2.

Chapter 2 also addresses the question of what problems recycling would alleviate. Besides environmental concerns (see the following section), the discussion is often framed in terms of security of supply: OECD countries find it undesirable to be dependent on a single supplier such as China for virtually the entire supply of rare earths. Additionally, most of the basic processing facilities that are needed to produce neodymium magnets are to be found in either China or Japan. Insofar that measures to reduce resource dependency focus on recycling, these should not only emphasize the recovery of NdFeB from waste, but also the production capacity to reprocess the End-of-Life magnets into new material.

From the resource scarcity perspective we think that in the near future recycling neodymium will be able to contribute very little, due to the distributed nature of the applications. The fact that the whereabouts of a critical metal such as neodymium can only be traced for such a small fraction of the total use is undesirable because it makes it very difficult to formulate specific policy on for example what sectors to prioritize with respect to efforts to increase security of supply. We suggest that if neodymium is to be used sustainably, a concerted effort must be made to categorize the applications in which it is possible to create a closed-loop and only use Neodymium for these applications. The potential of recycling can be increased significantly if neodymium can traced from mine to material, product and finally to waste.

7.2 The environmental burdens of NdFeB production and the prospects of recycling

With respect to environmental impact of primary neodymium production, we found that if the primary production process of NdFeB is technically advanced (i.e. high process efficiencies, end-of-pipe emission controls), most of the impacts are related to energy use. Technically less advanced production processes also incur a large human toxicity penalty, which highlights the significant improvement potential for technical improvements in production processes. Our results indicate that a low-tech production process has double the GHG emissions of a high-tech process, while the Human Toxicity indicator increases by an order of magnitude (see Chapter 3 for detailed results).

We also found that in the baseline scenario of Chapter 3, 64% of the total neodymium input is lost along the production chain. Half of this loss occurs during the beneficiation process of REE containing ore. Peiró and Méndez report that recovery rate during beneficiation is expected to rise to 75% by 2016.[4] Such an improvement to the recovery rate in this process has the potential to significantly reduce supply side constraints of all REEs, not only neodymium, and should be prioritized over process improvements later in the production process.

With respect to recycling, we analysed two different processes: the traditional shredder–based process and a novel hydrogen–decrepitating process. Our results (see Figure 7) indicate that the choice of recycling method is of significant influence on the environmental impact, with hydrogen decrepitation scoring significantly better. However, the most important difference between the two recycling processes is not adequately reflected in the environmental indicators: recycling through shredding results in very low recovery rates (<10%) of NdFeB. Because the discussion on the use of rare earths is framed in terms of scarcity more than environmental damage, this is a serious issue not addressed through LCA.

We conclude that the value of recycling of neodymium is highly dependent on the method of recycling. Although from an environmental point of view recycling will always be an improvement over primary production, the large losses of material incurred while shredding the material puts serious doubts on the usefulness of this type of recycling as a solution for scarcity. Furthermore, our LCA also shows that technological progress can make a significant difference in the environmental impact of producing neodymium magnets from primary sources.

7.3 The mechanisms along the NdFeB supply chain providing resilience in response to supply constraints and disruptions

The research presented in Chapter 5 shows that resilience is a useful concept for investigating the dynamics of the NdFeB supply chain. It comprises aspects of resistance to disturbance, rapidity of response, and flexibility, *i.e.* the ability to switch between alternatives.

We found that the following concrete mechanisms are primarily responsible for this resilience. On the supply side *diversity of supply* allows for more variety in sources of raw material, potentially reducing the impact of a disruption or constraint on the remainder of the supply chain; *stockpiling* acts as a buffer that lessens the impact of temporary supply disruptions. On the demand side there is *improving material properties*, where magnet producers have responded to supply constraints by improving the properties of NdFeB, thus greatly reducing the required amount of dysprosium for high temperature resistant magnets, and *substitution*, where some producers substituted NdFeB magnets with other magnets, while others switched to a completely different technology that did not rely on permanent magnets. The three most common types of substitution are:

- Material substitution: the requirement of using magnets remains in the final product design, but this requirement is met with a different material (e.g. replacing NdFeB magnets with samarium-cobalt magnets).
- Technological substitution: a product is redesigned to operate without any magnets at all (e.g. replacing a direct drive with a geared wind turbine).
- Grade optimization: a high performance magnet is substituted by a low performance magnet with a lower REE content. This can be done almost instantly. Our impression is that Japanese manufacturers tried to obtain their material at any cost, while European manufacturers sometimes opted for temporarily using much lower grades of NdFeB, accepting that their products would not perform as advertised, although for obvious reasons this is a sensitive topic.

The main stabilizing/destabilizing forces in the system are the feedback loops, of which the economic feedback loop (i.e. price mechanism) is the most important. Figure 14 illustrates how all the feedback loops and mechanisms are connected to the supply chain.

Not all responses to the 2010 REE crisis contributed positively to system resilience. We note the two most explicitly 'negative' responses, in the sense that they aggravated rather than relieved the crisis. The first is panic buying by Japanese companies, who tried to increase their stockpile only after the Chinese export quotas came in full force. This contributed greatly to the price increases. The second is illegal mining and smuggling of Chinese rare earths (estimated at 40% of the official production).[5] Although smuggling increases the diversity of supply and thereby the resilience of the sector, illegal mining has devastating environmental and social effects. [6]

7.4 A quantification of the resilience mechanisms of the NdFeB supply chain

The most salient of the findings presented in Chapter 6 is that the aggregate of substitution actions was the most significant system response. Substitution is highly dependent on the specific application. We found that some producers rapidly adapted to the increased prices by switching NdFeB for samarium-cobalt magnets, while others temporarily used lower-grade NdFeB magnets. A more thorough substitution type requiring product redesigns followed a year or two after the disruption. Overall, roughly 10% of the total market volume was substituted each year. Our research indicates that realistically up to 20-50% of NdFeB demand will be substituted, depending on future market conditions (i.e. price). Use of dysprosium as an alloying element was also reduced significantly, both by substituting dysprosium-rich NdFeB alloys for other alloys and by changing the production method of temperature-resistant NdFeB magnets.

Non-Chinese primary production also responded within a year. However, as seen in Figure 18, in terms of absolute production the ramp up was smaller than that of substitution (4% of total market volume per year, compared to 10% for substitution). Since truly new primary production capacity takes 4 to 13 years to come online, this relatively quick increase in primary production can be attributed to increased production of REEs in mines that normally only mine other metals, and for whom the increased REE price suddenly made co-production of REEs worthwhile.

Significant stockpiles were available at the beginning of the disruption. However, in the perception of NdFeB consumers, these stockpiles were not large enough to cover the time needed to implement measures such as substitution. This caused some actors to acquire more material at any cost, driving the price of REEs significantly higher than otherwise would have happened. Thus, rather than cushioning the supply disruption by releasing material from the stockpile, additional stockpiling actually worsened the disruption into a crisis. Interviewees indicated that the current level of stockpiling is 6 to 12 months for Japanese car companies, while European companies generally have a 2 to 5 week stockpile.

Finally, recycling is of note primarily because of its trivial impact on the market, due to the problems with collecting and processing NdFeB magnets from waste electrical and electronic equipment WEEE discussed in Chapter 2.

Taken together the resilience responses were of sufficient magnitude that the supply chain should have experienced less of a price shock than it actually did, especially considering the ease of substitution and the size of stockpiles relative to the magnitude of the disruption. In the following section we turn to analyzing the supply chain as a whole to understand why this was so.

7.5 Summary conclusions on overall NdFeB supply chain resilience

The supply chain as a whole was able to compensate for the 2010 disruption in less than two years. The combined effect of substitution and increasing non-Chinese production is shown in Figure 18. Two dynamics deserve to be highlighted: between 2010 and 2012 the resilience mechanisms were not able to compensate for the drop in production. During this same period some actors were increasing their stockpiles which led to a temporary increase in REE demand (section 6.3.5). Other actors compensated by drawing on their own stockpiles, using illegally sourced materials or even stopping their production altogether. After 2012, the resilience mechanisms overshot the gap in primary production. Substitution in this period can be interpreted as compensation for the demand growth that would have occurred post-2010 had there been no disruption.

