Mapping stocks and flows of neodymium

Assessment of neodymium production and consumption in the Netherlands in 2010 and 2030

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Für dad.

Preface

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Summary

Materials are the basis of the modern global economy. Neodymium is one particular metal that is ubiquitous in laptops, magnetic resonance imaging (MRI) machines, automotive catalysts (and still many more products) and recently, vital to a decarbonizing economy as it is used in the highly-efficient permanent magnet motor of plug-in hybrid electric vehicles and in increasingly favoured direct-drive wind turbines. What would happen if the supply of neodymium was obstructed? What if supply could not keep up with an increasing appetite for neodymium applications? These supply bottlenecks form the basis of the concept of materials criticality, the nexus of supply risk and economic importance.

Neodymium has been identified as critical by virtually every criticality assessment hitherto with its primary production monopolized one country. Moreover its significance to an increasingly digitized world and a green economy leaves the world potentially vulnerable in times of supply constraints. There are however mechanisms that can reduce criticality. One particular cogent tool, recycling, enables the harvesting of the neodymium urban mine once neodymium-containing products become waste. The cascading effects of recycling not only enable diversification of our supply mix but secondary recovery of neodymium has substantially reduced adverse environmental impacts compared to virgin extraction.

With neodymium recycling rates <1%, this research aims to determine the brevity of the neodymium urban mine as a criticality reduction measure by quantifying neodymium stocks and flows for 2010 and 2030. It will describe the global neodymium supply-demand-geopolitical dynamics from 1990-2015 in order to provide a broader framework in which neodymium criticality can be assessed. Understanding the products into which neodymium applications flow will be addressed with the development of the Neodymium Sector-Product Portfolio, a tool that acts as a matrix for inventorying all products using one of seven neodymium applications and assigning those products to one of six economic sectors. Finally the Portfolio will be extended to include neodymium compositions per product.

Using material flow analysis this research will model and characterize stocks and flows of those neodymium-containing products in the Sector-Product Portfolio using the Netherlands 2010 economy as a case study. The assessment will compare neodymium results in this research with the existing literature in order to discuss discrepancies on neodymium hotspots and problematic flows. Finally a theoretical potential of secondary neodymium will be derived based on neodymium demand.

Through the application of scenario mapping, the 2010 results, in combination with product evolution parameters, will provide the foundation upon which a 2030 neodymium future will materialize. With the expected large market uptake of electric mobility and wind energy, the modeling results will illustrate if neodymium flows mirrored 2010. Moreover by offering a potential neodymium scenario in the future, policymakers and EOL system managers and recyclers can be alerted to these forthcoming flows now.

Finally this research will conclude by determining if secondary recovery of the neodymium from products quantified in this research will reduce the neodymium supply risk to a non-critical state. It will reflect on the criticality dialogue and offer recommendations for integrating circularity in current production-consumption patterns.

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Glossary

ARN	Automobiel Recycling Nederland
BAU	Business-as-usual
BGS	British Geological Survey
CBS	Centraal Bureau voor de Statistiek
CF	Cooling and freezing
CNG	Compressed natural gas
CRM	Critical raw material
CRT	Cathode ray tube
DDPM	Direct-drive permanent magnet (wind turbines)
DFIG	Doubly fed induction generator
EEE	Electrical and electronic equipment
ELV	End-of-life vehicle
EOL	End-of-life
EPI	Environmental Performance Index
EU	European Union
FCC	Fluid cracking catalyst
GDP	Gross domestic product
Gg	Gigagram
GVA	Gross value added
GWP	Gross world product
HDD	Hard disk drive
HHI	Herfindahl-Hirschmann Index
HREE	Heavy rare earth element
ICE	Internal combustion engine
IEA	International Energy Agency
IPCC	International Panel of Climate Change
IT	Information technology
LCA	Life cycle assessment
LCI	Life cycle inventory
LED	Light emitting diode
LHA	Large household appliances
LNG	Liquefied natural gas
LREE	Light rare earth element
MFA	Material flow analysis
MW	Megawatt
NdFeB	Neodymium-iron-boron (permanent magnet)
NiCd	Nickel cadmium (battery)
NiMH	Nickel-metal-hydride (battery)
OECD	Organisation for Economic Co-operation and Development
OEM	Original equipment manufacturer
PC	Personal computer
PCB	Printed circuit board
PHEV	Plug-in hybrid electric vehicle
POM	Put-on-market
ppm	Part per million
PV	Photovoltaic
RAI	Foundation for Bicycle and Automotive Industries

REE	Rare earth element
REO	Rare earth oxide
RMI	Raw Materials Initiative
ROW	Rest of world
SHA	Small household appliances
SmCo	Samarium cobalt (permanent magnet)
SSD	Solid state drive
TREE	Totale rare earth element
UNU	United Nations University
US	United States
USDOE	United States Department of Energy
US-EPA	United States Environmental Protection Agency
USGS	United States Geological Survey
WEEE	Waste electrical and electronic equipment
WGI	World Governance Index
WTO	World Trade Organization
YAG	Yttrium-aluminium-garnet laser

1 Introduction and rationale

The progressive development of man is vitally dependent on invention. It is the most important product of his creative brain. Its ultimate purpose is the complete mastery of mind over the material world, the harnessing of the forces of nature to human needs".
-Nicola Tesla

An emergent property of life on earth is the state of continuous change and innovation. One of the most profound anthropogenic developments was the invention of tools for hunting and much later, fire for food preparation. Being able to use technologies for meat consumption facilitated a fundamental development in our ancestors' diets – from fruits and nuts to a diet richer in other nutrients (Gibbons 2015). From the invention of paper in China in 200 BC to eyeglasses in Italy in 1286 onward to the modern steam engine by James Watt in 1765 and the incandescent light bulb by Thomas Edison in 1879, a trend emerges: new technologies require an increasingly heterogeneous mix of materials (Tsien 1985; Ilardi 2007; Ayers 1989; Israel 2000).

Simultaneously societies are also digesting more materials, although a decoupling of resource use and economic growth has been observed in some countries (Voet, Oers, and Nikolic 2004). One of the first digital computers was built in Pennsylvania, USA in 1939 and weighed 30 tonnes; yet, its materials composition was rather simple (K. A. Zimmermann 2015). Modern computers are much smaller but also have larger processing power and a broad range of functionalities which is made possible with a broad range of materials, from copper and nickel to gold, europium and cobalt.

The supply of virgin raw materials needed for these technologies is finite and can only be extracted as long as they are available in the lithosphere. Sufficient and swift enough supply to meet growing demand is becoming a modern-day challenge due to an increasing global population and increasing welfare. The world metabolism increased by a factor of 8 in the 20th century alone. To ensure adequate resource supply, sustainable resource strategies have been incorporated into most raw materials legislation in the industrialized world (Krausmann et al. 2009). Yet the developed world comprises only 18% of the world population (OECD 2015). As poorer countries begin to industrialize, their appetite for products and materials will also increase unless resource use-economic growth decoupling strategies are adopted early on (Krausmann et al. 2009).

Unfortunately this resource challenge is not uniform across all materials. Some materials are more abundant in the lithosphere than others. Silicon is rather ubiquitous in the earth's crust (28% by weight) compared to vanadium (0,02% by weight) (Reuter 2013; Wolfram Research 2015). Certain materials may also be easily substituted in certain products, such as aluminium capacitors for tantalum capacitors (Nakatani 2013); others can also be recovered efficiently in end-of-life (EOL) products as is the case with gold from printed circuit boards (PCBs) (Chancerel and Finkbeiner 2010). Some metals, such as the rare earth elements (REEs) are co-mined and only extracted as long as their carrier ores are in demand (Sprecher, Kleijn, and Kramer 2014). What emerges is the concept of materials criticality.

Supply risk and economic importance of a particular material have become the two accepted indicators for determining the magnitude of criticality (European Commission 2014; US Department of Energy 2011). Yet the criticality of a material can be reduced if sound resource strategies such as dematerialization or EOL recycling are implemented (Rademaker, Kleijn, and Yang 2013). One such material group that has dominated the materials criticality literature in recent years due to the misnomer of their name and the geopolitical confrontation in 2011 over extraordinary price increases are the REEs (Erdmann and Graedel 2011; Glöser et al. 2015; Nassar, Du, and Graedel 2015).

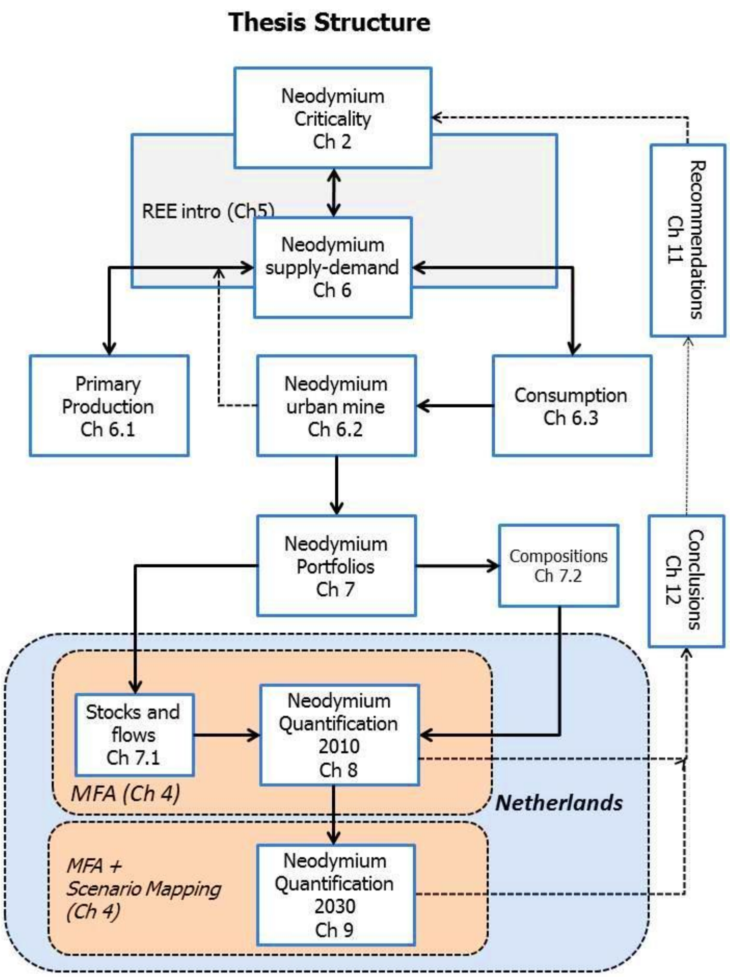


Figure 1: Thesis structure demonstrating the complexity and interconnectivity of each Chapter with the arrows with dotted lines signifying MFA results and their influence on resource policy

This research will investigate and model the life cycle of one particular REE – neodymium. Neodymium has become increasingly vital to the global economy with increasing demand for neodymium-iron-boron (NdFeB) permanent magnet applications in electronics as well as its importance to clean technologies such as plug-in hybrid electric vehicles (PHEVs) and wind turbines (Hatch 2011). Illustrated in Figure 1, on a meta-level this research will discuss neodymium criticality using three different methodological approaches. It will then explore and quantify global primary production patterns of neodymium and consumption of its applications. Against this supply-demand backdrop, this research will quantify the stocks and flows of neodymium through the Dutch economy in 2010 using material flow analysis (MFA).

Looking forward into the future, the analysis will map a possible neodymium landscape in 2030 using MFA and scenario mapping based on Dutch resource strategy and renewable energy targets, projected economic growth and product trends.

The aim will be to measure and reflect on the 2010 Dutch industrial metabolism in order to gather insights on potential future neodymium dynamics, flow characteristics and final destinations to inform resource policy going forward.

1.1 Research questions

Demand for neodymium applications, especially for neodymium iron boron (NdFeB) permanent magnets, has increased drastically since the 1980s with their widespread applications in electronics such as hard disk drives (HDDs) and motors in personal computers (PCs), laptops and smartphones. More recently NdFeB permanent magnet applications have become paramount to decarbonizing strategies and clean technologies, such as in wind turbines and PHEVs (Hoenderdaal et al. 2013). Rademaker, Kleijn, and Yang 2013 posited that NdFeB permanent magnet growth will increase from 2010-2015 at a higher rate than all other REE applications. Such spikes in demand can lead to unstable and turbulent market conditions should supply not keep up, potentially resulting in supply bottlenecks, increased material prices and even material shortages (Alonso et al. 2012).

Such an increase in neodymium demand was met with a restriction in supply in 2011 when the chief neodymium-producing country, China, introduced strict export quotas on all REEs due to increasing domestic demand and lower ore grade yields. This resulted in increased prices for all REEs ranging from 500-1000% increases compared to 2010 prices for some REEs (Schüler et al. 2011; Binnemans et al. 2013; D. Kingsnorth 2013). What followed was a threefold response:

1. Because the United States (US) and European Union (EU) relied on China for virtually 100% of REE imports, both the US and EU joined by Japan responded with a formal complaint to the World Trade Organization (WTO) which was upheld by the WTO in 2014 (Humphries 2013);
2. Targeted discussion on the need for sound resource policy including research into substitution possibilities and recycling technologies to recover REEs and reintroduce them to the commodities market (Smith Stegen 2015);
3. Investments in exploration of REE deposits and the re-opening of an existing mine in the US (Habib and Wenzel 2014).

This research will investigate and quantify the role of the neodymium urban mine in curbing demand for virgin neodymium. It will use the Netherlands as a case study and utilize MFA to model the flows of neodymium through the Dutch economy in 2010, disaggregated per sector per product. Using the 2010 results as a benchmark, this research will use scenario mapping to provide a potential closed-loop neodymium future in the Netherlands in 2030 based on projections in population and gross world product (GWP) growth, trends in product development, governmental targets for renewable energy and sustainable transportation and other statistical assumptions in the literature. Against this the rationale for this research has been established with the following main research question:

With increasing global demand for neodymium, to what extent could secondary neodymium (i) reduce neodymium criticality as well as (ii) the demand for virgin neodymium incorporated into products put on the market in the Netherlands in 2030 using 2010 as a reference year?

In order to determine the role of the Dutch neodymium reservoir, this research will quantify and characterize (i) the amount of neodymium put on the market (POM) in the Netherlands, i.e. sales of neodymium-containing products, (ii) the size of the neodymium stock and (iii) how much neodymium enters the Dutch waste stream. For this reason the following sub-questions will be explored as their cascading results cumulatively answer the main research question:

- SQ1: Is it possible to model historical neodymium primary production rates from 1990-2015 and their geographical source of extraction?
- SQ2: Is it possible to quantify and analyse neodymium supply-demand dynamics over time in order to substantiate its criticality?
- SQ3: Which sectors and products incorporate neodymium applications in their design? S
- SQ4: Are neodymium compositions available for all products incorporating neodymium applications?
- SQ5: Are there sufficient data on stocks and flows of neodymium-containing products in the Netherlands in 2010?
- SQ6: How can a neodymium future in the Netherlands in 2030 be ascertained with uncertainty regarding evolution in the neodymium landscape?

The results of this research will provide an overview of neodymium distribution per sector, highlight the large and problematic product streams as well as characterize the EOL destinations. The subsequent conclusions will be useful for various stakeholders along the value chain and support the development of sound resource policy

It is imperative to emphasize two forces influencing the practical implementation of the results of this research – the theoretical potential of secondary neodymium in the Netherlands.

First the system boundary of this research is described in detail in Chapter 4.1.1 and does not include the entire neodymium recycling chain. While including discarding from the consumer and collection/not collected, pre-processing techniques such as manual dismantling, and recycling technologies such as hydrometallurgy, are not within scope. Modeling the entire recycling chain would certainly reduce the theoretical potential of secondary neodymium due to thermodynamic and dissipative properties as well as material losses in shredder residues and smelter slags (Chancerel et al. 2009). This research aims to only model the size of the theoretical potential vis-à-vis the neodymium waste stream due to the lack of one dominant recycling technology.

Secondly, and building on the previous remark, quantification of the theoretical potential of secondary neodymium does not imply the Netherlands can practically become self-sufficient and establish a neodymium circular economy on its own. This is due to the current neodymium supply chain regime where China not only acts as the dominant stakeholder of virgin extraction, supplying 85% of neodymium but also monopolizes the intellectual property and expertise required for separation and refining into usable grades with necessary specifications (Schüler et al. 2011; Smith Stegen 2015). What’s more the economic value-added through the conversion and manufacturing of neodymium into intermediate and (semi-)finished products sold worldwide is carried out predominately by China (Bleiwas and Gambogi 2013). This would imply that even after modeling the theoretical potential of neodymium in EOL products in Chapters 8 and 9, neodymium modeled would have to be recovered from its products and either manufactured into new goods outside of the Netherlands or provided to industries in the Netherlands using neodymium.

2 Criticality

Resource criticality has been widely accepted as the nexus between *security of supply* and *economic significance*. When a particular material is plotted on this matrix the magnitude of criticality can be quantified based on the values resulting from these indicators. The chief purpose of a criticality assessment is to identify critical raw materials (CRMs), design sound resource policy and steer industry strategies to ensure a continuous, sustainable supply stream of CRMs to economies (USDOE 2011, European Commission 2014; Humphries 2013; Glöser et al. 2015).

Materials criticality is however not a new phenomenon; the term *critical raw material* was first used in 1939 in the US 'Strategic and Critical Materials Stockpiling Act' which was a response to potential supply constraints during World War II (Glöser et al. 2015). The materials dilemma further permeated US political discourse after World War II as war-torn countries' appetites for materials increased as these countries needed to rebuild. At the same time potential supply security was exacerbated by dwindling national reserves and a re-structured materials marketplace due to decolonization. For this reason in 1951 the US established the so-called Paley Commission with the ultimate aim of developing materials strategies in order to ensure an adequate supply stream of these materials (Kleijn 2012). Even though the issue of materials criticality was addressed early on, there are many interconnected, complex forces that led to supply shortages later.

The cobalt crisis of 1979 was one particular non-fuel mineral instability arising from (i) a cobalt supply landscape monopolized by Congo (former Zaire) and (ii) political instability in Congo and neighbouring Angola (Alonso, Gregory, and Field 2007).

Congo and next-door Zambia produced approximately 70% of the global supply of cobalt in the 1970s. The extracted cobalt was transported on one railroad to Angola for export. The Angolan Civil War in 1975 shut down the rail line disrupting exports; fortunately the US had enough cobalt in national stockpiles that consumers and downstream markets were not affected or did not notice. The unrest in Angola persisted and in 1978 Angolan rebels cut the electricity lines powering the cobalt mines and attacked the ex-pats working in the mines resulting in mass evacuations. This led to widespread speculation and concern over cobalt supply shortages while there was a simultaneous, indirectly-related, increased demand for cobalt applications. Consequently prices increased by a factor of 11 from US$ 8.800/t in 1975 to US$ 99.000/t in 1979, remaining at this level until 1982. Producers and markets were consequently forced to find substitutes, develop new technologies and recover secondary cobalt (Alonso, Gregory, and Field 2007).

The cobalt criticality scenario demonstrates the *supply risk* associated with, on the one hand, lack of diversification in upstream production channels and on the other, adverse impacts of the political landscape in producing countries. During the cobalt crisis, criticality reduction mechanisms such as substitution (e.g. zinc-based alloys) and expansion of cobalt recycling (e.g. recycling doubled) reduced the supply risk substantially (ibid).

The neodymium and broader REE primary production landscape is strikingly similar to the cobalt example with virgin extraction, refining and manufacturing into intermediate parts and components concentrated in one country – China (Oakdene Hollins and Faunhofer ISI 2014). According to one expert, China is the only country that can even process the heavy rare earth elements (HREEs) (Smith Stegen 2015).

This chapter will explore three methodologies for identifying a material as critical. Two of the methodologies were developed at the governmental level and measured the criticality of a short-list of candidate materials, although their rationale and methodological framework differ in scope. The EU used *supply risk* and *economic importance* while the US measured a list of materials against *supply risk* and *importance to a clean energy economy*. The third criticality assessment was developed by researchers at Yale University and assessed individual REEs against a comprehensive and robust range of metrics and sub-metrics.

Against a list of terms and definitions used in the criticality discourse, the next chapter will explain the scope and key findings of each framework providing the fundamental criticality context for assessing the case of neodymium in-depth.

2.1 Definitions

Contemporary raw material criticality assessments have varied in their goal and scope, methodology and consequently, indicators and metrics for measuring criticality. For example a criticality assessment from Oakdene Hollins incorporated the indicator *risk of natural disaster* in the broader *supply risk* indicator group while none of the three described in this research consider this (Erdmann and Graedel 2011). The criticality analysis from the EU included *environmental implications* in its assessment as environmental regulations could hamper virgin extraction of some metals while the USDOE did not incorporate environmental indicators in its study (Glöser et al. 2015).

In order to stymie confusion among terminology and nomenclature, below is a list of the key definitions needed for the more elaborated descriptions of the EU, USDOE and Yale University assessments of CRMs.

Criticality of a material refers to a materials influence on a national or global economy should its supply become restricted. Temporal dimensions can also be incorporated, e.g. short-term or medium-term, as can a spatial dimension, e.g. national or global (Achzet and Helbig 2013). Glöser et al. 2015 explain that *critical raw material* differs from a similar term, *strategic material,* as *strategic materials* almost always refer to military or national security. This research will only consider critical raw materials.

Supply risk is a broad indicator category used across most criticality assessments. Supply risk refers to the likelihood that supply could be restricted (Glöser et al. 2015). Erdmann and Graedel 2011 examined 10 criticality methodologies and 9/10 incorporated supply risk in their analysis.

Concentration is an indicator contributing to the supply risk score. Concentration addresses the amount of reserves or primary production of a particular material in a country compared to the rest of the world (ROW). Most often concentration is quantified using the **Herfindahl-Hirschmann Index (HHI)**, an index ranging from 0-10000 (Sievers and Tercero 2012).

Additional indices results are combined with the **HHI**. The governance of a country is quantified using the **World Governance Index (WGI)** and the ecological impacts of the mining sector is captured in the **Environmental Performance Index (EPI)** with environmental consequences as such quantified using **life cycle assessment (LCA)** (European Commission 2014; Nassar, Du, and Graedel 2015)

Substitution is an indicator contributing to supply risk and measures how easily a material can be replaced by another material. Substitutability can apply to different scales including material, component or even product-specific making it a difficult metric to quantify (Erdmann and Graedel 2011).

Recycling is a waste reduction mechanism that uses materials in discarded products as inputs in new products instead of raw materials (Chancerel and Finkbeiner 2010). In this sense recycling rates are determined by the ratio of secondary recovered material used in new products compared to virgin material (Reuter 2013).

Economic importance is a broad indicator category used differently in all three criticality assessments. The EU addresses the importance of a material to the overall economy; the USDOE measures the significance of a material to green technologies; Yale University determines economic importance through material assets and national economic importance.

Using these terms and definitions as a foundation for understanding the concept of criticality, the next three sections will briefly explore the aim and methodology of the criticality assessments from the EU, USDOE and Yale University. Despite differences in each assessment, an analysis of criticality approaches falls outside the scope of this research; comprehensive analyses of criticality assessments can be found from Erdmann and Graedel 2011, Glöser et al. 2015 and Achzet and Helbig 2013. Instead the rationale is to demonstrate that the three studies identify neodymium as critical using three different approaches.

2.1 Criticality assessments

The three criticality assessments described in this Chapter deviate in their aim and scope as well as approach and methodology. For each criticality assessment it is inherently challenging to identify and/or generate all data needed to measure criticality as often datasets are limited, incomplete or not existing. For example in the case of neodymium supply risk, the Yale study relied on scientific estimations and extended characterization of Chinese production statistics to determine neodymium oxide concentration per deposit; disaggregated, complete neodymium production statistics do not exist (Nassar, Du, and Graedel 2015). Quantifying economic significance is also laborious as one material will have different levels of importance to various sectors (European Commission 2014).

Table 1 provides an overview of the indicators covered in each study as well as the aim and method used. The following sections will elaborate further on each criticality assessment.

Study	Supply risk	Economic Importance	Environmental impact	Short term (0-5 yr)	Mid term (5-10 yr)	Long term (10+ yr)	National / Global	Aim	Method
EU	X	X	X	X	X		national	Identification of CRMs based on supply risk and economic importance	Matrix
USDOE	X			X	X		national	Importance of REEs and other metals to a clean energy economy	Matrix
Yale	X	X	X		X	X	both	Address criticality of the REEs more comprehensively using quantified/transparent datasets	Matrix

Table 1: Summary of the indicators and methodologies used as well as the aim of the criticality assessments from the European Commission (2014), US Department of Energy (2011) and Nasser, Du & Graedel (2014)

2.1.1 European Commission

The European Commission established the Raw Materials Initiative (RMI) in 2007 with the aim to guide EU policy toward a more resource-efficient economy. The scope of the RMI was to concentrate on non-fuel minerals as energy dependence has already received significant political attention in the last decade. One of the activities outlined in the RMI work plan was to carry out routine criticality assessments and consequently identify CRMs for the EU economy (European Commission 2008).

The aim of the EU criticality assessment is to identify materials with (i) a high economic significance to the EU economy and (ii) an elevated supply risk (European Commission 2014). The criticality assessment was carried out under the EU Ad-hoc working group on defining critical raw materials. The methodology was developed in cooperation with the Joint Research Centre and measured a list of materials across two indicators, *supply risk* and *economic importance*. The materials are plotted on a matrix and those exceeding a certain threshold in both matrices are designated as critical.

From the 2010 assessment, a list of 14 abiotic CRMs was developed; in 2014 the list was updated and 20 were identified with three biotic materials added to the list (European Commission 2014). Below is a short description of the approach to each indicator.

Economic Importance

The economic significance of a material to the EU economy was measured by determining the end-uses and products for each material which were subsequently allocated to one of the 17 identified EU mega-sectors. Using the Eurostat-published gross value added (GVA) per mega-sector, the economic importance of each assessed material is generated and scaled to EU GDP. In the equation below EI is the economic importance which is generated in EUR and adjusted to a 0-10 scale, A_s is the demand of a material in a mega-sector and Q_s is the Eurostat-defined GVA of the mega-sector (Erdmann and Graedel 2011; Oakdene Hollins and Faunhofer ISI 2014).

$$EI = \sum_{s} A_s Q_s$$

Criticality results were disclosed in Annexes D and E in a separate Fraunhofer / Oakdene Hollins report commissioned by the EU Directorate-Generate Enterprise. The light rare earth elements (LREEs) which includes neodymium received a 5,2 out of 10, just over the threshold of 5,0 to be considered critical. Comparatively vanadium scored 9,1 and tantalum a 7,4 but did not exceed the *supply risk* value needed to be designated critical (Oakdene Hollins and Faunhofer ISI 2014).

Supply risk

Overall supply risk is quantified by combining the results of three sub-indicators – substitutability, recycling rates and geographical location of country concentration. Country concentration is measured by synthesizing the results on concentration of primary production of a particular material and in one score, the corresponding country's governance score as defined by the WGI and in another score, the environmental regulatory landscape as per the EPI. Overall supply risk score is a composite score between 0-10 determined by the equation below where SR is supply risk, σ is the substitutability, ρ refers to the secondary material:virgin material demand percentage and HHI_{WGI} aggregates virgin extraction concentration and the country's governance into one value:

$$SR = \sigma(1-\rho)HHI_{WGI}$$

Substitutability measures the ease at which a particular material can be substituted without loss of performance on a scale from 0-1. The EU quantified substitutability of a material in a particular product which was assigned to one of 17 mega-sectors; subsequently substitutability is aggregated at the material-mega-sector level (Oakdene Hollins and Faunhofer ISI 2014).

The recycling rate is generated as the percentage of a secondary material used in new products compared to virgin material on a scale of 0-1 where 0 denotes a very high recycling rate and 1 means no secondary recovery take place. A higher recycling rate will reduce supply risk for a material (ibid).

Concentration and geographical prevalence are examined against the HHI. This index was adjusted to incorporate good governance using the WGI and environmental aspects using the EPI. The WGI is published by the World Bank and addresses factors such as political stability and control of corruption which could hamper material supply in producing countries (The World Bank 2015). The EPI comes from Yale University and measures the protection of human health from adverse environmental impacts and to what extent a country protects the environment (Hsu et al. 2014). Stringent environmental regulations in producing countries could stymie supply, e.g. if mines are forced to close or compliance is too costly. The EU nonetheless favours sound environmental legislation in producing countries due to their capability to manage or mitigate risks (Oakdene Hollins and Faunhofer ISI 2014).

Two values for supply risk are generated, one using WGI, the other EPI. Supply risk is measured between 0-5; any value above 1 is considered critical in terms of supply risk. The LREEs, including neodymium, scored a 3,1 and 3,0 for supply risk-WGI and –EPI, accordingly. Interestingly the CRM having the highest supply risk are the HREEs followed by neodymium and the LREEs.

One of the core advantages of the EU approach is the measurability and transparency of the approach supported by robust data. However, there are weaknesses in the methodology due to over-simplification, especially for the economic importance (EI) indicator. To calculate the EI of a material the aggregated *GVA per mega-sector* is used which does not take into consideration potentially varying magnitudes of *GVA of specific products within a mega-sector*. Moreover EI indicators are also not qualitatively weighted implying that the GVA of all mega-sectors is uniform. The latter is specifically addressed in the approach from the USDOE discussed in the next sub-section as the aggregated clean energy sector is weighted as more important than other sectors.

2.1.2 US Department of Energy (USDOE)

The aim of the criticality assessment carried out by the USDOE is to examine the relevance of the REEs and other materials to a US green economy with special attention to renewable energy applications such as photovoltaics (PV) and wind energy. The analysis of each material is qualitative with minimal support from quantitative data. Most quantitative information comes from supply-demand forecasting per material per clean technology. Results were generated for the short-term (0-5 years) and the medium-term (5-15 years) (US Department of Energy 2011; Erdmann and Graedel 2011).

This report was finalized in 2011 and builds on and updates the criticality analysis carried out in 2010. Results from the criticality assessment are plotted on a criticality matrix with *supply risk* and *importance to a clean energy economy* representing the main axes. The analysis was extremely REE-driven and examined their contribution to individual products instead of broader mega-sectors (US Department of Energy 2011).

Importance to a clean energy economy

Assessing the material significance to clean energy was carried out by evaluating 12 clean technologies and applications with special attention to fluid cracking catalysts, high-efficient lighting and permanent magnets for wind turbines and PHEVs. Values for this indicator category were generated and weighted by measuring clean energy demand (75%) and substitutability (25%).

The analysis is very qualitative and is based on different supply-demand scenarios for a particular material against (i) primary production activities and (ii) different penetration rates of the 12 clean technologies. The results range from 0-4 for the short- and medium-term and can be plotted on one axis of the criticality matrix; additionally qualitative criticality profiles are generated for each material.

In the short-term (0-5 years), neodymium was assigned a 3 positioning it in the high range of economic importance. Only four other elements received the maximum value of 4, all HREEs. Contrastingly in the medium-term (5-15 years), neodymium receives a 4, the highest score allowed. Reasons for a high risk to clean energy are based on different supply-demand scenarios. Supply potentials include (i) the 2010 production baseline, (ii) 2010 + Mt Weld production, (iii) 2010 + Mountain Pass production and (iv) 2015 estimated supply. Demand options are generated from a business-as-usual (BAU) scenario as well as low- and high-penetration clean energy rates. Criticality therefore becomes a function of shortages.

Although the qualitative approach was described in the report, it is unclear exactly how values were assigned, removing some legitimacy. Consequently this methodology does not allow for repetition of results and leads to difficulty in comparing results.

Supply risk

In order to determine the supply risk of a material, the USDOE identified five variables that have been weighted and applied to each material. *Basic availability* contributes 40% to supply risk and addresses sufficient supply of a material against demand. This qualitative indicator builds on supply-demand projections as well as updates and expansions of the material reserve base and new/existing mine activities. *Political, regulatory and social factors* constitute 20% and address the political stability and primary production regulatory framework of primary producing countries. *Producer diversity*, 20%, outlines the diversification of upstream producers. *Competing technology demand*, 10%, focuses on non-fuel/energy sectors and their demand for CRMs. Finally *codependence on other markets*, 10%, characterizes the material as a co-product, by-product or main product of the mineral ore.

Qualitative results were generated on a scale from 0-4 for each indicator for both the short- and medium-terms. In the short-term neodymium received a 3 which is designated as high-risk; only three other materials were identified as having a higher supply risk, again all HREEs. Neodymium maintained the 3 value for the medium-term.

Along with this research, the USDOE analysis contains a lot of uncertainty. Contrasted to the EU methodology, the USDOE lacks robust, quantitative datasets and is dependent on projected technological developments and supply scenarios. The USDOE study also failed to incorporate recycling in its assessment which can influence the industrial metabolism of primary materials. For example the USGS carried out an analysis of the role of recycling in the US metals industry and after assessing the recycling rates of 26 metals, the average recycling rate was 40% by weight demonstrating the recycling potential in curbing demand for virgin material (Sibley 2011).

2.1.3 Yale University

The Yale University criticality assessment was carried out by Nassar, Du, and Graedel 2015 and aims to analyse the criticality of individual REEs using a comprehensive, quantitative methodological framework that is transparent and can be easily replicated. For this reason the Yale study differs substantially from the EU and USDOE, especially in the breadth of its indicators. The methodology also integrates temporal, medium- and long-term, as well as spatial dimensions, national and global levels. The national analyses were carried out within the context of the US and China, respectively. Additionally the scope of this assessment was limited only to the REEs, examining each REE individually.

<table>
<tr><th colspan="4">Supply risk</th><th>Environmental Implications</th><th colspan="4">Vulnerability to Supply Restriction</th></tr>
<tr><td rowspan="6">Medium-term</td><td rowspan="2">GTE</td><td>DT</td><td rowspan="2">Long-term</td><td rowspan="8"></td><td rowspan="8">National</td><td rowspan="2">I</td><td>NE</td><td></td></tr>
<tr><td>CF</td><td>MA</td><td rowspan="5">International</td></tr>
<tr><td rowspan="2">S&R</td><td>HDI</td><td rowspan="6"></td><td rowspan="3">S</td><td>SP</td></tr>
<tr><td>PPI</td><td>SA</td></tr>
<tr><td rowspan="2">GP</td><td>WGI-PV</td><td>ER</td></tr>
<tr><td>GSC</td><td rowspan="3">SU</td><td>IRR</td></tr>
<tr><td colspan="3" rowspan="2"></td><td>IR</td><td rowspan="2"></td></tr>
<tr><td>GII</td></tr>
</table>

Table 2: Indicator categories and sub-indicators for the criticality assessment of the individual REEs, carried out by Nassar, Du & Graedel at Yale University (2015)

Table 2 demonstrates the methodological framework which uses three broad indicator groups – *supply risk*, *environmental implications* and *vulnerability to supply restriction* – with the temporal layer embedded in *supply risk* and the geographical element applied to *vulnerability to supply restriction*. The average scores are calculated at the most disaggregated level; then the scores at the second most disaggregated level are averaged to generate a value for each indicator group. The next three sections describe each indicator group and the criticality results for neodymium.

Supply risk

Supply risk of the REEs was measured in the medium-term (5-10 years) and the long-term (decades). The supply risk results build substantially on the individual REE primary production figures and locations of extraction. Nassar, Du & Graedel use 2008 as a base year and relied on the production quantities from the *Chinese Society of Rare Earths* to estimate 2008 REE production per province. These figures are supplemented with REE primary production figures from Brazil, Russia, India and Malaysia with estimations per country for individual REE production.

Geological, technical and economic (GTE): Depletion time (DT) and companion metal fraction (CMF)
Results for the depletion time (DT) rely on literature from governmental reports and geological surveys in order to gauge the size of reserves and resources. Recovery rates during virgin extraction were estimated based on 40-60% in Bayan Obo, 50% in Sichuan and 75% for the ion absorption deposits; 50% in Russia's bastnaesite mines; no recovery rates were identified for the other locations therefore USGS

primary production data was used for Malaysia, Brazil and India (Nassar, N.T., Du, X., Graedel 2015). DT results were generated on a scale from 0-100 with no risk of depletion for all REEs based on current production rates.

REEs are byproducts of other minerals, such as iron ore or ilmenite concentrate. Thus far it has not been economically viable to mine REEs as the main product except in the case of a few mines in the southern provinces of China (Schüler et al. 2011; Nassar, Du, and Graedel 2015). The Yale University assessment uses this assumption and calculates CF as the relative economic value of each individual REE with a larger economic value yielding a lower CF score. In this assessment the CF scores ranged from 84,3 for yttrium to 98,4 for praseodymium. Neodymium fared with a 94,9.

Referring back to Table 2, total GTE values are the average score of DT and CF and plotted on a scale of 0-100 with 100 being most critical. While neodymium CF score was very critical total GTE indicator value was only 47,5 for both the medium- and long-term.

Social & regulatory (S&R): policy potential index (PPI) and human development index (HDI)
This indicator group addresses the political and social landscape in upstream producing countries. The S&R value is based on the scores of established indices. The PPI provides scores to countries and jurisdictions on overall mining policy and its influence on investment. It gathers data on environmental regulations, taxation instruments and rates as well as political stability and openness to trade (Cervantes, Green, and Wilson 2014). Nassar, Du & Graedel adjusted the pertinent REE-producing country scores to their 0-100 criticality range with PPI scores falling between 54-55 for all REEs; neodymium received a 54,95.

The HDI is a composite index published annually by UNDP measuring human development across three criteria, life expectancy, education and income, according to UNDP (2015). All REEs received a score between 67-68, neodymium a 67,41.

Again, the average of HDI and PPI was calculated to determine overall S&R score; neodymium received a 61,2 falling into the more critical range.

Geopolitical (GP): worldwide governance indicators / political stability and absence of violence / terrorism (WGI-PV) and global supply concentration (GSC)
Similar to S&R this indicator group investigates the political landscape and terrorism vulnerability in the country of production (WGI-PV) as well as the HHI, or the production concentration of each REE within political borders compared to the total production in the rest of the world (ROW).

The EU methodology also used all six WGI indicators in its supply risk assessment but Nassar, Du & Graedel use only one, the political stability and absence of violence contribution to the WGI. The authors did not clarify why they only chose this WGI indicator but evaluating the methodology is not within the scope of this research. Scores for all REEs were between 70-71 with neodymium receiving a 70,46, on the higher spectrum of the criticality range.

Global supply concentration refers to the HHI or the ratio of REE production within each producing country compared to ROW production. The GSC results spanned from 89-99 with neodymium calculated as 99,2.

Consequently total GP score for neodymium was an 84,8 which would be considered relatively high, according to Nassar, Du & Graedel. However when the total supply risk is calculated – the average of GP, S&R and GTE, neodymium scores only a 64,5 in the medium-term and a 47,5 in the long term demonstrating a lower supply risk than other analyses. Nassar, Du & Graedel cite methodology as the main cause in the disparity, e.g. individual REE analysis, country-specific, long-term horizon. The next indicator category addresses environmental implications using LCA impact assessment results to determine the neodymium outcome.

<table>
<tr><th colspan="4">Supply risk</th></tr>
<tr><td rowspan="6">Medium-term
64,5</td><td rowspan="2">GTE
47,5</td><td>DT
0</td><td rowspan="2">Long-term
47,5</td></tr>
<tr><td>CF
94,9</td></tr>
<tr><td rowspan="2">S&R
61,2</td><td>HDI
67,4</td><td></td></tr>
<tr><td>PPI
55,0</td><td></td></tr>
<tr><td rowspan="2">GP
84,8</td><td>WGI-PV
70,5</td><td></td></tr>
<tr><td>GSC
99,2</td><td></td></tr>
</table>

Table 3: Neodymium supply risk indicator results for each disaggregated indicator level, Nassar, Du & Graedel (2015)

Environmental Implications (EI)

The adverse environmental implications resulting from virgin metals extraction are the focus of the second indicator group. This analysis uses LCA to measure the effects across 18 impact categories with normalization and weighting using ReCiPe1.06 (world) H/H method. Due to the lack of comprehensive LCI data only bastnaesite mining in China was considered in the EI assessment; results may have illustrated more detrimental impacts if the radioactive xenotime and monazite mining would have been considered (Schüler et al. 2011).

Results were generated to reflect the 2006-2011 average REE prices and the Bayan Obo individual production and subsequently adjusted to a 0-100 scale. Neodymium scored a very low 6,1, highlighting a disconnect in the public perception and media associated with REE mining in China (MIT 2015; The Guardian 2014).

Vulnerability to Supply Restriction (VSR)

Referring back to Table 2, VSR integrates two spatial dimensions – national (US, China) and international. The national analysis incorporates results from the *Importance*, *Substitution* and *Susceptibility* indicators; international only the first two. The evaluation is carried out like the previous two indicators with all results adjusted to a 0-100 scale.

Importance (I): material assets (MA) and national economic importance (NE)

Material assets build on the consumption of REE-containing applications based on demand statistics from the USGS. International MA is calculated by quantifying the ratio of REE stock per person to overall REE stock + REE reserve base. Because no data exists for national REE stocks, the research adjusted consumption to be relative to national GDP of China and the US.

MA international values were much less critical due to the current large REE reserve base, although the HREEs received higher values than the more ubiquitous LREEs. Nonetheless the scores ranged from 3,0 for cerium to 16,5 for dysprosium; neodymium only had a value of 7,4.

MA national values deviated between China and the US. China's results demonstrated a low criticality score for neodymium – 10,9 while the neodymium result for the US was higher by a factor of 3, 35,8. The reason for the deviation is due to the higher REE stock per capita rates in the US than China.

The national economic importance does not include the international dimension. NE was 'calculated as the product of apparent consumption and market price per REE for China and the US relative to GDP' (Nassar, N.T., Du, X., Graedel 2015). Results were subsequently scaled to reflect the 0-100 criticality range used throughout the analysis. Because REE consumption was higher in China than the US, Chinese neodymium NE value was higher, accordingly. The importance of neodymium to China was 24,2 and 0,5 for the US.

Substitutability (S): substitute performance (SP), substitute availability (SA), environmental impact ratio (ER), net import reliance ratio (IRR)
To determine the substitute performance the researchers at Yale University identified all REE applications and the distribution percentage of each REE per application. If there were substitutes identified and they were available for each REE per application, their performance was then rated as not applicable, poor, adequate or good. This approach was mostly qualitative with the substitution data ascertained from the literature. The average substitute performance score for neodymium across all applications 46,0

The substitute availability scores also deviated across the individual applications per REE. The criticality results for substitute availability (SA) were much more dire than substitute performance (SP), demonstrating that whilst substitutes may be available, they may themselves be critical. Neodymium received a 100 for magnets, ceramics and auto catalysts and an average value of 87,5.

The environmental impact ratio (ER) was calculated as 'the product of 50 times the ratio of the EI score of the substitute and REE, adjusted to 0-100', according to Nassar, Du & Graedel. Neodymium results were relatively critical with a 61,2.

Finally the net import reliance ratio (IRR) was determined for China and the US as the ratio between (consumption – domestic production / consumption). Due to the concentration of primary production in China, it received 0 for all REEs whilst the US received 100 for all HREEs and 82,2 for neodymium due to minimal production at Mountain Pass/California in 2008.

