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

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6 Quantification of resilience in the NdFeB supply chain

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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.

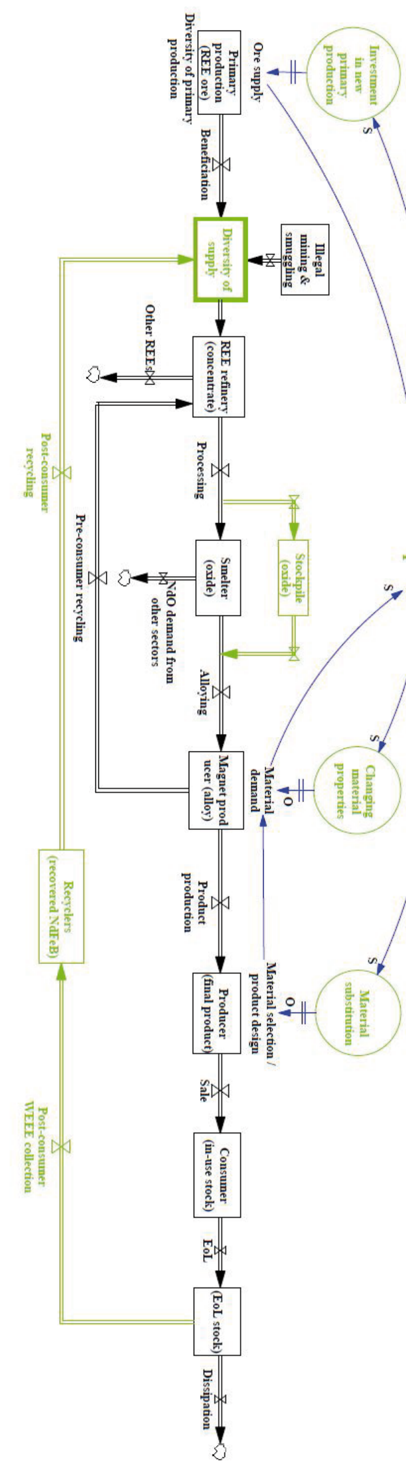

Figure 15 The conceptual model of the NdFeB supply chain (black) and the associated resilience mechanisms (green) as developed in our previous paper.[3] The blue arrows indicate the direction of influence: S = same, O = opposing.

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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.

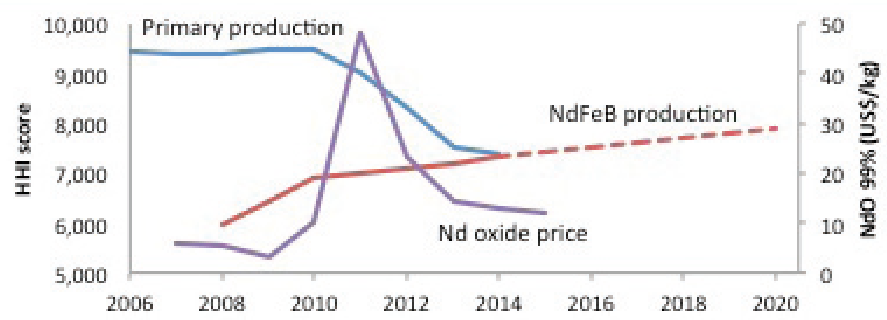

Figure 16 Herfindahl-Hirchman Index of REE primary production and NdFeB magnet production showing the extreme concentration of REE production in China prior to the 2008 crisis and its subsequent redress. The dotted line for market concentration of NdFeB production is based on industry forecasts for the 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]

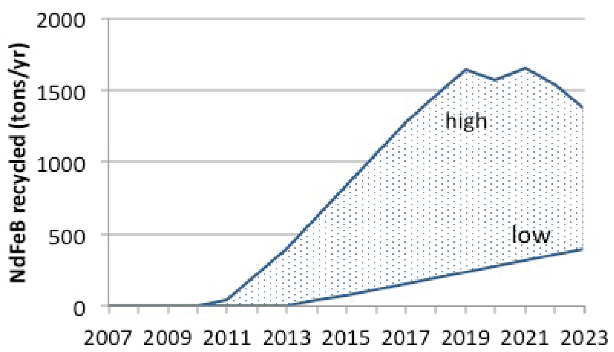

Figure 18 Quantification of the potential for NdFeB recycling. High and low refers to upper and lower boudary scenarios.

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.