It is reasonable to believe that the NdFeB supply chain system has become more resilient and diversified as a results of the crisis, which was caused as much by maladaptive system response (actors engaging in emergency stockpiling behavior) as by the initial disruption itself. While it is debatable to what extent a two-year response time can be seen as resilient, there is every indication that a new disruption will be dealt with more quickly, because a lot of the groundwork for the resilience mechanisms has already been done. However, for the system to be truly resilient, the current stockpiles should be large enough to provide resilience until the other mechanisms can take over. What this means exactly is highly dependent on the type of actor and product, but our interviewees indicated that one should generally aim for a 3-9 month stockpile. Given that our research indicates that the current level of stockpiling is 6 to 12 months for Japanese, and 2 to 5 weeks for European car companies, increased stockpiling might be advisable, especially for European companies (this might also be the case for other western companies, however, this was outside the scope of this research project).

The fact that substitution and replacement of primary production, and not recycling, were the main resilience mechanisms has important implications for the idea of a 'circular economy'. Many reports on the circular economy will implicitly or explicitly adhere to reasoning along the lines of circularity being an easy fix for stagnating economies, resource constraints and climate change. For example, the Ellen McArthur Foundation writes that 'resource productivity remains hugely underexploited as a source of wealth, competitiveness and renewal',[7] and the International Solid Waste Association says that 'price signals for raw materials are a key driver in any change to the circular economy'.[8]

The case study of Chapters 5 and 6 provided an example where a supply disruption and subsequent price peak did not nudge a system towards circularity in any appreciable degree. Although our study only discusses the effect of a single supply disruption, it is relevant to the overall discussion on material scarcity because of the significance and duration of the disruption. If a two-year disruption causes almost no movement towards more effective material use, then this implies that quite a long period of sustained material constraints will be necessary for a production-consumption system to naturally evolve towards a circular configuration.

If not effective in nudging a transition towards circularity, the REE crisis did have a different effect. Figure 16 shows that market concentration, as measured by the HHI indicator, is now higher for NdFeB production than for primary production, with production capacity increasingly being concentrated in China. This is not likely to be a problem from a supply chain disruption point of view, because sufficient technical capacity to produce NdFeB outside China exists. It does however show that the Chinese goal of leveraging its market dominance in REE production to force production further in the value chain to China is successful.

One last issue is the status of the NdFeB supply chain as a complex adaptive system. One of the defining elements of a complex system is that the agents inside the system act more or less blindly, which gives rise to unplanned emergent behavior. Based on the reconstruction in this thesis, one would argue that the NdFeB supply chain was a complex system at the beginning of the crisis, with many of its actors only dimly aware – if at all – of what was going on elsewhere in the system. The panic buying in late 2010 is a typical example of a positive feedback loop activated because of limited systemic awareness of actors. However, after the crisis the intense scrutiny of the entire supply chain resulted in a much higher level of supply system understanding of the actors involved, thereby removing significantly their earlier myopia. Additionally, one could argue that through vertical integration of actors, both through acquisitions and takeoff agreements, the structure of the system itself has also become less complex.

7.6 Resilience from the actor perspective

The above section discussed the overall outlook of the NdFeB supply chain. We now turn to a discussion of what the results of this research project mean for the actor in the supply chain. This actor-oriented perspective is particularly relevant for supply chain resilience because the benefits of resilience-enhancing measures are often not bestowed on the actors who bear the costs of enhanced resilience. Clearly such unbalance in risks and rewards for individual actors is not helpful to move the system to greater resilience. We will discuss the actors along the NdFeB supply chain, working from the end-product back to the mine (see also Figure 9).

7.6.1 The producer of finished products

Both substitution and recycling are crucially dependent on product design. Implementation of these resilience strategies therefore relies on the producer of the finished product. Furthermore, the use of NdFeB magnets is in principle a good match with novel sustainable business models, such as take-back systems or product-service systems. This is due to the relatively long life-time of a properly sealed NdFeB magnet compared to other components in an average consumer product.

The producer of finished products also has the option of stockpiling REE containing components. However, from an overall supply chain point of view stockpiling makes more sense when done by the smelter operator, who can store rare earths in their powder oxide form instead of as finished components (this will be explained in more detail in the smelter operator section below). The initiative for this type of stockpiling will probably still have to be taken by the finished product producers, as this actor should communicate with the smelter operator to ensure enough stockpile is reserved to cover the time period required for substitution. This requires a direct connection between two actors, which normally are connected only indirectly, via the magnet producer. Additional connections increase the supply chain complexity, which, as we have seen in 4.2.3, can have difficult to predict effects on the stability of the overall system (both negative and positive).

Of all the actors, the producer of the finished NdFeB containing product has the most options for supporting resilience mechanisms, and therefore, arguably, should take the lead in achieving overall supply chain resilience. At minimum, the producer should have a plan for REE substitution and an assessment of implementation time. Both stockpiling and design-for-substitutability can be relatively costly, so a future methodological development would be to calculate the monetary value of resilience and then compare the costs of maintaining a stockpile and designing a highly substitutable product.

7.6.2 The waste manager and recycler

Waste managers face several challenges, such as changing preferences in product design and specification that are not conducive to recycling, strong fluctuations of commodity prices, lack of cohesion and detail in quality standards for recyclable materials, and competition from primary production.

Competition from virgin material is an especially significant barrier. The size of the virgin raw material sector is such that even the largest recycling plants are an order of magnitude smaller than mining sites, while simultaneously having to deal with the fact that waste has a far more complex composition than ore, thus necessitating more unit operations per ton material produced.[9]

Institutionally, the recycling sector is also at a disadvantage. A comprehensive analysis at the EU or Dutch national level is not available, but Johansson et al. compared the governmental support (in the form of direct and indirect subsidies) for the Swedish metals mining and recycling sectors.[1] Their results show that the value added/tonne of metal produced is 114€ for mining and 151€ for recycling, for a similar distribution of metals. One would expect that the Swedish government would therefore support recycling and primary production at least equally. However, they found that mining is subsidized 6.6x higher on a per tonne basis than recycling (2€/tonne versus 0.3€/tonne). They also note that mining is exempt from a landfill tax for their mining waste. If this tax-exemption is also counted as a subsidy, they would receive a massive 737x higher subsidy relative to recycling (221€/tonne). A salient detail is that Swedish subsidies for R&D are 4.5x higher for the mining sector than recycling.[10]

After much consideration we must conclude that the best way forward for the waste management sector is to lobby both at the national and EU level for rules, regulations and subsidies that at minimum provide a level playing field with the mining sector. In a recent report, ISWA recommended that the waste management sector lobby for the following policies (taken directly from the report):[8]

Policies to push recovered materials onto the market (push policies):

- Landfill diversion targets or bans for landfilling of organic waste, recyclable material streams and combustible waste.
- Landfill Tax to encourage alternative treatment options such as energy recovery or recycling.
- Incineration Tax to encourage recycling above incineration.
- Recycling and Recovery targets for specific waste streams.
- Polluter pays policies, such as Extended Producer Responsibility (EPR). Such policies hold producers and importers responsible for the end of life of materials placed on the market and can help to internalize external costs involved in the recovery of secondary raw materials such as those arising from the increased complexity of products.

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[1] Although Sweden is not completely comparable to the Netherlands, it is of interest because it shows how another EU country values its primary and secondary metals sector, and this comparison can be used to argue that the secondary metals market is undervalued by policymakers.

Policies that help to create market demand for secondary materials (pull policies):

- Green taxes (eco-taxes) on consumption and production e.g., taxes on plastic carrying bags, packaging.
- Funds to support environmental performance. e.g. European Commission Eco-Innovation which has one of the aims to encourage the design of innovative products using recycled material and facilitate material recycling.
- Green Public procurement –public authorities to procure goods produced from or with a certain fraction of secondary raw materials.
- Industry target on use of recovered materials in production and manufacturing.
- Innovative fiscal changes to drive behavior change such as reductions in VAT or tax credits for secondary raw materials, recycled products or accelerated depreciation for assets purchased for re-use of recycling of waste materials. Global examples now exist in China, Korea, Mexico and the USA.
- Waste sector engaging in waste prevention and newly emerging circular business models such as where companies offer products as services seeking to retain ownership and internalize benefits of circular resource productivity.

