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]

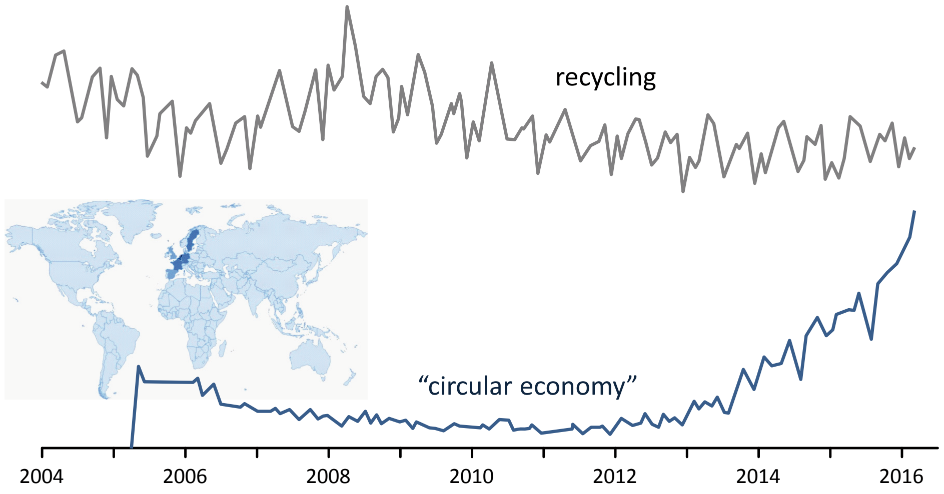

Figure 1. A Google Trends analysis of the interest in the topics 'circular economy' and 'recycling'. In absolute terms, circular economy was ca. 100-fold less popular than recycling. For 'circular economy' the regional distribution of interest in the term is shown, showing it to be a very European interest.

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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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