Total Substitutability score was generated internationally, for the US and China with a 69,2, 62,5 and 54,8 respectively. The scores do not illustrate an extremely high criticality and the primary reason for the deviation is the concentration of primary production activities in China.

Susceptibility (SU): net important reliance (IR) and global innovation index (GII)
The final indicator in the broader VSR group addresses only the national dimension. The net import reliance (IR) is taken directly from the net import reliance ratio (IRR) in the previous section. Neodymium scored an 82,2 for the US and a 0 for China. The GII ranks countries based on how conducive the

following indicators are to innovation: institutions, human capital and research, infrastructure, market sophistication and business sophistication (Dutta 2012). GII under the US scored 28,7 for neodymium while China's GII neodymium value was a more critical 56,8.

Total SU results for the US ranged lowest for neodymium with 55,4 to a higher 64,3 for some LREEs and all HREEs. China's SU scores were the same for all, a non-threatening 28,4.

Aggregated VSR values were delineated among the three spatial dimensions addressed illustrated in Table 4 – international, US and China. Globally scores were in the range of 15,1 for samarium to 38,3 for neodymium; US-centric scores were lowest for samarium 41,3 while neodymium fared with a 45,3; finally China's neodymium score stood at a non-critical 33,6.

<table>
<tr><th colspan="3">Vulnerability to Supply Restriction (US)</th><th colspan="3">Vulnerability to Supply Restriction (China)</th></tr>
<tr><td rowspan="8">National (US)
45,3</td><td rowspan="2">I
18,1</td><td>NE
0,5</td><td rowspan="8">National (China)
33,6</td><td rowspan="2">I
17,6</td><td>NE
24,2</td></tr>
<tr><td>MA
35,8</td><td>MA
10,9</td></tr>
<tr><td rowspan="4">S
62,5</td><td>SP
46,0</td><td rowspan="4">S
54,8</td><td>SP
40,9</td></tr>
<tr><td>SA
87,5</td><td>SA
90,8</td></tr>
<tr><td>ER
61,2</td><td>ER
84,8</td></tr>
<tr><td>IRR
55,2</td><td>IRR
2,7</td></tr>
<tr><td rowspan="2">SU
55,4</td><td>IR
82,2</td><td rowspan="2">SU
28,4</td><td>IR
0</td></tr>
<tr><td>GII
28,7</td><td>GII
56,8</td></tr>
</table>

Table 4: Neodymium vulnerability to supply restriction results for the US and China, Nassar, Du & Graedel (2015)

Advantages of the Nassar, Du & Graedel methodology is that it is very robust and gauges the magnitude of criticality for individual REEs across multiple indicators and dimensions. A high degree of transparency is also maintained in the quantification process establishing a high level of legitimacy. It can also be applied to any metal, not just the REEs, ensuring that results for one metal can be compared for another. Comparatively results illustrate a much lower magnitude of criticality for the REEs than the EU and USDOE. This could be due to reference year – 2008 – but also due to the national focus taken assessing criticality from US and Chinese perspectives.

Table 5 illustrates adjusted short- to medium-term supply risk scores for the LREEs (EU) and neodymium (USDOE and Yale University). The results do not deviate significantly, especially for the EU and Yale. However comparison of economic importance results differ due to the scope of analysis: the EU addressed LREE significance to the aggregated EU economy; the USDOE qualitatively analysed neodymium importance to clean energy; and Yale University assessed the amount of neodymium in use per capita divided by the total neodymium in use stock + total neodymium reserve base.

	Supply risk	**Supply risk adjusted to 0-100**	**Economic importance**	**Economic importance adjusted to 0-100**

EU	3,1 / 5	62	5,2	52,1
USDOE	3 / 4	75	3	75
Yale	64,5	64,5	12,4	7,4

Table 5: Neodymium (USDOE and Yale University) and LREE (EU) criticality results for supply risk; supply risk for the Yale University and USDOE assessments was from the medium-term results; supply risk adjusted to a 0-100 scale; economic importance for the USDOE represents the medium-term result; economic importance from the Yale study is the international criticality score

Different goals of each assessment as well as the deviating temporal and spatial dimensions and the age of the datasets result in a lack of comparability. Nassar, Du & Graedel had to use 2008 data due to lack of availability for more current data which would likely increase criticality results, especially after 2010-2011 (Smith Stegen 2015). This will be partially demonstrated in this research as global neodymium supply-demand dynamics have been synthesized in Chapter 6.3. It would moreover be argued that the researchers from Yale University diluted the importance of neodymium to the global economy by comparing its significance to total GDP instead of the segment(s) of the economy using neodymium applications. Nonetheless neodymium has been identified as critical from the EU and USDOE; it also received scores above 50 in 56% of all indicators, above 60 in 44% of all indicators and above 70 in 31% of the indicators from Yale University.

Criticality conclusions

Complexity associated with determining neodymium criticality emerges from describing three methodologies. The geographical and temporal parameters in addition to the degree of aggregation will substantially influence criticality results. Moreover this chapter illustrated the significance of quantitative assessments as they are transparent and easily replicated. Although all three assessments described varied in breadth and scope, neodymium still appeared in differing magnitudes of criticality.

3 Literature review

Research on neodymium is relatively nascent in the literature compared to that of other materials, especially of fuel minerals for which extensive assessments are available. Only in the past decade has the REE debate permeated academic and industrial discourse due to the dubious results from criticality assessments in Chapter 2.1 and the neodymium supply risk and price fluctuations observed in 2010-2011 discussed in Chapter 6.

The literature review synthesis in Table 6 provides detailed insights into the CRM-REE-neodymium discourse, albeit with different system boundaries and in most cases, a limited scope. The approach and rationale of the literature review is visualized and in Figure 2 and moreover reflects the structure of this research illustrated in Figure 1 in Chapter 1. Figure 2 demonstrates the complexity and potential circularity of the criticality discussion. The dotted lines represent the current, incomplete gaps in the neodymium literature landscape which this research aims to fill, namely the theoretical potential of secondary neodymium in products on (i) neodymium demand and (ii) consequently, its criticality.

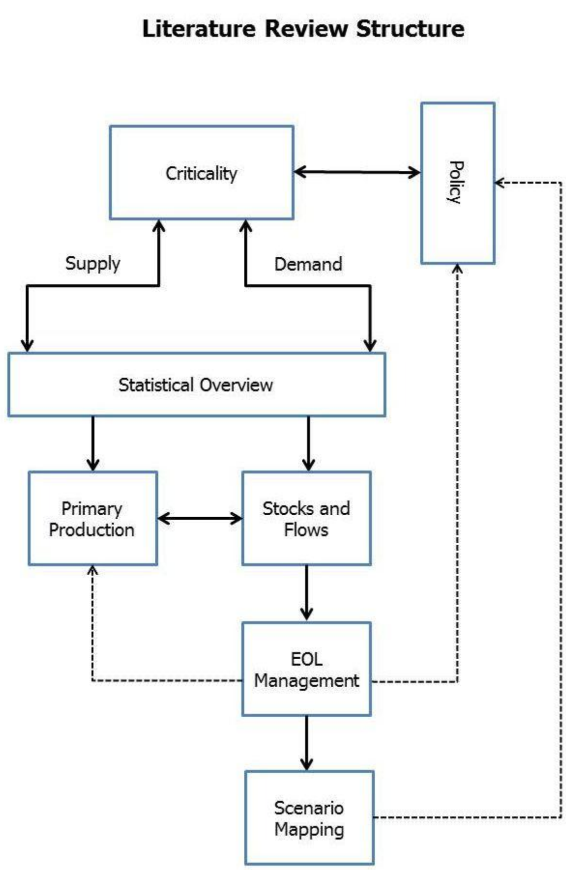


Figure 2: Illustration of the structure of the literature review approach of this research thereby reflecting the meta-structure of this work in Figure 1 in Chapter 1

For upstream neodymium activities a few researchers offer aggregated REE production estimates and less often, demand figures. Thus far no research exists that provides comprehensive, disaggregated neodymium supply-demand datasets and country of extraction over a span of 25 years. This research synthesized the incomplete neodymium data from Du and Graedel 2011a and the British Geological Survey, generating a high-resolution snapshot of the neodymium supply-demand landscape since 1990.

At the product level, most of the research attempting to quantify secondary neodymium is limited to NdFeB permanent magnets, which is to a certain extent substantiated since the literature has indicated NdFeB permanent magnets absorb 76% of all neodymium flowing into use, worldwide. However most of the research only quantifies the NdFeB permanent magnets in HDDs in laptops and PCs and more recently PHEVs and direct drive permanent magnet (DDPM) wind turbines; this is due to the lack of compositions in other product groups as well as unavailable product flows data for other neodymium-containing products. This over-emphasis on NdFeB permanent magnets in select electronics acts as a blind spot to other, perhaps more problematic and larger neodymium flows. This can lead to a gap in mapping and characterizing neodymium flows and missed policy and technological opportunities.

Finally, various individual REE material flow analyses (MFA) have been carried out but can be differentiated from this research for the following reasons:

- Habib and Wenzel 2014 undertook a robust MFA in Denmark but only addressed Danish flows of neodymium and dysprosium in 2012 and a forecast for 2035 with a more limited product scope than this research. Results were not contextualized to the broader REE supply-demand landscape.
- Hoenderdaal et al. 2013 investigated dysprosium demand in permanent magnets in 2050 based on upper- and lower-bound assumptions. This study also embeds the results into a fundamental supply-demand discussion but is not applied to a particular country or region and only addresses wind turbines, PHEVs and electric bikes and HDDs, industrial motors and speakers.
- Rademaker, Kleijn, and Yang 2013 explored flows of neodymium and dysprosium in permanent magnets in wind turbines, PHEVs and HDDs in laptops and PCs from 2011-2030, even incorporating it into the broader criticality and supply-demand debate. However, many neodymium applications such as batteries and many electronics such as white goods, were not included in this analysis.

Criticality	
US Department of Energy 2011, European Commission 2014, Nassar, Du, and Graedel 2015	Development of methodologies to assess criticality of non-fuel minerals
Wager 2011	Scan of various criticality methodologies integrating environmental and social dimensions for sustainable CRM governance
Achzet and Helbig 2013	Reviewed 15 criticality methodologies, applied them to indium and assessed differences in indicators and results
Erdmann and Graedel 2011	Compared various criticality methodologies identifying several criteria not yet considered in hitherto criticality methodologies
Glöser et al. 2015	Reviewed various criticality assessments concluding classical risk assessment was overlooked leading to non-uniform results
Smith Stegen 2015	Assessed supply risk dimensions of REEs often overlooked (entire supply chain) using permanent magnets as an example
Policy	
Tse 2011	Synthesis of Chinese REE policy and strategies going forward
L. Zhang et al. 2015	Using the Lerner Index and BP neural network, assessment of the effectiveness of Chinese REE policy since 1985
Statistical overview	
USGS	REE annual yearbooks providing annual summaries on REE production and consumption, pricing, trade, world overview, outlook and granular import/export data
MIT	Compiled a global overview of REE mines and reserves with scarce data on production and consumption
BGS	Archives collated all REE primary production amounts and the disaggregated geographical distribution of production
Du and Graedel 2011a	Estimates of disaggregated REE primary production from 1995-2007 based on individual REE distributions in 7 REE mines
Supply-Demand	

Humphries 2010, Humphries 2013	Outlined the chief end-uses and demand of REEs while explaining supply chain bottlenecks and policy options for the future
Hatch 2011	Provides a detailed overview of REE applications, current and planned primary production as well as projected demand for individual REEs
Schüler et al. 2011	Explored detailed supply data, including mining data, ore grades and concentrations, followed by fabrication and manufacturing processes, REE applications and demand in 2008 and future projections
D. J. Kingsnorth 2012, D. Kingsnorth 2013	Indicated supply-demand-pricing figures from 2008-2012 with projections from 2016-2020
Lynas 2010	Detailed supply-demand figures for 2010 and forecasts onward to 2014
Du and Graedel 2011c	Generated 2007 disaggregated supply data for 10 REEs as well as life cycle flows per REE assessed
Goonan 2011	Assessed global REE demand for 2008 with disaggregated demand per REE per application
Gschneidner 2015	Indicated demand for REE applications
Du and Graedel 2013	Calculated global end-use distributions for all REE applications per REE for 1995 and 2007
Primary production (supply)	
Orris and Grauch 2002	On behalf of the USGS inventory of all known REE deposits worldwide
Schüler et al. 2011	Inventory of ongoing and planned REE primary production activities as well as descriptions of the process
United States Environmental Protection Agency 2012	Description of the REE primary production process with emphasis of the environmental implications of mining
Du and Graedel 2011a	Detail a summary of the REE production process
Sprecher, Kleijn, and Kramer 2014	Description of the REE extraction, processing and refining processing from carrier ore to REO to REE
Hatch 2011	Collated all Chinese production for 2010 as well as ongoing REE exploration projects
Buchert 2012	Denoted the production outputs per mine in China as well as a synopsis of ongoing REE exploration projects
Stocks and flows (demand)	
Yano, Muroi, and Sakai 2015	Mapped potential REE recovery yields from PHEVs in Japan from 2010-2030
Du et al. 2015	Compared input-driven / output-driven approaches to ascertain insights into critical metal use in vehicles
Sprecher, Kleijn, and Kramer 2014	Quantified the potential of secondary neodymium in HDDs to demand for neodymium in HDDs and NdFeB permanent magnets in 2017 and 2023
Habib et al. 2014	Quantified current and future potential for secondary recovery of neodymium and dysprosium from NdFeB magnets in Denmark
Zimmermann, Rehberger, and Gößling-reisemann 2010	Analysis of stocks and flows of wind turbines in Germany and secondary recovery opportunities for neodymium based on DDPM market share forecasts
Constantinides 2013	Synthesis of existing literature on the role of REEs in the automotive industry
www.bovag.nl	Inventory of new automobile registrations per fuel type in the Netherlands as well as total stock and total ELVs
Peiró, Méndez, and Ayres 2013	Mapped complex relationships between carrier ores and scarce byproducts, their in-use distributions to estimate potential for recycling
EOL management and recovery technologies	

Schüler et al. 2011	Provided a compository of current recycling technologies per REE application with a specific focus on permanent magnet recycling as well as requirements for a recycling system in Europe
Resende and Morais 2010	Investigated hydrometallurgical application to computer monitors for recovery of yttrium and europium
Shirayama and Okabe 2008	Explored recovery rates of neodymium and dysprosium through leaching experiments of permanent magnets
Ueberschaar and Rotter 2014	Assessed the recycling chain of HDDs in Germany
Okabe et al. 2003	Conducted experiments on the recovery of neodymium from permanent magnets using pyrometallurgical techniques
Binnemans et al. 2013	Reviewed pyrometallurgical and hydrometallurgical technologies for recovery of REEs in permanent magnets, NiMH batteries and phosphors
Scenario mapping	
Hoenderdaal et al. 2013	Project future supply of dysprosium in 2050 based on PHEV/wind energy/HDD growth trends with upper- and lower-bound scenarios
Ren21 2012	Renewable energy report with targets going forward in the future
Habib and Wenzel 2014	Quantified neodymium and dysprosium in NdFeB permanent magnet flows in Denmark in 2012 and estimation on stocks and flows for 2050 and 2100 based on upper- and lower-bound scenarios
Rabobank International 2012	2020 outlook on the renewable energy landscape in the Netherlands based on current situation
Iea 2013	Status quo and global outlook for PHEV uptake until 2020
Rademaker, Kleijn, and Yang 2013	Mapped the waste flows of neodymium and dysprosium in NdFeB permanent magnets in wind turbines, EVs and HDDs from 2011-2030
Alonso et al. 2012	Evaluated potential future supply of dysprosium and neodymium based on various wind energy and PHEV scenarios over the next 25 years

Table 6: Inventory of literature on various dimensions of REEs and particularly neodymium across the entire life cycle in order to determine and justify the academic baseline upon which this research will build

Consensus on the criticality of neodymium is assessed and well-understood in the literature. Moreover compared to other REEs, especially the HREEs, neodymium has been addressed by a growing number of researchers. Nonetheless these assessments have only targeted one link in the neodymium life cycle or examined the amount of neodymium flowing into an under-represented subset of neodymium-containing products. This research will attempt to fill that gap using the Netherlands as a case study and 2010 as a reference year for generating a potential 2030 neodymium outlook. Moreover this research strives to cultivate and offer a neodymium mapping approach that can be tailored and replicated in other countries.

4 Methods

In order to answer the research questions outlined in Chapter 1 and subsequently fill the neodymium research gaps identified in Chapter 3, this research will use MFA and scenario mapping to model and interpret neodymium flows in the Netherlands in 2010 and 2030, respectively. The following two sub-sections will introduce both methods and describe how they will be adjusted and applied in this research.

4.1 Material Flow Analysis (MFA)

Material flow analysis (MFA) is an analytical tool that enables quantification of (i) inflows, (ii) stock changes and (iii) outflows of a particular material within a spatial and temporal boundary. Because it is fundamentally built on the principle of mass balance from the first law of thermodynamics – the law of mass conservation, all flows of the corresponding substance entering, moving through or leaving the system boundary must be accounted for as exhibited in Figure 3 (Bringezu and Moriguchi 2002; van der Voet 2002). Essentially MFA describes the industrial metabolism of a particular substance within an economy, a concept first described by Ayres (Kleijn, Huele, and Van Der Voet 2000). As such MFA enables the quantification, mapping and assessment of a particular material through a society and accordingly, identification of problematic flows or material leakages. This information will subsequently alert policymakers to adjust legislation and optimize systems to maximize collection and recovery, a pillar of circular economy.

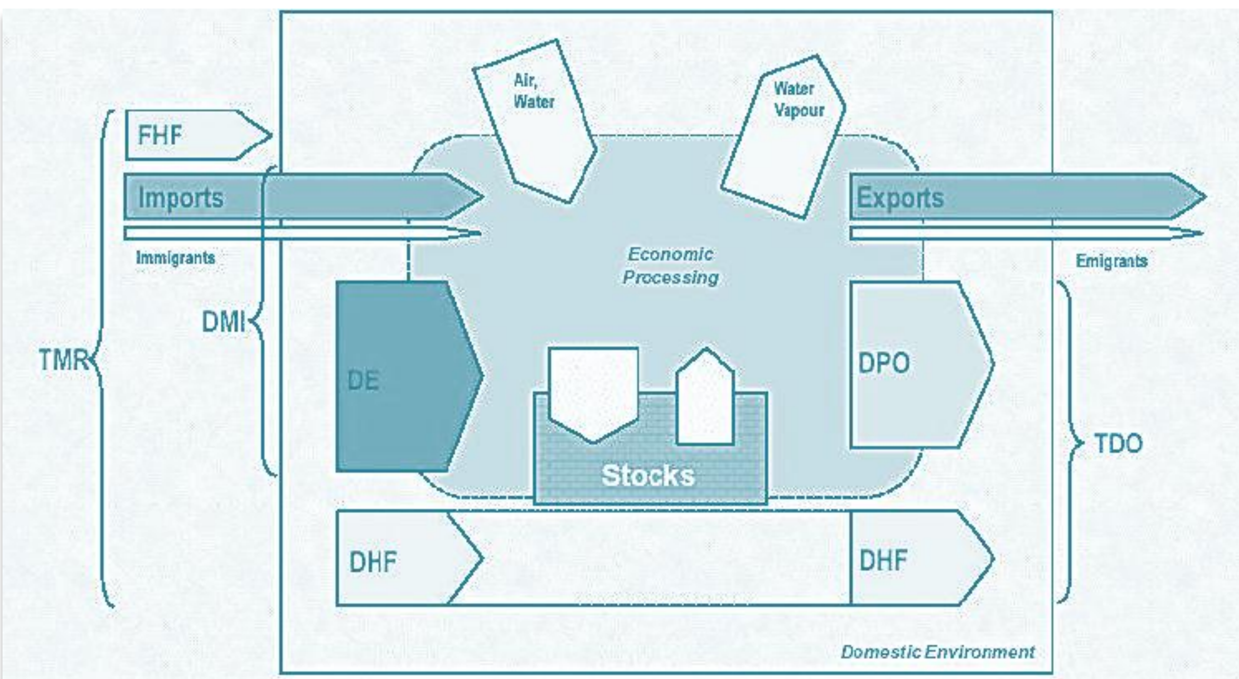


Figure 3: Basic MFA model demonstrating how flows permeate, interact in and leave an economy, Matthews et al (2010); TMR: total material requirement, FHF: foreign hidden flows, DMI: domestic material input, DE: domestic extraction, DHF: domestic hidden flows, DPO: domestic processed output, TDO: total domestic output

MFA is carried out in three steps, according to Bringezu and Moriguchi 2002:

1. Defining the spatial and temporal boundary
2. Inventory and quantification of inflows, outflows and stocks of the material under assessment

3. Interpretation of the results.

Assumptions have to be made in every MFA and form the parameters that define how wide or limited the scope will be. Assumptions are moreover dependent on many factors such as data availability or the time and aim of the MFA. Adjusting the parameters can substantially influence the results (Van der Voet 2002).

4.1.1 System Boundaries

The Netherlands contains a repository of robust, reliable and continuously updated datasets for a range of sectors and products. Entities like the Dutch Centraal Bureau voor de Statistiek (CBS) and the Foundation for the Bicycle and Automotive Industries (RAI) provide not only publicly available datasets but also projections going forward in the future. Moreover United Nations University (UNU) conducted a comprehensive quantification of stocks and flows of electronics in the Netherlands in year 2010, at that time the first time such a comprehensive assessment was carried out. Due to the availability and reliability of data on neodymium-containing products in the Netherlands, in addition to the author's host university at TU Delft / Leiden University, the MFA spatial boundary will be the Netherlands.

The temporal dimension of the MFA also depends on the year(s) in which sound, accessible data is available. Based on the literature review in Chapter 3, the electronics sector absorbs a large amount of neodymium flowing into use per year. Because the UNU quantification of stocks and flows of electronics was modeled for 2010, this year will also serve as the temporal parameter of the static MFA.

Determining the temporal parameter for the dynamic MFA conducted in the scenario mapping exercise in the future was more challenging. It necessitated a balance: selection of a year far enough to ensure new products with long lifespans enter the waste stream but also not too far into the future due to the complexity and inherent uncertainties in product evolution, according to Schumpeter (Rosenberg 1996). Electronics have much shorter lifespans compared to automobiles and wind turbines. And because the PHEV market is still nascent with only 16.000 PHEVs and 122 full EVs sold in the Netherlands in 2010 combined with long lifespans at 20 years, they will not enter the waste stream in large volumes for at least 20 years (BOVAG 2015). Simultaneously the first DDPM wind turbines were erected in 2004 with comparable life spans at 20 years (T. Zimmermann, Rehberger, and Gößling-reisemann 2010; Habib et al. 2014). For these reasons the dynamic MFA for a potential neodymium future will be 2030.

The neodymium applications described in Chapter 6.3 – permanent magnets, batteries, metallurgical alloys, colouring agents, ceramics, catalysts and other – flow into products. This research will attempt to create an exhaustive inventory of all of these products and assign them to a particular economic sector, resulting in the Neodymium Portfolios in Chapter 7. However not all products will be modeled in this research for two reasons. The most constraining bottleneck was the lack of stocks and flows data for certain neodymium-containing products, such as mischmetal-containing lighters and ignition devices or glass incorporating neodymium as a colouring agent. Furthermore the absence of neodymium compositions for certain products also influenced which products would be included in the scope of this research, especially due to lack of time and capacity to carry out laboratory measurements on, e.g. neodymium amounts in power tools.

Finally this research will only model the first step of the recycling chain and therefore, only the theoretical potential of secondary neodymium; incorporation of recovery rates from various hydro- or pyro-metallurgical recycling technologies are not included as these recovery technologies have not been implemented at the industrial level and current neodymium recovery rates are <1% (Reuter 2013). The first step of the recycling chain will nonetheless be delineated by *collection*, *uncollected*, *export* when possible. Determining which channels neodymium enters after disposal will consequently shed light on how efficient or lackluster the current Dutch management system performs at collection.

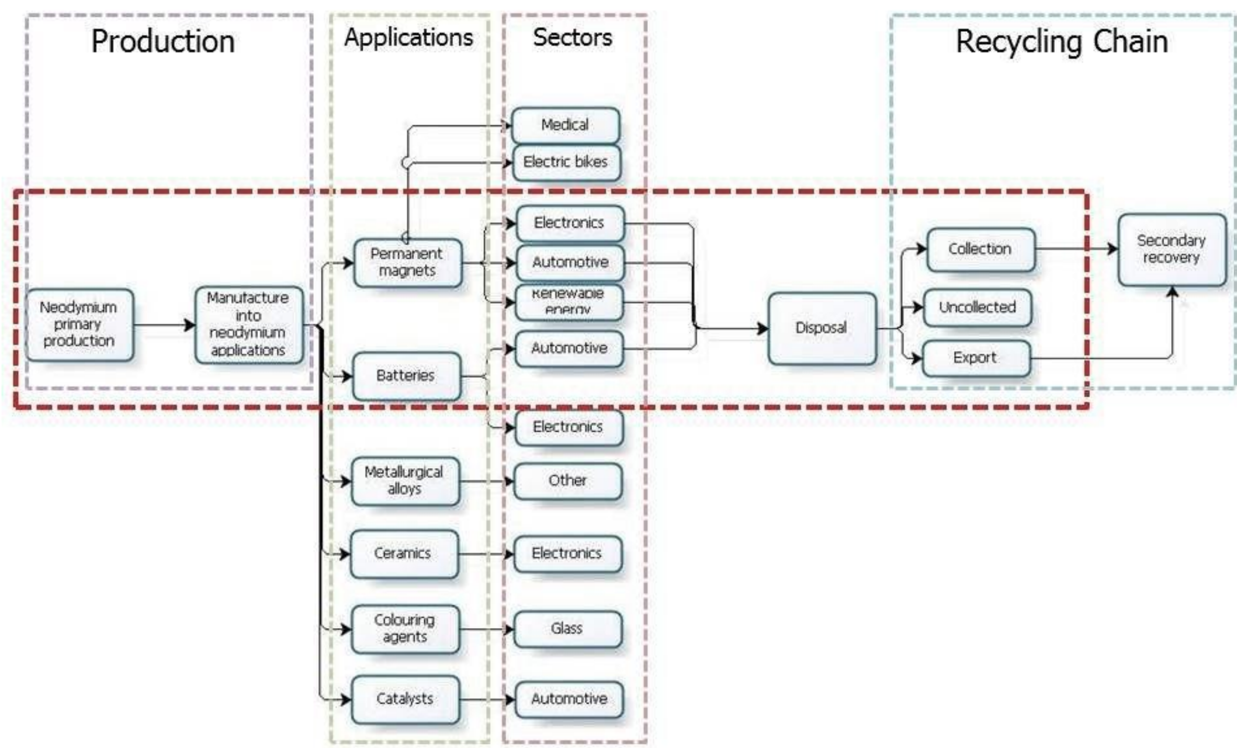


Figure 4: System boundary of this research denoted by the red dotted line; the other dotted lines refer to the main dimensions of the neodymium value chain beginning with primary production and manufacture into neodymium applications, the sectors into which the neodymium applications flow followed by product disposal and EOL management

Determining the scope and system boundary was an iterative process that culminated in the flow chart in Figure 4. Most daunting was determining which products would be modeled due to availability and robustness of stocks and flows and compositions data. However this research posits that approximately 75-80% of all neodymium in the Netherlands could be accounted for in this system boundary, based on the neodymium into-use distributions adapted from Goonan (2011) – 76% in permanent magnets and 5% in batteries. The next section will explore the main data requirements for carrying out the MFA as well as the sources per sector. Decisions of detailed data decisions will be explained in Chapter 7 and Chapter 8.

4.1.2 Data requirements

Data required to model neodymium stocks and flows in the Netherlands are provided the grey literature complemented by consultations with experts in industry and academia which will be described in detail in Chapter 7 and Chapter 8. Because this research uses MFA as the analytical tool for generating results, there are particular variables required to model neodymium flows and are listed in Table 7. For each product in the Neodymium Portfolios, the following variables were inventoried per product.

Variable	**Description**	**Unit**
Put on market (POM) / new registrations / installed capacity	Depending on the product group, refers to new products containing neodymium that penetrate the Dutch economy in the year of analysis	kg, kg/inh, MW, units
Stocks	Refers to the number of products containing neodymium that are in use during the year of assessment	kg, kg/inh, MW, units
Waste generated	Neodymium-containing products that reach EOL and are discarded during the year of assessment	kg, kg/inh, MW, units
Average weight	Average weight of products containing neodymium is required for certain datasets, e.g. POM data in total kg/inh	kg
Population	Number of inhabitants in the Netherlands needed for certain datasets, e.g. POM data in total kg/inh	
Average lifespan	Required for dynamic modeling for predicting future flows	years
Composition	Concentration of neodymium per a specific value of those products containing neodymium, e.g.	wt%wt%, g/kg, kg/unit, g/MW-1

Table 7: List of variables required for modeling neodymium flows in the Netherlands

The variables in Table 7 enabled completion of the template Neodymium Portfolios in Table 8 which will be completed and presented in Chapter 7.

Neodymium Sector-Product-Compositions Portfolio							
Sector	Product	Component	Product weight [kg]	Component mass [kg]	Nd mass [kg]	Nd concentration[%]	Source
Application 1							
Sector 1	Product 1	Component					
	Product 2	Component					
	Product 3	Component					
	...						
Sector 2	Product 1	...					
	Product 2	...					
	...	...					
	...	...					
	...	...					
Sector 3	...	...					
Sector 4	...	...					
Application 2							
Sector 2	...	...					
Application 3							
Sector 2	...	...					

Sector 4	...	...					

Table 8: Neodymium Sector-Product Portfolio template collating all products and corresponding sectors containing neodymium applications that were used as the foundation for carrying out the static and dynamic MFAs

The Neodymium Portfolios also establish the rudimentary data foundation needed for carrying out the dynamic MFA in the Netherlands in 2030. However, contrary to 2010, modeling neodymium flows in 2030 is inherently uncertain and requires assumptions and statistical parameters that define the boundary conditions of the future neodymium landscape. The widely-accepted method for generating a potential future is scenario mapping which will be combined with MFA in this research to visualize neodymium stocks and flows in 2030.

4.2 Scenario mapping

Scenario mapping is a method that illustrates a coherent, consistent and plausible description of a possible future state of the world, according to the IPCC. Scenarios are neither predictions nor forecasts; they are potential snapshots into the future which are determined based on particular parameters and assumptions. Such scenarios can inform policymakers or relevant stakeholder groups about how and to what magnitude policy actions can influence the future (Mahmoud et al. 2009).

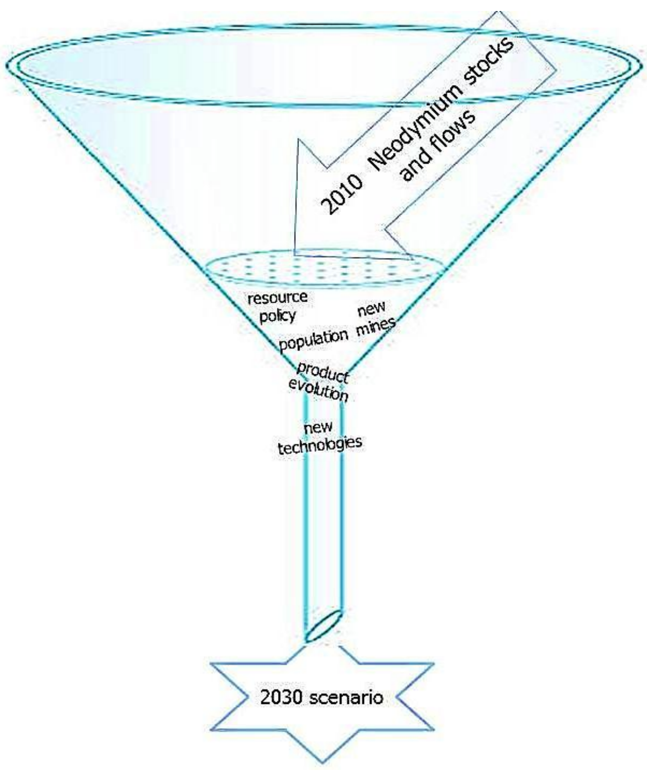


Figure 5: Visualization of how scenario mapping parameters influence results for the future

Because the future generated using scenario mapping is dependent on the chosen parameters and assumptions used in an assessment, it is both inherently uncertain but also advantageous and flexible. For example there are many uncontrollable, unknown future forces that can influence how products and technologies evolve and are consumed as well as societal and environmental changes as the future unfolds. These include, among others, population growth and changes in wealth, discovery of new, high-grade neodymium deposits but also evolution in DDPM wind turbines and solid state drives (SSDs). For this reason scenario mapping parameters should be consistently monitored and adjusted to reflect the perturbations in these indicators; different portraits of the future can lead to different policy actions taken today (Habib and Wenzel 2014; Hoenderdaal et al. 2013; Mahmoud et al. 2009).

This research will combine dynamic MFA with scenario mapping in order to describe a potential neodymium future in the Netherlands in 2030. This future neodymium scenario will use 2010 as the baseline year upon which future stocks and flows rates will build. Neodymium parameters will be described in detail in Chapter 9 and be constructed based on indicators and targets from the

International Panel On Climate Change (IPCC), Dutch governmental agencies, the Centraal Bureau voor de Statistiek (CBS) and the International Energy Agency (IEA).

5 Rare earth elements (REEs)

5.1 Introduction

The 15 lanthanide elements plus scandium and yttrium are the so-called REEs shown in Figure 6. They are all found in nature and contain many similarities in their chemical composition resulting in a challenging separation process (Walters and Lusty 2011). Paradoxically the REEs are not rare at all and are quite prevalent in the lithosphere; for example, cerium is more abundant in nature at 60ppm than copper (Polinares 2012).

The REEs are also typically separated into the light rare earths (LREEs) and the heavy rare earths (HREEs). LREEs are traditionally more abundant in nature than their counterparts and are easier to separate and refine (Hatch 2011).

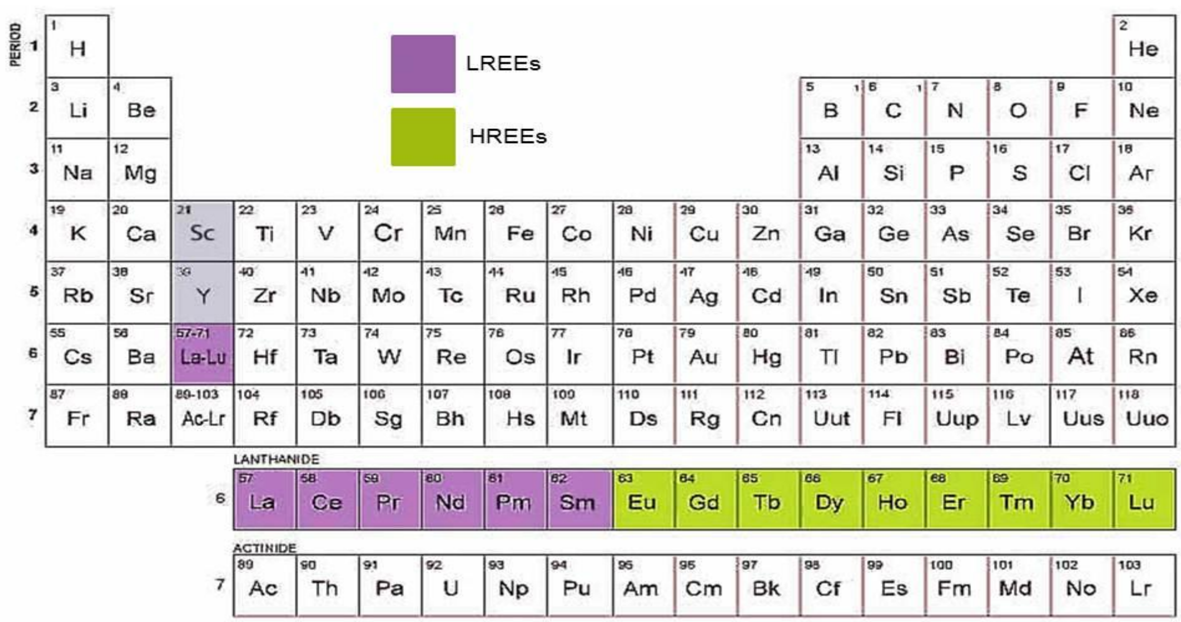


Figure 6: Periodic table with the distinction of LREEs and HREEs plus Scandium and Yttrium, EURARE project (2015)

According to the USGS the current known REO reserve base totals 110 million tonnes; this figure corresponds to the part of the reserve base that could be economically extracted. However this figure will likely increase in the future with ongoing REE/REO exploration activities (Schüler et al. 2011; Alonso et al. 2012). It will be imperative to delineate between the terms REE and REO. The rare earths are extracted with their carrier ore and refined into their oxide, e.g. Nd_2O_3. In the following separation step hydrometallurgical processes are applied and they are diluted to rare earth elements (REEs) which are the form needed for manufacturing into most REE applications (Du and Graedel 2011b). The REE:REO ratio is 1:0,85; REO will only be used in this research within the context of reserves and the first stages of the production process (Goonan 2011).

REO geographical distribution is not representative of the current primary production panorama. China currently produces and refines 87% of global REO amounts with the remainder coming from the US, Australia, Russia, India and others (Habib and Wenzel 2014). However China contains only 38% of known reserves followed by former Soviet States with 19%, the US with 13%, Australia with 5% and the amalgam of other countries comprising 22% of REO reserves, according to the USGS (Schüler et al. 2011).

Rare earths are co-mined and extracted as a by-product of various types of carrier ores such as bastnaesite and loparite. REEs are not mined as the primary output due to the lack of economic viability; instead their carriers ores, such as iron or bastnaesite ore, are the main products (Alonso et al. 2012). Individual REO distribution per deposit and subsequent ore grade are a function of the carrier ore type.

Bastnaesite, a carbonate mineral found in carbonatites and some igneous deposits, is the most common carrier ore of (L)REEs. Ore grades are relatively high ranging from 1-8%; Mountain Pass in the US and Bayan Obo in China are both bastnaesite deposits. Monazite is another REE base metal and is a phosphate rock commonly found in placer deposits with LREEs but also more HREEs than bastnaesite. Monazite also contains thorium, a radioactive element, which has resulted in decreased demand for monazite-producing REEs due to environmental implications associated with its waste management (United States Environmental Protection Agency 2012; Bleiwas and Gambogi 2013). Concentration of HREEs are highest in the ion absorption deposits in the seven provinces of Southern China containing >80% of global HREEs (Yang et al. 2013). Other carrier ores include xenotime, loparite, eudialyte and uranium tailings. Detailed information on all ore types can be found in Appendix A1 to this research.

5.2 Primary production process

Between 1966 and 1984 approximately 50% of global supply of REEs came from the bastnaesite Mountain Pass mine in California, US. Starting in 1985 China began to exploit its REE deposits and subsequently export REE concentrates until it exceeded US REE production and export capacity in 1990. The end of the so-called Mountain Pass Era began in 1990 as the REE Chinese Dominance Era commenced. China not only extracted, separated and refined REEs but also expanded to manufacturing semi- and intermediate products such as permanent magnets and batteries (Gschneidner 2015). This lack of diversification in production sources resulted in high concentration of REE primary production in China supported by the results of the criticality assessments in Chapter 2.

This virgin extraction and further processing of REEs is very energy and chemical-intensive and carried out through a cumulative series of separation, milling and refining processes. The type of mining and refining processes differ across the various ore types, the ore grade and size and location of the deposit etc.

For example a bastnaesite mine would be classified as a hard rock mine and would be mined either above ground in open-pit or underground (Schüler et al. 2011). After bastnaesite rock is extracted, acid roasting techniques are applied to liberate the rare earth sulfate ($RE_2(SO_4)_3$) from the carbonate and fluoride rock. Cold water is applied to the rare earth sulfate and filtered to generate a leachate; after the leachate impurities are removed through the elevation of the pH, a caustic soda (NaOH) is applied to the rare earth containing leachate forming rare earth precipitate. An acidic mixture, mostly in the form of HCl is applied to the precipitate resulting in a rare earth chloride ($RECl_3$) (Sprecher, Kleijn, and Kramer 2014).

It is important to note at this point, the rare earths are still bundled together and are further separated based on the deviating basicity levels of each REE. Individual REOs at a purity level of 99,99% are achieved by mixing the $RECl_3$ solution with an organic solvent tailored to liberate only one REO (ibid). This is nonetheless very difficult and requires sophisticated technology due to the similarities of REO chemical composition (Schüler et al. 2011). Finally an electrolytic reduction step is applied to the REO in order to obtain the REE required for most REE applications (Sprecher, Kleijn, and Kramer 2014).

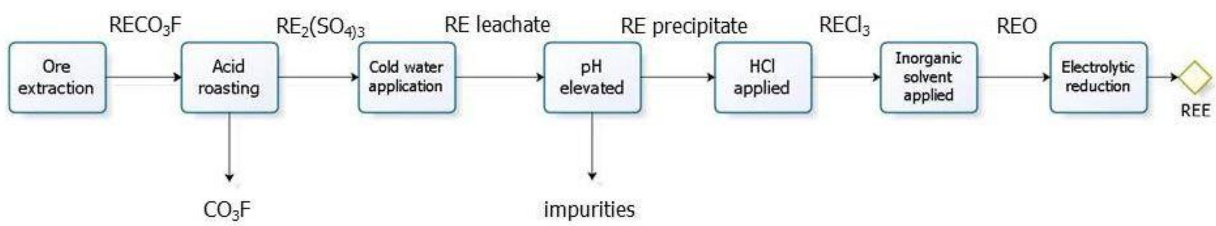


Figure 7: Primary production process of REE from bastnaesite ore, adapted from Sprecher, Kleijn and Kramer (2014)

The knowledge and intellectual property to carry out these refining and separation processes described above and demonstrated in Figure 7 is currently monopolized by the Chinese notwithstanding some LREE processing taking place outside China most notably at the Lynas refining centre in Malaysia and the Molycorp plant at Mountain Pass, California, USA (Polinares 2012); however Molycorp filed for bankruptcy and ceased operations in June 2015 (Forbes 2015). Prior to the opening of Lynas and Molycorp, bastnaesite ore was extracted in another part of the world, exported to China for refining, separation and manufacturing into applications and products and imported back into those countries (Smith Stegen 2015).

5.3 Applications

After REEs have been processed and refined they are used in many different applications. One of the earliest widespread applications of REEs was mischmetal (an alloy of lanthanum, cerium, neodymium and praseodymium) used in flintstone in 1903. Flintstone was an alloy comprising 70% mischmetal and 30% iron which provided the spark to ignite fires in gas mantles. In 1915 mischmetal became more ubiquitous as it was used for traditional lighter flints, still used to this day (Krishnamurthy and Gupta 2005). The HREE europium phosphors were also early REE uses required for the production of colour television in the 1960s (Gschneidner 2015). Still, other more ubiquitous applications include neodymium in NdFeB permanent magnets and the use of lanthanum in automobile catalysts (Constantinides 2013). Their elemental properties in Table 9 provide an indication of the types of industries and sectors using REE-containing applications and products.