In fact, the EU has very recently (03/12/2015) published its circular economy package, with legislative proposals on waste.[2] Unfortunately the author of this dissertation cannot help but be disappointed in the rather vague and non-committal text contained within. For example:

“As a first step, and under the framework of the Ecodesign directive, the Commission has developed and will propose shortly to Member States mandatory product design and marking requirements to make it easier and safer to dismantle, reuse and recycle electronic displays (e.g. flat computer or television screens).”

Specifically on the recycling of critical materials the CE package has the following to say:

“The Commission is encouraging Member States to promote recycling of critical raw materials in its revised proposals on waste.”

Clearly, the ISWA has its work cut out for it.

As a final comment on the role of recycling, despite the extensive attention given to REEs in the scientific and policy literature, the results of this dissertation indicate that, since there seems to be no serious limitation on REE supply from a geological point of view, there is no special moral obligation towards future generations to reduce REE usage, or increase to recycling rates. The environmental benefits of REE recycling – and of REE use in general – should be compared to other options for improving environmental performance through a regular LCA exercise. This also underlines the need to resolve the issues with LCAs for REEs about lack of characterization factors for radioactive and acidic waste (also part of the recommendations for future research).

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[2] http://ec.europa.eu/environment/circular-economy/index_en.htm

7.6.3 The magnet producer

Given the volatility of the NdFeB market, resilience for NdFeB producers is found in product diversification more than anything else. Magnet producers could gain competitive advantage by offering their clients consultancy services on how to design products where one type of magnet is easily substituted for another type, also supplied by said magnet producer. Furthermore, magnet producers can play the vital role in communicating between the stockpile holding smelters and those final product producers that wish to have a stockpile. In this sense they could act as a kind of insurance broker.

7.6.4 The smelter operator

Metallic neodymium is highly susceptible to oxidation, thus the most ideal chemical form for storage is neodymium oxide. Furthermore, there are many different grades of NdFeB magnets, which makes it much more feasible to stockpile the raw material for all of these different grades than to stockpile each grade individually. This puts the smelter operator in a crucial position, because stockpiling of neodymium makes most sense at this step in the supply chain. However, while REEs are usually a small percentage of the overall material costs of a product, for the smelter operator the costs of REOs is very significant. For a product manufacturer a three-month stockpile of REO would not be a significant investment compared to overall business expenditure, while a supply disruption would cause a significant loss of income because the product cannot be made. For the smelter operator on the other hand, the costs of stockpiling are high compared to overall business expenditure, while the benefits to its business are less than for the manufacturer. Arguably, this goes a long way to explaining 2010 situation of insufficient stockpiling.

7.6.5 The REE miner and refiner

Because the extraction process of REEs is highly dependent on the exact mineralogy of the ore, the options of the REE mining and refining actors must be considered together. As discussed in Chapter 3, REE mining and refining need not be unduly burdensome on the environment, but if not done properly it can be. It is often commented that Chinese REE mines are much more environmentally damaging than western counterparts. However, it seems that lack of respect for the environment is pervasive in the mining industry overall. For example, as recently as April 2014 Molycorp was fined in California for violating environmental regulations.[11] The activities of Australian REE miner Lynas in Malaysia are also illuminating. Its REE refining plant (LAMP) was held up significantly over lawsuits regarding the environmental impacts. An NGO commissioned report shows that this was at least partially justified given the seemingly lax attitude of Lynas towards meeting the legitimate concerns of the local population (legitimate considering the fact that a previous REE refinery in the same area had caused massive pollution).[12]

In Chapter 5 we concluded that one of the policy options to improve resilience is the reduction of red tape surrounding the opening of mining sites to reduce the response time to demand increases. The fastest track towards achieving that is for mining actors to take their environmental obligations seriously. One of the main arguments given for the lack of attention to costly environmental measures is that REE prices are on average so low that REE mining would not be profitable when done in an environmentally sound manner. The obvious solution to this is more self-regulation. End-users of REEs could enforce global environmental standards on miners through the use of for example certifications. When every mining actor complies with environmental regulations, this would create a level playing field.

A second recommendation relevant to the mining and refining actors is to support R&D that focuses on expanding the use of those REEs that are co-mined in excess, for example cerium. On the long term this would increase the overall profitability of REE mines.

7.7 Resilience in material supply chains compared to other criticality approaches

The concepts for explaining why crises in material supply chains happen have been subject of study for decades, if not longer (e.g. the classical hog cycle). Recently this work has centered on the concept of material criticality. The first major studies on criticality were mostly based on empirical observations. While this is initially the most obvious approach, it also inherently leads to a type of 'after-the-facts' analysis. This can be seen with REEs, which were recognized as critical only after they had actually become critical. For example Nasser (2015) writes: "Committees of the European Commission (EC 2010, 2014) arbitrarily set a boundary for critical/not critical designation and subsequently classed the rare earths as a group as critical. The US DOE (2010) also imposed a cutoff and then designated Dy, Eu, Tb, Nd, and Y (out of nine REEs examined) as critical." A more complete discussion of recent work on material criticality can be found in Graedel & Reck.[13]

In the remainder of this section we will contrast the criticality approach with resilience, the main difference being that criticality tries to determine what the probability and impact of significant disruptions are, while resilience takes for granted that disruptions (the predictable as well as the unpredictable) will happen eventually and instead focusses on the ways and means by which a supply chain can deal with disruptions. This is perhaps best illustrated by looking at the criticality framework of Graedel et al.[14] as applied to REEs by Nassar et al,[15] who's conclusions are generally in line with the discussion in this chapter, namely that criticality is highly dependent on substitution potential, and that the criticality of REEs is less than found in previous criticality studies.

Nevertheless, significant differences can be found. The main unit of both resilience mechanisms and system disruption as used in Chapter 5 is '% of total market/year'. Although these data are not necessarily easy to find, once available this allows for a consistent comparison across the resilience mechanisms and even different supply chains. In contrast, the criticality framework as developed by Graedel and co-workers uses 16 indicators covering a very wide variety of topics such as Depletion Time, Human Development Index, Substitute Performance, Net Import Reliance Ratio and Global Innovation Index. These indicators are transformed to fit on a 1-100 scale and summed using weighing factors. The result is a three-dimensional graph comparing elements on Supply Risk, Vulnerability to Supply Restrictions and Environmental Implications.

Besides the obvious dissimilarity in breadth and complicatedness resulting from diverging indicator choices, the most salient difference is that the resilience framework is focused on the dynamic aspects of the supply chain; how it changes over time in response to disturbances and incorporating non-linear responses through the explicit use of feedback loops, while Graedel et al. acknowledges that non-linearity plays an important role in complex supply chains, their framework essentially generates a static snap-shot of criticality. This dynamic aspect of supply constraints is incredibly important, and therefore we would go so far as to hypothesize that one can define the criticality of a material in terms of how resilient its supply chain is.

On a perhaps more philosophical note, both the reliance on weighing factors and the widely disparate set of indicators are problematic, because they show an underlying assumption of how the world works, or should work, rather than being based on a 'neutral' theoretical framework (i.e. complex adaptive systems theory). For example, the Graedel framework uses the human development index and environmental impact as an indicator for criticality, which, based on experience with conflict minerals and rare earth elements, seems to be as much wishful thinking as actually of relevance when assessing the supply of these materials to the market.

7.8 Recommendations for future research

The fact that rare earth metals are dominantly mined in China and that Chinese mining is not properly covered by statistics and verified environmental modelling makes for a scarcity of data – both economic and environmental. One aspect is that neither the LCA presented in Chapter 3, nor other LCAs on REEs[16-19] address the issue of radioactive waste connected to rare earth production. This is due to a combination of uncertain data and a lack of appropriate characterization factors. Along the same lines, the characterization factor for hydrogen fluoride carries an order of magnitude uncertainty, and factors for emissions of acids into water, and waste treatment of REE processing are not available at all. Current LCA results therefore probably significantly underestimate the true environmental impact of REE processing. It is recommended to implement or refine these characterization factors.