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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

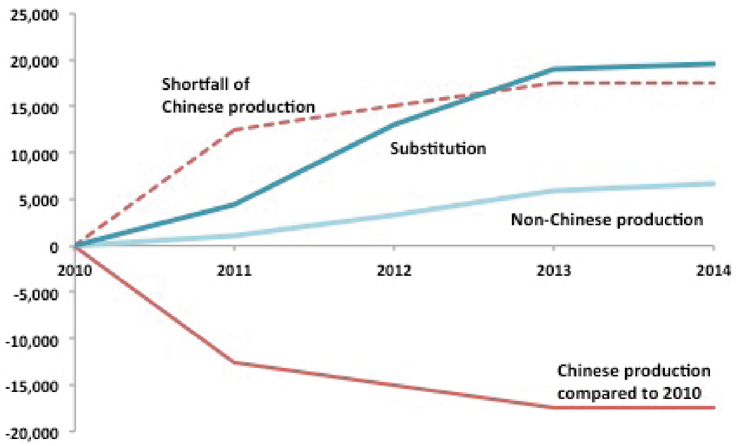

Figure 19 Chinese REE production shortfall and the combined effect of the compensating resilience mechanisms.

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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

6.5 References

1. Dijkema, G.; Basson, L. Complexity and Industrial Ecology. *Journal of Industrial Ecology*. 2009, pp 157–164.
2. Meerow, S.; Newell, J. P. Resilience and complexity: A bibliometric review and prospects for industrial ecology. *Journal of Industrial Ecology*. 2015.
3. Sprecher, B.; Daigo, I.; Murakami, S.; Kleijn, R.; Vos, M.; Kramer, G. J. Framework for Resilience in Material Supply Chains, With a Case Study from the 2010 Rare Earth Crisis. *Environmental Science & Technology*. American Chemical Society June 2, 2015, pp 6740–6750.
4. Hurst, C. *China's Rare Earth Elements Industry: What Can the West Learn?*; Institute for the Analysis of Global Security, 2010.
5. Xu, L.; Marinova, D.; Guo, X. Resilience thinking: a renewed system approach for sustainability science. *Sustainability Science*. October 14, 2014, pp 123–138.
6. Walker, B.; Pearson, L.; Harris, M.; Mäler, K.-G.; Li, C.-Z.; Biggs, R.; Baynes, T. Incorporating Resilience in the Assessment of Inclusive Wealth: An Example from South East Australia. *Environmental and Resource Economics*. 2010, pp 183–202.
7. Cimellaro, G. P.; Reinhorn, A. M.; Bruneau, M. Framework for analytical quantification of disaster resilience. *Engineering Structures*. November 2010, pp 3639–3649.
8. Milman, A.; Short, A. Incorporating resilience into sustainability indicators: An example for the urban water sector. *Global Environmental Change*. October 2008, pp 758–767.
9. Rare earth products exchange in good operation: experts. *Xinhua News Agency*. October 7, 2014.
10. Simpson, E. H. Measurement of diversity. *Nature*. 1949, p 688.
11. http://www.justice.gov/atr/herfindahl-hirschman-index.
12. Gambogi, J. *Mineral Commodity Summaries 2015*; USGS, 2015.
13. 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. *Environmental Science & Technology*. March 12, 2014, pp 3951–3958.
14. *Rare Earth Market Outlook: Supply, Demand and Pricing from 2014-2020*; Adamas Intelligence, 2014.
15. *http://www.arultd.com/rare-earths/pricing.html*.
16. Binnemans, K.; Jones, P. T.; Blanpain, B.; Van Gerven, T.; Yang, Y.; Walton, A.; Buchert, M. Recycling of rare earths: a critical review. *Journal of Cleaner Production*. Elsevier July 15, 2013.
17. Sprecher, B.; Kleijn, R.; Kramer, G. J. Recycling Potential of Neodymium: The Case of Computer Hard Disk Drives. *Environmental Science & Technology*. August 19, 2014, pp 9506–9513.

6

18. Nassar, N. T.; Du, X.; Graedel, T. E. Criticality of the rare earth elements. *Journal of Industrial Ecology*. 2015.

19. Permanent magnets are key, says Siemens wind power expert. *Electronics Weekly*. May 28, 2014.

20. ND-FE-B PERMANENT MAGNET WITHOUT DYSPROSIUM, ROTOR ASSEMBLY, ELECTROMECHANICAL TRANSDUCER, WIND TURBINE. April 24, 2014, pp 1–8.

21. EU. *Critical raw materials for the EU*; The Adhoc Working group on defining critical raw materials, 2010.

22. *Critical Materials Strategy*; U.S. Department of Energy, 2011.

23. Meadows, D. H. Indicators and information systems for sustainable development. Sustainability Institute 1998.

24. Meadows, D. *Thinking in systems: A primer*; Chelsea Green Publishing, 2008.