For example the magnetic properties of neodymium have made it indispensible to the NdFeB permanent magnet industry and consequently, vital to the electronics, renewable energy and automobile sectors. Lanthanum is also necessary as a fluid cracking catalyst which is required for the conversion of crude oil into lighter, usable hydrocarbons in the automotive sector (Goonan 2011). Only in the past decades have the REEs become increasingly paramount to various applications and industries (Du and Graedel 2011c; Goonan 2011).

REE	Catalytic	Magnetic	Electrical	Chemical	Optical
Lanthanum	X		X	X	X
Cerium	X		X	X	X
Praseodymium		X	X	X	X
Neodymium	X	X	X		X
Samarium		X			
Europium					X
Gadolinium		X			X
Terbium		X			X
Dysprosium		X			X
Holmium					X
Erbium					X
Ytterbium					X
Yttrium					X

Table 9: Elemental and chemical properties per REE, Lynas (2010)

Catalysts

There are two types of catalysts that use REEs for their performance – fluid cracking catalysts (FCCs) and automotive catalysts. FCCs are used in the petroleum industry to create usable end-products such as fuel and gasoline from crude oil by interacting with hydrogen in the complex hydrocarbons (Hatch 2011). Contrastingly when petroleum is combusted in automobiles, automotive catalytic converters contain REEs to reduce the toxins and pollutants in the engine exhaust (Walters and Lusty 2011).

REEs used: cerium, lanthanum, neodymium, praseodymium

Permanent magnets

Permanent magnet applications in the renewable energy (direct-drive permanent magnet wind turbines), automotive (PHEVs) and electronics (motors, magnetic cooling etc) have increased substantially since the early 1980s when NdFeB permanent magnets replaced the former samarium cobalt (SmCo) magnets due to increased magnetism and higher performance (Walters and Lusty 2011). NdFeB permanent magnets are especially ubiquitous as they can be used in small motors in smartphones but also as massive permanent magnet motors in direct-drive permanent magnet wind turbines (Buchert 2012).

REEs used: neodymium, dysprosium, gadolinium, praseodymium, terbium

Ceramics

A diverse application category REEs are incorporated in a variety of in-use distributions using ceramics. Ceramic capacitors and semi-conductors are used widely in the electronics sector (Buchert 2012); REEs are also used in ceramics to increase the strength as well as high-temperature superconductors. They are also used as a colourant in ceramic products and in various other ceramic applications (USDOE 2011).

REEs used: cerium, lanthanum, neodymium, praseodymium, yttrium

Glass

REEs are used in glass applications as decolourisation agents (oxidizing green iron pigment in glass) (Walters and Lusty 2011). REEs also enable glass to absorb UV light and are crucial to the production of yttrium-aluminium-garnet (YAG) lasers used in the electronics and medical sectors (American Chemistry Council 2014)

REEs used: cerium, lanthanum, neodymium, praseodymium, yttrium

Metallurgical alloys
REEs are added to steel, aluminium and other metals to produce alloys with the desired properties and characteristics. One example is the use of mischmetal, an alloy consisting of an REE-mixture of lanthanum, cerium, neodymium and praseodymium used from lighter flints to larger metallurgical applications (Goonan 2011; Peiró, Méndez, and Ayres 2013).

REEs used: cerium, lanthanum, neodymium, praseodymium

Batteries
Mischmetal also plays a role in the production of nickel metal hydride (NiMH) batteries which currently comprise a large market share for all PHEVs (USDOE 2011). Smaller NiMH batteries are also used in everyday electrical appliances.

REEs used: cerium, lanthanum, neodymium, praseodymium, samarium

Phosphors
REEs play a large role in the development colour transmission in visual display devices – from colour in television screens to the liquid crystal displace in a smartphone (Goonan 2011). They are also instrumental in fluorescent and light emitting diode (LED) lighting (Deubzer et al. 2012).

REEs used: cerium, europium, gadolinium, lanthanum, terbium, yttrium

According to Goonan 2011 the total estimated into-use flow, i.e. REE-containing products put-on-the-market (POM) in 2008 amounted to approximately 130 Gg with the largest applications being glass, catalysts and permanent magnets, respectively. The individual REEs with the highest demand were cerium, lanthanum and neodymium. The 2008 into-use distribution datasets per application per REE can be found in Annex A2 to this research.

To ascertain the magnitude of demand for the LREEs and HREEs, the Sankey diagram in Figure 8 demonstrates and characterizes the size of the allotment of each REE to the corresponding applications.

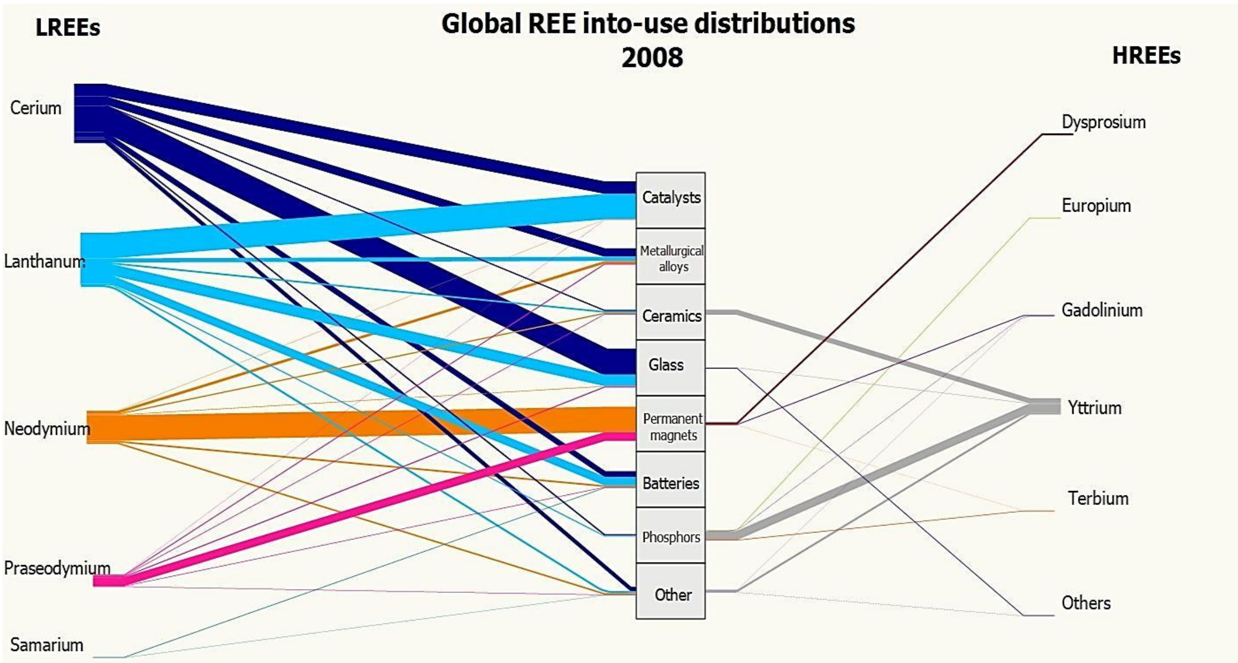


Figure 8: Sankey diagram indicating the various magnitudes of the into-use flows of the individual REEs in 2008, categorized per H/LREE, created by Crock (2015) with data from Goonan (2011)

The disaggregated into-use distribution data in Figure 8 do not reflect or incorporate the size of the in-use stocks which were estimated at 440 Gg in 2007, approximately 3,5 times larger than the 2008 into-use distribution (Du and Graedel 2011b). For example whilst the into-use flow of neodymium amounted to 23,9 Gg in 2008, Du & Graedel estimated the global in-use stock of neodymium at 137 Gg or 31% of total REE in-use stock in 2007. Unfortunately no individual, disaggregated global REE figures were available in the literature for 2008.

The remainder of this research will zoom in on neodymium exclusively. It will explore the neodymium supply-demand metabolism and geopolitical dynamics from 1990-2015 by synthesizing production and consumption datasets that have hitherto remained disconnected for such a lengthy time span. An exclusive neodymium portfolio comprising all products and sectors containing neodymium applications will be developed along with neodymium compositions per product. Building on this neodymium data-supported foundation, MFA will be used to quantify the neodymium stocks and flows in the Netherlands in 2010.

6 Neodymium

As one of the LREEs, neodymium tends to be more ubiquitous in the lithosphere than the HREEs at 27ppm but still less prevalent than other LREEs such as cerium (43-60ppm) and lanthanum (30ppm). (United States Environmental Protection Agency 2012; Polinares 2012). The majority of extraction and primary production of neodymium has been concentrated in China since 1994 with demand for its applications increasing since 1990. This has led to an expansion in the size of the neodymium urban mine as well as in the heterogeneity of the products containing it. Unfortunately the neodymium urban mine has not yet been exploited due to lacking infrastructure to manage and facilitate it combined with the absence of financial incentives and the pertinent recovery technologies (Reuter 2013). However this harvesting of the urban mine is now being considered a necessary strategy for reducing neodymium dependence on producing countries with positive environmental impacts associated with stymied virgin extraction.

This chapter will explore neodymium supply-demand fluctuations from 1990 until 2015. Supply will keep up with demand until 2010 when the geopolitical landscape, and especially Chinese REE policy, becomes more turbulent directly resulting in supply shortages, widespread speculation and consequent impacts on neodymium prices.

6.1 Primary production

Primary production of neodymium has generally increased during the period 1990-2015, with minor fluctuations due to economic crises or supply constrictions (Alonso et al. 2012). This general increase corresponds to the evolutionary spike in demand for neodymium applications required for a sustainable, decarbonized economy which includes the renewable energy, electric mobility and electronics sectors (Binnemans et al. 2013; iNEMI 2014).

Obtaining comprehensive historical data on neodymium primary production per annum currently does not exist in the literature notwithstanding first estimates by Du and Graedel 2011a. Using a bottom-up approach, they extrapolated individual REE production per annum from 1995-2007 based on the REE distribution of the 8 REE producing mines at the time, of which seven were in China and one in the US (Du and Graedel 2011a). Results were generated using the following methodology:

i. Determination of the TREE production per mine per year
ii. Based on deposit type and available literature, determine the neodymium REE distribution per mine
iii. Multiplication of (i) by (ii) to determine neodymium production per mine per year
iv. Addition of all neodymium production values per mine for total neodymium production per year
v. Generation of an annual neodymium production ratio per year

Losses to mining tailings and slags are included in final disaggregated production figures at 25% and 5%, accordingly. Sources for distribution figures come from the Chinese Society of Rare Earths (2008), the USGS (2008), Proceedings from the 15^{th} Rare Earths Resources Conference (1981), Proceedings of the Impact of Neodymium-Iron-Boron Materials on Permanent Magnets (1986) and Nakamura, S (1988).

Because this research aims to quantify neodymium supply from 1990-2015 and Du and Graedel 2011a only provide neodymium production data for 1995-2007, production data gaps exist for 1990-1994 and 2008-2015. TREE production data was consequently ascertained from the archives of the British

Geological Survey (BGS) for 1990-1994 and 2008-2012; TREE production statistics for 2013-2015 were obtained from Dudley Kingsnorth of Curtin University and Roskill Consulting, respectively.

What emerges from comparing the TREE datasets from Du and Graedel 2011a and the BGS is a consistency in the magnitude of apparent under-calculation by Du and Graedel 2011a as illustrated in Table 10. TREE estimates from Du and Graedel 2011a were between 75-84% of BGS figures for 11 out of 13 years with outliers of 72% and 90%, respectively. Consultation with the BGS was undertaken with a confirmation that in collaboration with the USGS, consulting groups and routine comparisons with the grey literature, BGS TREE production figures are the most robust available.

Year	**Du & Graedel TREE [Gg]**	**BGS TREE [Gg]**	**Du & Graedel : BGS Ratio**
1995	64,0	77,4	83%
1996	69,0	84,7	81%
1997	68,2	76,0	90%
1998	64,3	82,6	78%
1999	65,4	87,6	75%
2000	67,9	80,3	84%
2001	72,8	88,6	82%
2002	75,6	96,3	78%
2003	78,3	95,7	82%
2004	83,9	103,1	81%
2005	100,7	122,0	83%
2006	111,1	137,2	81%
2007	89,8	124,7	72%

Table 10: Total rare earth element (TREE) primary production worldwide for 1995-2007 from Du & Graedel (2011) and the British Geological Survey (BGS); the fourth column highlights an under-calculation by Du & Graedel

Unfortunately the BGS does not disaggregate the TREE datasets into individual REE production figures; Du and Graedel 2011a did provide these estimations and therefore, the individual neodymium production percentages per annum. This research will reconcile and combine the two datasets by (i) applying the neodymium annual production percentage (of TREE) from Du and Graedel 2011a to (ii) the TREE production figures from the BGS. The result is an adjusted neodymium primary production amount per year in Figure 9, thereby providing the supply dimension of the production-consumption dynamics. Complete description and datasets can be found in Annex A3 to this research.

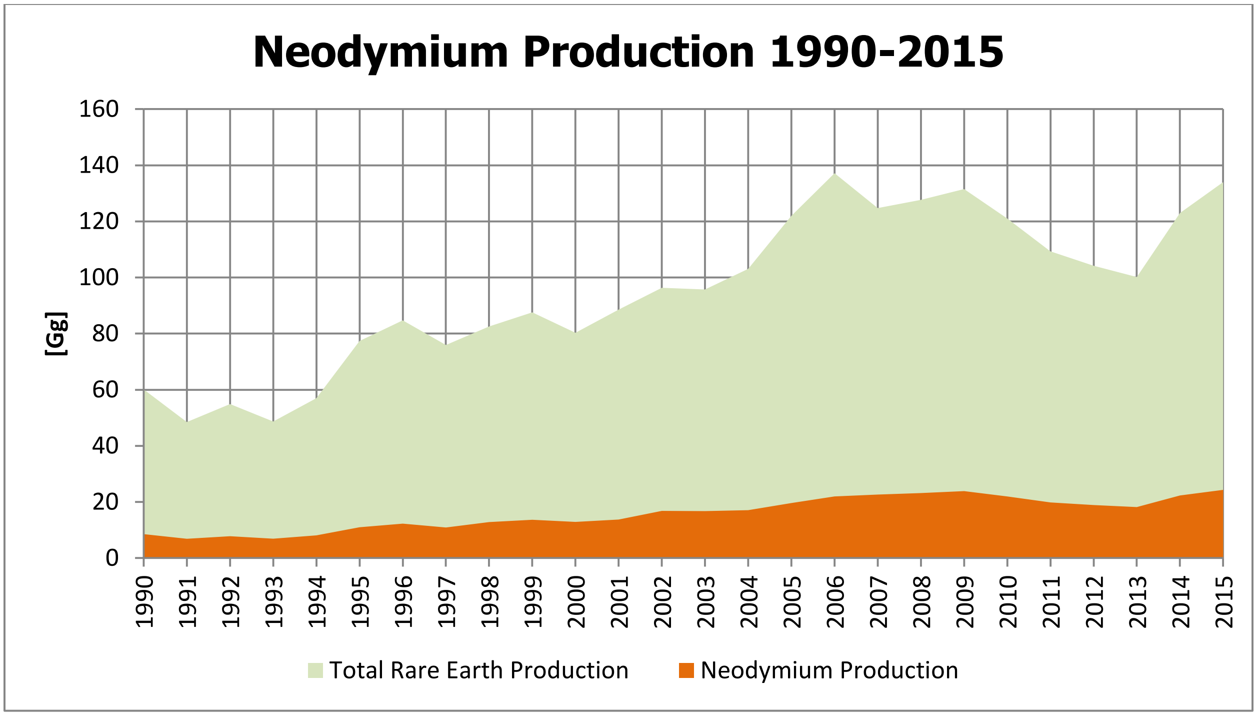


Figure 9: Neodymium production [Gg] per year based on the neodymium percentage of TREE production from Du & Graedel 2011a with subsequent neodymium percentage applied to TREE production statistics from the British Geological Survey (BGS) from 1990-2013 and Roskill and Kingsnorth, 2014-2015

Because the years 1990-1994 and 2008-2015 were missing from the Du & Graedel (2011) dataset, this research applied the 1995 neodymium percentage to the BGS TREE figures from 1990-1994; similarly the 2007 neodymium percentage was used for BGS TREE figures from 2008-2015. There is a degree of uncertainty in this approach as most likely, neodymium production as a percentage of overall REE production will have increased further after 2007, especially with the increase in demand for permanent magnets, predicted to have a higher growth rate than all other REE applications from 2010-2015 according to Rademaker, Kleijn, and Yang 2013 and D. J. Kingsnorth 2012.

Accompanying this increase in neodymium production has been the decrease in diversification of producing countries. China has maintained an upstream monopoly on neodymium extraction, refining and manufacturing into (semi-)finished products due to cheaper labour costs, limited environmental legislation and the technological and metallurgical know-high required for refining (Smith Stegen 2015). This tight grip was loosened slightly in the past five years with the re-opening of the Molycorp mine in the US and Lynas mine in Australia, demonstrated in Figure 5 (note that Australia figures are not high enough to appear above the US or ROW). However both mines have underperformed from their foreseen 20 Gg per year and recently, struggled to maintain positive balance sheets due to decreasing prices and turbulent markets with Molycorp filing for bankruptcy and halting all operations in 2015 (Forbes 2015). This demonstrates the challenge to diversify upstream production processes in developed countries while remaining competitive in a fickle marketplace; it is likely that China will maintain and even increase its supply stronghold. Data and sources to Figure 10 can be found in Annex A4.

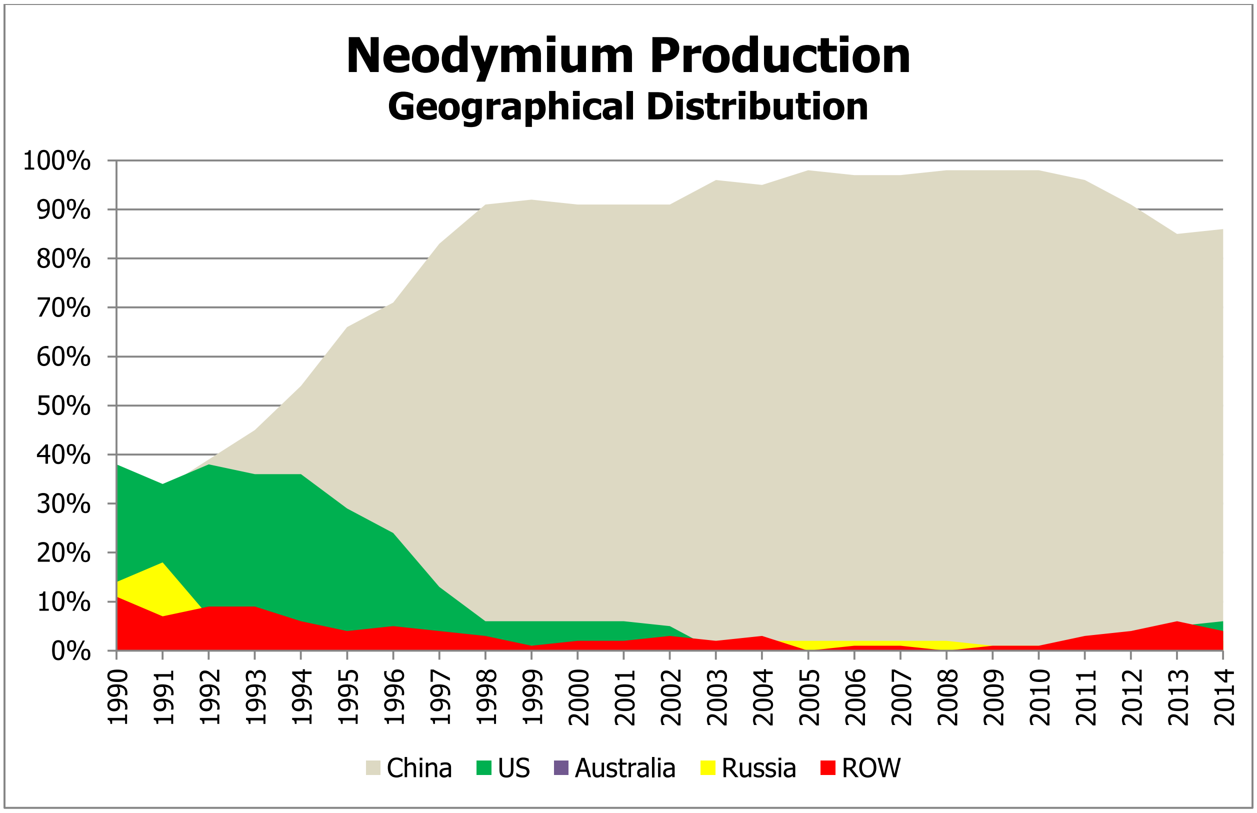


Figure 10: Geographical distribution of neodymium primary production, 1990-2014, based on data from the BGS archives, Habib et al (2014) and the USGS REE mineral summary (2015)

Other rare earth exploration activities are currently still nascent and in exploratory phases. For example it is unlikely that the planned REE mining projects in Greenland will be further developed in the short-term due to lower global REE prices (Brookings Institute 2015); the future for other mining and processing projects is unclear even though the EURARE project has identified significant deposits in Sweden, Spain, Greece and Turkey (Turner 2015).

Forecasting future virgin supply is a challenging feat due to the discrete and interconnected forces that influence supply. However an emergent property of reduced neodymium supply observed in the past five years has been the potential elasticity of primary production activities as the market responded to dwindling production through expanding mining activities in the US, Australia and elsewhere (Sprecher et al. 2015). Moreover recycling and recovery of neodymium from post-consumer scrap can certainly impact the primary neodymium supply. For example in the US recycled paper provides the supply of approximately 40% of the materials needed for production of new paper without which, would come from trees (The National Recycling Coalition 2005). Legislation regulating the production of resources can also stimulate or reduce supply. The REE export quotas enforced in 2010 by the Chinese reduced production and export to the developed world resulting in a cascade of responses, including research on recycling and substitution, accordingly (Smith Stegen 2015; L. Zhang et al. 2015). The complex neodymium supply landscape is a function of many interconnected forces that can influence its expansion or restriction.

6.2 Secondary supply

Secondary deposits vis-à-vis the urban mine are also rich sources of materials. It is estimated that 30% of the silver urban mine is in electronics and as will be explained in the next chapter, 76% of global neodymium consumption entered the urban mine via permanent magnets (Forbes 2014). However in order to carry out 'urban mining' one has to know where to find the secondary deposits; consequently products containing these materials have to be identified followed by modeling of the product life cycle. If it emerges from this mapping that neodymium-containing products enter a landfill or incinerator, formal collection channels and necessary waste management systems have to be constructed to ensure these products enter the recycling chain.

Even if products containing neodymium, such as computers and end-of-life vehicles (ELVs), already enter a formal collection stream, neodymium is hitherto not recovered (Reuter 2013). Instead neodymium enters the recycling chain and usually becomes oxidized ending up in smelter slag (Buchert 2012). In the developed world this is due to a combination of low collection rates, absence of economies of scale and lack of recycling technologies.

Using the case of HDDs in PCs, recyclers only have the technologies to currently recover precious metals such as the platinum groups metals (PGMs), gold and silver (Chancerel and Finkbeiner 2010). To be able to recover secondary neodymium, recycler flow sheets would have to be adjusted to liberate the NdFeB permanent magnets and the technologies further developed to an industrial scale for recovery to have an impact (Binnemans et al. 2013). However with the threat of neodymium supply security and increasing demand for neodymium-containing products, research and pilot projects have been established to investigate and test neodymium recovery technologies; some small-scale projects have recovered high-purity, secondary neodymium through hydro- and pyrometallurgical techniques (Okabe et al. 2003; Binnemans et al. 2013).

In one particular study Sprecher, Kleijn, and Kramer 2014 assessed the theoretical potential of the NdFeB permanent magnet urban mine in HDDs considering market trends in neodymium concentrations in two sizes of HDDs. Using HDD stocks and EOL data from the Dutch WEEE compliance schemes in combination with hydrometallurgical decrepitation recovery rates from Binnemans et al. 2013, they concluded 28% of 2010 NdFeB permanent magnet demand in HDDs could have been met by recycled HDDs; this potential increases to 57% in 2017, substantiating the potential of secondary neodymium in HDDs. The results from this MFA demonstrates a much bleaker neodymium-HDD potential which will be described in the MFA carried out in this research in Chapter 8.

While recycling technologies and recovery rates are crucial to determining the role of neodymium recycling in reducing demand for virgin neodymium, this research will only address the amount of neodymium entering the waste stream, i.e. the theoretical potential of secondary neodymium. This research will subsequently highlight how the theoretical potential of secondary neodymium deviates across different product groups due to product lifespans and differing demand growth. Ultimately this will enable one to gauge the extent to which secondary supply could curb primary demand; but the recovery technologies and recovery rates are not within the scope of this work.

Production conclusions

Although there is sufficient literature available on the aggregated primary production of REEs per year, there is a lack of reliable data for individual REEs bar estimates from Du and Graedel 2011a. Due to an apparent under-calculation from Du and Graedel 2011a, this research applied the neodymium percentage of total REE (TREE) production from Du and Graedel 2011a to the TREE figures from the British Geological Survey generating annual neodymium primary production figures. Moreover the monopolized upstream production by China was illustrated in the geographical distribution over time, validating neodymium criticality should Chinese supply be restricted. However the neodymium urban mine could reduce such supply vulnerabilities if a system is financed and the necessary recovery technologies up-scaled to an industrial level.

The next chapter will explore how neodymium demand has evolved in relation to supply. The applications absorbing neodymium will be described followed by an assessment of the supply-demand dynamics which emerged from the geopolitical landscape.

6.3 Global demand for neodymium applications

Demand for neodymium-containing products over time reflects the corresponding production trajectory – a general increase. This yearning for neodymium is primarily due to the increase for one neodymium application, the neodymium-iron-boron (NdFeB) permanent magnet because of its contribution to a decarbonizing global economy and importance to the modern electronics sector (Gutfleisch et al. 2011). For example electric mobility has relied heavily on the NdFeB permanent magnet motor as well as the mischmetal-containing nickel-metal-hydride (NiMH) battery (Du et al. 2015). Simultaneously its market share in direct-drive permanent magnet (DDPM) wind turbines has been increasing over the years due to low maintenance requirements and improved efficiencies compared to the conventional asynchronous motor-driven turbines (Hoenderdaal et al. 2013; Y. Zhang 2013). These product trends have cumulatively resulted in an increase in demand for neodymium; all applications incorporating neodymium are described below.

Permanent Magnets

Contemporary sintered NdFeB permanent magnets were invented in 1983 and ultimately replaced the former SmCo permanent magnets due to their magnetic strength and higher torque – 2,5 times stronger than SmCo magnets (Kazawa 2011; Schüler et al. 2011). Historically permanent magnets were used for rotating large motors but have become increasingly relevant for small motors in daily applications, such as HDDs in laptops and PCs or the motor required for rolling up automatic windows in an automobile (Kazawa 2011; iNEMI 2014). Chief industrial sectors using permanent magnet applications in their products are the electronics, automobile and medical sectors.

Metallurgical Alloys

Mischmetal is a neodymium-containing alloy consisting of lanthanum, cerium, neodymium and praseodymium. Neodymium comprises approximately 16% of the REE portion of mischmetal (US Department of Energy 2011).

Mischmetal is most often added directly to iron and steel to remove sulfur and in the case of neodymium, to remove gases from steel alloys. Sectors responsible for the largest share of metallurgical alloys are the construction and automotive sectors (American Chemistry Council 2014).

Batteries

Nickel cadmium (NiCd) batteries were replaced by NiMH batteries to a large extent, which also uses the aforementioned REE alloy, mischmetal. Mischmetal reduced the weight of the NiCd batteries while simultaneously increasing battery performance, extending battery life and phasing out the hazardous metal, cadmium (American Chemistry Council 2014). NiMH batteries range from small batteries for household appliances to larger battery cells for PHEVs (Hatch 2011; Buchert 2012). The automotive sector is one of the largest sectors comprising 50% of global NiMH battery demand due to increase in sales of PHEVs (Constantinides 2013).

Ceramics and Glass

The two neodymium applications that can be used in ceramic and glass products are colouring agents (ceramics and glass) and metallurgical alloys (ceramics).

Neodymium colouring agents in glass are responsible for giving glass a red hue but can also be used as UV-light reflecting additives to sunglasses; neodymium as a colouring agent can also be added to ceramic products (Walters and Lusty 2011). When neodymium-containing mischmetal is added to ceramic capacitors, e.g. in electronics, it strengthens and stabilizes the capacitors increasing their lifespans and reducing maintenance (Walters and Lusty 2011).

Catalysts

While catalysts can take on the function of automotive catalysts and fluid cracking catalysts (FCC) for petroleum refining, neodymium is only marginally used in automotive catalysts and not at all in FCCs (Goonan 2011). In automobiles catalysts are used to reduce harmful emissions from exhaust in a conventional automobile (Gschneidner 2015).

The existing demand data landscape is very inconsistent. Ascertaining comprehensive demand data for all neodymium applications from 1990-2015 was not possible; prior to 2005 no data is available in the literature. Even after 2005 quantifiable data was provided only for one year per source and was most often published as total aggregated neodymium demand or demand for one particular neodymium-containing product. Disaggregated neodymium demand across all applications was nonetheless found for one year, 2008, by Goonan 2011 for the USGS. Goonan 2011 concluded that global neodymium demand represented 18% of TREE demand. In the same assessment permanent magnets comprised 76% of this 2008 neodymium demand. The 2008 global neodymium demand distribution is visualized in the waffle chart in Figure 11. Complete data can be found in Annex A5 to this research.

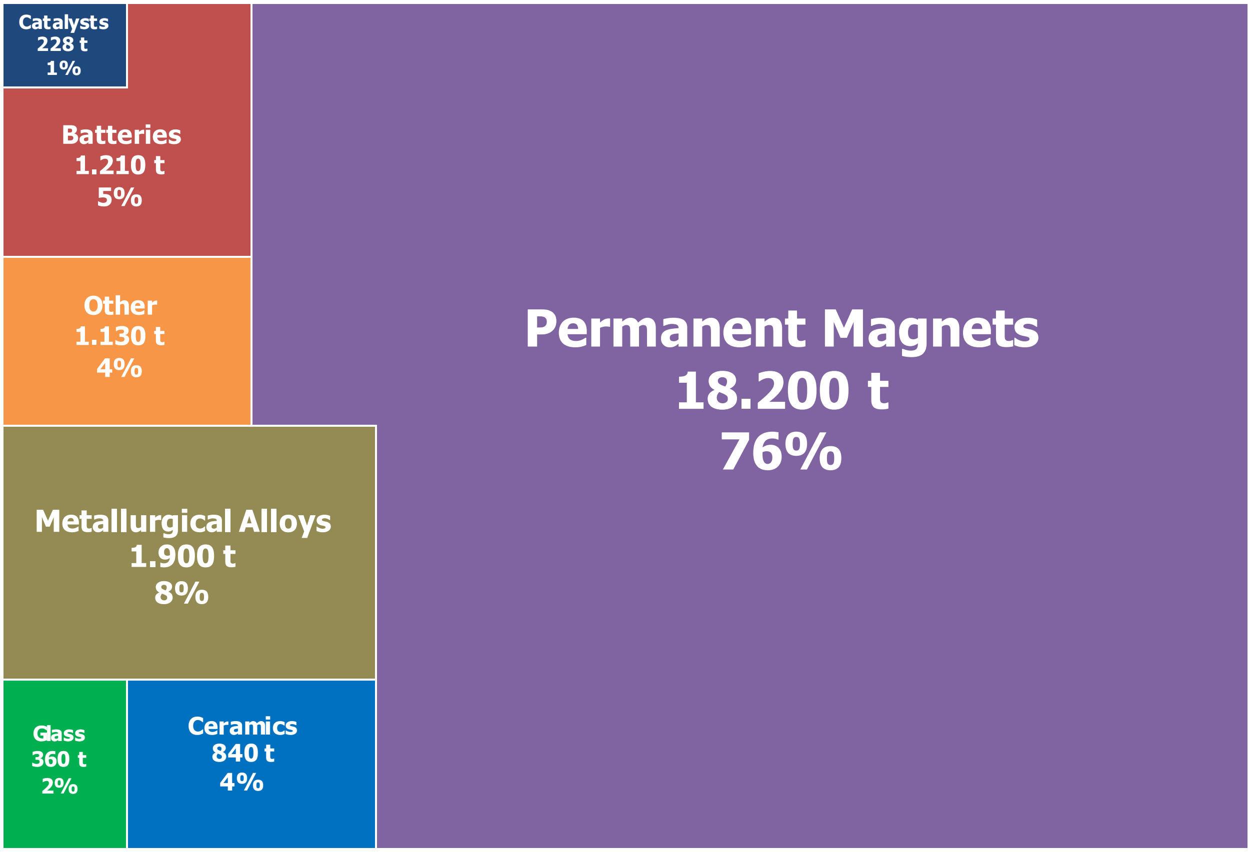


Figure 11: Waffle chart exhibiting the 2008 neodymium demand distribution across REE applications based on data from Goonan (2011)

Dudley Kingsnorth, a professor at Curtin University in Australia, is one of the leading REE experts worldwide, disseminating summaries of the REE global landscape annually. One of the pillars of the REE summaries is the annual TREE demand, although figures are always aggregated. This research will therefore extrapolate 2009-2015 neodymium demand building on the complete 2008 neodymium demand dataset from Goonan 2011.

1. Annual neodymium demand: In order to determine this figure, the neodymium demand per TREE demand calculated by Goonan 2011 at 18% will be applied to aggregated TREE demand datasets from D. J. Kingsnorth 2012 and D. Kingsnorth 2013.
2. Neodymium demand distribution: in order to generate the neodymium demand distribution for each application, the 2008 neodymium demand distributions per neodymium application from Goonan 2011 will be applied to the annual neodymium demand calculated in the previous step.

The four applications absorbing the majority of neodymium are permanent magnets, metallurgical alloys, batteries and ceramics, illustrated in Figure 12. The entire dataset can be found in Annex A5 to this research.

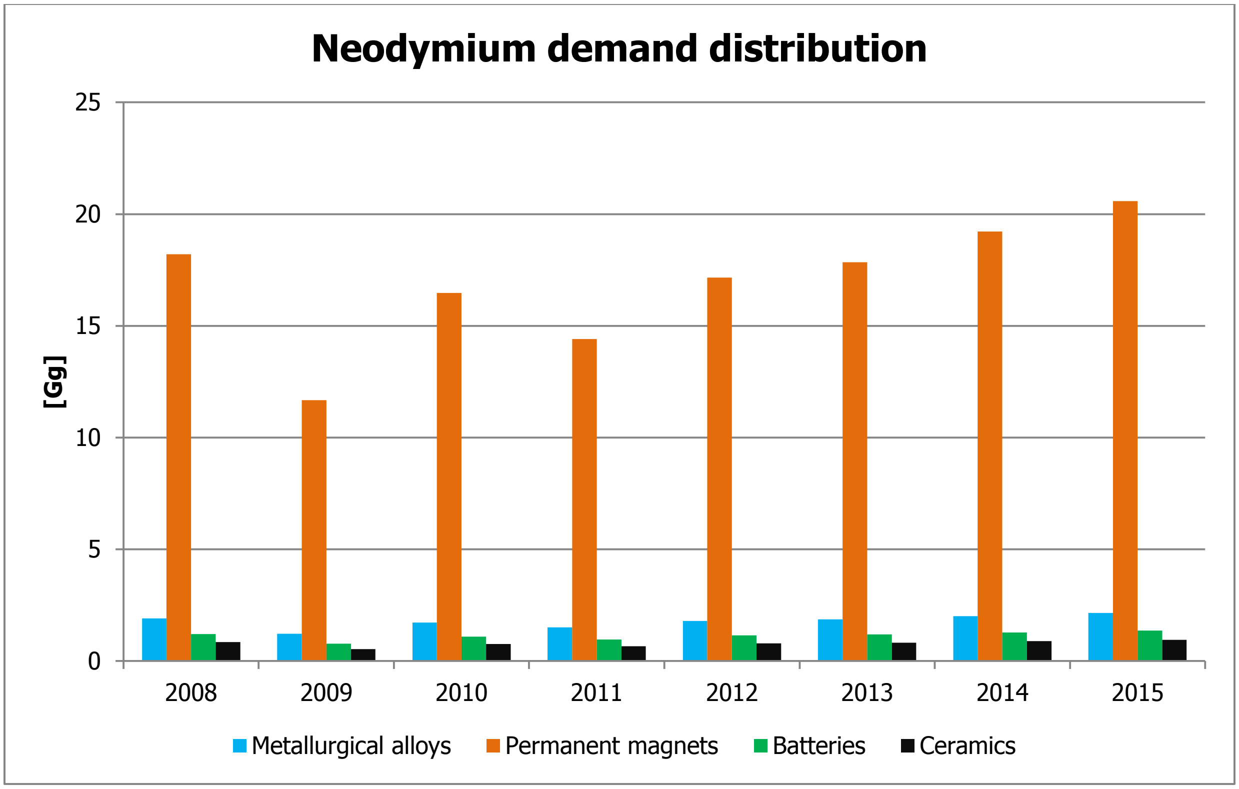


Figure 12: Neodymium demand distribution with the four largest neodymium applications, dominated by permanent magnets, Kingsnorth (2012; 2013) data for 2009-2015 adjusted with Goonan (2011) figures from 2008

Because of the uncertainty in the methodological approach, the disaggregated neodymium demand per application in Figure 12 is only an estimate. It is unlikely that the increases or decreases in demand would have been uniform across all REE applications, especially for permanent magnets, which were expected to increase by 10-15% from 2010-2015 but ceramics only by 6-8% for the same period (Rademaker, Kleijn, and Yang 2013; D. J. Kingsnorth 2012). Historically the USGS mineral yearbooks provide qualitative descriptions of demand perturbation across most REE applications; these summaries are only representative of the US economy. This research will nevertheless assume that neodymium demand will increase proportionately with aggregated TREE demand from 2009-2015.

It is clear from Figure 12 and consistent with the literature that permanent magnets absorb the most neodymium across the neodymium applications spectrum. This is predominately due to the high concentration of neodymium in NdFeB permanent magnets, broad use in a heterogeneous mix of products and low substitutability (Rademaker, Kleijn, and Yang 2013). Metallurgical alloys which also include the mischmetal alloy comprising lanthanum, cerium, neodymium and praseodymium used in flint and torch devices follows second followed by the NiMH battery industry and trace or even insignificant amounts in glass, catalysts and other.

Demand conclusions

Using the limited demand data available in the literature, the neodymium demand dataset built on the research from Goonan 2011 for the USGS. That report quantified global individual REE demand per application for 2008 from which the neodymium percentage of TREE demand was applied to TREE demand from Kingsnorth for 2009-2015. This research now has the necessary data required for exploring the neodymium supply-demand fluctuations over time and will synthesise the geological and geopolitical forces leading to the supply crisis beginning in 2009.

6.4 Fluctuations in supply-demand

Modern smartphones contain NdFeB permanent magnets in their loudspeakers (Buchert 2012); smartphone sales have increase from 122 million in 2007 to 1.2 billion in 2014 (Statista 2015c). Laptops and PCs have them in their HDDs, loudspeaker magnets as well as optical drives (Habib et al. 2014; Buchert 2012); the laptop-PC-tablet market increased from 377 million units in 2010 to 655 million units shipped in 2015 (Statista 2015a). Every day household appliances such as vacuum cleaners and white goods incorporating NdFeB permanent magnets are increasing their market share, according to consultations with permanent magnet manufacturers and original equipment manufacturers (OEMs). And PHEVs use large amounts of neodymium in their permanent magnet motors and NiMH batteries (Hoenderdaal et al. 2013); in 2012 global full-EV stock was at 180.000 with a target of 20 million in 2020 (Iea 2013) Supply of these products is only possible insofar a fluid supply stream of the materials required for their production remains accessible.

While the neodymium price increases in 2010-2011 are well-documented in the literature, the fundamental supply-demand curves of neodymium are nowhere to be found. Using the disaggregated neodymium primary production data from Du and Graedel 2011a and the BGS from Chapter 4.1 and the disaggregated neodymium demand figures from Goonan 2011 and D. Kingsnorth 2013 in Chapter 4.3, supply-demand over time is generated and visualized in Figure 13.

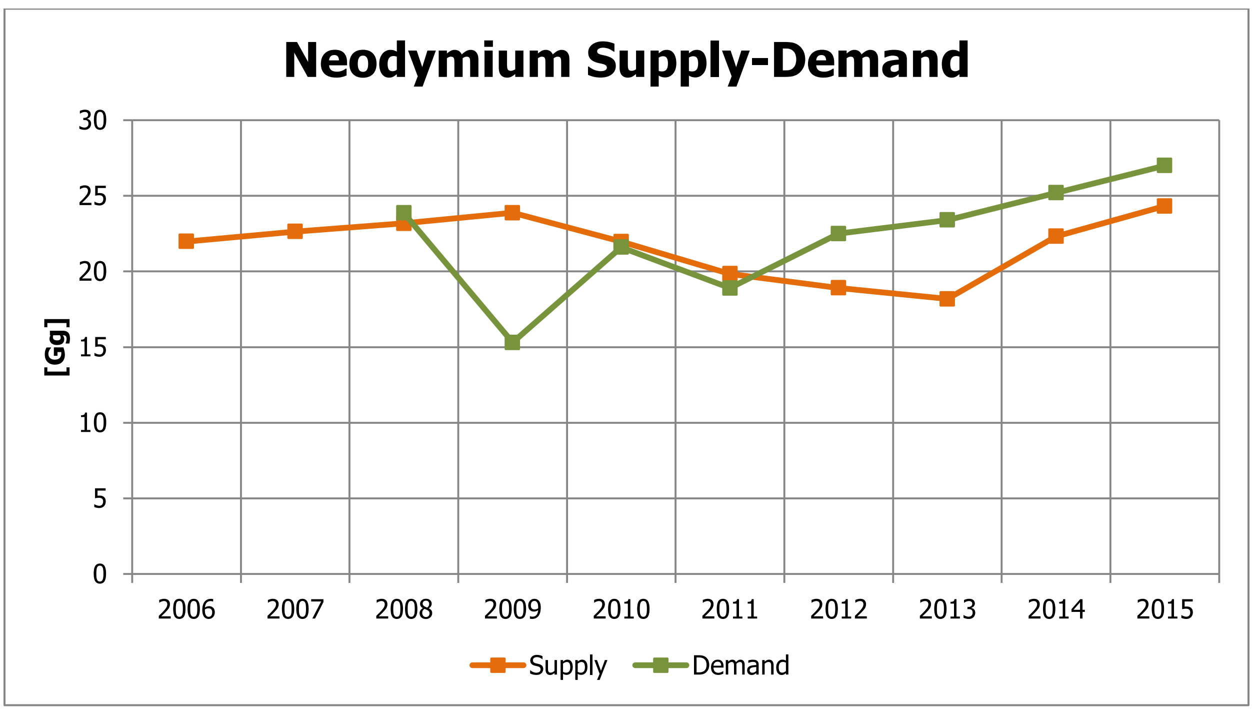


Figure 13: Primary production of neodymium 2006-2015, BGS adjusted figures based on disaggregated REE production dataset from Du & Graedel (2011); neodymium demand generated by applying Goonan (2011) neodymium demand percentage of TREE demand for 2008 to Kingsnorth (2013) demand figures for 2009-2015

The supply-demand graph in Figure 13 became an emergent property of the neodymium geopolitics and economic climate that unfolded over the years. When analysing the supply-demand curve, it is crucial to remember conventional microeconomic theory which states that the price of a material or good will sway until the market reaches equilibrium, i.e. supply = demand. If the supply of a particular material or good does not meet demand, i.e. a shortage occurs, and the price for this material or good will increase (Blaumol & Blinder 2015). Alternatively an overabundance of supply usually leads to a drop in price for that particularly good.