In closing, resilience in industrial ecology is an exciting topic, and there are quite a lot of avenues of future research. On the one hand the resilience framework presented in this dissertation can be broadened via application to case studies other than NdFeB. On the other hand the framework can be deepened by connecting resilience to methods generally used in the IE community, such as input-output modeling, substance flow analysis, mass flow analysis and life cycle assessment. Resilience is a popular topic in the supply chain research field, so a connection to that field would be of interest. In Chapter 6 quantification of resilience was done through data collected from interviews and literature sources. This quantification could be improved upon by drawing on more data sources such as trade statistics, as for example was done in Mancheri,[20] and implementing the dynamic model for the resilience system that is shown in a qualitative form in Chapter 5. In order to test hypotheses about how various resilience mechanisms could be implemented and optimized various kinds of modeling should be employed. Using an agent based modeling (ABM) approach seems like a natural fit for investigating resilience from an emergent system property perspective, and could build upon the work of Riddle et al., who built an ABM of the Nd and Dy supply chains to explore possible future supply and demand trajectories.[21] A network analysis based approach can be used to investigate interactions between different supply chains and could be based on databases such as EXIOBASE or ecoinvent.

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Summary

This dissertation is the culmination of over four years research on the rare earth element neodymium in the context of the 2010 REE crisis. Neodymium is a generally recognized 'critical' material with a relevant application in the form of NdFeB magnets, both for sustainable energy technologies as well as the wider economy. The NdFeB supply chain makes for an interesting industrial ecology case study for two reasons. Firstly, there is more than enough REE bearing ore available across the globe. This implies that any supply constraints emerge as a consequence of dysfunctional supply chain; not because of the element's resource scarcity. Secondly, the neodymium supply system is relatively small, both in number of actors involved and time between the disruption and stabilization of the system.

This dissertation answers four main research questions:

1. What are the material flows of neodymium for NdFeB magnets, and how much can be made available for recycling?
2. What are the environmental burdens of NdFeB production, and how does recycling alleviate this burden?
3. What type of mechanisms along the NdFeB supply chain provide resilience in response to supply constraints and disruptions
4. Of all the possible resilience mechanisms, which played the largest role in the aftermath of the 2010 REE crisis?

In essence, this research project found that not much NdFeB is available for recycling because the vast majority ends up in small and difficult to locate applications. Provided you manage to find a significant quantity of NdFeB, the environmental impact of recycling can be an order of magnitude lower than primary production. Primary production of REEs can have an environmental impact in the same order of magnitude as primary production of aluminum, but only if modern production techniques are used. Although there are a number of resilience mechanisms, overall we find that substitution (in its various forms) was the most relevant one.

Besides directly answering the research question, this dissertation also reflects on the broader question of how actors in the NdFeB supply chain can change their behavior to limit their exposure to an unforeseen yet inevitable future crisis.

Samenvatting

Deze dissertatie is de uitkomst van meer dan vier jaar onderzoek naar het zeldzame aardenelement (REE) neodymium, in de context van de 2010 REE crisis. Neodymium wordt in het algemeen gezien als een van de 'kritieke' materialen, vooral vanwege het gebruik van dit metaal in permanente NdFeB magneten. Deze magneten worden onder meer gebruikt in duurzame energie technologieën. De NdFeB bevoorradingsketen is om twee redenen interessant als casus voor een industriële ecologie dissertatie. Ten eerste zijn er wereldwijd meer dan genoeg REE ertsen. Dit impliceert dat eventuele problemen met de toevoer niet het gevolg zijn van inherente schaarste, maar van een dysfunctionele bevoorradingsketen. Ten tweede is het systeem rond NdFeB magneten relatief klein, zowel in termen van aantal actoren en de tijdspanne tussen de verstoring die ten grondslag lag aan de crisis in 2010, en de daaropvolgende stabilisatie van het systeem.

Deze dissertatie poogt een viertal onderzoeksvragen te beantwoorden:

1. Wat zijn de materiaalstromen van het neodymium in NdFeB magneten, en welke fractie daarvan is eventueel beschikbaar voor recycling?
2. Wat is de milieubelasting ten gevolge van NdFeB productie, en in hoeverre kan recycling deze milieubelasting verlagen?
3. Welke mechanismen in de NdFeB bevoorradingsketen zijn verantwoordelijk voor de weerbaarheid (*resilience)* die het neodymiumsysteem vertoonde in reactie op verstoringen en toevoersproblemen rond 2010?
4. Welke van de mogelijke weerbaarheidsmechanismen speelde de grootste rol in de nasleep van de 2010 crisis?

Het meest saillante resultaat van dit onderzoek is dat er nauwelijks NdFeB beschikbaar is voor recycling. De overgrote meerderheid wordt gebruikt in kleine hoeveelheden, hetgeen verzameling – of überhaupt traceren – van neodymium een economisch bijna ondoenbare taak maakt. Als je desalniettemin aan recycling begint dan kan de milieubelasting een ordegrootte lager zijn dan de milieubelasting die bij primaire productie optreedt.

De primaire productie van zeldzame aardmetalen heeft een milieubelasting van dezelfde ordegrootte als die van aluminium – maar alleen als moderne productiemethoden worden gebruikt. Hoewel er meerde weerbaarheidsmechanismen zijn geobserveerd, geeft ons onderzoek aan dat substitutie het meest relevante mechanisme was.

Behalve het direct beantwoorden van de onderzoeksvragen reflecteert deze dissertatie ook op de bredere vraag van hoe actoren in de NdFeB bevoorradingsketen hun gedrag kunnen veranderen om hun blootstelling aan een onvoorziene doch niet te voorkomen toekomstige crisis te verminderen.

Acknowledgements

After reading the first draft of this dissertation my *hooggeschatte promotor* observed that I had used the word 'interesting' far too often. From a scientific writing point of view de-interestingifying the text was for the better, but it did rob my dissertation of the main sentiment I somehow wanted to convey. From the late nights spent on understanding the chemistry of rare earth processing to the many, many discussions on the geopolitical games played by China and admiring the Japanese countryside from inside a Shinkansen, zipping around Japan in pursuit of interviews with experts from all across the NdFeB supply chain. It was all incredibly interesting.

To start I would like to thank those who made this research project possible: Frans Bekkers, who came up with the amazing idea of combining a PhD with a traineeship at a waste management company, Rene Kleijn, for agreeing to by my daily supervisor with all that that entails, and Derk Bol, who made a lot of the legal, financial and administrative things happen. I would like to thank my advisor, Gert Jan Kramer for his patient guidance and inspiration in all matters scientific. I would like to thank my managers, fellow trainees / young professionals and colleagues at Van Gansewinkel, for keeping my feet on the ground and my scientific work firmly rooted in waste. I would like to thank Ichiro Daigo, Shinsuke Murakami and all my other Japanese friends and colleagues for welcoming me in Japan and making my time there unforgettable. I would like to thank Matthijs Vos, for the detailed proofreading of the resilience chapters, and all of the above and others in the industrial ecology, M2i, and broader scientific community for the many extensive and interesting discussions. I would like to thank my great many friends, both in the Netherlands and across the globe, for all the great adventures of the non-scientific kind. I would like to thank my parents, brother and other family members for their unwavering support. And above all I would like to thank my grandmother Zimira. Our frequent visits to natural history museums were the start of my scientific career.

Curriculum Vitae

Personal information

Family name : Sprecher
First name : Benjamin
Date of Birth : 26 July 1985
Place of Birth : The Hague, Netherlands

Education

- Mar 2016 – current: Postdoctoral researcher at the Yale University School of Forestry and Environmental current sciences
- Mar 2011 – Jun 2016: PhD researcher at M2i / Institute for Environmental Sciences (CML), Leiden University Jun 2016 In the area of recycling and resource scarcity, with a focus on rare earth elements.
- Apr 2014 – Sep 2014: Guest researcher at Tokyo University, Department of Materials Engineering. Focus on data Sep 2014 collection, collaborating on paper writing.
- Sep 2013 – Dec 2013: Guest researcher at Delft Technical University, Faculty of Technology, Policy and Dec 2013 Management. Focus on learning dynamic and agent based modelling.
- May 2015 – Jun 2015: Consultancy for UNEP and Royal Government of Bhutan. Environmental impact of paper use and options for improvement.
- 2011 – 2013 : Management traineeship Van Gansewinkel Groep.
  Training focussed on project management and personal development at the biggest waste management company of the Netherlands.
- 2008 – 2010 : Master Industrial Ecology.
  Master's thesis: decision modelling of investment opportunities (CML & Van Gansewinkel). Electives: Environmental Biotechnology, Technologies & Economics of Future Energy Systems of Europe. *Faculty of Science, Leiden University*
- Sep 2007 – Jan 2008: Combined bachelor thesis for SMST & psychology in Guayaquil, Ecuador.
  The influence of industrial wastewater on a large mangrove forest located next to Guayaquil, with a focus on combining environmental sciences and psychology to gain a more complete understanding of the problems surrounding this beautiful nature area. *ESPOL, Ecuador*
- 2004 -2008 : Bachelor Psychology.
  Specialization: Social & Organisational psychology* *Faculty of Social Sciences, Leiden University*
- 2003 -2008 : Bachelor Sustainable Molecular Science & Technology (SMST). *Faculty of Sciences, Leiden University*

- 1997 -2003 : Secondary education.
  Profile: Natuur & Techniek. *Scholengemeenschap Dalton-Vatel, Voorburg*
- 1989 -1997 : Primary education.
  Montessorischool Nieuw Vreugd en Rust, Voorburg

Work experience

- Feb. 2009 – now: Freelance journalist and Columnist
  Mainly in the Leiden University newspaper Mare. At first I mostly wrote articles and reports on subjects related to the university and student life. For the past five years I have a regular column. Amongst others, I also published an article in 'het Agrarisch Dagblad', a cover article for the Dutch New Scientist (formerly NWTmagazine) and a travel report on Ukraine for the newspaper NRC.Next.
- 2011 – 2015 : Work experience during PhD
  Teaching responsibilities: organising the Minor Sustainability for two years. Lectures on sustainable waste management, life cycle assessment and system dynamics, including guest lectures at other universities, supervising master theses, etc.
- 2014 – now : Volunteer for the 'Stichting Duurzame Horeca Leiden'
- 2012 – now : Secretary of the interuniversity organisation of environmental science departments.
- 2003 -2012 : Employee Regent Ingredients.
  International marketing & sales of food ingredients. Customer visits: amongst others in in Hungary, Japan, Colombia, Ecuador, and Curacao. Supplier visits: amongst others in Malaysia, England, Japan, Israel and the USA. Fair attendance: amongst others VitaFoods (Genève), FIChina (Shanghai) and FII (Paris). Development and maintenance of the website and CRM system.
  Regent Ingredients, www.regent.nl, Rijswijk, Netherlands
- 2005-2006 : High school lectures on university life.
  Visiting high schools to give presentations on SMST and student life in Leiden. *Leiden University*
- Summer 2004, : Sailing instructor Summer camp for children aged 6 to 10.
  Zeilschool op de helling, Friesland

* Due to administrative issues with doing two bachelors at the same time I never received my actual psychology diploma. Complete list of grades is available on request.

Publications

- *Quantification of Resilience in the NdFeB supply chain.*
  Benjamin Sprecher, Ichiro Daigo, Matthijs Vos, Rene Kleijn, Shinsuke Murakami, Gert Jan Kramer (under review).
- *Framework for identifying resilience in the supply chain of critical materials, with a case study on neodymium magnets*.
  Benjamin Sprecher, Ichiro Daigo, Shinsuke Murakami, Rene Kleijn, Matthijs Vos, Gert Jan Kramer. Environmental Science & Technology. 2015 49 (11), 6740–6750.
- *Recycling Potential of Neodymium: The Case of Computer Hard Disk Drives.*
  Benjamin Sprecher, Rene Kleijn, and Gert Jan Kramer. Environmental Science & Technology 2014 48 (16), 9506-9513.
- *Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets.*
  Benjamin Sprecher, Yanping Xiao, Allan Walton, John Speight, Rex Harris, Rene Kleijn, Geert Visser, and Gert Jan Kramer. Environmental Science & Technology 2014 48 (7), 3951-3958.

APPENDIX

Chapter 2 Supporting information

In the supplemental information we describe the collection experiment that was set up to determine the number of HDD's available in the Dutch ICT scrap. We also give a cursory analysis of the relative benefit of recycling the NdFeB magnet in the HDD, compared to the HDD itself.

Collection experiments

The majority of ICT scrap in the Netherlands is collected at municipal collection stations, known as *milieustraten*. Full container loads are sold to the highest bidding WEEE processing firm. These firms must first depollute the ICT scrap. This is done via manual sorting. Batteries, monitors and printer cartridges are removed, both for legal reasons and because they can be hazardous in later processing stages. Additionally, valuable items such as cables and aluminium and printed circuit boards are separated. This depolluted ICT scrap is then shredded and sorted using gravity based sorting techniques such as water tables and wind-shifters. This results in various fractions of materials that are then sold onwards.

Because of security concerns it is customary that HDDs from companies and servers are collected separately and processed by firms specialized in the secure destruction of data. These can be collected for recycling relatively easily.

Separating HDDs out of the general ICT scrap is only feasible at the depollution stage, because of the low intrinsic value of HDD's compared to the cost of manual labour. We tried to experimentally assess what the recovery rate of this step is. These experiments were located at the Geldrop processing plant of the Dutch electronics-recycling firm Coolrec. This plant performs the depollution process of ICT recycling, where polluting (e.g. printer cartridges) or valuable components are hand-removed by teams of six to eight workers standing by a conveyor belt.

Over a four-month period, 167 containers containing in total 1343 tons of ICT scrap from four different Dutch cities were processed, with staff having received instructions to separately collect all the HDD's they could easily retrieve. Not all HDDs could easily be collected, because some were screwed tight in computer casings. In total 2566 HDDs were collected.

The researchers also participated with the experiment, analysing 27 tons of e-waste originating from three locations and noting the total number of HDD's, and whether they were recovered by factory workers or not. In our sample of three containers with 27 tons of ICT scrap the personnel collected 112 HDD's, or 4.2 HDD per ton. We were able to collect and additional 27 HDDs that could have been collected by the personnel. In the sample of 27 tons, 205 HDDs were noted as not collectable. These figures imply that 35% to 40% of HDDs contained in personal computers can be easily separated from general ICT scrap, with the remainder destined to be shredded. This also corresponds with the experience of the plant manager, who estimates that roughly 40% of personal computers arrive with their HDDs not enclosed in the case. We speculate that this is because consumers prefer to either re-us their HDDs or remove them to assure that the data on the HDD is securely destroyed.

Table 1 HDD collection statistics.

	Collected	Collected by researcher	Not collected
Number	112	27	205
Kg's	62	17	

Environmental benefits

Looking at the potential benefits of recycling allows us to put the results in an environmental context. Table 2 compares the CO_2 emissions of producing and recycling NdFeB and aluminium. Although NdFeB has a higher emission per kg, the amount used in a typical HDD is much smaller. Therefore relative importance of recycling the aluminium content is higher. Also, these figures indicate that aluminium recycling is more efficient than NdFeB recycling, widening the gap even more.

Table 2 CO2 emissions (avg HDD = 15 gr NdFeB and 500 gr Al).

	Primary NdFeB	Recycled NdFeB	Primary Aluminium	Recycled Aluminium
Per kg	19	3.25	12	1.38
Per HDD	0.29	0.049	6	0.69

Note that the CO_2 emission figures for NdFeB are based on Sprecher et al.,[1] while those of aluminium are based on the ecoinvent 2.3 database. Therefore they are not directly comparable and should only be taken as a rough indication to get some sense of order of magnitude.