The drop in demand in 2009 was a consequence of the global financial crisis which led to declining wages in the EU, contraction of household income and increasing unemployment in the EU – from 6,7% in 2008 to 9,0% by the end of 2009 (Europäische Kommission (Hrsg.) 2009). The implications for neodymium demand contributed to a turbulent marketplace from 2009-2011 with lower demand for neodymium-containing products in 2009 followed by a rebound in 2010, an observation consistently reported in the literature (D. J. Kingsnorth 2012).

Curiously, even as markets and demand begin to stabilize after 2011, Chinese production output of neodymium continued to decrease, ultimately leading to a short-lived shortage of neodymium and speculation thereof (Sprecher et al. 2015). This resulted in:

i. Soaring trading prices of neodymium;
ii. Initiation of neodymium exploration activities and feasibility assessments of its extraction;
iii. New product designs for phasing out neodymium or replacing it with substitutes; and
iv. A multilateral complaint to the World Trade Organization (WTO) by the US, EU and Japan (Sprecher et al. 2015; Habib and Wenzel 2014).

Emerging from the rare earth crisis, the resilience of the neodymium market was observed after the price increases in 2010 through a resistance-rapidity-flexibility framework developed by Sprecher et al. 2015. Sprecher et al. 2015 observed that capacity was directed to diversify upstream sources as well as efforts to investigate material and technological substitution, although full substitution is currently not possible without substantial performance loss. Downstream resilience activities, nonetheless, were negligible due to the absence of economies of scale in neodymium recycling with worldwide neodymium recycling rates less than 1% (Ueberschaar and Rotter 2014; Reuter 2013).

The next sub-section will explore Chinese raw material strategy as well as the political landscape leading to the supply restrictions implemented by the Chinese.

REE political landscape, 1985-present

From 1985-2003 China had established a resource policy that would stimulate consumption and export of its REEs, including attractive tax rebates for importing countries. This was enabled by cheap Chinese mining labour and a lack of environmental regulation. Consequently the only other REE-producing mine at this time in Mountain Pass, California, USA, suspended operations in in 2003; China subsequently secured its powerful position as the largest REE supplier (>95%) worldwide (L. Zhang et al. 2015).

Unnoticed by the global community, China embarked on a new resource strategy era starting in 2005, reversing many policies implemented since the 1980s (L. Zhang et al. 2015). Humphries 2013 indicated that around the same time, 2005, a cascading of events in China led to a new approach to REE policy and ultimate REE export restrictions as such. On the one hand, Chinese domestic consumption for REEs began to increase in parallel with decreasing ore grades, signaling to the Chinese government that domestic shortages could become a reality. Simultaneously as Chinese welfare increased, Chinese labour costs began to rise as well as introduction of domestic environmental regulation, pushing up the costs of production (Humphries 2013).

The Chinese government responded with an REE policy that led to the abolishment of hitherto REE tax rebates on imports, export tariffs were imposed on REE goods and the Chinese government expedited the vertical integration of the hitherto decentralized REE industry (e.g. the consolidation of expertise and processes across the supply chain). The Chinese reaction with the furthest-reaching ripple effects was the introduction of the REE production and export quotas which were drastically increased starting in 2010 (Y. Zhang 2013).

Chinese exported 60 Gg of REEs in 2007; this was decreased to 50 Gg by 2009 and 30 Gg in 2010 and 2011 (Humphries 2013). This led to a rocky REE market with speculation over material shortages. As a result, the price of neodymium increased by 1400% in 2011 leading many OEMs and manufacturers to cancel permanent magnet contracts with downstream suppliers, according to an interview with REE researcher, Komal Habib. Consequently the US, EU and Japan submitted a formal complaint to the WTO in 2012 citing that domestic Chinese producers and consumers were lowering the regulatory playing field that would benefit Chinese firms and consumers (ibid). The WTO upheld the complaint in 2014 expressing that China broke international trade law and China lifted all export quotas in 2015 (The Guardian 2015). Figure 14 combines (i) the evolution in neodymium supply-demand from previous chapters, (ii) neodymium trading prices from www.hastingsraremetals.com and (iii) the chief REE geopolitical events over time. Complete dataset and sources can be found in Annex A6 to this research.

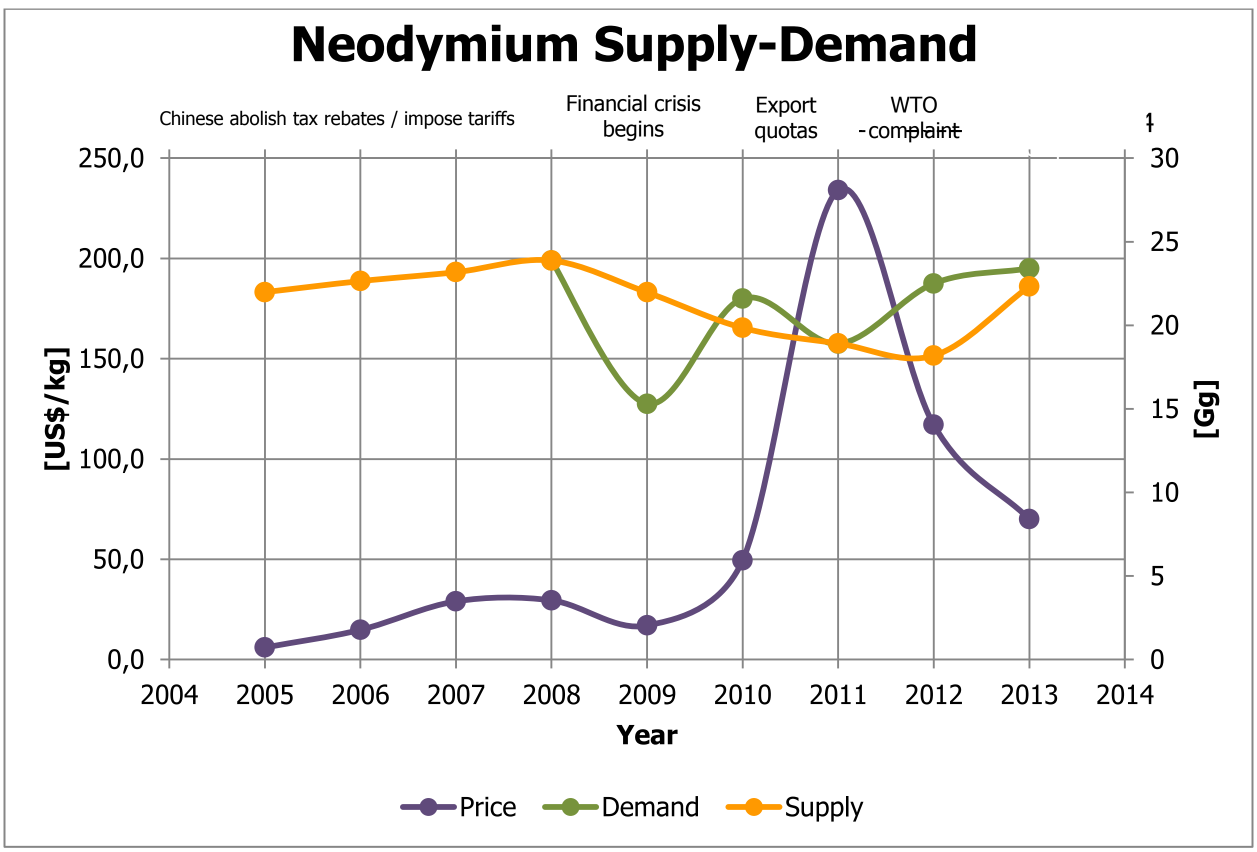


Figure 14: Supply-demand dynamics juxtaposed against neodymium trading prices and geopolitical forces

Attempting to loosen Chinese grip on REE supply, the Molycorp mine at Mountain Pass, US re-opened following the implementation of export quotas from China; Lynas started extracting REEs at the Mt Weld, Australia mine. Both had expected to produce 20 Gg per year but due to the fall in prices, the Molycorp mine suspended all REE operations in 2015 and Lynas is failing to remain profitable (Home 2015; Smith Stegen 2015).

Supply-demand conclusions

The 2015 global REE supply panorama is beginning to look strikingly similar to the late 1990s / early 2000s when lack of profitability from non-Chinese production pushed Molycorp to suspend its REE operations in 2003 (Schüler et al. 2011). China went from supplying 27% of global REEs in 1990 to 96% by 2003 according to the production datasets generated in this research; it went from a marginal stakeholder to the only stakeholder.

Subsequently when the stream of REEs merely trickled in 2010-2011, OEMs and nations alike panicked. However, this time the demand landscape is very different. The economic significance of and appetite for REEs, especially neodymium, is not comparable to 1985, 1990 or 2003 as neodymium is vital in the shift to decarbonisation strategies and clean energy (US Department of Energy 2011; Habib and Wenzel 2014). The remainder of this research will map and quantify the role of one criticality reduction mechanism in the Netherlands, recycling, in order to exploit the neodymium urban mine using a domestic, readily available supply source.

Similar to cobalt substitution with other alloys and secondary recovery upgraded to current cobalt recycling rates of 25-50%, the resilience of the neodymium market was observed after the price increases in 2010 through a resistance-rapidity-flexibility framework developed by Sprecher et al. 2015. Sprecher et al. 2015 observed that capacity was directed to diversify upstream sources as well as efforts to investigate material and technological substitution, although full substitution is currently not possible without substantial performance loss. Downstream resilience activities, nonetheless, were negligible due to the absence of economies of scale in neodymium recycling with worldwide neodymium recycling rates less than 1% (Ueberschaar and Rotter 2014; Reuter 2013).

7 Neodymium portfolios

Thus far this research has illustrated the overwhelming consensus on the criticality of neodymium due to its relevance to the global (decarbonizing) economy and its potential supply risk due to increasing demand for neodymium applications combined with the Chinese monopoly on supply. Chapter 6.3 highlighted each neodymium application and provided examples of their use. The Neodymium Portfolios described in this chapter will build on the fundamental understanding of neodymium properties and will identify and be divided into the following Portfolios

i. **Neodymium Sector-Product Portfolio**: In this Portfolio all products containing neodymium applications and intermediate products will be identified and assigned to a particular sector
ii. **Neodymium Compositions Portfolio**: An extension of the Neodymium Sector-Product Portfolio, the Neodymium Compositions Portfolio will inventory the neodymium compositions per product

The information and data in both Portfolios currently does not exist in the literature in such a comprehensive form. Most of the literature related to neodymium covers select applications, most often NdFeB permanent magnets and batteries, as well as select products, most often HDDs in laptops and PCs as well as PHEVs and recently, DDPM wind turbines. This can be demonstrated by the research from Schüler et al. 2011, Du and Graedel 2013, D. J. Kingsnorth 2012, Smith Stegen 2015, Hoenderdaal et al. 2013, et al.

Another emergent property of this synthesis was the inconsistency and lack of harmonization in neodymium nomenclature and terminology. For example neodymium *applications* and the *products* into which they are incorporated are often used interchangeably. For example Habib and Wenzel 2014 refer to permanent magnets as *applications* while Schüler et al. 2011 and Hoenderdaal et al. 2013 refer to both permanent magnets and laptops as *applications*. Rademaker, Kleijn, and Yang 2013 denote that laptops and PCs are both *products* and *applications*. This research intends to harmonize these terminologies and datasets behind them using the Neodymium Sector-Product Portfolio as a structured vehicle demonstrating the differences and clarifying any confusion and inconsistencies.

In order to develop the Neodymium Sector-Product Portfolio, this research collated and reconciled the patchwork of neodymium-containing products in the grey literature and undertook expert consultations with stakeholders in academia and industry. The result was a comprehensive depiction of the entire neodymium landscape without the defined system boundary. The bulk of the grey literature sources are found in the literature review in Chapter 3 and the consultations are described in Annex A7.

The Neodymium Sector-Product Portfolio was easily extended to integrate neodymium compositions per product, which are needed to model the mass flow. Incorporating the compositions data into the Neodymium Sector-Product Portfolio is especially useful since there is a lack of consistent, up-to-date and harmonized data on neodymium compositions across all products and sectors. Indicating neodymium compositions also informed the definition of the MFA system boundary illustrating where composition gaps exist in the literature.

7.1 Sector-Product Portfolio

The Neodymium Sector-Product Portfolio will provide a comprehensive and condensed overview of products and sectors absorbing neodymium applications. It could also be perceived as a 'living list' and updated as products enter and drop off the list, accordingly. Additionally where data was available, the component containing the neodymium application is also indicated, although this is not known in all cases. The template in Table 8 from Chapter 4.1.2 is completed in Table 11 below.

Sector	Product	Component
PERMANENT MAGNETS		
Electronics	Laptops	Voice coil accelerator (HDD)
		Spindle motor (HDD)
		Spindle motor (optical)
		Magnetic cooling device
	Desktop PC	Voice coil accelerator (HDD)
		Spindle motor (HDD)
		Spindle motor (optical)
		Magnetic cooling device
	Smartphones	Loudspeaker
		Switches
		Microphone
	Tablet	
	mp3 players	
	Microphones	
	Headphones	
	Loudspeakers	
	DVD players	
	Refrigerators	Compressor
	Freezers	Compressor
	Microwaves	
	Air conditioners	Motor
	Washing machines	Motor
	Dryers	Motor
	Vacuums	Motor
	Electric toothbrushes	Motor
	Shavers	Motor
	Power tools	Motor
Automotive	Plug-in hybrid electric vehicle (PHEV)	EEE
		Motor
	Electric vehicle (EV)	EEE
		Motor
	Passenger vehicle (ICE)	EEE
Renewable energy	Wind turbine	DDPM motor (gearless)
Medical	MRI	
Other	Electric bicycles (EBs)	Motor
	Circulator pumps	
	Industrial applications	
CATALYSTS		
Automotive	Catalytic converter (ICE)	
BATTERIES		
Automotive	NiMH batteries for PHEV & EVs	
CERAMICS		
Electronics	various	Capacitors
Coulouring agent	Ceramic products	

GLASS		
Coulouring agent	Glass products	
METALLURGICAL ALLOYS		
Other	Lighters and torches	Flint ignition devices
	Mischmetal	

Table 11: Neodymium Sector-Product Portfolio for all neodymium applications which also includes the component containing the neodymium application if known

From Table 11 the electronics sector appears to contain the 56% of all neodymium-containing products as the electronics sector comprises 19 of a total 34 products. Meanwhile NdFeB permanent magnets are the most dominant among the neodymium applications with 79% of all products absorbing NdFeB permanent magnets. This latter figure could reflect the neodymium demand distribution calculated by Goonan 2011 with NdFeB permanent magnets comprising 76% of all neodymium demand in 2008. But the Neodymium Sector-Product Portfolio cannot be used to gauge the amount neodymium distributed across all applications and sectors; compositions per product and corresponding sales data per product are needed to determine this.

It should nonetheless be emphasized that especially the electronics sector has benefited from NdFeB permanent magnets as they have enabled further miniaturization of products with maintained or even increased performance (Habib et al. 2014). However within the electronics sector the literature seems to direct a disproportionate amount of attention to NdFeB permanent magnet use in HDDs (laptops and PCs) and loudspeakers (audio systems and headphones), as underscored by six of the most comprehensive neodymium studies hitherto in Table 12. The results from the MFA in Chapter 8 will either verify or disprove this imbalance especially due to the increasing market share of white goods and small household appliances incorporating NdFeB permanent magnets (Habib and Wenzel 2014).

Source	HDDs	Smart-phones	Loud-speakers	White goods	Small household appliances	Tools
Habib & Wenzel (2014)	X	X	X	X	X	X
Schüler et al (2011)	X	X	X			
Büchert et al (2012)	X	X				
Du & Graedel (2011)	X		X			
Du & Graedel (2011a)	X		X		X	
Hoenderdaal et al (2013)	X		X			
Rademaker, Kleijn & Yang (2013)	X					

Table 12: Overview of electronic products and components covered in seven assessments centred on neodymium distribution / incorporation in products

Not all sectors and products in the Neodymium Sector-Product Portfolio in Table 11 are included in the scope of the MFA and scenario mapping due to lack of data on stocks and flows. This will be highlighted in following section, Chapter 7.1.1, which describes the data sources and which products are covered by these data sources.

7.1.1 Data sources

In order to model stocks and flows of neodymium in the Netherlands using the bottom-up approach applied in this research, stocks and flows data of neodymium-containing products must also be available.

Such data was ascertained for most products containing a permanent magnet and most batteries but was lacking for metallurgical alloys, catalysts, colouring agents and ceramics. The next sections describe the sectors for which data was available with a description of the source.

Electronics

Data on waste electrical and electronic equipment (WEEE) stocks and flows were provided by the research and academic arm of the United Nations, United Nations University (UNU), from their WEEE quantitative assessment – *Future Flows Report*. The UNU study was carried out in the Netherlands for 2010, updated to reflect 2012 data and complemented by a UNU assessment on WEEE statistics and lifespan methodology by Balde et al (2015). The chief aims of the *Future Flows Report* were to (Huisman et al. 2012):

i. Provide a robust and granular quantitative assessment of WEEE generated in the Netherlands in 2010 in order to inform collection target setting at the political level, e.g. in the EU Recast WEEE Directive 2012/19/EU;
ii. Demonstrate and characterize WEEE flows to highlight the performance of the WEEE compliance schemes but also where they can improve by signaling leakages and uncertainty of end-destinations.

Consequently Huisman et al. 2012 quantified EEE put-on-market (POM) in cooperation with CBS, residence times of products from GfK and subsequently, the Dutch EEE stock, hibernating EEE that has not yet been discarded and WEEE generated that enters the waste stream. The WEEE stream was further characterized to illustrate formal collection and complementary recycling, export, WEEE entering the municipal waste stream and WEEE not documented (Huisman et al. 2012).

Automobiles

Automobile stocks and flows data were provided by one centralized database from BOVAG and the Rijwiel en Automobiel Industrie (RAI) Vereniging and complemented by a consultation with an expert at Automobiel Recycling Nederland (ARN). RAI is an association in the Netherlands that represents 500+ manufacturers and importers of automobiles in the Netherlands (www.rai.nl) whereas BOVAG is a stakeholder platform serving the interests of >10.000 entrepreneurs specializing in the mobility sector (www.bovag.nl). ARN is the end-of-life vehicle (ELV) compliance scheme in the Netherlands founded by RAI, BOVAG and other organizations. ARN is tasked with automobile management at EOL regulated by the EU ELV Directive 2013/28/EU aiming for an 85% reuse and recycling rate and a 95% reuse and recovery rate (http://ec.europa.eu/environment/waste/elv/).

Contrasting to EEE penetration data in the form of POM, market penetration of automobiles was based on new registrations. These new registrations were disaggregated based on fuel type and therefore enabled granular modeling of all vehicle types, including delineation among PHEVs and conventional automobiles with an ICE. Such disaggregation was crucial to this assessment as NdFeB permanent magnet motors and NiMH batteries are used in PHEVs but not conventional automobiles. Unfortunately end-of-life vehicle (ELV) datasets were aggregated into one figure with waste stream characterized by collected, uncollected and exported.

Wind turbines

Data on individual wind turbines in the Netherlands were very detailed and provided by www.thewindpower.net, a global database providing figures at the country-province-municipality-level.

The Dutch datasets were disaggregated per province and municipality and denoted the number of wind turbines, year of installation, capacity (MW), wind turbine manufacturer and if known, type of gearbox.

This research manually inventoried all Dutch wind turbines and their capacity as of 2015 per province/municipality; this inventory totaled 1577 turbines and cumulative 3000MW since 1997. Unfortunately no EOL data was available which is most likely because (i) wind energy is still relatively nascent, (ii) the long residence times of wind turbines resulting in (iii) no end-of-life wind turbines in significant quantities (Larsen 2009).

Emerging from the availability of data, not all sectors, products and neodymium applications have sufficient stocks and flows datasets available for modeling in this research. Even for those products and sectors covered by stocks and flows data, statistical assumptions on, for example, the market share of a product group containing neodymium, have to be derived in Chapter 8. The Neodymium Sector-Product Portfolio will be further amended with the extension of neodymium compositions discussed in the next sub-section, Chapter 7.2.

7.2 Compositions Portfolio

Extending the Neodymium Sector-Product Portfolio to neodymium compositions per product is pre-requisite for determining the mass flow in the Netherlands. Moreover this compositions repository is especially useful as there is (i) a lack of synthesized data on neodymium compositions per product and (ii) disparities among researchers on the units used leading to difficulties in comparisons. For example Habib and Wenzel 2014 illustrate their neodymium composition as a percentage of the weight of the permanent magnet which differs per product; Buchert 2012 denote neodymium as mg per product; Rademaker, Kleijn, and Yang 2013 use a fixed neodymium percentage per permanent magnet weight for all products assessed. This research will harmonize all compositions to denote kg of neodymium per product.

7.2.1 Data sources

Electronics

One of the most neodymium data-rich sectors was the electronics sector, especially with extensive research on NdFeB permanent magnets in HDDs in laptops and PCs carried out by Ueberschaar and Rotter 2014, Habib et al. 2014 and Buchert 2012. The description of each analysis from the aforementioned researchers can be found in Annex A8 to this research.

PCs and laptops

This research will use the 2,15g neodymium per laptop from Buchert 2012 due to the comprehensive, disaggregated neodymium composition for all four NdFeB permanent magnets..

Buchert 2012 did not assess PCs. Habib et al. 2014 and Ueberschaar and Rotter 2014 did but only ascertained the size of one NdFeB permanent magnet – the voice coil accelerator in the PC HDD omitting three other permanent magnets. To determine the weight of all four NdFeB permanent magnets in the PC, the following calculation was made. Because the results from Habib et al. 2014 concluded the weight of the voice coil accelerator in the laptop HDD to be 28% of the weight of the voice coil actuator in the PC HDD, this research will assume that the other laptop NdFeB permanent magnets are also 28% of the

PC NdFeB permanent magnets. However Buchert 2012 is the only source to quantify the neodymium weight for all four magnets. Consequently this 28% was applied to all four laptop NdFeB permanent magnet figures from Buchert 2012 to obtain the weight of all four PC NdFeB permanent magnets in Table 14. Total was 7,75g neodymium per PC.

	Büchert (2012)	Überschaar & Rotter (2015)	Habib et al (2014)	This research (2015)
Laptop		*Nd [g]*		
Voice coil accelerator (HDD)	0,72	1,90	1,03	0,72
Spindle motor (HDD)	0,32			0,32
Spindle motor (optical)	0,46			0,46
Loudspeakers	0,65			0,65
TOTAL	**2,15**	**1,90**	**1,03**	**2,15**
PC [g]		*Nd [g]*		
Voice coil accelerator (HDD)		3,70	3,85	2,61
Spindle motor (HDD)				1,15
Spindle motor (optical)				1,67
Loudspeakers				2,33
TOTAL		**3,70**	**3,85**	**7,75**

Table 13: Neodymium composition in NdFeB permanent magnets in laptops and PCs

Smartphones

Analysis of neodymium composition in smartphones was assessed by both Buchert 2012 and Habib et al. 2014. Buchert 2012 determined the neodymium content in the NdFeB permanent magnet in the loudspeaker at 0,05g per smartphone. Habib et al. 2014 determined the neodymium content at 0,19g per smartphone. As a result this research will assume neodymium composition in smartphones to be the average of Habib et al. 2014 and Buchert 2012 totaling 0,12g neodymium per smartphone shown in Table 15.

	Buchert (2012)	Habib et al (2014)	This research (2015)
Smartphone		*Nd [g]*	
Loudspeakers	0,05		
Not indicated		0,19	
TOTAL	**0,05**	**0,19**	**0,12**

Table 14: Neodymium composition in NdFeB permanent magnets in smartphones

Other EEE

Compositions research on the remaining EEE dwindled substantially with Habib et al. 2014 being the sole source of compositions data. This is most likely due to the fact that NdFeB permanent magnets receive more attention in the literature than other neodymium applications. It seems the results from one study from Du and Graedel 2011a attempting to estimate in-use distributions of REEs across different products could have been perceived as conclusive by subsequent researchers, disincentivizing further compositions research on other EEE. That study concluded 34% of 2007 NdFeB permanent magnet use was in PCs which was used to validate the limited electronics scope in follow-up research, e.g. from Rademaker, Kleijn, and Yang 2013 and Ueberschaar and Rotter 2014.

This research also proposes this disproportionate attention on HDDs in PCs and laptops could be due to many historical and contemporary MFAs carried out on the economically lucrative HDDs due to their precious metal content of gold, silver and palladium (Chancerel et al. 2009). It could also be due in part to the nebulousness and relatively new market share of other EEE containing NdFeB permanent magnets, such as refrigerators or washing machines (Schüler et al. 2011). Validation of the neodymium composition results from Habib et al. 2014 on the remaining EEE in Table 15 could subsequently steer and balance neodymium focus to other neodymium hot spots in the electronics sector.

	Habib et al (2014)
Product	*Nd [g]*
Loudspeakers	0,44
DVD/CD players	0,49
Fridges	75,4
Freezers	142,1
Microwaves	31,9
Airconditioner	145,0
Washing machine	301,6
Dryer	156,6
Vacuum cleaner	26,1
Electric shavers / toothbrush	0,30

Table 15: Neodymium composition in NdFeB permanent magnets in other EEE per piece

Fortunately the electronics sector was rich in neodymium compositions data for most EEE included in the Neodymium Sector-Product Portfolio. The automotive sector is another important neodymium reservoir as most automobiles contain EEE, such as compact disk (CD) players, automatic windows and even the motor driving the windshield wipers (Yano, Muroi, and Sakai 2015). The PHEV market also absorbs neodymium with its incorporation in the motors and batteries (Kazawa 2011).

Automobiles

Electric mobility in the automotive sector has gained momentous market share in Europe in the past few years. One of the first PHEVs, the Toyota Prius, has sold over 6 million units since it was launched in 1997 while the full EV, Nissan Leaf, has sold over 100.000 units (Amsterdam Roundtable Foundation 2014). PHEVs like the Toyota Prius use neodymium-containing NiMH batteries as an alternative to toxic, lower performing lead acid batteries and a higher performance NdFeB permanent magnet motor (Constantinides 2013).

There have been various studies carried out to quantify the amount of neodymium in NiMH batteries in PHEVs. Bauer et al 2011, Habib and Wenzel 2014 and the US Department of Energy 2011 determined the neodymium composition in the mischmetal per NiMH battery unit. Results from all three sources indicate that neodymium comprises approximately 4,7% of the weight of the battery amounting to 200-300g neodymium per NiMH battery. Subsequently the average was used at 250g neodymium per NiMH battery in PHEVs.

Habib et al. 2014 and Hoenderdaal et al. 2013 addressed the neodymium availability in NdFeB permanent magnet motors in PHEVs. Hoenderdaal et al. 2013 determined 580-695g neodymium per PHEV which was based on a 30% neodymium wt%wt% in NdFeB permanent magnets. Habib et al. 2014 estimated neodymium composition per NdFeB permanent magnet motor to be 620g which was an estimate based on figures from the existing literature and consultations with a prominent NdFeB permanent magnet manufacturer in China. To reconcile these figures, the average of the Hoenderdaal et al. 2013 range was calculated; then the average of Hoenderdaal et al. 2013 and Habib et al. 2014 was calculated, totaling 630g neodymium per NdFeB permanent magnet motor in PHEVs.

Both conventional automobiles with an ICE and PHEVs contain many EEE which require NdFeB permanent magnets for the functionality. These EEE range from loudspeakers to the motor in the anti-lock brake system. Depending on the year of manufacture, most of these EEE incorporate a NdFeB permanent magnet and therefore contribute to the neodymium reservoir in the automotive sector (Du et al. 2015; Constantinides 2013).

The neodymium composition in EEE that will be used in this research will be the result from the measurements carried out by Widmer et al. 2015, an assessment which used both input- and output-driven approaches. An input-driven methodology determines total metal mass as a sum of its composition in components; total metal mass in an output-driven approach is quantified by the metal content of the shredder fractions. The methodology and description of the analysis used by Widmer et al. 2015 can be found in Annex A9.

Neodymium total in EEE in ELVs was used for the mid-range car at 2,4g neodymium per ELV. Results from the neodymium compositions in the NiMH battery, NdFeB permanent magnet motor and EEE in ELVs are synthesised below in Table 16.

	Habib & Wenzel (2014)	USDOE (2011)	Habib et al (2014)	Hoenderdaal et al (2013)	Widmer et al (2015)	This research (2015)
Product				*Nd [g]*		
NiMH Battery for PHEV	200-300	200-300				250
Permanent magnet motor for PHEV			620	640		630
EEE in PHEVs and conventional vehicles with ICE					2,4	2,4

Table 16: Neodymium composition in NiMH batteries and permanent magnet motors for PHEV; neodymium composition in EEE in both PHEVs and conventional vehicles with an ICE

The literature on the importance of neodymium to the automotive sector, especially to PHEVs, is expanding but there tends to be uncertainty on the future of NiMH batteries in PHEVs due to a lack of consensus on the future role of Li-ion batteries in PHEVs (Yano, Muroi, and Sakai 2015). Young et al. 2013, Pesaran 2011, Alonso et al. 2012 forecast that NiMH batteries will be replaced by the lighter Li-ion battery while Vikström, Davidsson, and Höök 2013 and Yano, Muroi, and Sakai 2015 find the battery market too complex to forecast this development.

Wind turbines

Global wind energy installations doubled every three years from 2000-2010 (Wind Energy Foundation 2015; Gutfleisch et al 2011). In 2010 wind energy contributed to 40% of the additional renewable energy added to the market. Increasing in popularity are the direct-drive permanent magnet (DDPM) wind turbines with a currently-estimated 20% market share due to their higher efficiencies, reduction in maintenance due to the replacement of the gearbox and subsequently, faster payback times making them especially attractive to offshore wind farms (Pusha et al. 2011; Gutfleisch et al. 2011). DDPM wind turbines also require large NdFeB permanent magnets weighing in the range of 600-700kg per MW (Habib and Wenzel 2014; Hoenderdaal et al. 2013).

Due to the importance of neodymium to wind turbines, the following studies have quantified the neodymium content per NdFeB permanent magnet in DDPM turbines.

i. Habib et al. 2014 determined neodymium content at 198kg per NdFeB permanent magnet for a 1MW wind turbine based on existing data in the literature and consultations from industry stakeholders.
ii. Hoenderdaal et al. 2013 consulted industry experts, wind turbine manufacturers and governmental agencies to concluding permanent magnet size at 640kg with neodymium content totaling 194kg per MW.
iii. Zimmermann, Rehberger, and Gößling-reisemann 2010 was the only source to calculate the neodymium content for both 1,5MW and 2,5MW

This research will use the average neodymium composition of 195kg per MW from Hoenderdaal et al. 2013 and Habib et al. 2014 in Table 17 as their figures are more current in addition to maintaining consistency as this research builds on their compositions data for other products.

	Habib et al (2014)	Hoenderdaal et al (2013)	Zimmermann et al (2010)	This research (2015)
Wind turbine	*Neodymium [kg]*			
1MW (DDPM), 650kg NdFeB permanent magnet	198	194		196
1,5MW (DDPM), 900kg NdFeB permanent magnet			261	
2,5MW (DDPM), 1.400kg NdFeB permanent magnet			406	

Table 17: Neodymium composition per 1MW DDPM wind turbine with an NdFeB permanent magnet weighing 650kg, 1,5MW DDPM wind turbine with a NdFeB permanent magnet weighing 900kg and a 2,5MW DDPM wind turbine with a NdFeB permanent magnet weighing 1.400kg

The amalgam of Tables 13-17 is the Neodymium Compositions Portfolio. It becomes apparent that there are data gaps on (i) neodymium compositions and (ii) stocks and flows of products containing glass, catalysts, ceramics and metallurgical alloy applications. Unfortunately this research did not carry out any measurements or laboratory assessments on these products due to the cost of such measurements and lack of time and capacity. This lack of data influenced which products and sectors would be included in the scope of the MFAs in this research as highlighted in yellow below in Table 18. The full extension of the Neodymium Compositions Portfolio can be found in Annex A10 to this research.

Permanent magnets				
Sector	Product	Product stocks and flows data?	Compositions data?	Assessed in this MFA
Electronics	Laptops	yes	yes	yes
	Desktop PC	yes	yes	yes
	Tablet	yes	yes	yes
	Smartphones	yes	yes	yes
	mp3 players			

	Microphones			
	Headphones			
	Loudspeakers	yes	yes	yes
	DVD players	yes	yes	yes
	Fridges	yes	yes	yes
	Freezers	yes	yes	yes
	Microwaves	yes	yes	yes
	Aircons	yes	yes	yes
	Washing machines	yes	yes	yes
	Dryer	yes	yes	yes
	Vacuums	yes	yes	yes
	Electric toothbrushes	yes	yes	yes
	Shavers	yes	yes	yes
	Power tools	yes		
Automotive	PHEV	yes	yes	yes
	EV	yes	yes	yes
	Passenger vehicle (ICE)	yes	yes	yes
Renewable Energy	Wind turbine	yes	yes	yes
Medical	MRI		yes	
Other	Electric bicycles (Ebs)		yes	
	Circulator pumps		yes	
	Industrial applications		yes	
Catalysts				
Automotive	Passenger vehicle (conventional)			
Batteries				
Automotive	NiMH batteries for PHEV/Evs	yes	yes	yes
Ceramics				
Electronics	various			
Colouring agent	Ceramic products			
Glass				
Colouring agent	Glass products			
Metallurgical alloys				
Other	Lighters and torches			
	Casting of steel and iron			

Table 18: Neodymium Sector-Product Portfolio illustrating for which products stocks and flows and compositions data in the Netherlands was available; final column and subsequent yellow shading demonstrates which products will be included in the scope of the MFAs in Chapters 8 and 9.

Data quality

For those products for which compositions data were available highlighted in yellow above in Table 18, it proved challenging to objectively measure and compare the robustness of these datasets as each compositions analysis differed in methodology and scope. However data quality is a term not inherently objective; quality can vary depending on context and the attributes being assessed (Bobrowski, Marré, and Yankelevich 1999). As a result for this research data quality per product will be measured in two steps:

i. Quantitatively: Based on number of (peer-reviewed) sources containing compositions data per product using the scale in Table 19. Full table of results for all products in the Neodymium Sector-Product Portfolio, including the data sources per product, can be found in Annex A16 to this research.
ii. Qualitatively: Although most compositions are coming from peer-reviewed sources, this research will qualitatively assess each source using four variables: 1. If it was published in a peer-reviewed journal, 2. if the analysis incorporated an uncertainty analysis, 3. If the analysis carried out a sensitivity analysis and 4. Age of the source. Full description of results for all products in the Neodymium Sector-Product Portfolio can be found in Annex A16 to this research.

The final rating per product will be determined in two steps:

1. Step 1: Qualitative rating generated by calculating the average rating assigned to all individual sources per product
2. Step 2: Total score generated by determining the average of the final qualitative score from Step 1 with the quantitative score

Rating	Description	Designation	Quantity	Quality
1	poor	(red)	no sources	Assessed based on peer-review, uncertainty analysis, sensitivity analysis, age of source
2	fair	(green)	1 sources	
3	good	(blue)	2 sources	
4	excellent	(yellow)	3 sources	

Table 19: Scale measuring the data quality of neodymium compositions per product in the electronics, automotive and renewable energy sectors based on number of sources per product as well as a qualitative assessment of the source

Emerging from the assessment of compositions data quality is the substantial number of sources for PCs, laptops and wind turbines, all receiving the highest quantitative score, a 4. Electric mobility contained 2 sources each for neodymium compositions in the NdFeB permanent magnet motor and NiMH battery in PHEVs and EVs, respectively, likely due to the increases in global PHEV penetration and the future transition to a decarbonized society.

Noteworthy are the compositions for washers, dryers, refrigerators, freezers and air conditioners especially due to the size of their permanent magnets and consequently the quantity of neodymium per piece. Habib et al. 2014 did not dismantle these products and her compositions data came from a leading home appliance OEM and a leading NdFeB permanent magnet manufacturer. Although there has been mention in the literature and research projects to further research magnetic cooling and incorporation of the more efficient permanent magnet motors in many household appliances, consensus on the presence and size of NdFeB permanent magnets in these appliances has not been achieved.

Data quality assessment for all neodymium-containing products with at least one source can be found in Figure 15.

		Quantitative score			Qualitative score		Overall score	
Product	Sources	Quantity	Rating	Designation	Rating	Designation	Rating	Designation
PERMANENT MAGNET								
Laptops	Überschaar & Rotter (2015) Habib et al (2014) Rademaker, Kleijn & Yang (2013) Sprecher et al (2014) Buchert (2012) Hoenderdaal et al (2013)	5	4		3		4	
Desktop PC	Überschaar & Rotter (2015) Habib et al (2014) Rademaker, Kleijn & Yang (2013) Sprecher et al (2014) Hoenderdaal et al (2013)	6	4		4		4	
Tablet	Habib et al (2014)	1	2		2		2	
Smartphones	Buchert (2012) Habib et al (2014)	2	3		3		3	
Loudspeakers	Habib et al (2014)	1	2		2		2	
DVD players	Habib et al (2014)	1	2		3		3	
Fridges	Habib et al (2014)	1	2		2		2	
Freezers	Habib et al (2014)	1	2		2		2	
Microwaves	Habib et al (2014)	1	2		2		2	
Aircons	Habib et al (2014)	1	2		2		2	
Washing machines	Habib et al (2014)	1	2		2		2	
Dryer	Habib et al (2014)	1	2		2		2	
Vacuums	Habib et al (2014)	1	2		2		2	
Electric toothbrushes	Habib et al (2014)	1	2		2		2	
Shavers	Habib et al (2014)	1	2		3		3	
PHEV (EEE)	Widmer et al (2015)	1	2		4		3	
PHEV (Motor)	Habib et al (2014) Hoenderdaal (2013)	2	3		3		3	
EV (Motor)	Habib et al (2014) Hoenderdaal (2013)	2	3		3		3	
Passenger vehicle (ICE) (EEE)	Widmer et al (2015)	1	2		4		3	
Wind turbine	Habib et al (2014) Hoenderdaal et al (2013) Zimmermann et al (2010) Rademaker, Kleijn & Yang (2013)	4	4		3		4	
BATTERIES								
NiMH batteries for PHEV/Evs	Habib et al (2014) USDOE (2011)	2	3		3		3	

Figure 15: Compositions data quality quantitatively and qualitatively assessed per product per sector based on a scale from 1-4, where 4 = excellent (=3 sources); 3 = good (=2 sources); 2 = fair (=1 source) and 1 = poor (=0 sources); full list of qualitative results and complete description can be found in Annex A16 to this research

Neodymium Portfolios Conclusion

Chapter 7 introduced the Neodymium Portfolios. The Neodymium Sector-Product Portfolio inventoried all products containing neodymium applications and assigned them to a particular sector. Using this inventory this research consequently identified for which product stocks and flows datasets in the Netherlands were available. In the electronics and automotive sectors 80% of all corresponding products had sufficient and transparent data on their stocks and flows while 100% of products in the renewable energy sector had reliable data to determine stocks and flows. Unfortunately no stocks and flows data were identified for sectors or products containing catalysts, ceramics, glass or metallurgical alloys demonstrating a data gap for approximately 15% of neodymium flows according to Goonan 2011.

The Neodymium Sector-Product Portfolio was also extended to include neodymium amounts per product with a quantifiable methodology to assess data quality of each product. Similar to stocks and flows datasets, composition datasets were again missing for the catalysts, ceramics, glass and metallurgical applications which ultimately led to automatic omission of these applications from the scope of the MFAs in the next two chapters.

8 Quantification of neodymium flows in the Netherlands 2010

With all neodymium-containing products inventoried and corresponding compositions established, this Chapter will model their stocks and flows in the Dutch urban mine in 2010. Results will characterize the size of each product stream penetrating the Dutch economy and highlight their corresponding EOL destinations. This will not only reveal insights into the theoretical potential of secondary recovery but also exhibit the largest waste streams as well as illuminate leakages and losses.

8.1 Electronics

Neodymium in EEE that are discarded and enter the waste stream as WEEE can be re-introduced to the commodities market under ideal recycling and recovery conditions. This is one of the guiding principles of circular economy, namely to use waste (outflow) as a resource (inflow) thereby reducing demand for virgin material input. This sub-section will therefore, quantify neodymium-containing EEE streams as they are enter the economy and model and characterize their end-destinations enabling a robust scientific assessment to determine how much secondary recovery from products can stymie demand for virgin material in those products.

8.1.1 Assumptions

Although this research has created the rudimentary neodymium baseline needed for modeling stocks and flows in electronic products, there are still unknown variables that will be covered by assumptions based on consultations and the grey literature. These assumptions refer primarily to product average weight, average lifespan and the market share of products containing a neodymium application, explained in Table 20.

Characterizing the percentage of neodymium-containing products in EEE stock is challenging, especially since market share of white goods, cooling and freezing appliances, and household appliances containing neodymium applications is unavailable prior to 2003 and for personal care appliances, unavailable before 2007. This presents challenges in modeling the EEE stock at high levels of accuracy. External forces such as pricing dynamics can also influence the neodymium content in EEE. For example in cases where neodymium prices are very high, the praseodymium ratio is sometimes increased to reduce neodymium content (Rademaker, Kleijn, and Yang 2013). For this reason this research will assume the same corresponding market shares for stocks and WEEE as POM.

Finally assumptions were made regarding the individual WEEE generated waste streams. WEEE generated data was provided for all appliances. However, the characterization of the WEEE waste stream was aggregated into larger domains – large household appliances (LHA), cooling and freezing (CF), small household appliances (SHA) and information technology (IT). Moreover consumer behaviour trends were not included in EOL characterization. For example Wang et al. 2012 indicate that many consumers manually remove the HDD prior to disposal due to (i) the difficulty in ensuring all personal data is erased from the drive or (ii) to retain the monetary value of the HDD. The methodology for determining individual WEEE appliance per waste stream is described in Annex A13 to this research.

Electronics			
Assumption	Market share	Source	Note
Average product weight	varies per product	Balde et al. 2015	Applied to the total kg to calculate number of units
Average product lifespan	varies per	Balde et al. 2015	

	product		
Neodymium composition per product	varies per product	This research, Chapter 7.2.1, Annex A10	Applied to calculate neodymium flow per product
Market share containing neodymium			
washers	25%	Habib et al. 2014	Consultations with a leading NdFeB permanent magnet manufacturer in Japan as well as OEMs
dryers	25%	Habib et al. 2014	
refrigerators	30%	Habib et al. 2014	
freezers	30%	Habib et al. 2014	
airconditioners	30%	Habib et al. 2014	
microwaves	30%	Habib et al. 2014	
vaccuums	8%	Habib et al. 2014 & Business Insider 2014	
personal care	25%	Habib et al. 2014	
video	100%	Habib et al. 2014	
speakers	100%	Habib et al. 2014	
desktop pc	95%	Statista 2015	Shipments of HDDs v SSDs
laptop	95%	Statista 2015	Shipments of HDDs v SSDs
smartphone	100%	Buchert 2012	Market share data in Germany

Table 20: Assumptions and sources required for modeling EEE stocks and flows in the Netherlands in 2010

Further background information and detailed methodology for determining all assumptions in Table 20 can be found in Annex A11a to this research.