1. Sprecher, B.; Xiao, Y.; Walton, A.; Speight, J.; Harris, R.; Kleijn, R.; Visser, G.; Kramer, G. J. Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets. *Environ. Sci. Technol.* **2014**.

APPENDIX

Chapter 3 - Supporting information

Benjamin Sprecher[a,b,*], *Yanping Xiao*[c], *Allan Walton*[d], *John Speight*[d], *Rex Harris*[d], *Rene Klein*[b], *Geert Visser*[e], *Gert Jan Kramer*[b,f]

[a] Materials innovation institute (M2i)
[b] Leiden University, Institute of Environmental Sciences (CML)
[c] TU Delft, Department of Materials Science and Engineering
[d] University of Birmingham, School of Metallurgy and Materials
[e] Van Gansewinkel Groep
[f] Shell Global Solutions
**Corresponding author*. Tel.: +31 (0)71 527 1475. E-mail address: sprecher@cml.leidenuniv.nl

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List of tables

Rare earth oxide properties

Table 1 contains an overview of the rare earths taken into account in our study, with molecular weight, value and relative contribution to the rare earth content in ore.[1] This information is used extensively in the life cycle inventory, for determining conversion rates and allocation factors. Table 2 contains the composition of the REO produced in the solvent extraction process, as calculated by the authors. The calculations can be found in the supporting materials tables.

Table 1 properties of rare earth oxid.

Rare earth oxide	Molecular weight	Value $/kg[1]	In ore	Rare earth element	Molecular weight	In ore (g/kg ore)[2]
CeO_2	172.12	15	49.13%	Cerium	140.12	16.4
La_2O_3	325.81	13	28.15%	Lanthanum	138.91	4.92
Nd_2O_3	336.48	85	15.40%	Neodymium	144.24	2.7
$Pr_6 O_{11}$	1021.44	85	5.07%	Praseodymium	140.91	0.287
Eu_2O_3	351.92	1820	0.23%	Europium	151.96	0.041
Gd_2O_3	362.50	85	0.58%	Gadolinium	157.25	0.1
Sm_2O_3	348.72	32	1.16%	Samarium	150.36	0.21

1) Prices from www.metal-pages.com accessed 12-11-12.
2) As reported for ore from the Baotou mine.

Table 2 composition of 1 kg REO.

Oxide	Composition
Cerium oxide	49.3%
Lanthanum oxide	28.2%
Neodymium oxide	15.5%
Praseodymium oxide	5.09%
Europium oxide	0.231%
Gadolinium oxide	0.582%
Samarium oxide	1.16%

Details on used method

In this section of the supporting information we give some extra details on our used method.

The process of producing neodymium oxide is already described in the ecoinvent database. However, these two background processes are very general. The ecoinvent process ‘rare earth concentrate, 70% REO, from bastnäsite, at beneficiation’ contains all mining and beneficiation steps while the second process ‘neodymium oxide, at plant’ describes the solvent extraction process. For an improved approximation of environmental impacts we split the two processes from the ecoinvent database in five processes and describe these in more detail.

For determining raw material demand in the acid roasting and solvent extraction processes we made the standard assumption to use stoichiometric balances with an assumed 95% yield.[2]

Where no literature sources on transport distances were available we assume that solvents and chemicals used in rare earth refining are produced at the coast of China. The distance from coastal China to the city of Baotou is roughly 1900 km (measured with Google maps, using the average of a route from Baotou to several large industrial areas on China's eastern coast). In the methodological overview ecoinvent assumes that for transporting chemicals in Europe on average 600 km rail and 100 km lorry transport is involved.[2] We adapted this to 1800 km rail and 100 km lorry transport.

For base chemicals we also took carrier material in account (e.g. 1 kg 30% HCl also includes 2.3 kg water), as per ecoinvent example.

For energy use we used the ecoinvent background process describing Chinese 'electricity, medium voltage, at grid'.

Details on the life cycle inventory

LCA modeling of ore removal from mine

Our mining process models the production of 1 kg of ore containing 30% Fe and 4.1% REO. A recent inventory analysis of iron ore mining is given in Norgate and Haque,[3] on which we base diesel, electricity and explosives use.

We based our environmental in- and outflows on the ecoinvent background process 'iron ore, 46% Fe, at mine'. Because the mining process in Bayan Obo is equivalent to regular iron ore mining, environmental in- and outflows of our foreground process can be assumed to be the same as in the background process, after accounting for the difference in ore concentration.

The environmental inflows of rare earths are based on the mass balance. We added several environmental outflows related to radiation because of thorium containing dust that is created during mining, based on radiation emissions.[4]

Additional assumptions

- We neglected the overburden, topsoil and waste rock, as these are back-filled into the mine, as per ecoinvent example.
- Electricity was assumed to be generated on-site using the ecoinvent process 'diesel, burned in diesel-electric generating set'.
- Literature reports Fe contents of the Bayan Obo mine to be between 30 and 35%. We chose the lower estimate because over time the iron content of the ore will decrease.

Scenarios

- No differences between scenarios

LCA modeling of beneficiation of REE containing ore

Schuler et al.[5] estimate REO recovery rates of 40% for private and 60% for state-owned enterprises. We will assume an average 50% REO recovery rate. The ecoinvent background processes covering beneficiation of iron ore uses a 90% recovery rate of iron. We assume that the beneficiation process at Bayan Obo also attains a 90% recovery rate of iron. Using these recovery rates we calculate that the beneficiation of 30 kg of ore containing 4.1% REO and 30% Fe produces 1 kg of 61% REO concentrate[1] and 12.5 kg of 65% Fe concentrate.[2]

The milling and mechanical sorting of iron ore is described in the ecoinvent process 'iron ore, 65% Fe, at beneficiation'. Because beneficiation techniques used in the Bayan Obo mine can be assumed to be the same as in a normal iron ore mine we base the environmental in- and outflows per kg of processed ore on this process.[3] Chemicals and steam usage for the non-mechanical beneficiation processes are based on the ecoinvent reports.[1]

We also added radiation found in the tailings and dust as an environmental outflow, due to the thorium content of monazite. The tailings contain 0.028% ThO_2, corresponding to 1.0 kBq of radio nucleotide activity. A further 0.022 kBq is related to uranium.[4] Radiation related to dust emissions from the crushing process are estimated as follows: total dust emissions are 68 t per year.[5] Total annual production of the Bayan-obo mine in 2008 was 46.000 tons REO.[6] This means that ±1.3 kg of thorium containing dust is emitted per ton REO, equivalent to 2.1 gram per kg 61% REO ore concentrate. According to [4] this dust has a 232Th activity concentration of 1.4 Bq/g, meaning that dust related radioactivity is 0.0029 kBq.

Allocation

Allocation of impacts is done using economic value allocation. This allocation is rather difficult to make exactly, as the value of bastnäsite and xenotime is not available. We estimate that in 1 kg of crude ore 20% of the value is represented by iron ore while 80% is represented by the REO content.[4]

Additional assumptions

- Transport of ore from Bayan Obo to Baotou is modeled using ecoinvent process 'transport of coal in China using rail'. Transport of 1 kg coal by train is equivalent to 1 kg of ore. We assumed this to be equivalent, even though coal and ore differ by a factor 2 in density.[5] This assumption does not significantly impact the overall results of this LCA.
- Environmental in- and outflows for milling and sorting are comparable to regular beneficiation processes and are linearly adjusted for differences in ore concentrations.

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[1] 1 kg * (61%/4.1%) / 50% = 30 kg

[2] 30 kg / (65%/30%) *90% = 12.5 kg

[3] This means that we multiplied the actual figures of the ecoinvent background process by 18.1 to correct for the larger amount of ore processed per kg of economic outflow.