8.1.2 Results

Put on market (POM)

The *Future Flows Reports* dataset for products sold in 2010 in the Netherlands were portrayed in total kg; this was divided by the average weight per product to determine total number of products POM, accordingly. Huisman et al. 2012 validated all POM data from product registrations from the Dutch Centraal Bureau voor de Statistiek (CBS) These data were very granular and further complemented by stakeholder consultations with the OEMs, importers and retailers in the Netherlands (Huisman et al. 2012).

POM						
unit	*kt*	*kg/unit*	*%containing Nd*	*kg*	*t*	*%*
Item	**Total POM**	**Neodymium composition**	**Market share**	**Average weight**	**Neodymium in EEE**	**Neodymium share per product**
washers	48,5	0,302	25%	71,5	51,2	42%
dryers	13,3	0,157	25%	43,5	12,0	10%
fridges	40,9	0,075	30%	54,1	17,1	14%
freezers	9,9	0,142	30%	43,3	9,7	8%
aircons	5,9	0,145	30%	25,2	10,1	8%
microwaves	10,9	0,032	30%	22,2	4,7	4%
vaccuums	8,9	0,026	8%	5,8	3,0	2%

personal care	2,9	0,000	25%	0,5	0,4	0%
video	7,4	0,000	100%	2,7	1,3	1%
speakers	5,2	0,000	100%	2,1	1,1	1%
desktop pc	9,5	0,008	95%	8,8	7,9	6%
laptop	4,9	0,002	95%	3,2	3,1	3%
smartphone	0,4	0,000	100%	0,1	0,4	0%
TOTAL					**120,0**	

Table 21: Inventory of neodymium in EEE POM in the Netherlands in 2012 from Huisman et al. 2012; neodymium compositions from corresponding sources in Annex A10 and Chapter 7.2.1; market share containing neodymium applications from corresponding sources in Annex A11a; average weights from UNU; and subsequently total neodymium incorporated in each product totaling 122,2 tonnes in 2010

These figures in Table 21 provide a representative indication of detailed and disaggregated neodymium demand in EEE in the Netherlands in 2010 based on the parameters explained in Chapter 7.1.1 and Annex A11a. Contrary to the literature and results from Du and Graedel 2011a, Rademaker, Kleijn, and Yang 2013, Ueberschaar and Rotter 2014 and Buchert 2012, illustrated in Figure 16, washers and dryers absorbed 52% of all neodymium penetrating the Dutch economy in electronics in 2010; PCs and laptops comprised only 9% of all neodymium introduced in the electronics sector.

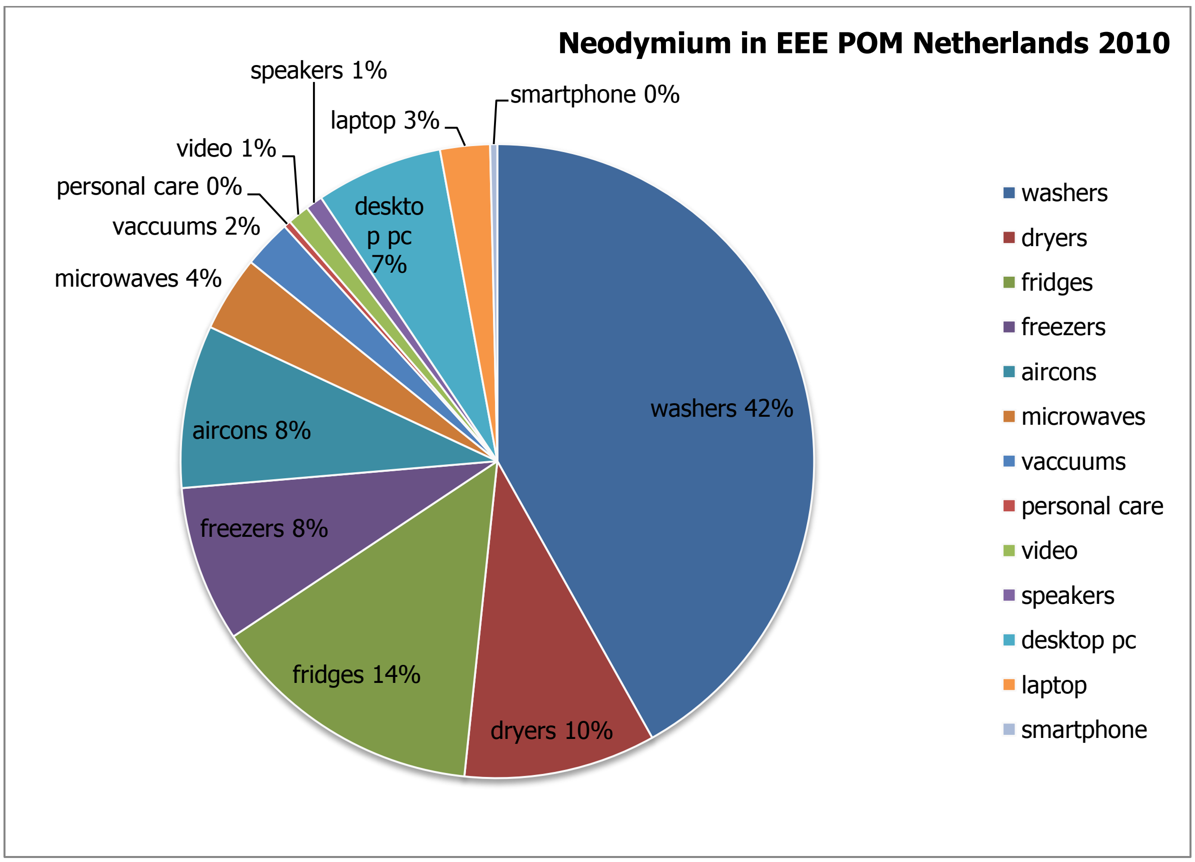


Figure 16: Distribution of neodymium in EEE POM in the Netherlands in 2010

This discrepancy in the results of this research compared to other neodymium assessments is highly dependent on (i) the market share assumption for white goods in this research combined with (ii) the size of the NdFeB permanent magnet in white goods compared to PCs and laptops. For this research these results are striking since the neodymium-EEE literature is dominated by assessments of the HDDs in PCs and laptops as illustrated by aforementioned researchers. This is moreover likely further exacerbated by the lack of sampling and chemical analyses carried out on white goods to investigate the market share containing an NdFeB permanent magnet as well as its size and neodymium composition. Market share increases for white goods and cooling and freezing appliances containing NdFeB permanent magnets is predicted in the future due to their increased efficiencies (MagFreeG Project 2015; Kazawa 2011).

Stocks

Comparatively EEE stock results reflect EEE POM datasets. For example, white goods acted as the vehicle for 51% of the neodymium in the Dutch EEE stock contrasted to IT products comprising only 6% demonstrated in Table 22. Again, to emphasize the reasons in the previous sub-section, this is likely due to the size of the NdFeB permanent magnet in white goods compared to the smaller magnets in IT products.

Additionally white goods have longer lifespans than IT products. For example on average a washer has a lifespan of 12,17 years while a laptop 5,18, according to UNU. Because white goods and laptop sales have increased gradually since 1995, white goods with longer lifespans will subsequently remain in the stock longer and enter the waste stream later (Kleijn, Huele, and Van Der Voet 2000).

STOCKS						
unit	*kton*	*kg/unit*	*%containing Nd*	*kg*	*t*	*%*
Item	**Total POM**	**Neodymium composition**	**Market share**	**Average weight**	**Neodymium in EEE**	**Neodymium share per product**
washers	553,5	0,302	25%	71,5	583,7	40%
dryers	187,2	0,157	25%	43,5	168,5	11%
fridges	517,5	0,075	30%	54,1	216,4	15%
freezers	223,7	0,142	30%	43,3	220,3	15%
aircons	39,7	0,145	30%	25,2	68,5	5%
microwaves	139,5	0,032	30%	22,2	60,1	4%
vaccuums	65,1	0,026	8%	5,8	22,0	1%
personal care	20,7	0,000	25%	0,5	3,1	0%
video	92,1	0,000	100%	2,7	16,8	1%
speakers	50,6	0,000	100%	2,1	10,5	1%
desktop pc	87,8	0,008	95%	8,8	73,5	5%
laptop	31,2	0,002	95%	3,2	19,9	1%
smartphone	2,2	0,000	100%	0,1	2,7	0%
TOTAL					**1466,0**	

Table 22: Inventory of the neodymium-containing EEE stock including total stock data [kton] from Huisman et al. 2012; neodymium compositions from corresponding sources in Annex A10 and Chapter 7.2.1; market share containing neodymium applications detailed in Annex A11a; average weights from UNU; subsequently total neodymium incorporated in each product totaling 1466 tonnes of neodymium in the 2010 Dutch stock

The salience of the theoretical potential of secondary neodymium in the Dutch EEE stock is 12 times larger than the reservoir of neodymium in EEE POM. As these products reach their EOL and become waste, they could substantially curb primary neodymium demand. This would however necessitate that products end up in the recycling chain after discarding which will be assessed in the next sub-section.

WEEE generated

The WEEE generated datasets from the *Future Flows* were not as granular as those for POM and stocks. Although total individual WEEE data were made available per appliance, the waste stream characterization categories – collected, uncollected and exported – were aggregated into the domains below. Description of the waste streams characterization categories can be found in Annex A12 to this research.

- **Large household appliances**: washers, dryers
- **Cooling and freezing**: refrigerators, freezers and air conditioners
- **Small household appliances**: microwaves, electric toothbrushes and shavers
- **Information technology**: PCs, laptops and smartphones

This research determined the individual product share per aggregated domain and subsequently applied this ratio to the three different waste streams in order to generate individual WEEE data per waste stream. The methodology and datasets can be found in Annex A13 to this research. It must however be emphasized that there is some uncertainty in this approach. For example some individual WEEE are disproportionately exported at higher rates than other products in the same aggregated domain which can be observed by the high exports of fridges and cathode ray tube (CRT) monitors (Huisman et al. 2012).

Finally the same market shares of products incorporating neodymium applications for POM and stocks were also applied to EOL data. Because select WEEE are likely older than the year in which NdFeB permanent magnets were incorporated in the design, the neodymium values generated for WEEE are likely too high; unfortunately the WEEE generated data was not characterized by age of the products. Such detailed EOL data would decrease the uncertainty of the values below.

WEEE Generated									
unit	*kt*	*%*	*kg/unit*	*% containing Nd*	*kg*	*t Nd*	*t Nd*	*t Nd*	*t Nd*
Item	**Total**	**Ratio per aggregated domain**	**Neodymium Comp.**	**Market share**	**Avg weight**	**Collected WEEE**	**Un-collected WEEE**	**Exported EEE +WEEE**	**Total WEEE**
washers	43,8	41%	0,302	25%	71,5	33,73	10,55	2,60	46,88
dryers	13,2	12%	0,157	25%	43,5	8,65	2,70	0,67	12,02
fridges	31,8	65%	0,075	30%	54,1	8,63	1,98	4,95	15,55
freezers	9,8	20%	0,142	30%	43,3	6,26	1,43	3,59	11,28
aircons	2,1	4%	0,145	30%	25,2	2,32	0,53	1,33	4,19
microwaves	8,6	8%	0,032	30%	22,2	2,71	0,87	0,37	3,95
vaccuums	6,8	6%	0,026	8%	5,8	11,13	3,58	1,52	16,24
personal care	2,1	2%	0,000	25%	0,5	0,23	0,07	0,03	0,34
video	10,1	9%	0,000	100%	2,7	1,33	0,43	0,18	1,95
speakers	5,4	5%	0,000	100%	2,1	0,82	0,26	0,11	1,20
desktop pc	11,7	24%	0,008	95%	8,8	6,03	1,83	2,62	10,48
laptop	2,9	6%	0,002	95%	3,2	1,12	0,34	0,49	1,95
smartphone	0,4	1%	0,000	100%	0,1	0,27	0,08	0,12	0,47
TOTAL						**83,0**	**25,0**	**19,0**	**127,0**

Table 23: Inventory of all WEEE generated including total WEEE generated data [kt] from Huisman et al. 2012; ratio of individual WEEE appliance per aggregated domain, see Annex A13 for methodology; neodymium compositions from corresponding sources, see Chapter 7.2.1 and Annex A10 for sources; market share containing neodymium applications from corresponding sources, see Annex A11a for calculations; average weights from UNU; total neodymium incorporated entering the WEEE waste stream totaling 126,5 tonnes in the Netherlands in 2010

Comparative to EEE POM and stocks datasets, large household appliances and cooling and freezing appliances are the largest sources of neodymium in WEEE in 2010 in Table 23. In fact PCs and laptops contributed only 8% and 1% of the total theoretical potential of secondary neodymium entering the waste stream in the Netherlands, respectively, while washing machines were responsible for 37% of neodymium entering the WEEE waste stream.

Approximately 65% of neodymium left the Dutch economy in WEEE generated in 2010 and entered a formal collection stream either vis-à-vis the WEEE compliance schemes or through complementary recycling. According to Huisman et al. 2012, 59% of all WEEE generated in the Netherlands was collected exhibiting comparable collection results. Reasons for the discrepancy could be due to neodymium-containing WEEE tending to be larger as is the case with washers, dryers, fridges and freezers and more valuable as is the case with PCs, laptops and smartphones than non-neodymium-containing WEEE, which could contribute to a higher collection rate.

When assessing the theoretical potential of secondary neodymium, total neodymium entering the WEEE waste stream was 127t compared to 122t POM through sales. This demonstrates an actual surplus if WEEE collection was maximized. Figure 17 illustrates the neodymium distribution for all products as total neodymium in WEEE generated, WEEE collected and the neodymium in individual EEE POM. In Figure 17 the neodymium in collected HDDs, optical drive and speaker magnet in PCs could provide 76% of the neodymium needed for PC manufacture in 2011 if PC sales remained the same as 2010. However if PC collection was increased by 18% in 2010 and 2011 PC sales remained the same as 2010, demand for virgin neodymium would be reduced to zero. Washing machines would still require primary neodymium as total EOL washing machines in 2010 provide only 92% of the theoretical neodymium for washing machines sold in 2010.

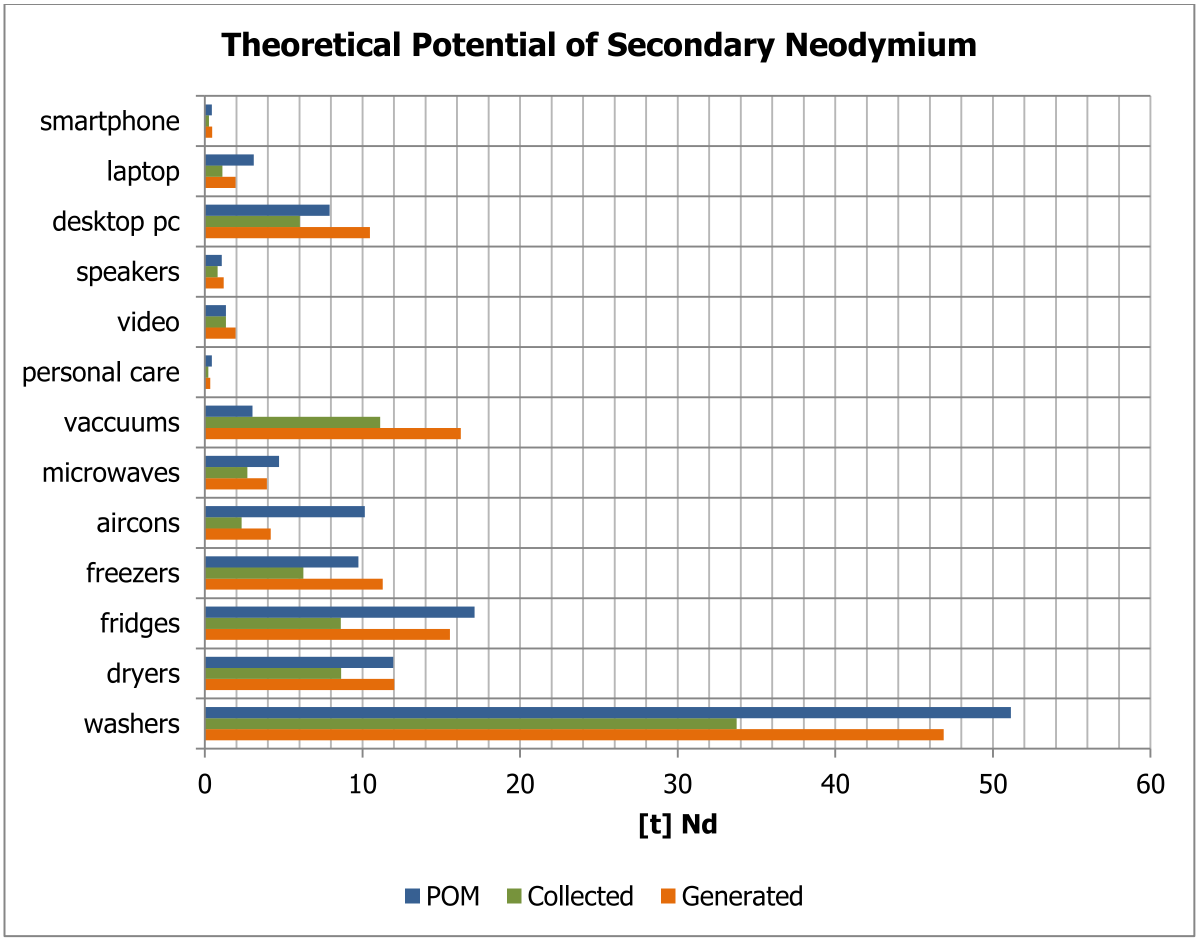
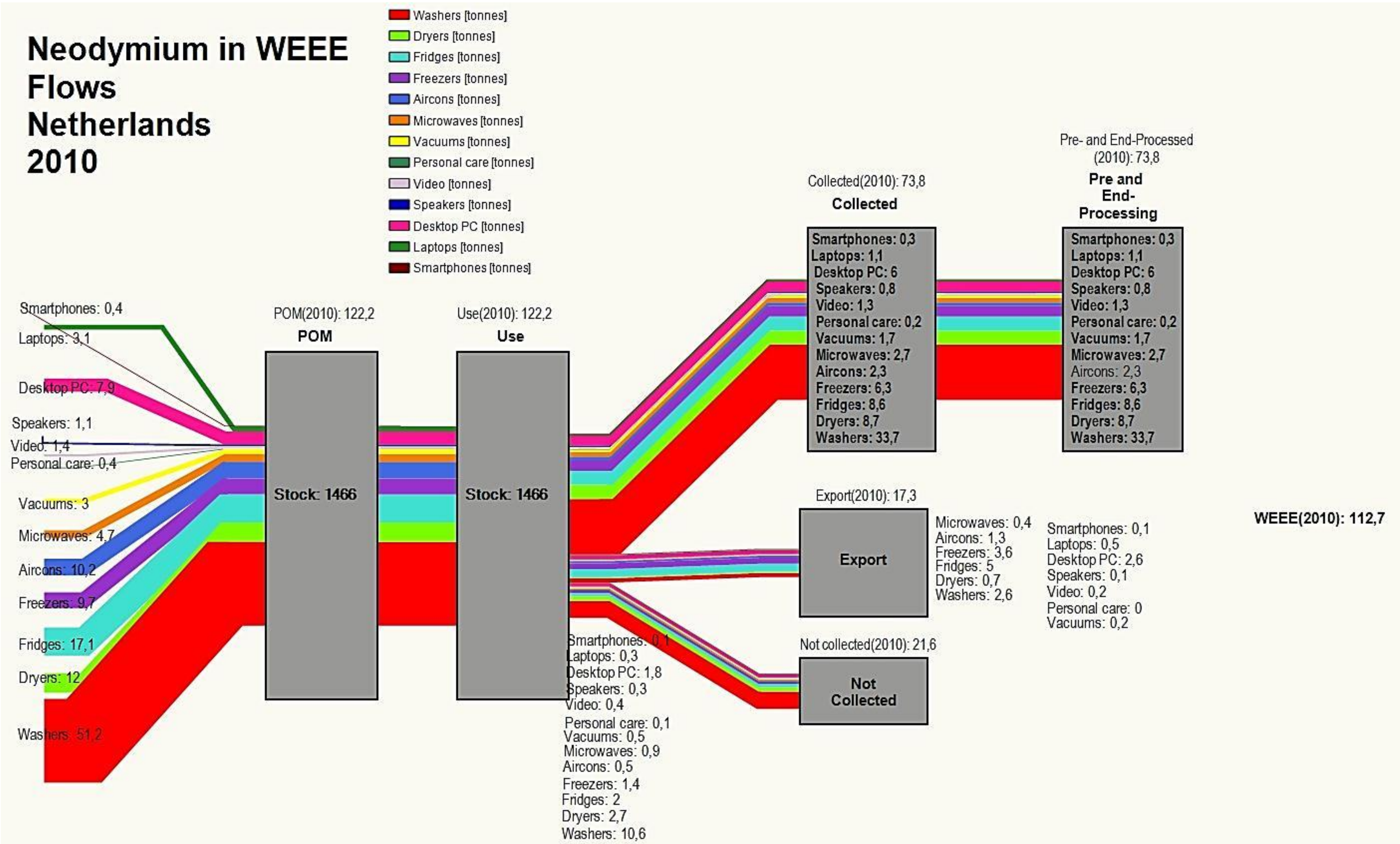


Figure 17: Demonstration of the neodymium distribution for WEEE as total generated and collected in the Netherlands in 2010 compared to the neodymium POM in the same appliances in the Netherlands in 2010

At the same time, 19% of neodymium-containing WEEE in 2010 was uncollected or not accounted for; this figure is comparable to the 18% of all WEEE in 2010 identified as uncollected or not accounted for from Huisman et al. 2012. Combined with exported neodymium-containing WEEE, roughly 35% of all neodymium discarded as waste in the Netherlands in 2010 left the Dutch economy in export or was not accounted for, e.g. instead entered a residual waste stream.

Although recovery is out of scope, it must be noted that 100% secondary recovery can never be achieved due to inherent laws of nature and thermodynamic losses notwithstanding manual dismantling and remanufacturing (Huisman 2003). Currently even when collected WEEE are sent to recyclers for materials recovery, the required neodymium recovery technologies do not exist on an industrial scale and neodymium is therefore lost as an oxide in the slags (Binnemans et al. 2013; Buchert 2012). Moreover if the NdFeB permanent magnets are not manually dismantled in a pre-processing stage before reaching a smelter, they will likely be shredded and pulverized or included with another fraction stream, such as ferrous fractions, subsequently resulting in dissipation or total losses (Chancerel and Finkbeiner 2010; Binnemans et al. 2013). For example Chancerel (2009) used MFA to quantify the mass flow of precious metals (gold, silver and palladium) in WEEE and determined that there were 62% less precious metals in fully shredded printed circuit boards (PCBs) compared to pre-shredded PCBs. It is nonetheless worth nothing that there will always be a minimum requirement of virgin metal in a product due to the loss of properties and performance of a metal over its in-use lifetime; this is a chief principle of the Second Law of Thermodynamics (Reuter 2013).

The next Chapter will explore the role of the automobile industry and its contribution to the neodymium urban mine in the Netherlands, especially with a strong uptake of PHEVs stimulated by government subsidies in recent years (Amsterdam Roundtable Foundation 2014).


Neodymium in WEEE Flows Netherlands 2010
Washers [tonnes]
Dryers [tonnes]
Fridges [tonnes]
Freezers [tonnes]
Aircons [tonnes]
Microwaves [tonnes]
Vacuums [tonnes]
Personal care [tonnes]
Video [tonnes]
Speakers [tonnes]
Desktop PC [tonnes]
Laptops [tonnes]
Smartphones [tonnes]
Smartphones: 0,4
Laptops: 3,1
Desktop PC: 7,9
Speakers: 1,1
Video: 1,4
Personal care: 0,4
Vacuums: 3
Microwaves: 4,7
Aircons: 10,2
Freezers: 9,7
Fridges: 17,1
Dryers: 12
Washers: 51,2
POM(2010): 122,2
POM
Stock: 1466
Use(2010): 122,2
Use
Stock: 1466
Smartphones: 0,1
Laptops: 0,3
Desktop PC: 1,8
Speakers: 0,3
Video: 0,4
Personal care: 0,1
Vacuums: 0,5
Microwaves: 0,9
Aircons: 0,5
Freezers: 1,4
Fridges: 2
Dryers: 2,7
Washers: 10,6
Collected(2010): 73,8
Collected
Smartphones: 0,3
Laptops: 1,1
Desktop PC: 6
Speakers: 0,8
Video: 1,3
Personal care: 0,2
Vacuums: 1,7
Microwaves: 2,7
Aircons: 2,3
Freezers: 6,3
Fridges: 8,6
Dryers: 8,7
Washers: 33,7
Pre- and End-Processed (2010): 73,8
Pre and End-Processing
Smartphones: 0,3
Laptops: 1,1
Desktop PC: 6
Speakers: 0,8
Video: 1,3
Personal care: 0,2
Vacuums: 1,7
Microwaves: 2,7
Aircons: 2,3
Freezers: 6,3
Fridges: 8,6
Dryers: 8,7
Washers: 33,7
Export(2010): 17,3
Export
Microwaves: 0,4
Aircons: 1,3
Freezers: 3,6
Fridges: 5
Dryers: 0,7
Washers: 2,6
Smartphones: 0,1
Laptops: 0,5
Desktop PC: 2,6
Speakers: 0,1
Video: 0,2
Personal care: 0
Vacuums: 0,2
Not collected(2010): 21,6
Not Collected
WEEE(2010): 112,7

8.2 Automobiles

Electric mobility in the automotive sector has gained momentous market share in Europe and especially the Netherlands since 2010. This was stimulated by generous governmental subsidies and tax incentives that not only resulted in a 5% PHEV market share of all new automobile registrations in 2013, but also the expansion of PHEV-infrastructure with 1,1 charging stations per vehicle (Mock and Yang 2014; Amsterdam Roundtable Foundation 2014).

PHEV technologies are substantially supported through the incorporation of neodymium applications. The neodymium-containing NiMH battery has been the market favourite battery as an alternative to toxic, lower-performing lead acid batteries. The NdFeB permanent magnet motor has high coercivity which leads to high efficiencies and longer lifespans as they are able to operate under high thermal conditions and resist demagnetization (Gutfleisch et al. 2011). With the share of the Dutch PHEV automobile stock expected to increase to 200.000 in 2020, it is likely that neodymium demand will increase proportionately in the automotive sector over this time frame.

8.2.1 Assumptions

There were various unknowns concerning the automobile sector. For example although new registrations of automobiles in the Netherlands in 2010 were delineated by fuel type allowing this research to identify the streams of PHEVs and conventional vehicles with an (ICE), the year and make and model were unknown. This could have implications on the type of battery used as well as vehicle lifespan and stock age (Constantinides 2013). Additionally the end-of-life vehicle (ELV) waste stream was aggregated without distinguishing fuel-type requiring assumptions on the characterization of the ELV waste stream. For this reason the assumptions below in Table 24 provided the parameters for modeling neodymium in the automotive sector in the Netherlands in 2010.

Automobiles			
Assumption	Item	Source	Note
Average product lifespan	20,2 years	Yano et al. 2015	
Neodymium composition per product	differs per auto type	This research, Chapter 7.2.1, Annex A10	Applied to calculate neodymium flow per vehicle
Market share of PHEVs containing NiMH batteries in 2010	100%	Vikström et al. 2013 Schüler et al. 2011	
NiMH battery replacement	0	Habib & Wenzel 2014	NiMH batteries will have the same lifespan as PHEVs
NdFeB permanent magnet motor market share	100%	Habib & Wenzel 2014 Hoenderdaal et al. 2013	NdFeB permanent magnet motors will have the same lifespan as PHEVs
PHEVs in the ELV waste stream in 2010	0	ARN	Consultation with the ELV recycling compliance scheme in the Netherlands
Neodymium distribution per fuel type			
Fuel type	EEE	NdFeB permanent magnet motor	NiMH battery

Petrol	X		
Diesel	X		
Vehicles powered by propane (LPG)	X		
PHEV	X	X	X
EV	X	X	X
High pressure gas	X		
Compressed natural gas (CNG)	X		
Liquefied natural gas (LNG)	X		
Biofuel	X		

Table 24: Assumptions and sources required for modeling stocks and flows in the automotive sector in the Netherlands in 2010

Further explanations of the assumptions can be found in Annex A11b to this research.

8.2.2 Results

New registrations

New vehicle registrations in the Netherlands were disaggregated per fuel type and made available from BOVAG and RAI, both platforms that represent stakeholders in the automobile sector in the Netherlands. When applying the corresponding neodymium compositions per fuel type it becomes clear that although petrol and diesel automobiles comprise 95% of all new vehicle registrations in the Netherlands in 2010, combined, they only contain 7% of all neodymium penetrating the Dutch economy via the automobile sector demonstrated in Table 25.

New registrations vehicles in Netherlands 2010								
unit	*vehicles*	*kg*	*t*	*kg*	*t*	*kg*	*t*	*t*
item	**total**	**Nd comp. (EEE)**	**Nd (EEE)**	**Nd comp. (motor)**	**Nd (motor)**	**Nd comp. (battery)**	**Nd (battery)**	**Total**
Petrol	364.054	0,002	0,874	0,00	0,00	0,00	0,00	0,9
Diesel	98.675	0,002	0,237	0,00	0,00	0,00	0,00	0,2
Vehicles powered by propange (LPG)	3.064	0,002	0,007	0,00	0,00	0,00	0,00	0,0
Hybrid	16.112	0,002	0,039	0,63	10,15	0,25	3,83	14,0
EV	122	0,002	0,000	0,63	0,08	0,25	0,03	0,1
High pressure gas	0	0,002	0,000	0,00	0,00	0,00	0,00	0,0
Compressed natural gas (CNG)	437	0,002	0,001	0,00	0,00	0,00	0,00	0,0
Liquefied natural gas (LNG)	0	0,002	0,000	0,00	0,00	0,00	0,00	0,0
Biofuel	169	0,002	0,000	0,00	0,00	0,00	0,00	0,0
TOTAL	**482.633**		**1,2**		**10,2**		**3,9**	**15,2**

Table 25: Inventory of all new vehicle registrations including total new registrations [number of vehicles] from BOVAG and RAI 2015; neodymium compositions for EEE, NdFeB permanent magnet motor and NiMH battery from sources outlined in Chapter 7.2.1 and Annex A10 ; total neodymium incorporated in each vehicle fuel type, totaling 15,2 tonnes in 2010

Figure 18 exhibiting the neodymium cogency of the PHEV stream is striking as PHEVs represented only 3% of all new registrations as total units but contained 92% of all neodymium in new registrations. The NdFeB permanent magnet motor alone was responsible for 67% of all neodymium introduced to the Dutch economy in the automotive sector. Emerging from these results is the significance of neodymium to electric mobility and in a broader sense, decarbonizing strategies; at the same time it becomes clear that an increase in electric mobility will have substantial impacts on neodymium demand.

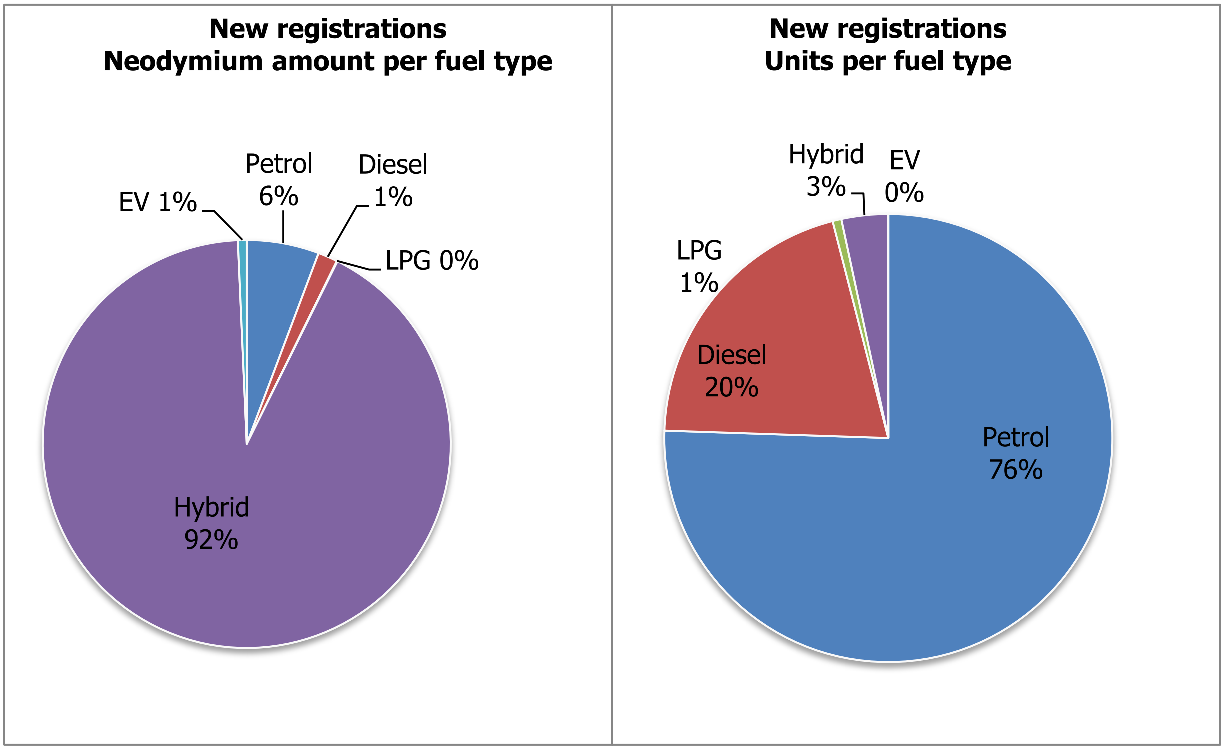


Figure 18: Illustration of the new automobile registrations in the Netherlands in 2010: left side, the neodymium amount entering the economy per fuel type; right side, units entering the economy per fuel type

Should PHEV registrations had been comparable to the registration of petrol fuel type in 2010, total neodymium consumption would have increased by a factor of 22 to 320t of neodymium. PHEV registrations similar to 2010 petrol registrations should not be underestimated as the Dutch government has set stringent and ambitious future PHEV targets at 200.000 units on the road in 2020 (Amsterdam Roundtable Foundation 2014).

Stocks

Vehicle stocks were also provided by BOVAG and RAI and were again disaggregated by fuel type. This granular overview was advantageous for this research due to the lack of disaggregated at EOL, which will be explained further in the next section.

Stock of vehicles in Netherlands 2010								
unit	*vehicles*	*kg*	*t*	*kg*	*t*	*kg*	*t*	*t*
item	**total**	**Nd comp. (EEE)**	**Nd (EEE)**	**Nd comp. (motor)**	**Nd (motor)**	**Nd comp. (battery)**	**Nd (battery)**	**total**
Petrol	6.370.781	0,002	15,29	0,00	0,00	0,00	0,00	15,29

Diesel	1.353.899	0,002	3,25	0,00	0,00	0,00	0,00	3,25
Vehicles powered by propange (LPG)	218.041	0,002	0,52	0,00	0,00	0,00	0,00	0,52
Hybrid	56.902	0,002	0,14	0,63	35,85	0,25	14,23	50,21
EV	238	0,002	0,00	0,63	0,15	0,25	0,06	0,21
High pressure gas	1.191	0,002	0,00	0,00	0,00	0,00	0,00	0,00
Compressed natural gas (CNG)		0,002	0,00	0,00	0,00	0,00	0,00	0,00
Liquefied natural gas (LNG)	0	0,002	0,00	0,00	0,00	0,00	0,00	0,00
Biofuel	1.467	0,002	0,00	0,00	0,00	0,00	0,00	0,00
TOTAL	**8.002.519**		**19,2**		**36,0**		**14,3**	**69,5**

Table 26: Inventory of all disaggregated vehicle stock from BOVAG and RAI 2015; including neodymium compositions for EEE, NdFeB permanent magnet motor and NiMH battery from corresponding sources in Chapter 7.2.1 and Annex A10; subsequent total neodymium incorporated in each vehicle fuel type, totaling 69,5 tonnes in 2010

The neodymium-containing EEE dataset is much higher than new registrations due to the volume of vehicles in use. In the previous sub-section new registrations accounted for 482.633 units across all fuel types totaling 1,16t of neodymium contained in EEE in vehicles or 8% of neodymium in new vehicle registrations in 2010. Considering much higher stocks, long vehicle residence times (20,2 years) and a relatively nascent PHEV market, it is not surprising that the neodymium content in EEE in stocks represents a higher proportion at 19,2t or 28%.

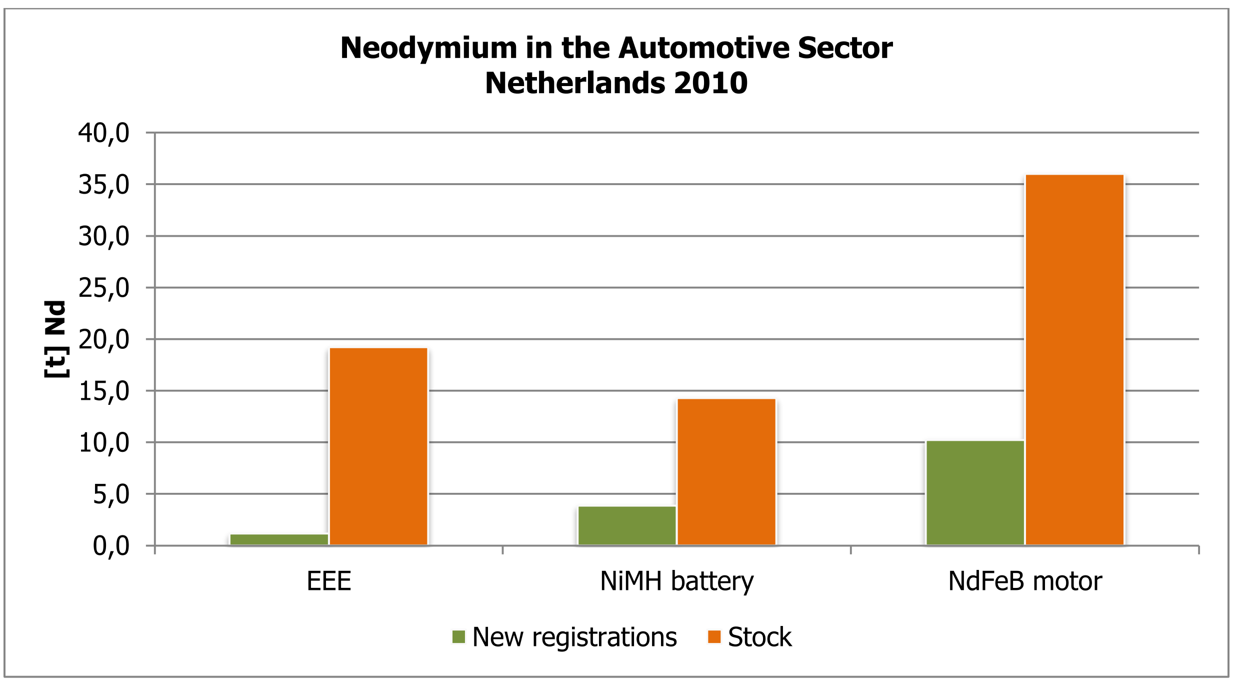


Figure 19: Comparison of the three sources of neodymium [t] in the automotive sector across all fuel types for new registrations and the automotive stock

Nonetheless the NdFeB permanent magnet motor and NiMH battery still comprise the majority of neodymium hibernating in vehicle stocks in the Netherlands in 2010, constituting 52% and 21%, respectively, visualized in Figure 19. This signifies the large role of PHEV neodymium demand in the Dutch automotive sector, considering PHEV only comprised 7,1% of total stocks in 2010 and have only been available commercially on the market in the past 18 years (Lake 2001).

ELV Generated

According to the available data, the ELV waste stream can flow through three channels, either formal collection, uncollected or export. Characterizing the ELV waste stream could have been a challenge since the dataset aggregated all fuel types but due to the nascent PHEV market and long lifespans, it was assumed that no PHEVs entered the waste stream in 2010.

End-of-life vehicles (ELVs)								
unit	*kg*	*units*	*t*	*units*	*t*	*units*	*t*	*t*
item	**Nd comp. (EEE)**	**collected**	**Nd**	**uncollected**	**Nd**	**export**	**Nd**	**TOTAL Nd**
All fuel types	0,002	215.975	0,52	33.033	0,08	250.245	0,60	1,2

Table 27: Inventory of aggregated ELVs from BOVAG and RAI 2015; only including neodymium compositions for EEE due to the nascent PHEV market, calculations can be found in Chapter 7.2.1 and Annex 10; total neodymium in EEE in ELVs in the Netherlands amounting to 1,2 tonnes in 2010

Table 27 demonstrates the negligible theoretical potential of secondary neodymium in EEE in ELVs in contrast to the theoretical potential of secondary neodymium in PHEVs once they enter the waste stream. This should alert policymakers and recyclers to the impending forthcoming flows of the PHEV stock as they begin to enter the waste stream in large quantities in 2030. As a result the ELV landscape will look remarkably different in the future than in 2010.

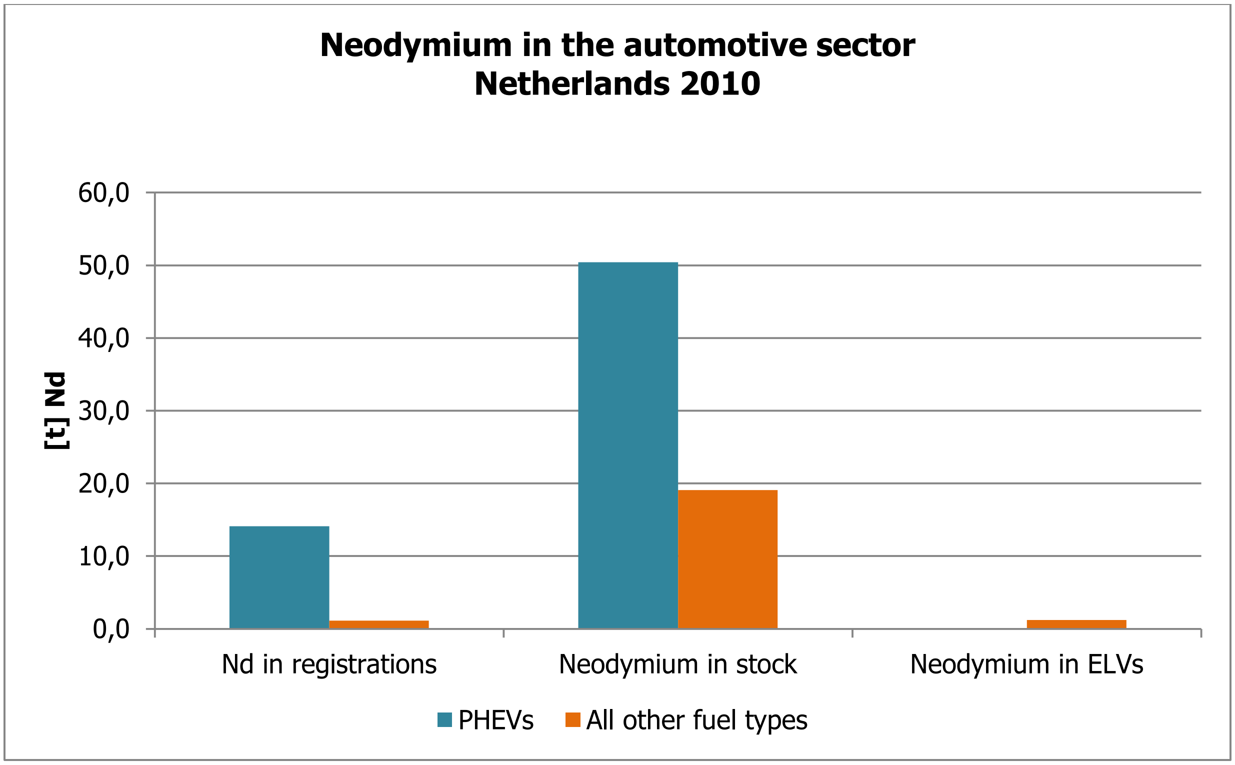
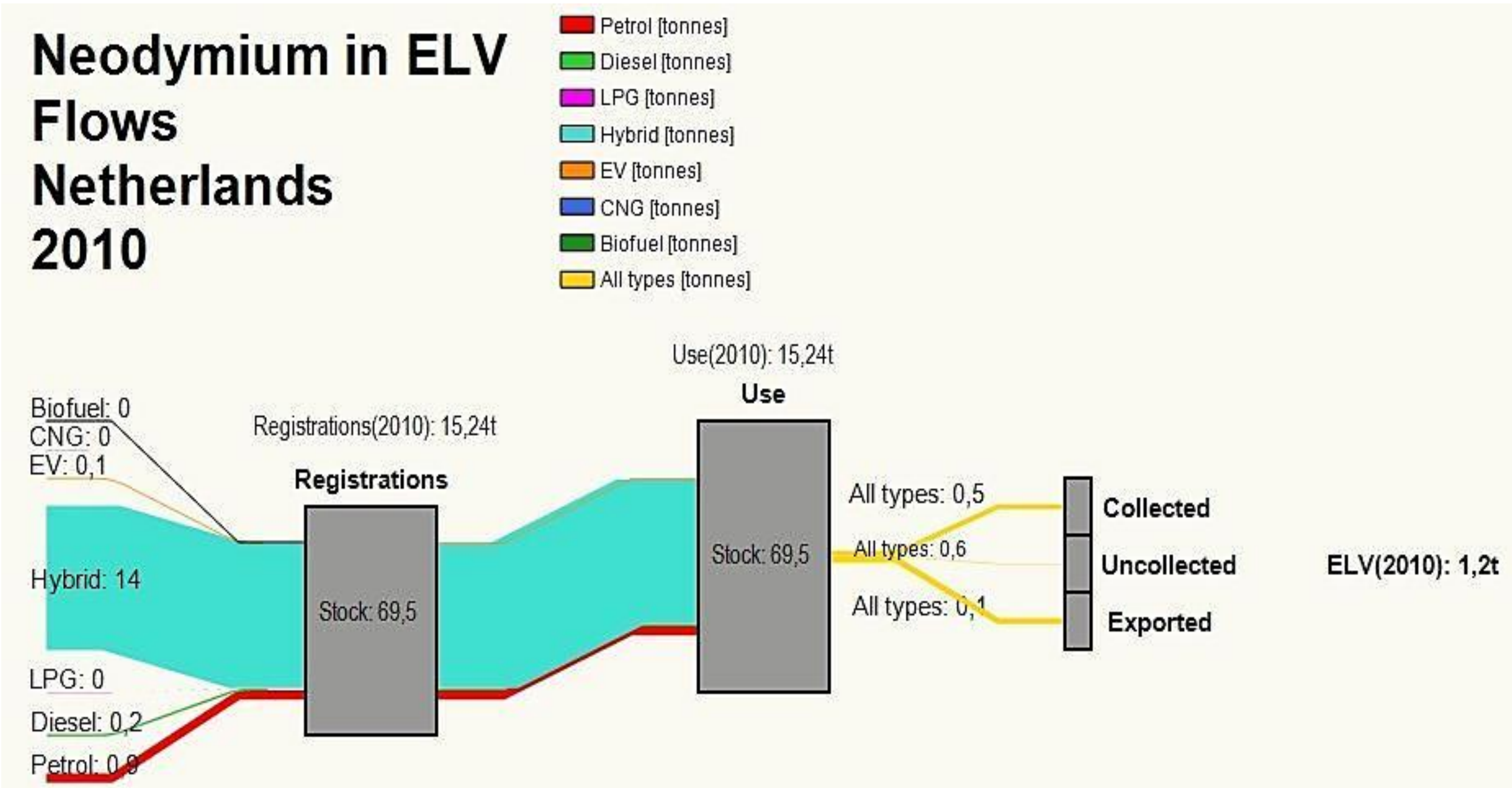


Figure 20: Illustration of the neodymium reservoirs in the automotive sector in 2010 delineated by PHEVs and all other fuel types

The Sankey diagram is the amalgam of the new registration, stocks and ELV datasets in this Chapter. It highlights how the stocks and flows of neodymium in automobiles oscillated through the Dutch economy in 2010.


Neodymium in ELV Flows Netherlands 2010
Petrol [tonnes]
Diesel [tonnes]
LPG [tonnes]
Hybrid [tonnes]
EV [tonnes]
CNG [tonnes]
Biofuel [tonnes]
All types [tonnes]
Use(2010): 15,24t
Use
Biofuel: 0
CNG: 0
EV: 0,1
Registrations(2010): 15,24t
Registrations
Hybrid: 14
Stock: 69,5
Stock: 69,5
All types: 0,5
All types: 0,6
All types: 0,1
Collected
Uncollected
Exported
ELV(2010): 1,2t
LPG: 0
Diesel: 0,2
Petrol: 0,9

8.3 Wind turbines

Like electric mobility, wind energy is also a relatively nascent field contributing to the dismantling of the fossil-fuel based economy. As of 2010 17% of global energy consumption was met by renewable energy sources; in 2011 wind power increased by 20% to 238 GW, the fastest growing renewable energy source worldwide (Ren21 2012). With the EU aiming to achieve 20% of its energy from renewable energy by 2020, the Netherlands will have to increase its renewable energy capacity from a meagre 4% in 2010 to 14% according to a report from Rabobank International 2012. According to the National Renewable Energy Action Plan from the Netherlands, wind power will represent the largest renewable source with 46% of the total Dutch renewable energy mix by 2020 (Rabobank International 2012).

The wind turbine landscape is also shifting from doubly fed induction generators (DFIG) toward high-efficient, low-maintenance direct-drive permanent magnet (DDPM) turbines, which are expected to be especially vital to the offshore wind market (T. Zimmermann, Rehberger, and Gößling-reisemann 2010). If the market share of DDPM wind turbines increases as forecasted by Hoenderdaal et al. 2013, Habib and Wenzel 2014 and Gutfleisch et al. 2011 and the Dutch renewable energy strategy comes to fruition, demand for neodymium in the Netherlands could increase substantially in the near future. However, secondary sources of neodymium will increase proportionately in the longer-term as DDPM enter the waste stream. For this reason the 2010 Dutch wind turbine and DDPM landscape will be quantified based on the assumptions in the next Chapter.

8.3.1 Assumptions

The assumptions in Table 28 provide the context for modeling neodymium in DDPM wind turbines in the Netherlands in 2010. Especially crucial will be the market share captured by DDPM wind turbines and the year they were introduced to the market. Refer to Annex A11c to this research for detailed description of individual assumptions.

Wind turbines			
Assumption	Item	Source	Note
Average product lifespan	20 years	Rademaker, Kleijn & Yang 2013	
Average neodymium composition	196kg per MW	This research, Chapter 7.2.1, Annex A10	Applied to calculate neodymium flow per DDPM wind turbine
Number of wind turbines in the Netherlands as per 2010	1700	www.thewindpower.net	Used to determine number of DDPM turbines based on DDPM market share
Market share of DDPM wind turbines in the Netherlands as per 2010	14%	Schüler et al. 2010 Habib & Wenzel 2014	Introduced in 2003 and market share of 14% in 2010; this research assumes 2% DDPM market share in 2004 with a 2% growth rate each year until 2010
DDPM wind turbines in EOL turbine waste stream in the Netherlands 2010	0	This research	Based on average lifespan + introduction to the market in 2003, not yet reached EOL

Table 28: Assumptions and sources required for modeling stocks and flows of neodymium in DDPM wind turbines in the Netherlands in 2010; detailed description of the assumption can be found in Annex A11c

8.3.2 Results

New installations and stocks

Data describing the wind turbine landscape in the Netherlands is rather comprehensive with some crucial gaps. As explained in Annex A11c, this research referred to wind turbine datasets at www.thewindpower-net and manually inventoried every known wind turbine in the Netherlands since 1990. If known, this research also indicated the year of installation, province and municipality, MW capacity and whether or not the wind turbine had a gearbox or DDPM. Of 1735 wind turbines erected in the Netherlands, the following information was known:

i. Year of installation: Year that the wind turbine was erected was known for 52% of all installations
ii. Capacity and number of turbines: These details were provided for 100% of all wind turbines
iii. Gearbox or DDPM: Distinction between the two types was known for only 12% of all wind turbines
iv. Province and municipality: This information was provided for 98% of all wind turbines inventoried

The year of installation and type of gearbox were the only indicators with high levels of uncertainty. The methodology for reducing this uncertainty is described in detail in Annex A11c to this research.

Table 29 illustrates the distribution of turbines installed per year in the Netherlands. Based on the DDPM market share per year and the neodymium composition per DDPM wind turbines, total neodymium penetrating the Dutch economy via DDPM wind turbines in 2010 was quantified.

Year	**Number of turbines added to stock**	**DDPM market share**	**Nd comp. per 1MW [kg]**	**Total Nd [t]**
1990	46	0%	196	0,00
1991	45	0%	196	0,00
1992	45	0%	196	0,00
1993	45	0%	196	0,00
1994	45	0%	196	0,00
1995	110	0%	196	0,00
1996	88	0%	196	0,00
1997	86	0%	196	0,00
1998	64	0%	196	0,00
1999	76	0%	196	0,00
2000	71	0%	196	0,00
2001	70	0%	196	0,00
2002	155	0%	196	0,00
2003	144	0%	196	0,00
2004	237	2%	196	0,93
2005	62	4%	196	0,49
2006	75	6%	196	0,88
2007	99	8%	196	1,55
2008	52	10%	196	1,02
2009	68	12%	196	1,60
2010	52	14%	196	1,43
TOTAL	**1735**			**7,9**

Table 29: Inventory of wind turbine stock as well as newly installed wind turbines in the Netherlands per year ascertained from www.thewindpower.net and described further in Annex A11c; DDPM market share per year based on data from Schüler et al. 2011 and Habib & Wenzel 2014 with further elaboration explained in Annex A11c; neodymium composition [kg] per 1MW DDPM wind turbine ascertained from Habib et al. 2014 and Hoenderdaal et al. 2013 and explained in Chapter 7.2.1 and Annex A10; total neodymium [t] added to the existing stock per year

The neodymium results were lower than expected with only 1,43t of neodymium added to the Dutch stock through DDPM wind turbines in 2010, especially considering the breadth of literature dedicated to DDPM research. The 2010 neodymium in DDPM wind turbines is comparable to the neodymium introduced to the Dutch economy in 2010 in CD/DVD/blu-ray players at 1,3t. Even the total neodymium stock in DDPM wind turbines in the Netherlands 2010 at 7,9t is smaller than the neodymium in the CD/DVD/blu-ray stock by a factor of 2.

When comparing the significance of the 2010 wind turbine market to the results in the automobile and electronics sectors, the 2010 neodymium consumption by wind turbines is marginal as demonstrated in Figure 21. However in terms of absolute products, only 7 DDPM wind turbines were installed in the Netherlands in 2010 contributing 1,43t of neodymium; in order to obtain the same amount of neodymium from CD/DVD/blu-ray players, 7,4 million have to be sold. Consequently the neodymium brevity of one wind turbine is much higher than one EEE appliance.

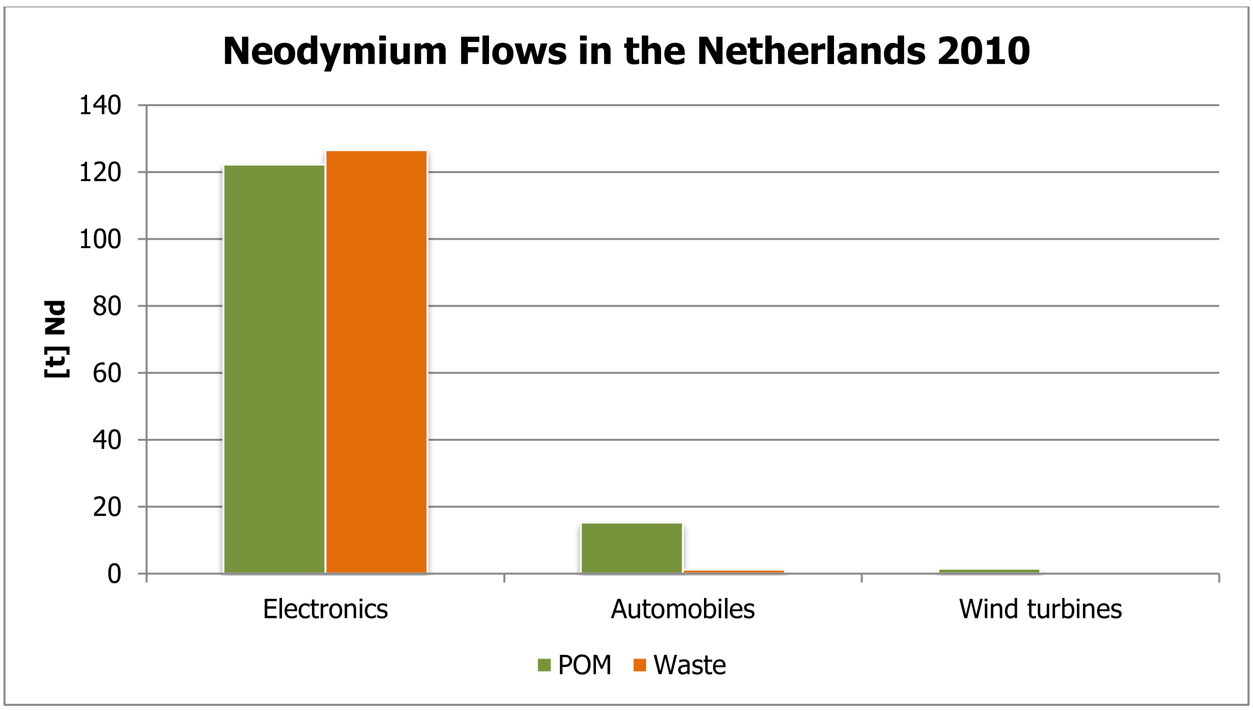
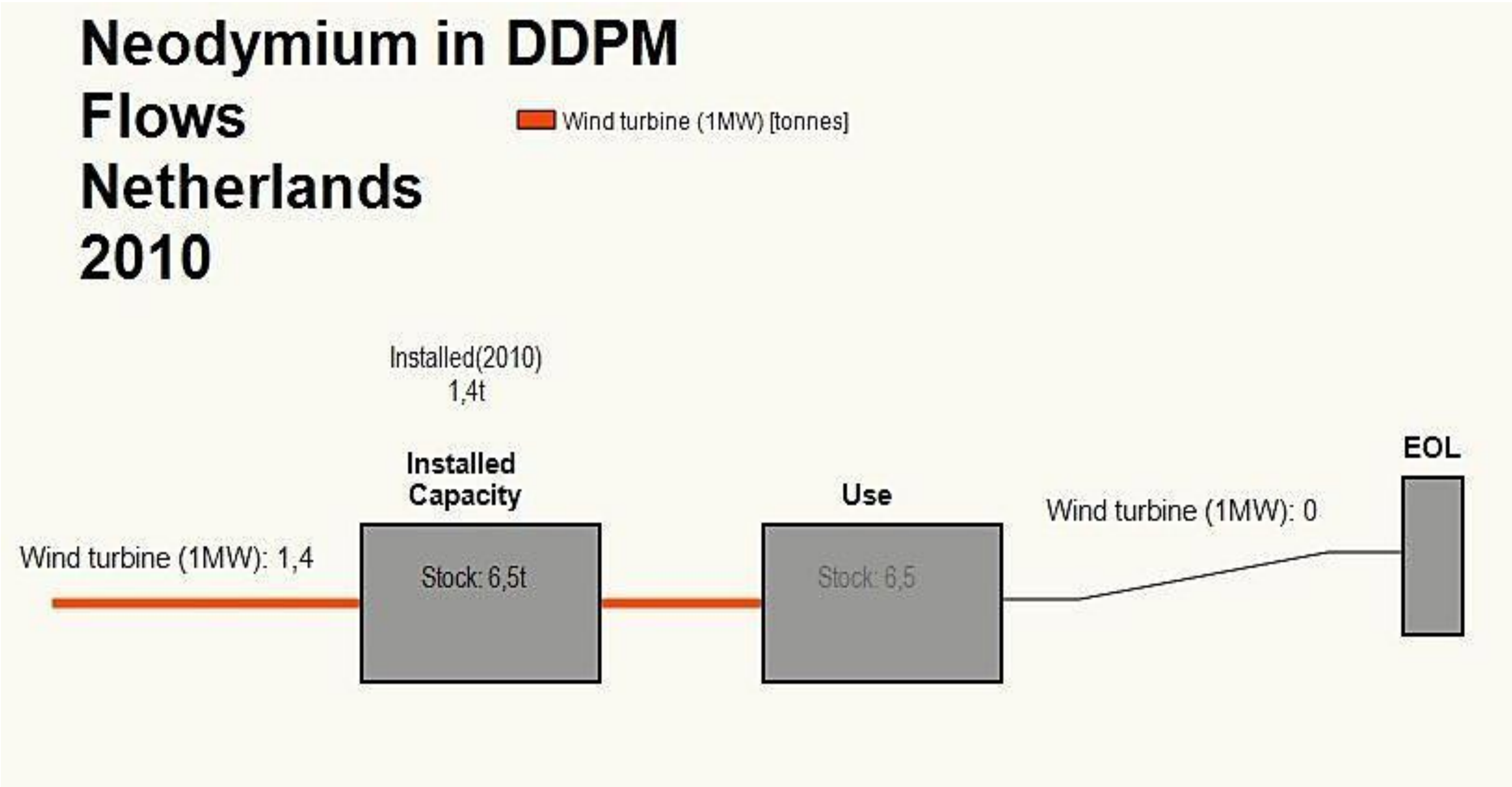


Figure 21: Illustration and comparison of the neodymium flows in the electronics, automobiles and renewable energy sectors in the Netherlands in 2010

The coalescence of the new installations and stock data offered in this Chapter is demonstrated in the wind turbine Sankey diagram on the next page. Should the cumulative wind energy installation targets for 2020 and 2030 in the Netherlands be realized and DDPM wind turbine market share increase to levels predicted by industry, neodymium demand will increase substantially. This will be discussed in Chapter 9 combining scenario mapping with MFA.


Neodymium in DDPM
Flows
Netherlands
2010
Wind turbine (1MW) [tonnes]
Installed(2010)
1,4t
Installed
Capacity
Use
EOL
Wind turbine (1MW): 1,4
Stock: 6,5t
Stock: 6,5
Wind turbine (1MW): 0

Discussion on neodymium MFA in the Netherlands 2010

Applying the tailored parameters to each neodymium-containing product outlined in Annex A11a/b/c, this Chapter applied neodymium compositions to product stocks and flows datasets to model and map neodymium in the Netherlands in 2010. This was not carried out without statistical uncertainties, especially with reference to the market share of neodymium-containing products. However market shares were supported by the literature and are found in the aforementioned Annexes.

Emerging from the modeling results was the significance of secondary neodymium in the 2010 waste streams of the three sectors quantified in this Chapter. In total the theoretical potential of secondary neodymium from the electronics, automotive and renewable energy sectors amounted to 128t or 92% of the modeled neodymium demand in the same three sectors in 2010 demonstrated in Figure 22. If all of these neodymium-containing products entered a formal collection stream, the salience of the theoretical potential of recycling could likely substantially reduce criticality should supply bottlenecks occur similar to 2010-2011.

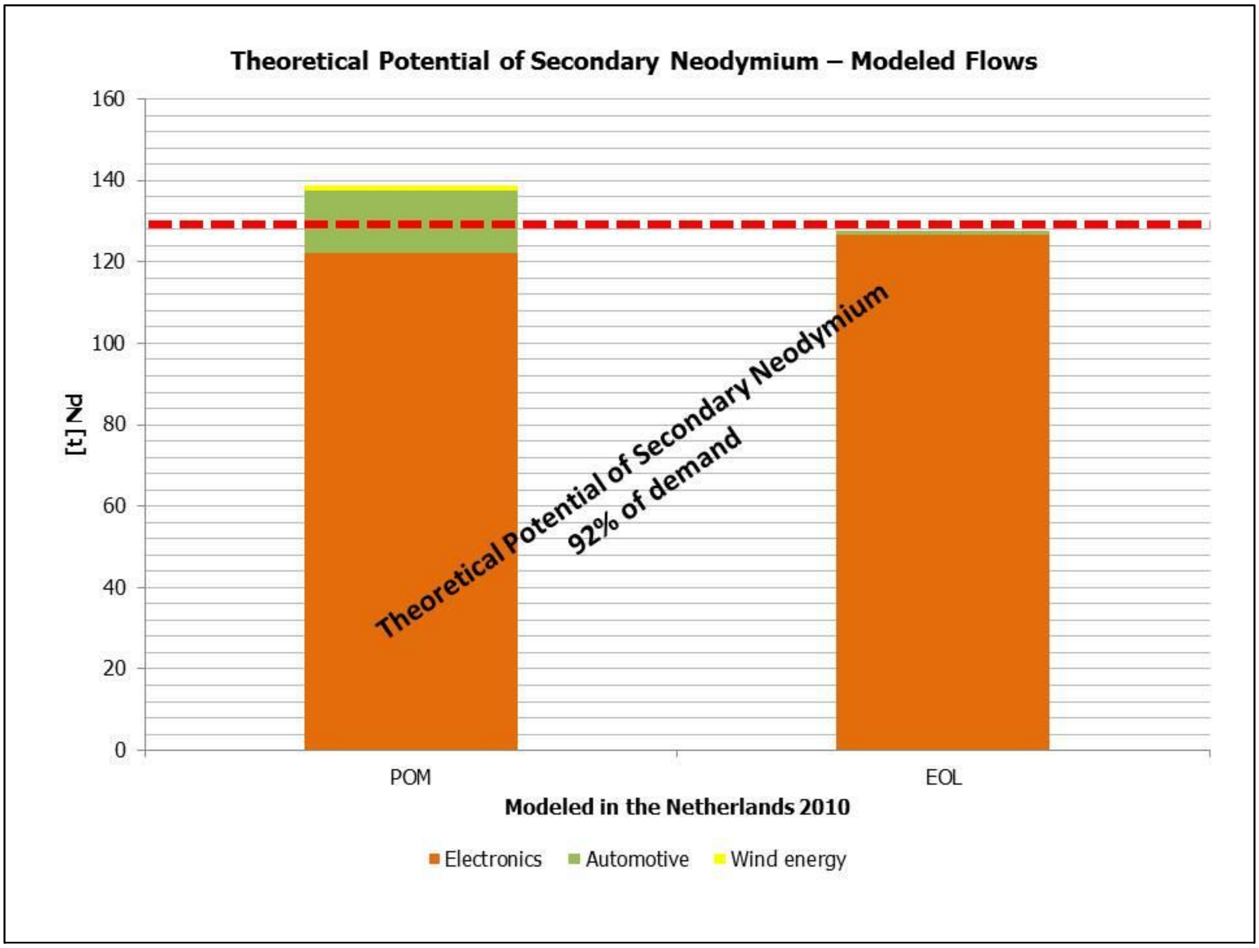


Figure 22: Illustration of the theoretical potential of secondary neodymium in the waste stream in the electronics, automotive and renewable energy sectors in the Netherlands in 2010

Virtually all secondary neodymium from the 2010 results is available in the WEEE stream due to the nascent electric mobility and DDPM wind turbine markets in combination with their long lifespans.

Assessing only the electronics sector demonstrates that 83t of neodymium-containing WEEE was collected in 2010 amounting to 60% of the neodymium entering the market through EEE sales.
Another interesting result was the significance of non-HDD streams in the electronics sector. Du and Graedel 2011a indicated that 36% of NdFeB permanent magnet demand in 2007 was via HDDs. Since then, the literature has devoted most neodymium-related attention to the HDD-containing PCs and laptops. The results from this MFA illustrate that the HDDs in PCs and laptops contained only 11t or 8% of all neodymium in permanent magnets across all three sectors. Washing machines and refrigerators were the largest consumers of neodymium in NdFeB permanent magnets comprising 38% and 13% of neodymium POM in this assessment, respectively.

According to the number of products and sectors outlined in the Neodymium Sector-Product Portfolio, this research modeled 54% of the total demand for neodymium in the Netherlands in 2010 across all products. This was determined assuming the 2008 neodymium demand distribution percentages per application from Goonan 2011, visualized in the waffle chart in Figure 6 and illustrated below in Table 30, were applicable to the Netherlands in 2010.

Neodymium application	Neodymium demand distribution percentage from Goonan 2011	Total products in the Sector-Product Portfolio	Total products modeled from the Sector-Product Portfolio	Percentage modeled
Permanent magnet	76%	27	19	53%
Alloys	8%	2	0	0%
Batteries	5%	2	1	1%
Ceramics	4%	2	0	0%
Other	4%	1	0	0%
Glass	2%	1	0	0%
Catalysts	1%	1	0	0%

Table 30: Neodymium demand distribution per neodymium application based on 2008 demand data from Goonan 2011; total products per neodymium application in the Neodymium Sector-Product Portfolio and number of those products modeled in this research, generating the ratio of neodymium applications modeled to those not modeled in this research

Consequently, this research was able to estimate the total neodymium demand in the Netherlands in 2010, totaling 253t of neodymium. Detailed calculations can be found in the Annex A15a to this research. As a result this research concludes that the theoretical potential of secondary neodymium in the modeled 2010 Dutch waste stream could reduce demand for primary neodymium by 51%.

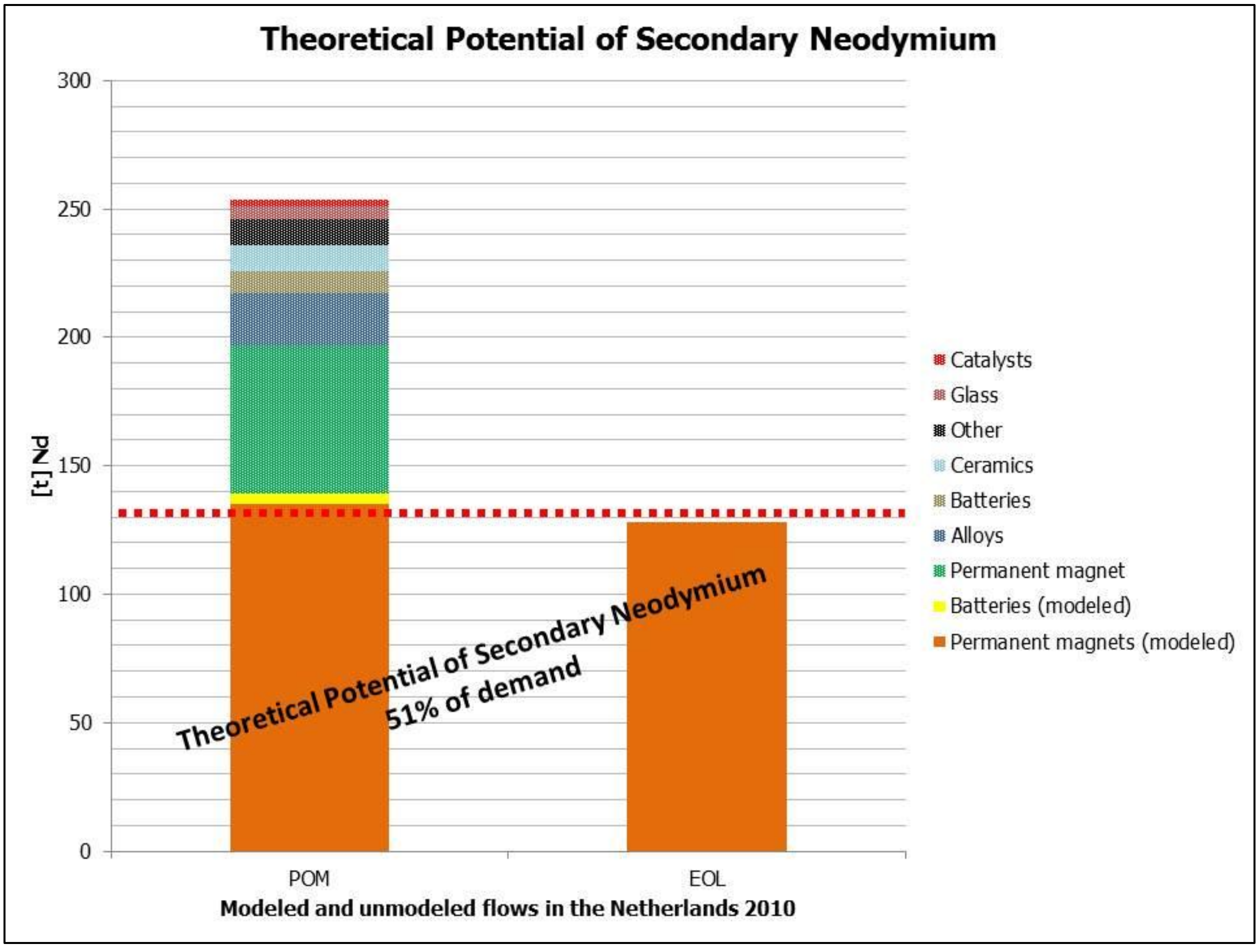


Figure 23: Theoretical potential of the 2010 modeled neodymium waste stream in the Netherlands calculated at 38% of total neodymium demand in the Netherlands in 2010 based on the neodymium demand distribution percentages per neodymium application ascertained by Goonan 2011

9 Quantification of neodymium flows in the Netherlands 2030

This research has highlighted the role of neodymium in the modern economy. Not only are its applications indispensable in products ranging from smartphones to MRIs, ceramic capacitors to wind turbines, but demand for its applications is increasing as illustrated in Chapter 4.4 (D. Kingsnorth 2013; Roskill 2012). While there were glimmers of hope in upstream primary production diversification after the effects of supply constraints were felt from Chinese export quotas, prices ultimately stabilized and the Chinese monopoly on neodymium production is slowly making a return.

However the neodymium urban mine is increasing proportionately to neodymium demand offering a potent and accessible secondary source of neodymium that has hitherto been neglected. The exact size of the neodymium urban mine was quantified and modeled for the Netherlands in 2010 in order to illustrate the salience of the neodymium reservoir above the ground. While the theoretical potential of secondary neodymium in the mature electronics sector was promising with the amount of neodymium in 2010 WEEE higher than 2010 EEE POM, the results were bleak for the automotive and renewable energy sectors. This was due to the nascent PHEV and DDPM wind turbine markets and their long lifespans.

This chapter will use scenario mapping and MFA to illustrate how a neodymium future in the Netherlands in 2030 could materialize. This will not be a prediction but instead, a potential and plausible future based on assumptions and parameters supported by targets from the Dutch government, academia and forecasts from industrial experts. Moreover projections on market development in the electronics, automotive and renewable energy sectors will be included to determine how each sector will grow. It must be emphasized that scenario mapping is highly uncertain, inherently complex and is intended to broaden perspectives to consider issues in the long-term that may not be acknowledged (Mahmoud et al. 2009).

9.1 Assumptions

Because scenario mapping is flexible and customizable, the potential 2030 neodymium future will build on the MFA assumptions and results in Chapter 8 and therefore, only model those products and sectors addressed in Chapter 8 (Mahmoud et al. 2009; Hoenderdaal et al. 2013). It will incorporate assumptions on product growth as well as market share based on literature review, governmental targets and forecasts from manufacturers, OEMs and industry experts.

One particular scenario mapping MFA indicator that is both inherently uncertain but fundamental to future material flows is the product growth rate. Contrasting to the renewable energy sector and electric mobility landscape where governmental targets, legislation and incentive packages guide wind turbine installation and PHEV sales, the growth of individual electronics relies substantially on the introduction of new and evolution of existing products and ultimately on the consumer. Moreover the heterogeneity and consolidation of functions across the electronics sector influences individual product growth over the long-term. For this reason forecasting both short-term and long-term growth rates of individual electronics is extremely challenging.

Moreover various forces can substantially impact individual product growth or even broader electronics sectoral growth. Take the case of tablets. In 2012 there was much industry hype behind the expected growth of tablets as they were expected to increase from 179 million shipments in 2013 to 427 million in 2017 with a compounded annual growth rate of 29% (Gigaom Research 2014). However two years later in 2015, the tablet tone changed dramatically. Sales slumped and were expected to reach only 233 million units in 2015 with a meagre 8% growth rate compared to 2014 sales. Reasons cited for the lackluster tablet performance were due to the introduction and market up-take of new, ultra-slim premium computers and smartphones with a larger screen (Tung 2015).

The solid state drive (SSD) / flash drive market is also evolving. Flash memory capacity is larger than the noisy HDDs and also do not require NdFeB permanent magnets (O'reilly 2015). However compared to HDDs, SSD prices are significantly higher than HDDs; if SSD prices continue to drop, price parity could be achieved and the SSD-market would quickly surpass the HDD landscape (Sliwa 2015). However when this occurs is contestable; some industry insiders predict it could happen in 2016 while others do not foresee competitive SSD prices in the near future (Sliwa 2015; Mearian 2015).

Such complexity, especially in the electronics sector, makes it extremely challenging to predict growth rates of individual products and subsequently, the growth rates used in this research should only be entertained as rough estimates and should be adjusted as each product evolves.

All 2030 assumptions for the electronics, automotive and renewable energy sectors as well as sources and rationale are described in Annex A14a/b/c to this research.

9.2 Electronics

9.2.1 Results

In order to determine the sales of individual neodymium-containing EEE appliances leading up to 2030, two linear growth rates were applied. The first growth rate of 2,5% was pegged to the median Gross World Product (GWP) figure from the IPCC (IPCC 2000) and applied to all products in Growth Cohort 1. The second growth rate applied to individual EEE in Growth Cohort 2 added an additional 2% to the GWP due to the significance of those products (Schüler et al. 2011). The market share of individual EEE containing neodymium applications and the neodymium compositions remained the same for 2030 as 2010 due to the uncertainty in product evolution illustrated in the previous sub-section. Detailed description of all parameters and assumptions can be found in Annex 14a to this research.

Stock dynamics and WEEE generated figures were determined based on the average EEE lifespans which were the same for 2030 as 2010. Reasons for this are again due to the uncertainty in product design and performance although the current trend tends to be shorter lifespans (Balde, K., Kuehr, R., Blumenthal, K., Fondeur Gill, S., Kern, M., Micheli, P., Huisman 2015).

EEE POM (2030), EEE stock (2030) and WEEE generated (2030) were calculated based on the following three formulas where *n* is the number of years following 2010 (2011: *n*=1, 2012 *n*=2, 2013 *n*=3, …), *g* is the annual growth rate, *x* is the lifespan of the product and *(n-1)* refers to the value from the previous year.

$$POM(n) = POM(2010) * g^n$$
$$GEN(n) = POM(2010) * g^x$$
$$STOCK(n) = STOCK(n-1) + POM(n) - GEN(n)$$

Once applied to data from base year 2010, the following results were generated for 2030 in Table 31.

unit	Growth rate	POM		STOCKS		EOL	
		EEE units (10.000)	t	EEE units (10.000)	t	WEEE units (10.000)	t
item		**total**	**Nd**	**total**	**Nd**	**Total EOL**	**Nd**
washers	2,5%	125	94,2	1.235	931,2	82	62,1
dryers	2,5%	56	22,0	672	263,0	35	13,7
fridges	2,5%	139	26,3	1.528	288,1	88	20,0
freezers	2,5%	42	17,9	757	322,8	22	9,5
aircons	4,5%	62	26,9	404	175,7	38	16,6
microwaves	4,5%	131	12,5	1.293	123,8	70	6,7
vaccuums	4,5%	409	8,0	2.635	51,6	260	5,1
personal care	4,5%	1.545	1,2	9.490	7,1	1.011	0,8
video	4,5%	727	3,6	6.306	31,0	448	2,2
speakers	4,5%	653	2,8	4.868	21,2	413	1,8
desktop pc	4,5%	285	21,0	2.014	148,3	185	13,6
laptop	4,5%	403	8,2	1.199	24,5	350	7,2
smartphone	4,5%	973	1,2	4.720	5,7	701	0,8
TOTAL			**245,9**		**2.394,0**		**160,0**

Table 31: Neodymium stocks and flows in the electronics sector in 2030 based on the assumptions outlined in Annex A14a

Based on the growth rates applied to individual EEE, the amount of neodymium entering the Dutch economy via the electronics sector in 2030 was 291,1t, twice as much as EEE POM in 2010. Meanwhile, neodymium in WEEE generated increased by 21% compared to 2010 figures and the neodymium stock grew by approximately 41%

Compared to 2010 data neodymium distribution across all EEE POM was similar, although the share of neodymium in white goods decreased from 52% to 47% which is due to the lower growth rate for white goods. Those products benefiting the most in neodymium share in 2030 in contrast to 2010 were air conditioners which increased by 3% and PCs in which neodymium POM increased from 6% to 9%. In total due to all EEE experiencing growth, neodymium totals increased among all product groups.

In 2010 the amount of neodymium in the WEEE waste stream was higher than the neodymium entering the economy in EEE POM, theoretically reducing the demand for primary neodymium in EEE by a significant amount. Even the amount of secondary neodymium in collected WEEE in 2010 could have theoretically covered approximately 70% of neodymium needed in EEE POM in 2010. In 2030 the neodymium entering the WEEE waste stream represented only 65% of the neodymium entering the Dutch economy. If the collection rate of neodymium-containing WEEE in 2030 was the same as 2010, only 104t of neodymium would have entered a formal stream, thereby reducing demand for primary neodymium in EEE POM by 42%.

When looking closer at the case of PCs, the high growth rate until 2030 illustrates the impact on the theoretical potential of secondary recovery. While neodymium in EOL PCs in 2010 comprising 132% of neodymium demand needed for PC manufacture in the same year, primary neodymium required for PC production in 2030 can only be reduced by 65% via neodymium-containing PCs entering the waste stream illustrated in Figure 24. Ultimately, because neodymium inflows are higher than the outflows due to consistent growth rates over a span of 20 years, the neodymium EEE stock reservoir swells for all products, especially those with the higher growth rates. .