[4] Price of 62% iron ore in September 2012 was 100$/mt, so 30% iron ore would be ± 50$/mt (www.indexmundi.com accessed 19-10-2012). Using pure REO prices (http://www.lynascorp.com/page.asp?category_id=1&page_id=25) we calculated that the REO content of 1 kg of crude ore is ± 1$/kg

[5] http://simetric.co.uk/si_materials.htm accessed 20-12-2012

Scenarios

Recovery rates of REE have increased with improving technology. Therefore we will use the low and high estimates from literature for our low and high-tech scenarios. We assume that recovery rate of iron also increases and therefore keep the allocation factor constant.

- Baseline: 50% REE recovery rate.
- Low tech: 40% REE recovery rate.
- High tech: 60% REE recovery rate.

LCA modelling of acid roasting

Our process models the production of 1 kg $RE_2(SO_4)_3$. The reaction requires 1.55 kg of H_2SO_4 per kg of ore, of which .999 kg is consumed, 0.0465 kg is emitted as in the form of gaseous SO_2[6] and 0.505 kg is assumed to be disposed to landfill. We approximate this with the process 'disposal, sulphidic tailings, off-site'. 0.16 kg of heavy fuel oil is consumed for heating purposes. Additionally, 0.154 kg CO_2, 0.0465 kg H_2O and 0.0816 kg of HF are emitted as a gas.[7]

The major reactions during acid roasting are:

$$2RECO_3F + 3H_2SO_4 = RE_2(SO_4)_3 + 2HF + 2CO_2 + 2H_2O$$

$$2REPO_4 + 3H_2SO_4 = RE_2(SO_4)_3 + 2H_3PO_4$$

In modern plants off gasses are almost completely scrubbed, leading to small emissions. However, anecdotal evidence indicates that some Chinese rare earth processing plants emit emissions directly to air. We assumed 70% scrubbing for our baseline scenario.

Assumptions

- The amount of SiF_4 is dependent on the quartz content of the ore. This is estimated to be quite low and is therefore neglected in our study.
- The reaction converts 95% of bastnäsite/monazite to rare earth sulfate.

Scenarios

- Baseline: 70% H_2SO_4 and HF gas scrubbing.
- Low tech: 30% H_2SO_4 and HF gas scrubbing.
- High tech: 95% H_2SO_4 and HF gas scrubbing.

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[6] H_2SO_4 forms 0.0465*(64/98)= 0.0305 kg SO_2

LCA modelling of leaching

For the production of 1 kg of 92% $RECl_3$, our leaching process consumes 1.77 kg of 61% rare earth concentrate from acid roasting, 1 kg of industrial grade hydrochloric acid (30%) and caustic soda. 9L of water is used per kg of ore. Water recycling rates could be very high for best practice processing plants. However, there is anecdotal evidence that more basic plants emit all of the wastewater into the environment or the large wastewater ponds surrounding Baotou. We assume a 50% recycling rate for our baseline scenario. Leaching efficiency is 96%.[7]

Additional assumptions

- There are significant emissions of H_2SO_4 and HCl into water reported in literature. However, because of the lack of impact factors available in ecoinvent, these emissions are neglected.

Scenarios

- Baseline: 50% wastewater recycling.
- Low tech: 0% wastewater recycling.
- High tech: 95% wastewater recycling.

LCA modelling of solvent extraction

Our process consumes 4.91 kg of leached 92% $RECl_3$ concentrate to produce 1 kg of 99.99% Nd_2O_3. As a side product we produce 3.87 kg of other rare earth oxides.

Both $RECl_3$ (253 g/mol) and P204 (322.42 g/mol) are used in a concentration of ± 1 mol/L, allowing us to calculate that we need 6.33 kg P204 / kg Nd_2O_3, of which 5% is consumed.[7] During the acid washing step 0.8 mol HCl (36.46 g/mol) is consumed per mol of $RECl_3$.[7] This means that we consume 0.72 kg HCl/Kg Nd_2O_3.[8] Furthermore, the process consumes 1.1 kg ammonium bicarbonate / Kg Nd_2O_3.[5] Other inputs (energy use, kerosene, capital goods) are based on the ecoinvent background process 'neodymium oxide, at plant'.

Allocation

We allocate environmental impacts using the economic value of the rare earth oxides, as described in the main article. The value of 1kg of neodymium oxide is $85.00, while the combined value of the other REO's is $78.55. For this allocation we count the praseodium content as neodymium, because in the production of NdFeB magnets it is used as such.

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[7] P204 is 322.43 g/mol, NdCl3 250.50 g/mol. Processing 1 kg $RECl_3$ requires 1.29 kg P204. In total we consume 1.29 * 4.91 * 0.05 = 0.317 kg P204.

[8] 0.03646*4 *4.91

Assumptions

- 95% recovery rate of rare earths
- The organic solvent is recycled with 95% efficiency
- Emissions of acids are not taken into account.
- Thorium related radiation factors are based on ecoinvent background processes.

Scenarios

- Baseline: 95% recovery rate, 95% organic solvent recycling.
- Low tech: 90% recovery rate, 90% organic solvent recycling.
- High tech: 99% recovery rate, 99% organic solvent recycling.

LCA modelling of Nd-oxide reduction

The Hall-Héroult process is modelled in the ecoinvent processes ‘aluminium, primary, at plant’. This process is based on data from a modern Norwegian aluminium smelter.

The molecular properties of Al_2O_3 and Nd_2O_3 are very different (Table 1). We assumed that the inflows, outflows and emissions of aluminium production are equivalent to that of neodymium production on a per mole basis and adjusted the data accordingly.[9] The neodymium electrolysis process has a recovery rate of 97%.[7]

Table 1 comparison of aluminium oxide and neodymium oxide.

Property	Al_2O_3	Nd_2O_3
Molar weight g/mol	101.961	336.48
Density g/cm^3	4.1	7.24
Heat capacity J/(mol*K)	79.04 (solid) 192.5 (liquid)	111.3
Melting point C	2040	2270
Kg material required for 1 kg output	1.92	1.20

Assumptions

- We assumed electrolysis using a fluoride system. An alternative production process is via the electrolysis of $NdCl_3$.
- All other Chinese metallurgy processes use heavy fuel oil for heating. For consistency we replaced the light fuel oil and natural gas heating system used in Norway with heavy fuel oil.

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[9] The ecoinvent process uses 18.83 mol Al_2O_3 (1.92 kg/0.102 kg/mol). Our process consumes 3.566 mol (1.20 kg/0.33648 kg/mol). Therefore we multiplied the ecoinvent environmental outflows with 0.189 (3.566 mol/18.83 mol). However, since heat capacity is not the same as molar weight flows related to heat by 0.26, based on the solid heat capacity of aluminium oxide. Electricity consumption is based on [7]. Other economic inflows (e.g. transport, disposal) are multiplied by 0.63 to account for the difference in weight.

Scenarios

Gorai and Jana[8] give an overview of the emissions of aluminium smelters over time, showing that emissions have reduced by a factor 50 between 1950’s technology and modern plants. Although it is safe to assume that not all Nd production in China is up to modern standards, we have found no information as to what it should be. Anecdotal evidence shows that processing conditions can be very primitive.[10] Therefore we assumed a baseline emissions level of 5x best available technology (equivalent to 1995 technology, as described in Gorai and Jana[8]). Our hi-tech scenario assumes best available technology while our low-tech scenario uses 25x the emissions of hi-tech, equivalent to a 1955 technological level. This does not include process related CO_2 emissions, since these are stoichiometrically determined. We assume that process related CO emissions are not filtered in any scenario and therefore also remain constant.

- Baseline: 5x emissions of best available technology.
- Low tech: 25x emissions of best available technology.
- High tech: ecoinvent Hall-Héroult process (best available technology)

LCA modelling of NdFeB alloying and strip casting

NdFeB alloy consists of 72 mass% iron, 27 mass% neodymium and 1 mass% boron. Therefore we use as inflows 0.72 kg iron pellets, 0.013 kg boron carbide[11] and 0.27 kg Nd.
Energy use of this process is based on experiments done with an experimental set-up. NdFeB alloy is assumed to be transported from Baotou to a magnet factory. As an example we take Ningbo Konit, responsible for 40% of worldwide production of NdFeB magnets used in HDDs.[12] Distance is 2,100 km by train,[13] increased by 50% to account for packaging materials, as per example of ecoinvent background processes.[1]

Assumptions

- We assume no NdFeB alloy is lost during strip casting.