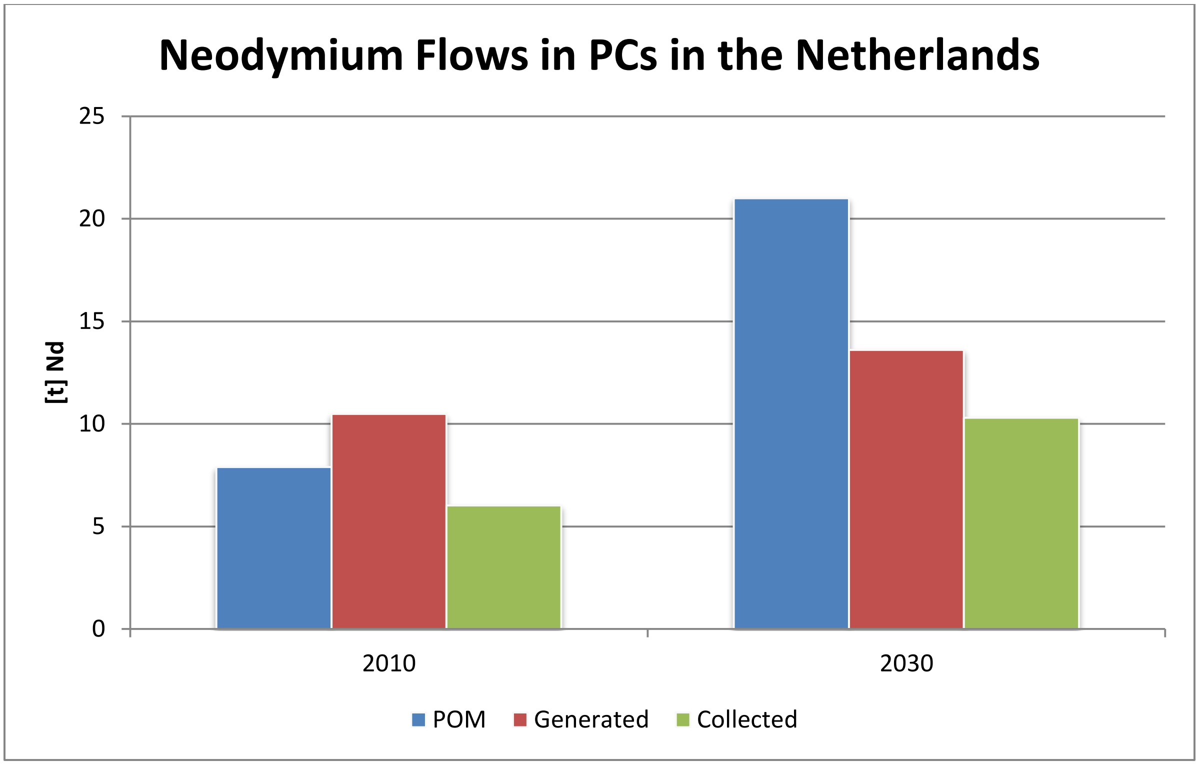
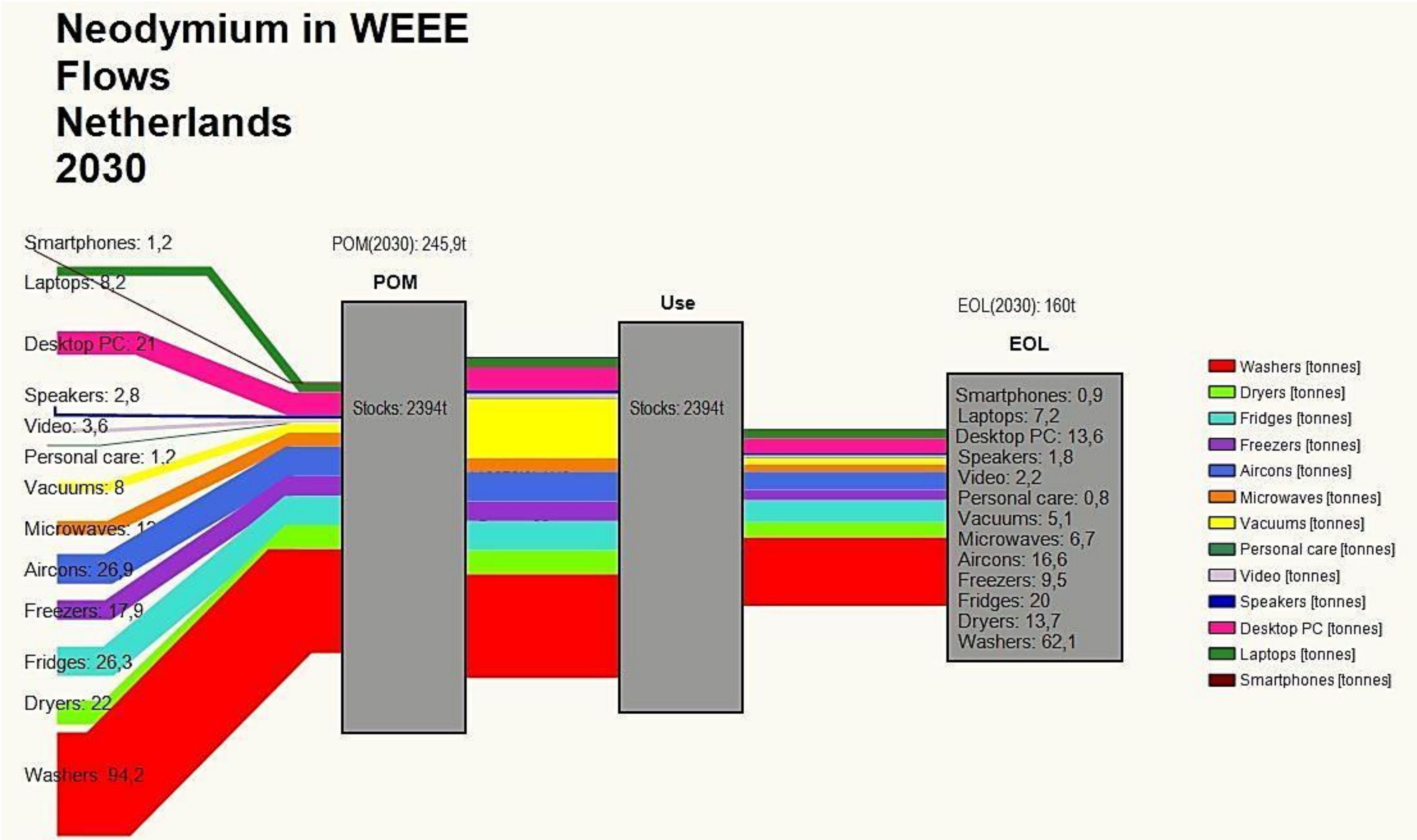


Figure 24: Comparison of neodymium flows in PCs in the Netherlands in 2010 and 2030 whereby neodymium demand for primary neodymium in PCs in 2010 could theoretically be met completely by secondary recovery compared to 2030 where the potential of secondary recovery of neodymium in PCs only covers 65% of the demand for neodymium in PCs

The results from the broader 2030 electronics MFA illustrate the inherent potential of the neodymium urban mine. Should the current EOL management of neodymium-containing WEEE continue for 2011-2030, 2420t of secondary neodymium will have been lost. Economically the intrinsic value of the neodymium lost in smelter slags or exports amounts to US$211 million, just in neodymium in WEEE from 2011-2030. Moreover and embedded in the larger geopolitical discussion outlined in Chapter 4.4 this also translated into missed opportunity for criticality reduction measures through reuse and recycling as total neodymium in EEE POM from 2011-2030 totaled 3411t; 71% of the total neodymium needed for electronic products sold in the Netherlands was in the electronics waste stream during the same period. If collected and treated properly and efficiently, criticality could be reduced substantially.

The 2030 neodymium flows in the electronics sector are illustrated in the Sankey diagram below.


Neodymium in WEEE Flows Netherlands 2030
Smartphones: 1,2
Laptops: 8,2
Desktop PC: 21
Speakers: 2,8
Video: 3,6
Personal care: 1,2
Vacuums: 8
Aircons: 26,9
Freezers: 17,9
Fridges: 26,3
Dryers: 22
Washers: 94,2
POM(2030): 245,9t
POM
Stocks: 2394t
Use
Stocks: 2394t
EOL(2030): 160t
EOL
Smartphones: 0,9
Laptops: 7,2
Desktop PC: 13,6
Speakers: 1,8
Video: 2,2
Personal care: 0,8
Vacuums: 5,1
Microwaves: 6,7
Aircons: 16,6
Freezers: 9,5
Fridges: 20
Dryers: 13,7
Washers: 62,1
Washers [tonnes]
Dryers [tonnes]
Fridges [tonnes]
Freezers [tonnes]
Aircons [tonnes]
Microwaves [tonnes]
Vacuums [tonnes]
Personal care [tonnes]
Video [tonnes]
Speakers [tonnes]
Desktop PC [tonnes]
Laptops [tonnes]
Smartphones [tonnes]

9.3 Automobiles

Results

The Netherlands has experienced a surge in PHEV sales in the past five years. Worldwide the Netherlands had the second-highest PHEV market share as of 2013, with PHEVs representing 5,6% of all new registrations and a 1900% growth rate from 2012-2013 (Mock and Yang 2014). In fact the Mitsubishi Outlander was the top-selling car among all vehicle types in November and December 2013. These spikes in sales were primarily driven by the generous subsidies offered by the government. For example in Amsterdam the municipality subsidized new PHEVs with a EUR 5.000 rebate on passenger vehicles and EUR 10.000 on taxi (Amsterdam Roundtable Foundation 2014). For company vehicles 25% of the vehicle price is included as income and consequently taxed; a waiver was granted and included in the PHEV subsidy packet (Mock and Yang 2014). In Amsterdam owners of PHEVs bypassed all waiting lists for parking permits, had free parking in many garages and were exempt from many annual automobile taxes (Amsterdam Roundtable Foundation 2014).

Using PHEV targets from the Dutch National Action Plan for Electric Driving, this research will build on the 2010 MFA results and apply a 6% linear growth rate for PHEVs and a 35% linear growth rate for full EVs. The corresponding growth rates are needed to achieve the 200.000 target by 2020.

New registrations of PHEVs and EVs in 2030 as well as the size of the stock and amount of ELVs generated in 2030 are illustrated in Table 32 and were calculated based on the following three formulas where n is the number of years following 2010 (2011: n=1, 2012 n=2, 2013 n=3, …), g is the annual growth rate, x is the lifespan of the product and *(n-1)* refers to the value from the previous year.

$$POM(n) = POM(2010) * g^n$$
$$GEN(n) = POM(2010) * g^x$$
$$STOCK(n) = STOCK(n-1) + POM(n) - GEN(n)$$

Item	**New registrations**			**Stocks**			**ELVs**		
	PHEV	EV	total	PHEV	EV	total	PHEV	EV	total
total units	51.673	49.321		491.531	189.565		15.925	115	
Nd (EEE) [t]	0,1	0,1	**0,2**	1,2	0,5	**1,6**	0,0	0,0	**0,0**
Nd (motor) [t]	32,6	31,1	**63,6**	309,7	119,4	**429,1**	10,0	0,1	**10,1**
Nd (battery) [t]	8,4	8,0	**16,4**	79,9	30,8	**110,7**	4,0	0,0	**4,0**
total Nd [t]	**41,1**	**39,2**	**80,3**	**390,7**	**150,7**	**541,4**	**14,1**	**0,1**	**14,2**

Table 32: Neodymium distribution across the EEE, NdFeB permanent magnet motor and NiMH batteries for PHEVs and EVs in the Netherlands in 2030

In contrast to 2010, the amount of neodymium penetrating the Dutch economy in 2030 through PHEVs and EVs totals 80,3t, an increase over 2010 by almost a factor of 6 due to annual linear growth rates not observed over such long time spans prior to 2010. This amount in new registrations could have reached 90t if the NiMH battery market share increased from 65% to the 100% figure used for 2010.

The cogency of a closed-loop neodymium economy for the automotive sector is tepid due to the long lifespans of PHEVs and EVs and the nascent market in 2010. In 2030 the theoretical potential of the neodymium waste stream for both PHEVs and EVs would only reduce demand for primary neodymium by

18%. This is nonetheless higher than 2010 where no PHEVs or EVs entered the waste stream. However if only 43% of all ELVs were collected in 2030 as was the case in 2010, 8t of neodymium will be lost in uncollected streams and export, combined. Figure 25 illustrates the 2030 neodymium landscape for PHEVs and EVs. Due to the higher growth rate for full EVs at 35%, 2030 signifies the year in which EV sales became virtually equal to PHEV sales.

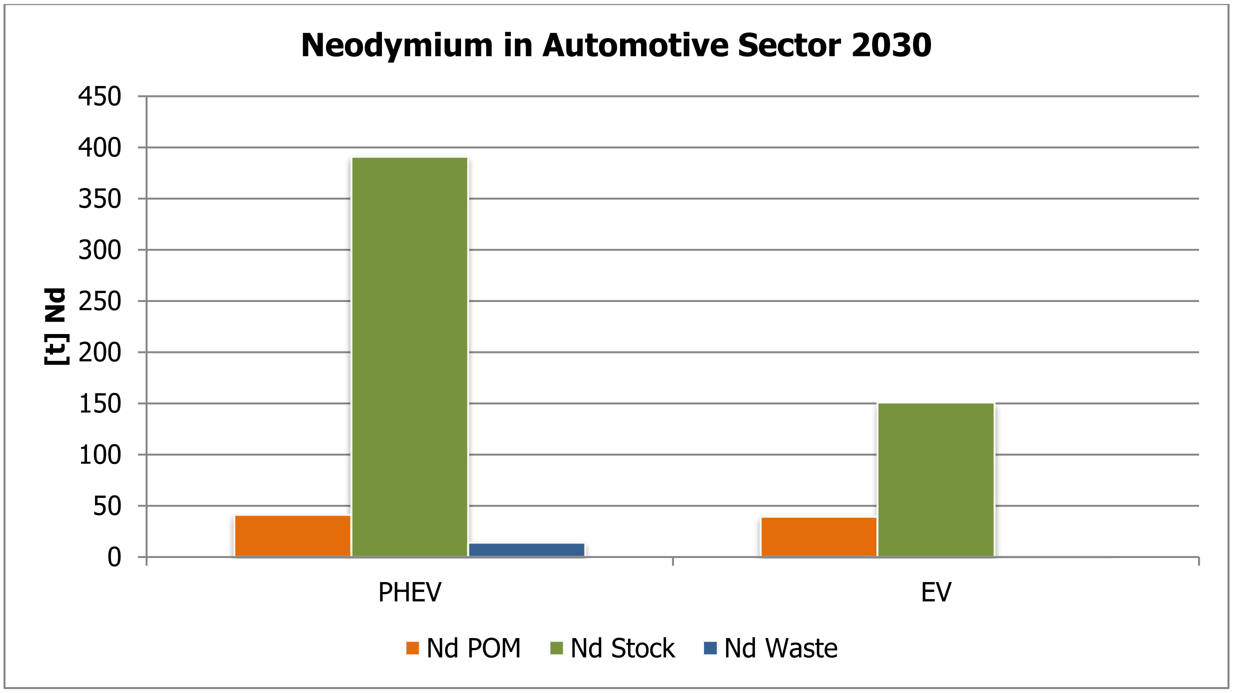
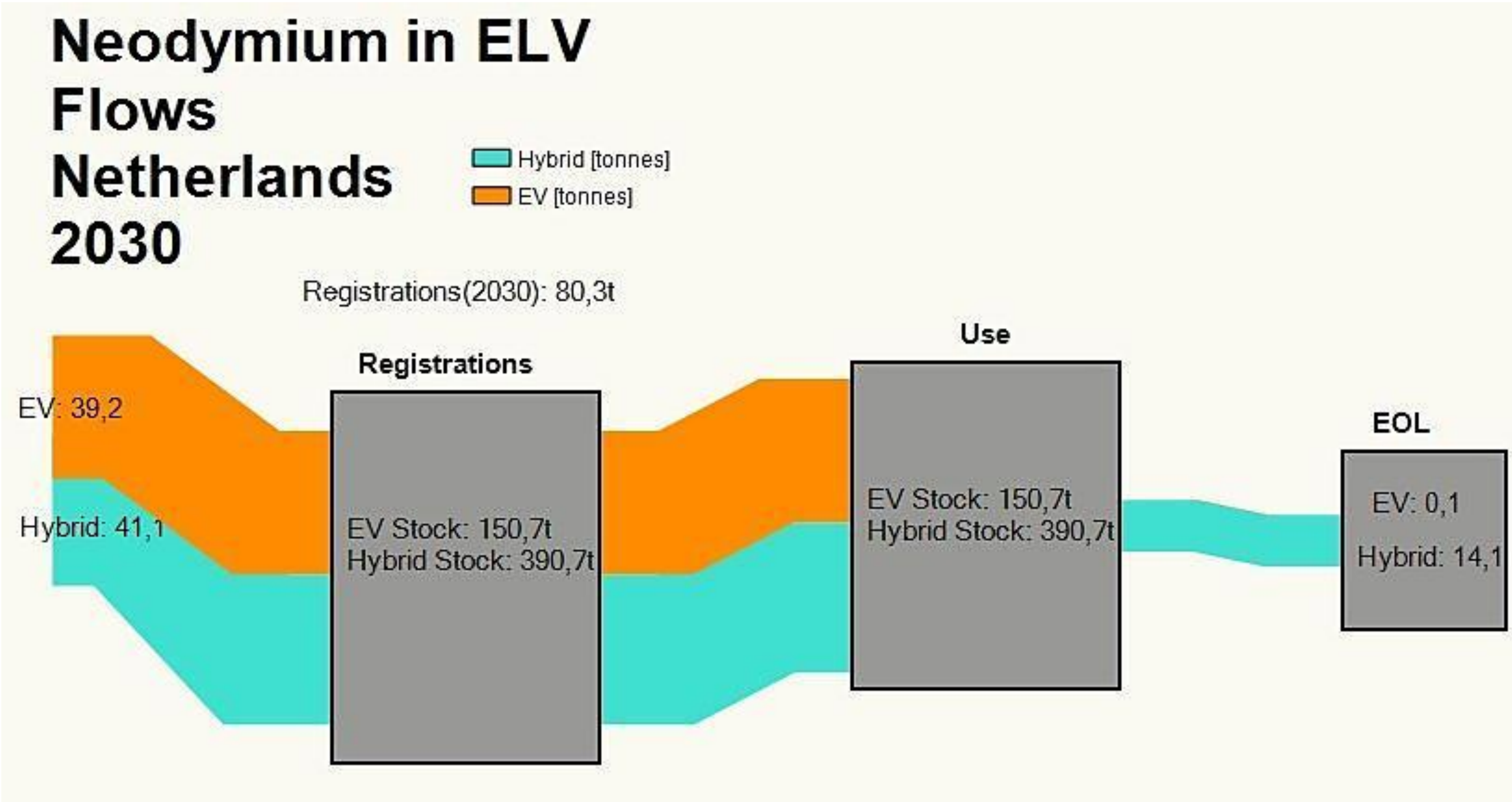


Figure 25: Illustration of the magnitude of neodymium in new registrations, stock and waste stream for both PHEVs and EVs based on the parameters described in Annex A14b

Moreover the size of the neodymium stock highlighted in Figure 25 illustrates the volume of forthcoming flows. If growth rates for only PHEVs would continue at 6% until 2040 with all other parameters remaining the same, the amount of neodymium entering the Dutch economy would total 73,6t and the total neodymium waste from PHEVs would increase to 22,7t. Consequently the theoretical potential of secondary neodymium would increase to 31% of total neodymium entering the economy in PHEVs.

Embedding the neodymium flows in the automotive sector into the circular economy discourse, from 2011-2029 approximately 180.000 PHEVs and EVs became waste. This amounts to approximately 160t of neodymium, equivalent to the all the neodymium entering the waste stream between 2011-2029 in smartphones, laptops, speakers and CD/DVD/blu-ray players. Should the current EOL management of ELVs continue, namely through large scale shredding and no removal of neodymium applications, large amounts of neodymium totaling US$13,5 million will be lost. Stocks and flows of neodymium in PHEVs and EVs are visualized in the Sankey diagram below.


Neodymium in ELV Flows Netherlands 2030
Hybrid [tonnes]
EV [tonnes]
Registrations(2030): 80,3t
Registrations
Use
EOL
EV: 39,2
Hybrid: 41,1
EV Stock: 150,7t
Hybrid Stock: 390,7t
EV Stock: 150,7t
Hybrid Stock: 390,7t
EV: 0,1
Hybrid: 14,1

9.4 Wind turbines

Results

With the Netherlands striving to fulfill its renewable energy targets by 2020, it will have to increase total energy consumption from renewable energy from the 4,9% in 2014 to 14% in 2020 according to CBS. To achieve this target, the Dutch government has proposed ambitious 2020 and 2030 projections of for renewable energy consumption of which wind energy is projected to contribute the most among all renewable energy sources at 43% (Rabobank International 2012).

In 2015 the total cumulative wind energy capacity was 2955 MW from 1577 wind turbines according to www.thewindpower.net. With an increase in wind energy expected to reach 8090 MW in 2020 and 18770 MW in 2030, installation of wind turbines will have to accelerate from an addition of 125 wind turbines in 2015 to 843 wind turbines per year from 2016-2020 and 1367 wind turbines from 2021-2030. For assumptions and exact calculations refer to Annex A14c to this research.

With increased efficiencies and reduced maintenance times, especially beneficial for offshore wind farms that are difficult to reach, Habib and Wenzel 2014 and Hoenderdaal et al. 2013 predict DDPM market share to increase to 20% by 2020 and 30% by 2030, based on consultations with NdFeB permanent magnet manufacturers and wind turbine producers. This research will apply the same DDPM market share with linear growth per year assumed. Methodology and exact DDPM market share results per year are found in Annex A14c to this research.

Based on all parameters applied to the 2010 wind turbine landscape, the 2030 DDPM stocks and flows were modeled with neodymium results in Table 33.

2030		**POM**		**Stock**		**EOL**	
unit	*kg*	*units*	*t*	*units*	*t*	*units*	*t*
Item	Nd composition	total	Nd total	total	Nd total	total	Nd total
DDPM Wind turbine	196	410	**80,4**	3.872	**758,9**	7	**1,4**

Table 33: Neodymium distribution in new DDPM wind turbine installations, stock and EOL DDPM wind turbines

The results demonstrate a significant increase in neodymium from 1,4t in 2010 to 80,4t expected in 2030. The stock size swelled by a factor of 96 compared to the size of the stock in 2010. This is due to the long lifespans of wind turbines combined with rapid DDPM wind turbine erections only after 2015. Only after 2040 will DDPM wind turbines enter the waste stream in significant volumes.

Scenario mapping has illustrated parallels in neodymium behaviour in the renewable energy and automotive sectors. Both sectors have only recently consumed neodymium as it enables and/or substantially contributes to high performance of products needed to shift from fossil-based regimes to a sustainable economy. The automotive sector only consumed neodymium in trivial amounts in select EEE, such as motors needed for the anti-lock brake system, windshield wipers, loudspeakers etc until 1997 when the first Toyota Prius was introduced to the market (Yano, Muroi, and Sakai 2015). Since then over 8 million PHEVs have been sold (Toyota 2015). This hunger for neodymium in wind turbines only materialized in 2003 as gearless turbines were able to be designed with the incorporation of a massive

NdFeB permanent magnet. Reduction in maintenance and downtime resulted in them becoming favoured but neodymium price volatility has stymied their rapid uptake (Habib and Wenzel 2014).

Discussion on neodymium MFA in the Netherlands 2030

Using 2010 MFA assumptions and results as an entry-point for the scenario mapping exercise carried out in this Chapter, the Dutch industrial metabolism increased for all neodymium applications, especially in the automotive and renewable energy sectors.

The results demonstrate the reduced theoretical potential of secondary neodymium in contrast to 2010 results. In 2030 407t of neodymium entered the Dutch economy; neodymium via electronics increased by a factor of 2 whilst neodymium in the automotive and renewable energy sectors grew by a factor of 5 and 55, respectively. Quantification of the modeled neodymium waste stream in 2030 demonstrated the theoretical potential of secondary neodymium waste stream to be 43% of 2030 demand, highlighted in Figure 26 below.

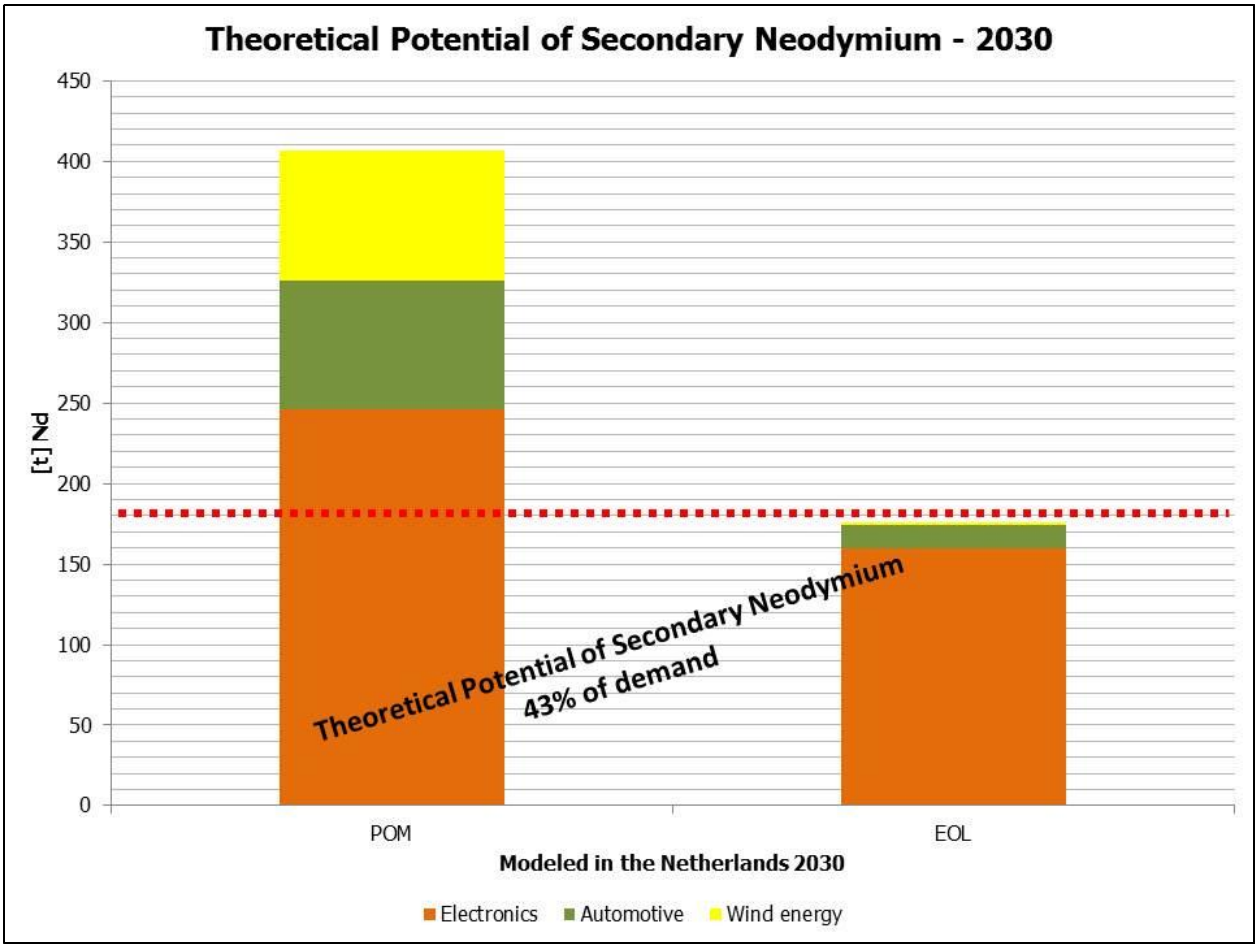


Figure 26: Theoretical potential of modeled secondary neodymium for reducing 2030 demand for primary neodymium

The reason for the reduced potential compared to 51% in 2010 is the growth in PHEV sales and DDPM installations since 2010, the long lifespans of those products resulting in a large neodymium stock. However these products will begin to enter the waste stream in larger quantities between 2040 and 2050 resulting in a higher theoretical potential of secondary recovery as long as growth rates decelerate.

Referring to the products in the Neodymium Sector-Product Portfolio, this research has again modeled 54% of all neodymium applications, as determined in Table 30 found in the conclusions of Chapter 8. Although it is likely that the percentage of neodymium demand per neodymium application will differ in 2030 compared to the 2008 demand distributions from Goonan 2011, this research will assume the figures will remain the same. If NdFeB permanent magnets consume 76% of all neodymium demand and 70% of all NdFeB permanent magnet containing products were modeled, total neodymium demand was calculated at 733t in 2030 in Table 34. Detailed calculations can be found in Annex A15b to this research.

	POM [t]	**EOL [t]**
Modeled		
Permanent magnets	390,1	171,5
Batteries	16,4	4,0
Not modeled		
Permanent magnets	167,2	
Alloys	58,7	
Batteries	20,3	
Ceramics	29,3	
Other	29,3	
Glass	14,7	
Catalysts	7,3	
Total neodymium demand NL 2030	**733,3**	**175,6**

Table 34: Estimated neodymium demand across all neodymium applications for 2030 based on distribution percentages from Goonan (2011); methodology can be found in Annex A14b.

Due to the long lifespans of the growing automotive and renewable energy sectors, neodymium primary demand in 2030 could have only been theoretically reduced by 24% using secondary neodymium in the 2030 Dutch waste stream visualized below in Figure 27.

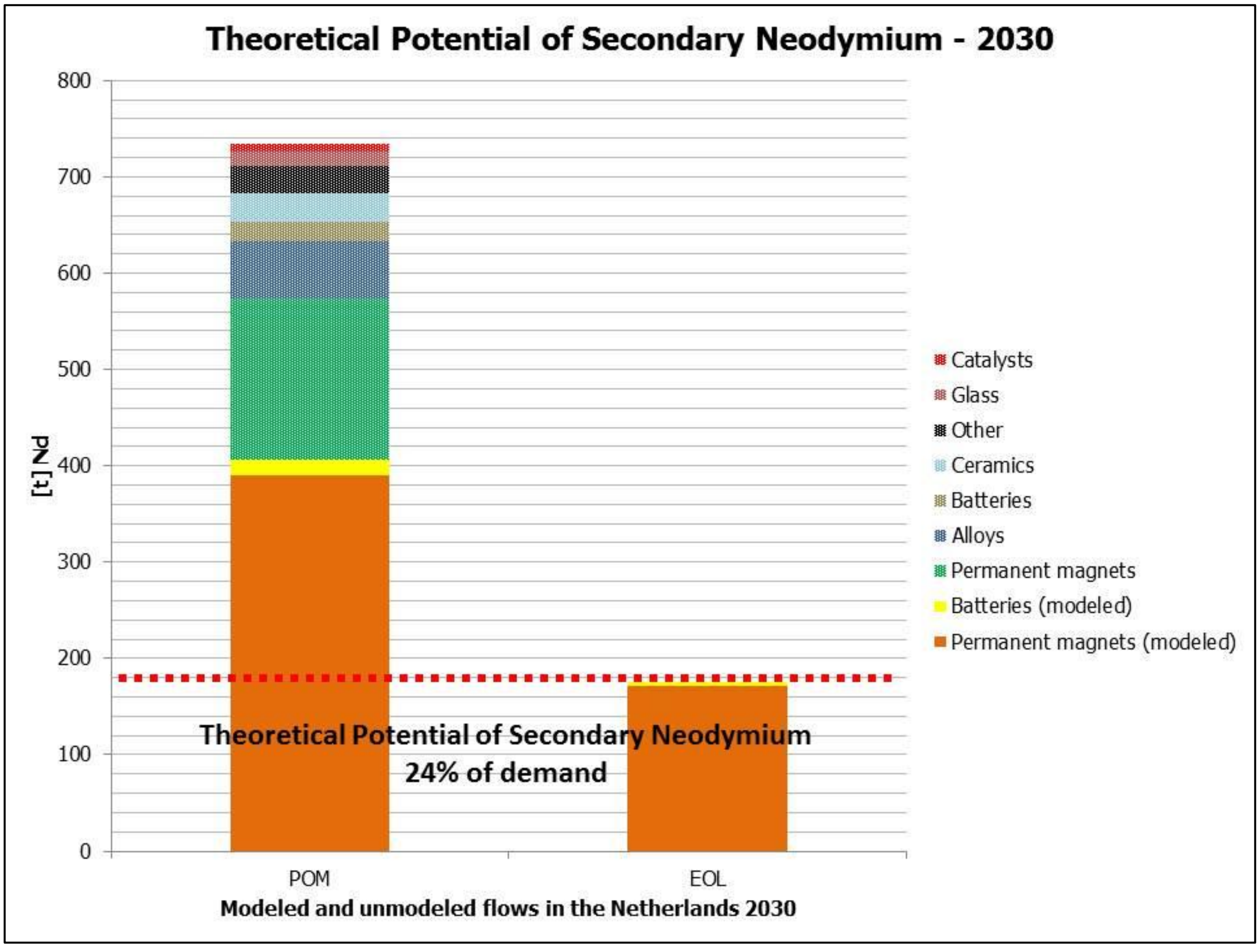


Figure 27: Theoretical potential of the modeled neodymium waste stream in 2030 based on neodymium demand distributions per neodymium application from Goonan (2011).

Because the 2030 theoretical recycling potential in Figure 27 is based only on modeled neodymium in the waste stream, the waste stream would likely increase should stocks and flows as well as compositions data on other NdFeB permanent magnet containing products become available; for example, for electric bikes and power tools. Moreover as metallurgical alloys, ceramics, glass and other application comprise 18% of neodymium demand, investigation on exact compositions and mapping could further reduce demand for primary neodymium, if collected and recovered accordingly.

10 Impacts on criticality

Referring back to the three criticality methodologies described in Chapter 2 and with the theoretical potential of secondary neodymium in 2010 and 2030 modeled in Chapters 8 and 9 of this research, respectively, the pertinent datasets are available to generate a new neodymium supply risk value for both 2010 and 2030 using the European Commission (EC) methodology in Chapter 2.1.1 under the following assumptions:

i. Supply=demand;
ii. China is the only source of virgin neodymium in 2010 and 2030 and its World Governance Indicator score remains the same for 2030 as 2010
iii. The neodymium stocks and flows modeled in the Netherlands in 2010 and 2030 is representative of global neodymium stocks and flows;
iv. All neodymium entering the waste stream in products collected in the Netherlands is recycled using the hydrometallurgical process cited by Sprecher, Kleijn, and Kramer 2014 with a 95% recovery rate.

The new supply risk will be generated for 2010 and 2030 against three different neodymium collection rates signified by the lower bound, business as usual (BAU) and upper bound scenarios based on assumptions illustrated in Table 35.

Sector	**Lower Bound**		**BAU**		**Upper bound**	
	Collection rate	Note	Collection rate	Note	Collection rate	Note
2010						
WEEE	35%	Arbitrarily chosen	65%	Collection rate of neodymium-containing WEEE in the NL 2010 from Chapter 8	100%	Highest maximum collection rate to demonstrate potential
ELVs	76%	Lowest ELV collection rate in EU27 in 2010 (Liechtenstein)	83%	Collection rate of ELVs in the NL 2010 according to Eurostat	95%	2015 recycling rate stipulated by the EU Directive on ELVs, 2000/53/EC
Wind	0%	No DDPM turbines entered the waste stream	0%	No DDPM turbines entered the waste stream	0%	No DDPM turbines entered the waste stream
2030						
WEEE	45%	2016 collection target under WEEE Directive 2012/19/EU	65%	2019 collection target under WEEE Directive 2012/19/EU	100%	Highest maximum collection rate to demonstrate potential
ELVs	76%	Lowest ELV collection rate in EU27 in 2010 (Liechtenstein), applied to 2030	83%	Collection rate of ELVs in the NL 2010 according to Eurostat, applied to 2030	95%	2015 recycling rate stipulated by the EU Directive on ELVs, 2000/53/EC
Wind	100%	Maximum collection due to massive size	100%	Maximum collection due to massive size	100%	Maximum collection due to massive size

Table 35: Assumptions on collection rates for WEEE, ELVs and EOL wind turbines for three different scenarios, lower bound, BAU and upper bound; results are subsequently applied to MFA results from Chapters 8 and 9 in order to calculate adjusted supply risk values for 2010 and 2030, respectively

After applying the assumptions from Table 35 to the theoretical potential of secondary neodymium in the WEEE, automotive and renewable energy sectors, neodymium amount recovered per sector per scenario are exhibited in Table 36.

Item	**Lower Bound**				**BAU**				**Upper Bound**			
	WEEE	ELV	Wind	Total	WEEE	ELV	Wind	Total	WEEE	ELV	Wind	Total
2010												
EOL total [t]	127	1,2	0	128,2	127	1,2	0	128,2	127	1,2	0	128,2
Collection rate [%]	35%	76%	100%		65%	83%	100%		100%	95%	100%	
Recovery rate [%]	95%				95%				95%			
Total recovered [t]	42,2	0,9	0,0	**43,1**	78,4	0,9	0,0	**79,4**	120,7	1,1	0,0	**121,7**
2030												
EOL total [t]	160	14,2	1,4	175,6	160	14,2	1,4	175,6	160	14,2	1,4	175,6
Collection rate [%]	45%	76%	100%		65%	83%	100%		100%	95%	100%	
Recovery rate [%]	95%				95%				95%			
Total recovered [t]	68,4	10,3	1,3	**80,0**	98,8	11,2	1,3	**111,3**	152,0	12,8	1,3	**166,1**

Table 36: Total neodymium recovery in the Netherlands in 2010 and 2030 based on collection rate and recovery rate assumptions in Table 38 for the EEE, automotive and renewable energy sectors building on the modeling resulting from Chapters 8 and 9 to this research

Against (i) the four neodymium assumptions outlined at the beginning of this Chapter in combination with (ii) the three different neodymium recovery scenarios illustrated in Table 36, an adjusted neodymium supply risk can be calculated using the following equation from the EC where overall supply risk score is a composite score between 0-10. This is determined by the equation below where SR is supply risk, σ is the substitutability, ρ refers to the secondary material:virigin material demand percentage and HHI_{WGI} aggregates virgin extraction concentration and the country's governance into one value. A SR>1 results in a supply risk designated as critical. For detailed steps on the calculation refer to Annex A17 to this research.

$$SR = \sigma(1-\rho)HHI_{WGI}$$

Item	**EC**	**Lower Bound**	**BAU**	**Upper Bound**
2010				
Recovered Nd [t]	NA	43,1	79,4	121,7
Theoretical Potential	NA	17%	31%	48%
Supply risk score	4,86	3,45	2,86	2,16
2030				
Recovered Nd [t]	NA	80	111	166

Theoretical Potential	NA	11%	15%	23%
Supply risk score	NA	3,7	3,5	3,2

Table 37: New neodymium supply risk generated using neodymium MFA results from Chapter 8 of this research which were adjusted to lower bound, BAU and upper bound scenarios accordingly; detailed calculations can be found in Annex A17 to this research

The results denoted in Table 37 demonstrate that even if neodymium in the electronics, automotive and renewable energy sectors are collected and subsequently recovered, neodymium supply risk remains critical in all three scenarios on 2010 and 2030 as it still exceeds 1. There are two dominant culprits for maintaining a critical supply risk, namely:

- A high HHI_{WGI} (6,2) score resulting from the high World Governance Indicator score for China and primary production monopolized by the Chinese
- the long life spans of neodymium-containing PHEVs and DDPM wind turbines and subsequent delays entering the waste stream, especially in 2030

However, although still critical, supply risk in 2010 was substantially reduced through neodymium recycling in the BAU and upper bound scenarios to supply risk levels of niobium (2,8) and indium (2,02), respectively (Oakdene Hollins and Faunhofer ISI 2014). Considering only downstream intervention, the 2010 and 2030 supply risks would only become non-critical if the collection rate of the neodymium-containing products modeled in Chapters 8 and 9 was increased to 80%. Supply risk could further be stymied with primary production diversification, a higher substitutability score or reduced WGI value for China.

11 Discussion and recommendations

In order to embed the 2010 and 2030 neodymium modeling results into a broader institutional framework, this Chapter will explore how the results can practically contribute to a more circular neodymium economy and which follow-up activities could be implemented. The necessary stakeholders who will be instrumental in the implementation of these recommendations have been explicitly identified although most of the recommendations require cooperative action of many stakeholders. Overview of each recommendation is show in Table 38.

Recommendation	Stakeholder	Description
PR1	Policymakers	Optimization of collection through a bill of materials
PR2		Establishment of collection rates for ELVs
PR3		Financing instruments for recycling
PR4		Creation of a secondary materials repository
RR1	Recyclers	Assessment of costs and neodymium yields
RCR1	Researchers	Improvement of neodymium primary production datasets, geological surveys to publish disaggregated REE figures
RCR2		Rectify neodymium application demand data
RCR3		Chemical analysis of neodymium composition in products containing catalysts, ceramics, glass and metallurgical alloys
RCR4		Measure data quality of existing compositions sources
RCR5		Widen MFA scope to include products containing neodymium catalysts, ceramics, glass and metallurgical alloys
RCR6		Widen MFA scope to include recyclability
RCR7		Integrate environmental and economic dimensions

Table 38: Compendium of results and the corresponding stakeholder group

11.1 Recommendations for policymakers

The European Union has prioritized sustainable access to materials as vital to its economy. With the implementation of the WEEE Directive 2012/19/EU and ELV Directive 2000/53/EC in 2003 and 2000 respectively, the European Union attempted to stymie the environmental and public health impacts associated with the production, use and disposal of (W)EEE and (EOL) vehicles. In 2008 the EC formally implemented the Raw Materials Initiative (RMI) which sustainably strives to meet the energy and materials needs of the EU while simultaneously stimulating employment opportunities. One pillar of the RMI is dedicated to improving waste flow statistics as well as secondary supply of materials through recycling. Under the RMI the European Innovation Partnership (EIP) on Raw Materials brings together stakeholders from government, industry, research and NGOs for agenda setting and steering of activities. One deliverable of the EIP was the Strategic Implementation Plan (SIP) which aims, among others, to reduce materials criticality through harvesting the urban mine (EU 2015).

In order to further support the initiatives and inform policy, the following recommendations address policymakers:

11.1.1 Optimize targets

The first link in the recycling chain is the collection of products that have been discarded as waste (Wang 2014). The WEEE Directive Recast 2012/19/EU, Article 7 set annual collection targets for each EU28 Member State. From 2019 onward Member States have a choice of achieving a collection rate of *65% of the average of EEE POM in the three preceding years in the entire EU* or *85% of WEEE generated in their* *territory* (European Commission 2012). In order to implement the legislation Member States have established WEEE compliance schemes responsible for organizing the collection and logistics of WEEE to recyclers. Compliance schemes are funded through the EEE producers based on producer market share per appliance and in the case of the Netherlands, the consumer contributes by paying an advanced recycling fee (ARF) at point of sale (Perchard 2011).

The ELV Directive 2000/53/EC, Article 7, lays out a recovery rate at 95% and recycling rate at 85% per vehicle starting 1 January 2015 but does not stipulate a collection rate like the WEEE Directive. The EOL management structure of ELVs is similar to WEEE with Rai Vereniging representing automobile producers and importers while Automobiel Recycling Nederland (ARN) manages the EOL processing and recycling of ELVs in the Netherlands through funding from the advanced recycling fee paid by the consumer (ARN 2007).

- PR1: Based on the results of the neodymium MFA in Chapter 8, only 65% of neodymium-containing WEEE were formally collected. Current collection targets are one dimensional: a percentage of total, aggregated mass of e.g. waste generated. In order to prioritize collection and to determine which products should enter which recovery stream, this research recommends further investigation into incorporating a bill of materials on products. The bill of materials would indicate the materials composition of each product. Establishing a bill of materials per product will however be challenging as supply chains for individual products are extensive and would require cooperation and compliance among all supply chain stakeholders, even in developing countries. Moreover considerable heterogeneity exists in individual product groups, e.g. as some laptops use SSDs while others HDDs. If, however, a bill of materials was possible, it could be connected to a point of sale (POS) at retailers with the material addition to an economy updated in real time. Furthermore the cascading impacts could optimize collection efficiency by establishing streamlined sorting and ensuring products enter an appropriate pre-processing stream. Result could be a diversified supply of neodymium via maximized material recovery.

- PR2: The ELV Directive 2000/53/EC does address collection in Article 5 but does not set collection targets. According to this research 500.000 vehicles entered the Dutch waste stream in 2010 but only 43% entered a formal collection channel; 50% were exported. It was unclear from the literature the reason for export but this research would recommend the establishment of collection rates to ensure ELVs enter a formal waste stream in the Netherlands.

- PR3: If the SIP is to be implemented, neodymium recycling rates also have to be stimulated from their current rates of <1%. Keeping in mind the intrinsic value of neodymium in 1t of PCs is 50€, policymakers should explore different financing instruments, such as a criticality tax, that could make neodymium recovery profitable, especially in products with a net-negative value after labour and treatment costs are absorbed. This will require cooperation with recyclers in order to understand current financial and operational business models.

11.1.2 Secondary materials repository

The experience made in this research demonstrated the challenge in determining the role of the urban mine because of the absence of disaggregated neodymium datasets, both from the supply side and its ultimate societal digestion. Consequently, without an accurate overview of the materials urban mine, it becomes impossible to accurately gauge the effectiveness of particular policy responses, such as recycling. Using the theoretical potential of secondary neodymium in the Netherlands as a global proxy, the modeling in 2010 and 2030 demonstrated the limited role of recycling in reducing criticality. Yet the data digging exercises and their synthesis expended tremendous amounts of time and capacity which could be circumvented through a centralized repository of the urban mine across all materials.

- PR4: In policy recommendation 1 (PR1) it was advocated to include a bill of materials on all products in order to identify corresponding materials composition. This recommendation would benefit from such a bill of materials as total sales of a particular product could shed light on materials entering an economy through that product. Such data could enter a web-hosted database at POS illustrating not only the size of the inflows, but their sources as well. Combined with average lifespans, such a repository would illustrate the metabolism of individual materials.

Illustrated in Figure 28 individual suppliers require material inputs in order to manufacture their products. If a compliance mechanism, most likely administered by OEMs, would require individual suppliers to disclose materials information per component, a bill of materials per product would be possible. As products are sold, materials information is funneled into a secondary materials repository. Interpretation of these results from the scientific community could inform policymakers and stakeholders in the recycling chain which product streams contain which materials. Ultimately better insights into the materials makeup of waste products can support EOL management including smart sorting, manual dismantling and appropriate pre-processing techniques.