LCA modelling of hydrogen decrepitation

Decrepitation consumes 0.43wt% hydrogen and 0.1 kwh electricity.[9] We used a background process for hydrogen consumption based on the electrolysis of water.

Assumptions

- We assumed that the material is not de-gassed at this stage.

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[10] Interview with industry sources
[11] 1 mass% B in NdFeB, 78 mass% B in B_4C = 0.0128 kg Boron Carbide input
[12] Personal communication industry sources
[13] maps.google.com route from Baotou to Ningbo Konit, Located at the Ningbo Economic & Technical Development Zone, Zhejiang, China.

LCA modelling of jet milling

Jet milling requires 1.8 kWh per kg of NdFeB. Losses during this process are negligible.[9]

LCA modelling of aligning and pressing

This process consumes 0.4 kWh per kg of NdFeB, and does not involve loss of material.[9]

Assumptions

- We assume die pressing is used, as this is the more common processing method in industry.
- The energy use for aligning is assumed to be negligible.

LCA modelling of vacuum sintering

Vacuum sintering 1 kg of NdFeB alloy requires 2.4 kWh of electricity.[9] We based the other emissions of our process on the ecoinvent process 'sinter, iron, at plant'.

Assumptions

- Sometimes hydrogen is recovered at this stage. However, this is not common and we assume that this is not the case.

LCA modelling of grinding and slicing

Grinding and slicing requires 1.4 kWh of electricity.[9] Losses of material are around 30-40% in China. Production in western countries is more efficient, with loss rates of 15-20%.[14] We assumed a loss rate of 30% for the baseline scenario.

Allocation

Because the recycled grinding losses have approximately the same value as the alloy, we use physical allocation according to the percentage recycled.

Scenarios

- Baseline: 30% loss rate, of which 50% is recycled.
- Low tech: 40% loss rate, none of which is recycled.
- High tech: 25% loss rate, of which 100% is recycled.

LCA modelling of electroplating

HDD neodymium magnets contain on average 10wt% nickel from their nickel coating. Using average nickel consumption per m^2 we calculate that 1 kg of magnet requires 0.068 m^2 of nickel coating. Moing et al.[10] give a life cycle inventory for the electroplating of 1 m^2 nickel coating.

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[14] Personal communication with industry sources.

Assumptions

- Our data is based on an LCA based on European technology, which might not be completely representative of Chinese electroplating facilities.
- We used sodium phosphate instead of trisodium phosphate
- We used a generic organic chemical instead of sodium glucanate
- We neglected use of sodium saccharinate (0.5 g/m2) for lack of data

Scenarios

Baseline and hi-tech: best-case scenario from Moing et al.[10]
Low tech: worst-case scenario from Moing et al.[10]

LCA modelling of recycling using manual dismantling

The environmental impact of the manual sorting and dismantling of the HDDs is assumed to be negligible. The hydrogen decrepitation is equivalent to hydrogen decrepitation of primary material. Because the recycled material has a smaller microstructure than primary material would have after decrepitation, low energy milling can be used instead of jet milling. We assume a 90% yield, to model a slight loss in functionality of the magnet compared to a primary magnet.[11]

All further processing steps are equivalent to the production process of primary NdFeB magnets, with the exception that medium voltage electricity from Great Britain is used instead of China.

Assumptions

- We used the best case electroplating process and improved this further by assuming that 90% of the nickel used is sourced from the ecoinvent background process ecoinvent 'nickel, secondary, from electronic and electric scrap recycling, at refinery', to model the fact that nickel can be recovered from the recycled magnet coatings.
- We assumed low energy milling to require half the energy of jet milling.

Allocation

The recycled electronic scrap has positive economic value, thus a part of the environmental impact of the entire production chain of the electronics in the scrap should be allocated to the output of the recycling process.[12] However, because the value of the electronic scrap can be assumed to be negligible compared to the retail value of the electronics before they became scrap, we allocate the entire environmental impact of the production chain to the use phase of the electronics.

The recycled magnet contains 10% nickel in the form of a coating. This is removed using a sieve, after hydrogen decrepitation. For our value based allocation we used a nickel price of 17$/kg[15] and 115$/kg for Nd,[16] neglecting the value of the iron and boron component in the magnet, resulting in a 5.2% allocation to nickel and 94.8% to the magnet.

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[15] http://www.indexmundi.com/commodities/?commodity=nickel accessed 28-01-2013

[16] http://www.mineralprices.com/ accessed 28-01-2013

LCA modelling of recycling using shredded HDDs

Recovery rates and energy use for shredding[17] HDDs are reported in Sprecher et al.[13] We assumed that the post-leaching process is equivalent to the high-tech scenario of primary material processing, with the following changes:

- All electricity use is based on Great Britain medium voltage instead of China medium voltage.
- Transportation distances are reduced to ecoinvent standard for generic transportation within Europe.
- We assume in the leaching process that the shredder residue is pure NdFeB magnet, of which 27 wt% is Nd.
- The product of the leaching process is 1 kg of $NdCl_3$, necessitating 1.96 kg of shredder residue.[18]
- The leaching process consumes 1.2 kg H_2SO_4 and 0.5 kg Cl_3, assuming a 20% loss.[19]
- The solvent extraction process is simpler, since we only need to extract neodymium, and not the other rare earth elements. We require 1.63 kg of 92% $NdCl_3$ for the production of 1 kg of Nd_2O_3.[20] All other inputs are reduced by 65.4% to account for the lower amount of material that needs to be processed.

Allocation

- As with the manually dismantled HDDs, we allocate the environmental impact of the production of electronics to the use phase, thereby leaving it out of the scope of this LCA.
- We need to allocate the energy use of shredding the hard drive, as this results both in shredded NdFeB fragment and shredded HDD encasing, which is sold as scrap aluminium. Allocation is fairly important as the energy use for shredding accounts for a large proportion of the total energy use of this recycling route. In line with the other allocation processes we apply a value-based allocation to the energy use of shredding the HDDs. However, a value-based allocation is difficult to make because there is no market price for NdFeB from shredded HDDs. We make the following calculation:
- HDDs are worth roughly 1.33 $/kg, with an average HDD weighing 0.5 kg, valued at 66.5 $ct. We assume that one HDD yields 5 grams of NdFeB magnets. This contains 1.58 grams of Nd2O3 equivalent[21], worth 13.4 $ct. Therefore 17% of impacts are allocated to NdFeB recovery and 83% to aluminium recovery.

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[17] Experiments based on an RS 30 type shredder, which consumes 22 kW and shredders 6 HDDs per minute, resulting in an energy use of 0.06 kWh per HDD.

[18] 3.68 mol Nd * 144 gr/mol /0.27 = 1.96

[19] 3.68 mol Nd consumes 11 mol H_2SO_4 and 11 mol HCl_3

[20] 6 moles of $NdCl_3$: 1.5 kg/0.92 = 1.63 kg.

[21] Mass fraction of Nd in Nd_2O_3 is 85.7%; 5*.27/.857= 1.58 gram

Normalised results

Table 4 contains the normalised results of our LCA.

Table 4 normalised results.

Name	Primary NdFeB magnet, baseline	Recycled NdFeB magnet via hand picking	Recycled NdFeB magnet via shredding	Unit
eutrophication potential	1.2E-12	4.8E-14	2.0E-13	Year
acidification potential	1.8E-12	1.1E-13	8.3E-13	Year
photochemical oxidation (summer smog)	4.7E-13	2.9E-14	2.2E-13	Year
climate change	6.3E-13	7.8E-14	2.4E-13	Year
Ionizing radiation	3.0E-13	1.8E-13	4.8E-13	Year
freshwater aquatic ecotoxicity	5.9E-12	2.2E-12	4.8E-12	Year
stratospheric ozone depletion	1.1E-14	4.1E-16	4.6E-15	Year
human toxicity	5.8E-11	1.4E-12	1.1E-11	Year

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