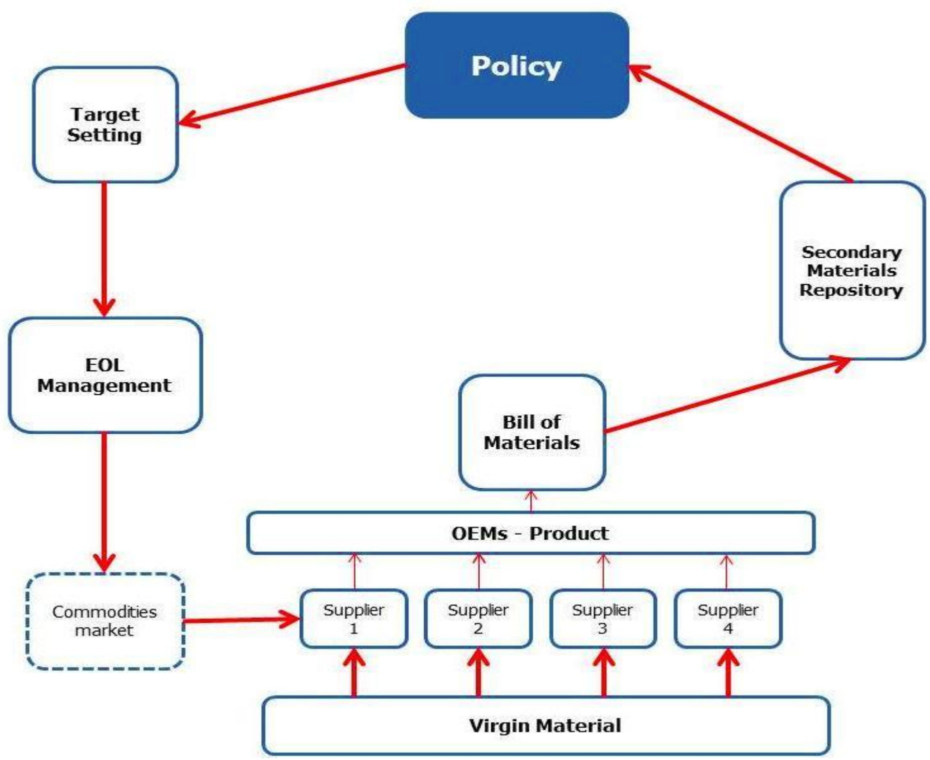


Figure 28: Flow chart illustrating the role of a bill of materials per product

11.2 Recommendations to recyclers

Although recycling was not included in the scope of this research, recyclers will play an instrumental role in the recovery of neodymium. Currently recyclers' flowsheets do not include recovery of neodymium due to the lack of recycling technologies and absence of economies of scale. If a batch of HDDs enters a smelter for recovery of precious metal content, neodymium is oxidized in the process and lost in slags (Voßenkaul, Kruse, and Friedrich, n.d.). As full ELVs are fed to a shredder, the neodymium is pulverized and not recovered from the residue.

- RR1: It is recommended to assess the economic implications and material yields from the last two steps of the recycling chain – pre-processing and end-processing – of different products. Assessment could be made using the matrix in Table 39.

	Labour				**Operational**				**Mass balance**		**Losses**	**Material value**	
Process	# employ-ees	wage/ hr [EUR]	# hrs	cost [EUR]	% building	building cost [EUR]	% equip	equip. cost [EUR]	Nd in [g]	Nd out [g]	Nd [g]	yield [EUR]	losses [EUR]
Pre-processing													
Manual dismantling													
Pre-shredding													
Fully-automated shredding													
End-processing													
Pyro-metallurgy													
Leaching													
Gas-phase extraction													
TOTAL													

Table 39: Potential material and economic assessment of neodymium pre- and end-processing

It is recommended that an analysis similar to the template in Table 38 be carried out in order to demonstrate the (lack of) economic and material salience on a practical level.

11.3 Recommendations to the research community

Emerging from the results of this research were opportunities to complement and strengthen the profile of neodymium generated in this work.

11.3.1 Supply-demand

- RCR1: Existing literature from the BGS and USGS provide comprehensive, although aggregated REE primary production datasets per country. The methodological approach taken to determine disaggregated neodymium supply data in this research is uncertain although likely to have improved first estimates from Du and Graedel 2011a as it reconciled their datasets with the BGS. Consequently it would be advantageous for the research community, in cooperation with the USGS, BGS or EuroGeoSurveys, to complement the production results in this work. It would moreover be recommended for all Geological Surveys to publish disaggregated primary production figures henceforth due to their deviating magnitudes of importance.

- RCR2: To calculate disaggregated neodymium demand from 2008-2015, this research applied the 2008 demand distributions percentages per neodymium application from Goonan 2011 to the aggregated REE demand datasets from D. Kingsnorth 2013. Because it is highly likely demand growth did not increase proportionately across all applications, it is recommended that follow up research improve these first estimates.

11.3.2 Compositions

- RCR3: Conduct neodymium compositions analyses on catalysts, glass, ceramics and metallurgical alloys. Due to the lack of these datasets, this research only identified compositions for 70% of the products in the Neodymium Sector-Product Portfolio. Neodymium quantities in products containing these applications are unknown but that does not imply insignificance. This research demonstrated that white goods and cooling & freezing appliances were the overwhelmingly main source of neodymium demand in the electronics sector, not the HDDs as reported by the majority of sources in the literature. Unidentified neodymium hotspots may emerge from these analyses.
- RRC4: Assess the data quality of existing compositions sources. This research attempted to measure the quality of compositions sources in Chapter 7.2.1 but more capacity should be devoted to comparatively examine how different approaches (e.g. input-driven vs. output-driven) of each source can influence results, similar to Widmer et al. 2015 in their assessment of scare materials composition approaches in ELVs.

11.3.3 MFA scope

- RRC5: Determining which neodymium-containing products were in scope in this research depended on the availability of compositions as well as stocks and flows data. As a result this research modeled 60% of the neodymium urban mine. Follow-up research should widen the scope to include products containing neodymium catalysts/glass/ceramics/alloys as well as electric bicycles and MRIs likely potent sources of neodymium.
- RC6: This research only modeled the first step in the recycling chain, collection/uncollected/export. The result led to the theoretical potential of secondary neodymium without quantification of the overall recyclability and recoverability associated with pre-processing and recovery. Including these steps in the scope will certainly lower the theoretical potential of secondary neodymium and provide insights into the recycling process. Therefore scope should be expanded in follow-up studies to include recyclability of neodymium-containing products.

11.3.4 Environmental-economic dimension

- RC7: Using LCA impact categories to explore the environmental dimension of neodymium primary production and its secondary recovery could contribute higher levels of legitimacy to its recovery. Such a comprehensive assessment could be further enhanced by measuring and comparing the costs precipitating from neodymium virgin extraction with EOL management and recovery.

This research modeled and characterized neodymium flows in the Netherlands and embedded the results into the broader supply-demand-criticality discussion. This chapter further contextualized the outcomes providing policymakers, recyclers and researchers with follow-up activities to improve and implement the results of this research.

12 Conclusions

Virgin extraction of neodymium and its manufacturing into durable products is monopolized by one country with 98% of its primary production coming from China in 2010. Neodymium applications are ubiquitous in modern-day electronics with neodymium-iron-boron (NdFeB) permanent magnets enabling higher power and miniaturization. Neodymium is moreover becoming increasingly relevant to a decarbonizing economy due to its relevance to electric mobility and wind energy. However, once these products become waste, >99% of secondary neodymium is lost due to the low formal collection rates, absence of economies of scale and nascent recycling technologies. With a cascading effect of (i) increased neodymium supply risk in combination with (ii) its economic importance, neodymium has been identified as critical by virtually all non-fuel mineral criticality assessments, including those from the European Union and US Department of Energy. For this reason this research attempted to determine the extent to which neodymium criticality could be reduced through quantifying the potential of the neodymium urban mine in 2010 and 2030, using the Netherlands as a case study. Analytical tools used to carry out this assessment were material flow analysis (MFA) and scenario mapping.

The conclusions generated in this research will be answered by returning to the six sub-questions and main research question.

SQ1: Is it possible to model historical neodymium primary production rates from 1990-2015 and their geographical source of extraction?

Obtaining complete, comprehensive data on neodymium primary production for 1990-2015 was impossible as they did not exist in the literature prior to this research notwithstanding under-calculated first estimates for 1995-2007. Therefore this research filled that gap by reconciling (and improving):

1. Annual neodymium primary production estimates with
2. Aggregated, annual REE production figures per country

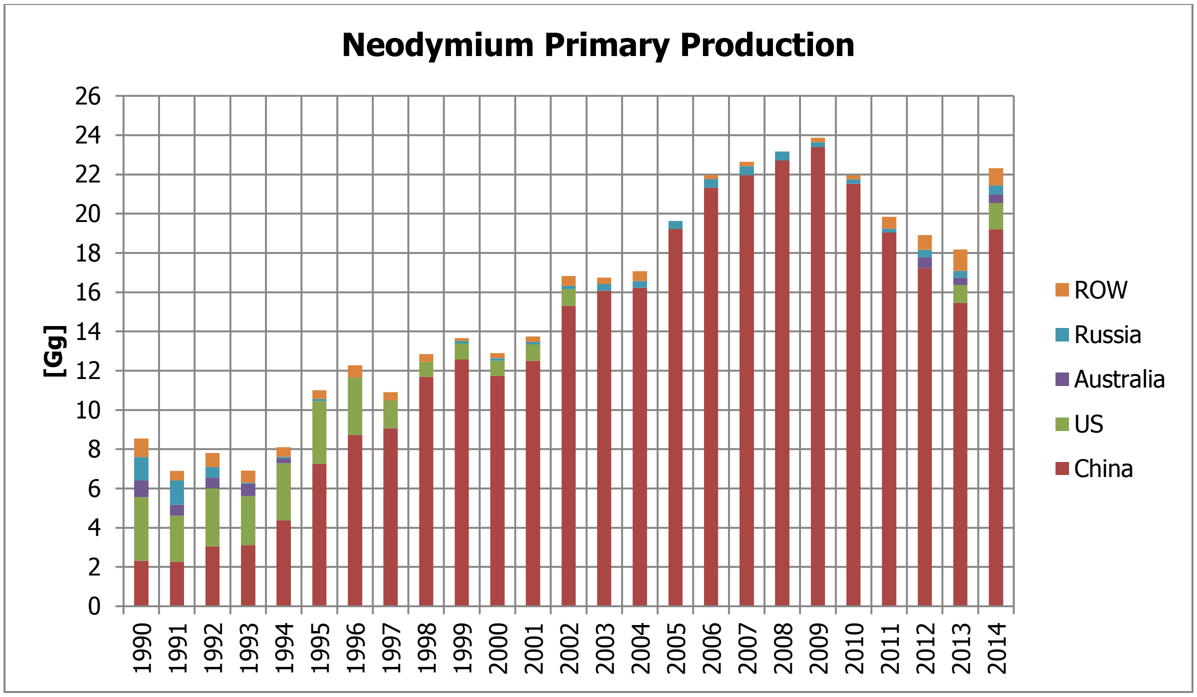


Figure 29: Primary production of neodymium and its geographical distribution, 1990-2015

It becomes clear in Figure 28 that primary production of neodymium has steadily increased since 1990 from 8,5Gg in 1990 to 22,3Gg in 2014. In the same timeframe diversification of supply generally decreased since 1990 as it became economically unviable for the developed world to exploit lithospheric neodymium, beginning in the mid-1990s. Incremental diversification of neodymium production commenced again in 2011 and demonstrated the cogency of the lithospheric buffer outside China, further supported by the fact that as of 2011, 52% of global REE reserves were outside China. Moreover, coalescing with the increase in supply diversification starting in 2011 with rampant mining exploration activities, the REE reserve base in China decreased from 48% in 2011 to 39% in 2014. Therefore primary production of neodymium is elastic and dependent on reserve base and concerted exploitation thereof.

SQ2: Is it possible to quantify and analyse neodymium supply-demand dynamics over time in order to substantiate its criticality?

Building on the results from SQ1 (supply), this research modeled the neodymium demand curve from 2008-2015 by applying neodymium demand distribution percentages per neodymium application to aggregated REE demand per year for the same timeframe.

Only a slight increase of 13% in global demand for neodymium was observed from 2008-2015 as it increased from 23,9Gg in 2008 to 27,0Gg in 2015. Partly to blame for mild demand growth was the financial crisis and decreased wages (Europäische Kommission (Hrsg.) 2009). However when a generally increasing demand was juxtaposed onto decreasing neodymium supply due to Chinese export quotas, the infamous rare earth crisis and speculation thereof ensued resulting in extraordinary price increases by 1400% in 2011 compared to previous years. The market responded and prices stabilized in 2012 as demand consequently decreased from 2010-2011, from 21,6Gg to 18,9Gg.

Discussed in Chapter 2 market resilience emerged from the threat of material shortages as neodymium stakeholders responded. Upstream, activities to boost supply efforts increased, including exploration of >20 new mines worldwide and the re-opening of the Molycorp mine in the US (Schüler et al. 2011). Simultaneously producers began canceling contracts with NdFeB permanent magnet suppliers and steered capacity toward finding neodymium substitutes and new product designs without neodymium. Downstream, vast research was carried out at the experimental level on recycling of neodymium although never expanded to industrial levels.

SQ3: Which sectors and products incorporate neodymium applications in their design?

In order to accurately model neodymium stocks and flows in the Netherlands, this research created the Neodymium Sector-Product Portfolio presented in Chapter 7.1. The Portfolio was used as a vehicle to spatially organize all 34 identified products containing one of 7 neodymium applications by assigning each product to one of 6 sectors.

The electronics sector contained 20 of all products absorbing neodymium illustrating the potency of individual EEE evolution on broader neodymium demand. At the same time the automotive sector comprised 5 products as electric mobility has gathered market traction in the past 10 years as the global economy is in transition to decarbonizing. Although this research illuminated the difficulty in predicting product trends, the Neodymium Sector-Product Portfolio demonstrated an inherent strength in shifting toward a neodymium circular economy: the collection of 75% of all neodymium-containing products is already covered by existing waste legislation – WEEE Directive 2012/19/EU and ELV Directive 2000/53/EC. If Member States meet their collection targets, these secured, secondary sources of neodymium will enter a formal EOL management system.

SQ4: Are neodymium compositions available for all products incorporating neodymium applications?

The Neodymium Sector-Product Portfolio was extended to include neodymium compositions per product, a prerequisite for quantifying the neodymium urban mine. However neodymium compositions were available for only 24 of the products, 23 of which contained a NdFeB permanent magnet. Of those products containing a permanent magnet, 15 were from the electronics sector, 3 from the automotive sector and 1 from the renewable energy sector.

Emerging from the analysis was those EEE with the highest amounts of neodymium per product were addressed substantially less than those products with the lowest neodymium compositions. White goods and cooling and freezing appliances, ubiquitous commodities, contain 73 and 28 times more neodymium per product than laptops, respectively; yet, HDDs in laptops were included in 100% of neodymium assessments and white goods and cooling and freezing in only one analysis. This research concludes that disproportionate compositions attention is likely dependent on a few factors:

- Net positive value of IT after recycling due to the presence of precious metals in HDDs adding another advantage to its analysis
- White goods and cooling and freezing appliances are large, bulky and difficult to dismantle, influencing its incorporation in compositions assessments
- Multiple use of one data source

Availability of compositions data for PHEVs and DDPM wind turbines was adequate which is likely due to their large neodymium requirements and the expectation they will overtake the electronics sector and become the chief end destinations of neodymium over the next 30 years.

SQ5: Are there sufficient data on stocks and flows of neodymium-containing products in the Netherlands in 2010?

There were three filters through which the cascading results from SQ3, SQ4 and this sub-question determined which neodymium-containing products in the Netherlands would be modeled in this research. First only those products in the Neodymium Sector-Product Portfolio with available compositions would be candidates; secondly only those candidates for which POM, stock and waste generated data for 2010 would be modeled.

The results demonstrated that 60% of all products in the Portfolio contained both (i) compositions and (ii) sufficient stocks and flows data in the Netherlands in 2010. From the total 20 products modeled, 15 were EEE, 4 automobiles and 1 renewable energy product. Neodymium in catalysts, ceramics, glass and metallurgical alloys were not modeled.

The absence / existence of waste legislation dictated for which neodymium-containing products accessible stocks and flows datasets were available. Because of the adverse environmental impacts on the environment due to their energy-intensive production and the potency of their hazardous material content, EOL management of WEEE and ELVs is regulated by the WEEE Directive 2012/19/EU and ELV Directive 2000/53/EC, respectively. In order to enforce and measure the effectiveness of these legislations, robust datasets on sales, stocks and EOL destinations have been generated and maintained. The management of products such as mischmetal-containing lighter flints or neodymium glass are not regulated thereby disincentivizing compilation of stocks and flows statistics.

As a result in order to model neodymium-containing products using only MFA, they must generally fulfill the following requirements:

- Filter 1 (product): They must be collated in the Neodymium Sector-Product Portfolio
- Filter 2 (composition): They must have a positive net value after EOL management and/or be small and easy to dismantle
- Filter 3 (stocks and flows): Their environmental impact from production, use and/or disposal must be negative

SQ6: How can a neodymium future in the Netherlands in 2030 be ascertained with uncertainty regarding evolution in the neodymium landscape?

Forecasting future product trends is inherently uncertain due to many external forces directly and indirectly influencing product growth and its consumption. The 2010 MFA results nonetheless provided a baseline upon which the neodymium landscape in the Netherlands could materialize, complemented by parameters on product growth, market share incorporating neodymium, product lifespans and EOL behaviour.

MAIN RESEARCH QUESTIONS: With increasing global demand for neodymium, to what extent could secondary neodymium (i) reduce neodymium criticality as well as (ii) the demand for virgin neodymium incorporated into products put on the market in the Netherlands in 2030 using 2010 as a reference year?

The results of the MFA in Chapters 8 and 9 illustrate the theoretical potential of secondary neodymium in products entering the Dutch waste stream in 2010 and 2030 at 51% and 24%, respectively, against total estimated neodymium demand in all products of the Neodymium Sector-Product Portfolio.

The 2010 results illustrate the cogency of the Dutch neodymium urban mine considering only 60% of the neodymium waste stream was modeled in this research. If the Dutch scenario is representative of the global neodymium landscape, neodymium virgin supply could have been substantially diversified thereby reducing dependence on China and stymieing the environmental impacts associated with primary production. Practically the results are grimmer. Only 84t or 65% of neodymium entering the Dutch waste stream in 2010 was formally collected; 16% was exported and 19% was uncollected. And no neodymium was recovered by recyclers in 2010 as the required technologies do not exist on an industrial scale due to the absence of economies of scale. Economically 2010 neodymium losses in the Netherlands total €8,3 million. Many different stakeholders share responsibility for this missed opportunity including policymakers, enforcement agencies, producers, consumers and recyclers.

In order to fulfill governmental wind energy and electric mobility targets, the PHEV and DDPM wind turbine market grew by a factor of 5 and 57 from 2010-2030, respectively. Due to rapid growth rates and long lifespans, the theoretical potential of secondary neodymium in 2030 at 24% was significantly lower than 2010 as the neodymium stock swelled. This should alert policymakers that even though the role of secondary neodymium may be marginal in 2030, it will increase substantially starting in 2040 due to the outflow delay.

The European Commission (EC) identified the REEs as having the most critical supply risk (4,9/5) of all other assessed minerals in 2010. When the EC supply risk formula in Chapter 2.1.1 was applied to three different recycling rates described in Chapter 10, neodymium still remained critical receiving a 2,2 in upper-bound collection-recycling and 2,9 in a business as usual (BAU) situation. The 2030 supply risk became more critical as it increased to 3,5 in the BAU scenario.

In a broader, systems context, materials weakness emerges from materials criticality. This research has demonstrated that although a total circular economy is ideal, it is not possible for all metals all the time. Moreover for some metals, like neodymium, recycling can reduce criticality but not completely. Exploitation of the urban mine is not a turn-key solution to material shortages but it is one diversification strategy that can contribute to a steady, sustainable supply.

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Appendix

A1 Extended description on REE carrier ores

In the two tables below are expanded descriptions of each REE and corresponding carrier ore.

REE	Distinction	Carrier ore	Prevalence [ppm]	Source
Lanthanum	LREE	bastnaesite, monazite	30	US-EPA
Cerium	LREE	bastnaesite, monazite	43-60	US-EPA, Polinares, BGS
Praeseodymium	LREE	bastnaesite, monazite	6,7	US-EPA
Neodymium	LREE	bastnaesite, monazite	27	US-EPA
Samarium	LREE	bastnaesite, monazite	5,3	US-EPA
Europium	HREE	monazite, xenotime	1,3	US-EPA
Gadolinium	HREE	monazite, xenotime	4	US-EPA
Terbium	HREE	monazite, xenotime	0,7	US-EPA
Dysprosium	HREE	monazite, xenotime	3,8	US-EPA
Holmium	HREE	monazite, xenotime	0,8	US-EPA
Thulium	HREE	monazite, xenotime	0,28-0,5	US-EPA, Polinares, BGS
Ytterbium	HREE	monazite, xenotime	2	US-EPA
Lutetium	HREE	monazite, xenotime	0,4	US-EPA
Yttrium	HREE	monazite, xenotime	24	US-EPA
Total	TREE		9,2	BGS

Ore	Description	Pro	Contra	Ore grade	Source
Bastnaesite	>A fluorocarbonate rock >Leading worldwide source of REEs historically been the predominate source of LREEs >Found primarily in vein deposits, metamorphic contact zones and pegmatites, forms carbonate-silica rocks with and related to alkaline intrusions	>High REO content >Well-developed extraction and processing methods	>Mainly contains only LREEs >Typically occurs in carbonates which can increase reagant consumption during processing	1 - 8 %	USGS, US-EPA, Polinares
Monazite	>Phosphate mineral rock containing REEs and also the radioactive element thorium >Can also occur together with xenotime but crystallises in different temperatures >Commonly occurs in placer deposits but also acidic igneous rocks and vein deposits >Generally contains the LREEs but can also contain HREEs, especially yttrium	>Weathered monazite has particularly higher REO contents with smaller uranium and thorium values >Contains more HREEs than bastnaesite >Well-developed extraction and processing methods	>Occurs along with radioactive material such as thorium and uranium	0,5 - 10%	USGS, US-EPA, Polinares
Loparite	>A titanite related to occurring in alkaline igneous rocks >Oxide containing niobium, REEs, sodium and titanium, occurs with certain alkaline rocks of magmatic origins	>Well-developed extraction adn processing methods >Titanium content	>Contains significant radioactive thorium and uranium >Contains mainly LREEs	2 - 3%	USGS, US-EPA, Polinares

Ion absorption clays	>Lateritic deposits contain ion-absorption clays that have rare earth ions absorbed into their mineral structure, make up principal supply of yttrium and HREEs	>Easy to process, low processing costs	>low TREO content >Mining techniques are not environmentally friendly	< 0,5%	USGS, US-EPA, Polinares
Eudialyte (silicates)	>Found in alkaline igneous rocks	>Has a favourable amount of HREEs	>The deposits are rather hard, requires more processing steps >High reagant consumption >Not well established processes	0,5 - 1,5%	USGS, US-EPA, Polinares
Xenotime	>Phosphate mineral, high in yttrium content and HREEs has been produced from cassiterite deposits in Malaysia and is a potential byproduct from the productiuon of particular heavy mineral placer deposits >Crystallises under higher temperatures and pressures >Contains also thorium and uranium	>High yttrium and HREE content >Well-developed extraction and processing methods	>Pure xenotime deposits are rare and small >Some have significant radioactive thorium and uranium	1 - 2%	USGS, US-EPA, Polinares
Uranium tailings		>Material has already been mined, reduces overall mining costs	>Variable composition >Y may be low >Processing is dependent on the amount of tailings	~5%	USGS, US-EPA, Polinares

A2 Rare earth demand distribution in 2008

Rare earth demand distribution across all REE applications for 2008 based on data from the Goonan 2011

REEs	Share	Catalysts	Ceramics	Glass	Metallurgical alloys	Permanent magnets	Batteries	Phosphors	Other	Total
Share		21,0%	5,0%	22,0%	9,0%	20,0%	9,0%	7,0%	6,0%	
Ce	32,7%	8,8	0,8	18,6	6,0		4,0	1,0	2,9	42,2
Dy	1,0%					1,3				1,3
Eu	0,3%							0,4		0,4
Gd	0,6%					0,5		0,2	0,1	0,8
La	29,9%	18,2	1,2	8,1	3,0	0,0	6,1	0,8	1,4	38,7
Nd	18,5%	0,2	0,8	0,4	1,9	18,2	1,2		1,1	23,9
Pr	6,8%	0,2	0,4	0,7	0,6	6,1	0,4		0,3	8,7
Sm	0,4%					0,0	0,4		0,2	0,5
Tb	0,4%					0,1		0,4		0,5
Y	9,0%		3,7	0,2				6,2	1,4	11,6
Other	0,4%			0,5					0,1	0,6
Total		27,4	7,0	28,4	11,5	26,2	12,1	9,0	7,5	129,2
unit: Gg										

A3 Neodymium primary production (1990-2015)

Graedel & Du (2011) determined total REE (TREE) production figures per year from 1995-2007 based on the production statistics from 7 mines in China and 1 mine in the US as is seen in column A. Individual rare earth distributions per mine were obtained by Du and Graedel 2011a based on literature from the Chinese Society of Rare Earths (2008), the USGS (2008), Proceedings from the 15th Rare Earths Resources Conference (1981), Proceedings of the Impact of Neodymium-Iron-Boron Materials on Permanent Magnets (1986) and Nakamura, S (1988).

Subsequent annual neodymium production in column B and neodymium production percentage of TREE figures in column C were generated per year. Due to the assumption that Du and Graedel 2011a under-calculated their REE production statistics when compared to TREE production figures from the British Geological Survey (BGS), the TREE production statistics from the BGS in column D will be used from 1990-2013 with 2014 and 2015 TREE production figures from Roskill and Kingsnorth. Neodymium production statistics per year were generated by multiplying column C by column D.

Note that the years 1990-1994 and 2008-2015 were not included in the scope of the research from Du and Graedel 2011a. Therefore the neodymium production percentage for 1995 was used for 1990-1994; the neodymium production percentage for 2007 was used for 2008-2015 even though this figure most likely increased based on the increasing trend observed in column C.

Year	Du & Graedel (2011)			BGS	**Reconciled**
	A	B	C	D	**C x D**
	TREE production [Gg]	Nd production [Gg]	Neodymium production per TREE [%]	TREE production [Gg]	**Adjusted neodymium production [Gg]**
1990			*14%*	60,1	**8,5**
1991			*14%*	48,5	**6,9**
1992			*14%*	54,9	**7,8**
1993			*14%*	48,7	**6,9**
1994			*14%*	57,0	**8,1**
1995	64,0	9,1	14%	77,4	**11,0**
1996	69,0	10,0	14%	84,7	**12,3**
1997	68,2	9,8	14%	76,0	**10,9**
1998	64,3	10,0	16%	82,6	**12,8**
1999	65,4	10,2	16%	87,6	**13,7**
2000	67,9	10,9	16%	80,3	**12,9**
2001	72,8	11,3	16%	88,6	**13,7**
2002	75,6	13,2	17%	96,3	**16,8**
2003	78,3	13,7	17%	95,7	**16,8**
2004	83,9	13,9	17%	103,1	**17,1**
2005	100,7	16,2	16%	122,0	**19,6**
2006	111,1	17,8	16%	137,2	**22,0**
2007	89,8	16,3	18%	124,7	**22,6**
2008			*18%*	127,7	**23,2**
2009			*18%*	131,5	**23,9**
2010			*18%*	121,0	**22,0**
2011			*18%*	109,3	**19,8**

2012		*18%*	104,2	**18,9**
2013		*18%*	100,2	**18,2**
2014		*18%*	123,0	**22,3**
2015		*18%*	134,0	**24,3**

A4 Neodymium primary production (1990-2015), geographical distribution

Geographical distributions of disaggregated neodymium primary production are not available in the literature. The BGS archives do however contain the REE geographical distribution of primary production. It is assumed that the geographical source of neodymium production is proportionate to that of total REE production. 1990-2012 figures come from the BGS. 2013 China data is from Habib et al. 2014; 2013 US, Australia, Russia and rest of world (ROW) amounts obtained from the USGS REE mineral summary 2015; 2014 amounts for all countries obtained from the USGS REE mineral summary 2015.

Year	Source	China	US	Australia	Russia	ROW
1990	BGS	27%	38%	10%	14%	11%
1991		33%	34%	8%	18%	7%
1992		39%	38%	7%	7%	9%
1993		45%	36%	9%	1%	9%
1994		54%	36%	3%	1%	6%
1995		66%	29%	0%	1%	4%
1996		71%	24%	0%	0%	5%
1997		83%	13%	0%	0%	4%
1998		91%	6%	0%	0%	3%
1999		92%	6%	0%	1%	1%
2000		91%	6%	0%	1%	2%
2001		91%	6%	0%	1%	2%
2002		91%	5%	0%	1%	3%
2003		96%	0%	0%	2%	2%
2004		95%	0%	0%	2%	3%
2005		98%	0%	0%	2%	0%
2006		97%	0%	0%	2%	1%
2007		97%	0%	0%	2%	1%
2008		98%	0%	0%	2%	0%
2009		98%	0%	0%	1%	1%
2010		98%	0%	0%	1%	1%
2011		96%	0%	0%	1%	3%
2012		91%	0%	3%	2%	4%
2013	Habib et al (2014)	85%	5%	2%	2%	6%
2014	USGS	86%	6%	2%	2%	4%

A5 Neodymium demand distribution (2008-2015)

In order to calculate disaggregated neodymium demand per year from 2009-2015, this research used 2008 disaggregated demand per REE per application from Goonan 2011 as a reference year. The 2008 dataset from Goonan 2011 determined the neodymium demand percentage by dividing neodymium demand by the TREE demand. Moreover the neodymium demand distribution across all applications was determined for each application.

For the 2009-2015 neodymium demand per application, this research uses annual TREE demand figures from D. J. Kingsnorth 2012; D. Kingsnorth 2013. To calculate neodymium demand per year, the neodymium demand percentage (18%) is applied to the TREE demand. Then the demand distribution percentages are applied to the annual neodymium demand.

Because such a comprehensive, cohesive disaggregated dataset does not yet exist in the literature, these are estimates and should be improved, especially due to non-uniform growth rates of each application.

Neodymium demand [Gg] (2008-2015)									
	Neodymium demand distribution	2008	2009	2010	2011	2012	2013	2014	2015
TREE demand		*129*	*85*	*120*	*105*	*125*	*130*	*140*	*150*
Catalysts	1%	0,2	0,1	0,2	0,2	0,2	0,2	0,2	0,3
Ceramics	4%	0,8	0,5	0,8	0,7	0,8	0,8	0,9	1,0
Glass	2%	0,4	0,2	0,3	0,3	0,3	0,4	0,4	0,4
Metallurgical alloys	8%	1,9	1,2	1,7	1,5	1,8	1,9	2,0	2,1
Permanent magnets	76%	18,2	11,7	16,5	14,4	17,2	17,8	19,2	20,6
Batteries	5%	1,2	0,8	1,1	1,0	1,1	1,2	1,3	1,4
Other	5%	1,1	0,7	1,0	0,9	1,1	1,1	1,2	1,3
Total		**23,9**	**15,3**	**21,6**	**18,9**	**22,5**	**23,4**	**25,2**	**27,0**
Neodymium demand of TREE demand	*18%*								

A6 Neodymium supply-demand-price-geopolitics matrix

Figure 14 datasets were supplemented by neodymium supply data from Annex A3; neodymium demand data from Annex A5; neodymium trading prices from 2005-2014 from www.hastingsraremetals.com; and finally the REE geopolitical landscape from Humphries (2013) and Zhang et al (2015).

Year	Demand [Gg]	Source	Supply [Gg]	Source	Nd price [US$/kg]	Source	Geopolitical events
2005			22,0	BGS adjusted based on neodymium production percentage from Du & Graedel (2011)	6,0	www.hastingsraremetals.com	Chinese abolish tax rebates
2006			22,6		14,8		
2007			23,2		29,0		
2008	23,9	Goonan (2011)	23,9		29,5		Financial crisis
2009	15,3	Kingsnorth (2013) adjusted based on neodymium demand distribution from Goonan (2011)	22,0		17,0		
2010	21,6		19,8		49,5		Export quotas
2011	18,9		18,9		234,0		
2012	22,5		18,2		117,0		WTO complaint from US/ EU/Japan
2013	23,4		22,3		70,0		
2014	25,2		24,3		58,0		WTO upholds complaint

A7 Stakeholder consultations

Consultations on products containing neodymium as well as compositions were carried out with the following researchers.

- Xiaoyue Du, Post-doctoral researcher at the Swiss Federal Laboratories for Materials Testing and Research (EMPA): Provided insights via email and a conference call on 28 May 2015 on neodymium use in EOL PHEVS and conventional automobiles
- Marlies Meijer, consultant at the ELV compliance scheme in the Netherlands, ARN: Discussion per email and a conference call on 21 April 2015 over the BOVAG ELV datasets on newly registered PHEVs in the Netherlands, especially on fuel type disaggregated and the implications this has on which cars contain neodymium; Marlies also provided insights on the waste stream characterization of ELVs
- Komil Habib, Post-doctoral researcher at the University of Southern Denmark: In email correspondence and a conference call on 27 November 2015, discussion on the permanent magnet distribution and market share in especially, white goods and wind turbines, based on her consultations with a leading permanent magnet manufacturer in China and particular OEMs in Europe

A8 Description of select neodymium chemical analyses – electronics

Neodymium composition in the electronics sector was carried out by researchers using different analyses, including both hydro- and pyrometallurgy. Approach and results can be found below.

Laptops and PCs				
Source	Laptop	PC	Description	Result
Büchert et al (2012)	X		>Comprehensive analysis of permanent magnets in laptops indicating the weight of all four permanent magnets – the voice coil accelerator and spindle motor in the HDD, a spindle motor for the optical drive as well as the loudspeaker magnets >Also provided the neodymium concentration per magnet	2,1 g per laptop
Überschaar & Rotter (2015)	X	X	>Used hydrometallurgy and worked with an Inductively Coupled Plasma-Optical Emission Spectrometry and Inductively Coupled Plasma-Mass Spectrometry to determine neodymium content per magnet; results were verified with x-ray fluorescence analysis >Only assessed the NdFeB permanent magnets in the HDDs omitting the spindle motor for the optical drive as well as the loudspeaker magnets	>1,9 g per laptop >3,7 g per PC
Habib et al (2014)	X	X	>Applied pyrometallurgical processes to the NdFeB permanent magnets in HDDs to demagnetize them; individual metals were identified using a field emission scanning electron microscope with energy-dispersive x-ray spectroscopy	>1,0 g per laptop >3,9 g per PC

A9 Description of select neodymium chemical analyses – automobiles

Neodymium composition in EEE in automobiles was determined by Widmer et al (2015) in an output-driven analysis described below.

Automobiles		
Source	Description	Result
Widmer et al (2015)	>Identification of strategic materials and 17 EEE hotspots was based on assessments carried out by Blaser et al (2011), Blaser, Widmer & Wäger (2012) and Wäger, Widmer & Müller (2011) + consultations with the Swiss Federal Office for the Environment >31 strategic materials were identified and two separate measurements were conducted to quantify strategic metal amounts in EEE in the shredder output >Sample composition was four-door, mid-size vehicles manufactured between 2003 and 2008 >Project strategic metal content was subsequently compared to the strategic metal content in the shredder fractions >Sample was prepared, all EEE parts were comminutized to <0,5 mm and final chemical analysis was carried out with an X-ray fluorescence spectrometer	>2,4 g per car (mid-range result)

A10 Neodymium Compositions Portfolio

Completed Neodymium Compositions Portfolio for all neodymium applications across all sectors and products. Descriptions detailing the determination of the compositions can be found in Chapter 7.2.1 in Tables 13-17

Neodymium Sector-Product Portfolio with Compositions							
PERMANENT MAGNET							
Sector	Product	Component	Product weight [kg]	Component mass [kg]	Nd mass [kg]	Nd concentration [%]	Source
Electronics	Laptops	Voice coil accelerator	3,2	0,0030	0,0007	24%	Büchert et al (2012)
		Spindle motor (HDD)		0,0011	0,0003	29%	
		Spindle motor (optical)		0,0016	0,0005	29%	
		Loudspeaker		0,0025	0,0006	26%	
		TOTAL		0,0082	0,0022	26%	
	Desktop PC	Voice coil accelerator	8,8	0,0108	0,0026	24%	Büchert et al (2012) adjusted with Habib et al (2014) data
		Spindle motor (HDD)		0,0040	0,0011	29%	
		Spindle motor (optical)		0,0058	0,0017	29%	
		Loudspeaker		0,0090	0,0023	26%	
		TOTAL		0,0295	0,0078	26%	
	Tablet		3,2	0,0034	0,0010	30%	Habib et al (2014)
	Smartphones		0,1	NA	0,0001	NA	Büchert et al (2012) Habib (2014)
	mp3 players		No data	No data	No data	No data	
	Microphones		No data	No data	No data	No data	
	Headphones		No data	No data	No data	No data	
	Loudspeakers		2,1	0,0015	0,0004	29%	Habib et al (2014)
	DVD players		2,7	0,0014	0,0005	35%	Habib et al (2014)
	Fridges	Compressor	54,1	0,2600	0,0754	29%	Habib et al (2014)
	Freezers	Compressor	43,3	0,5400	0,1421	26%	Habib et al (2014)
	Microwaves		22,2	0,1100	0,0319	29%	Habib et al (2014)
	Aircons	Motor	25,2	0,5000	0,1450	29%	Habib et al (2014)
	Washing machines	Motor	72,4	1,0400	0,3016	29%	Habib et al (2014)
	Dryer	Motor	43,5	0,5400	0,1566	29%	Habib et al (2014)
	Vacuums	Motor	5,8	0,0900	0,0261	29%	Habib et al (2014)
	Electric toothbrushes	Motor	0,5	0,0010	0,0003	30%	Habib et al (2014)
	Shavers	Motor	0,5	0,0010	0,0003	30%	Habib et al (2014)
	Power tools		No data	No data	No data	No data	
Automotive	PHEV	EEE	1.016	No data	0,0024	No data	Widmer et al (2015)
	PHEV	Motor	1.016	3,05	0,06	2%	Habib et al (2014) Hoenderdaal et al (2013)
	EV	EEE	1.016	No data	0,0024	No data	Widmer et al (2015)
	EV	Motor	1.016	3,05	0,63	21%	Habib et al (2014) Hoenderdaal et al (2013)
	Passenger vehicle (ICE)	EEE	1.016	1,43	0,33	23%	Widmer et al (2015)
Renewable Energy	Wind turbine	DDPMG motor (gearless) / 1MW	NA	650	196	30%	Hoenderdaal et al (2013) Habib et al (2014)
Medical	MRI		67	860	181	21%	Habib et al (2014)
Other	Electric bicycles (Ebs)	Motor	No data	0,300	0,090	30%	Hoenderdaal et al (2013)
	Circulator pumps		No data	0,055	0,014	25%	Habib et al (2014)
	Industrial applications		No data	0,055	0,014	25%	Habib et al (2014)
CATALYSTS							
Automotive	Passenger vehicle (conventional)	Catalytic converter	No data	No data	No data	No data	
BATTERIES							
Automotive	NiMH batteries for PHEV/Evs	Battery	80	80	0,25	2,30%	USDOE (2011) Bauer et al (2011) Habib et al (2014)
CERAMICS							
Electronics	various	Capacitors	No data	No data	No data	No data	
Colouring agent	Ceramic products		No data	No data	No data	No data	
GLASS							
Colouring agent	Glass products		No data	No data	No data	No data	
METALLURGICAL ALLOYS							
Other	Lighters and torches	Flint ignition devices	No data	No data	No data	No data	
	Casting of steel and iron		No data	No data	No data	No data	

A11a Assumptions for 2010 neodymium MFA – electronics

The table below illustrates the assumptions and sources pertinent for modeling EEE stocks and flows in the Netherlands in 2010.

Electronics			
Assumption	Market share	Source	Note
Average product weight	varies per product	Balde et al. 2015	Applied to the total kg to calculate number of units
Average product lifespan	varies per product	Balde et al. 2015	
Neodymium composition per product	varies per product	This research, Chapter 7.2.1	Applied to calculate neodymium flow per product
Market share containing neodymium			
washers	25%	Habib et al. 2014	Consultations with a leading NdFeB permanent magnet manufacturer in Japan as well as OEMs
dryers	25%	Habib et al. 2014	
refrigerators	30%	Habib et al. 2014	
freezers	30%	Habib et al. 2014	
airconditioners	30%	Habib et al. 2014	
microwaves	30%	Habib et al. 2014	
vaccuums	8%	Habib et al. 2014 & Business Insider 2014	
personal care	25%	Habib et al. 2014	
video	100%	no source	
speakers	100%	no source	
desktop pc	95%	Statista 2015	Shipments of HDDs v SSDs
laptop	95%	Statista 2015	Shipments of HDDs v SSDs
smartphone	100%	Buchert 2012	Market share data in Germany

<u>Average product weight</u>: Ascertained for all EEE modeled in this research from Annex 3 of the report by UNU in collaboration with the Task Group on Measuring E-waste from the Basel Convention, Balde, K., Kuehr, R., Blumenthal, K., Fondeur Gill, S., Kern, M., Micheli, P., Huisman 2015.

<u>Average product lifespan</u>: Obtained for all EEE modeled in this research from UNU-internal. Lifespans information can be provided upon request.

<u>Neodymium composition per product</u>: See Chapter 7.2.1 and Annex A10 for sources and methodology.

<u>Washers and dryers</u>: Market share obtained from Habib et al. 2014 and is based on consultations with a leading NdFeB permanent magnet manufacturer in Japan + OEMs. Market share determined to be 25% for all washers and dryers POM after 2003.

<u>Air conditioners and refrigerators</u>: Market share obtained from Habib et al. 2014 and is based on consultations with a leading NdFeB permanent magnet manufacturer in Japan + OEMs. Market share determined to be 30% for all air conditioners and refrigerators POM after 2003.

<u>Freezers</u>: No data but assumed to have same market share as refrigerators, i.e. 30% POM after 2003.

CD/DVD players and speakers: No market share data was found. However because there is no substitute that would enable the same miniaturization as NdFeB permanent magnets in the drives of the CD/DVD players or loudspeakers without a different design or without loss of performance, as is the case with the SSD in laptops and PCs, this research will assume a 100% market share.

Laptops and PCs: Market share obtained from Statista 2015b and is based on the total shipments of HDDs vs. SSDs in 2012, denoting an approximate 95% market share for HDDs (no data available for 2010).

Smartphones: Market share obtained from Buchert 2012 and is based on market share of smartphones in Germany in 2010. This assessment assumed 385kg of neodymium would be available from the 7,7million smartphones sold in Germany in 2010 á 0,05g neodymium per smartphone. This amounts to a 100% market share.

Vacuums: Market share of robotic vacuums obtained from Habib et al. 2014 and is based on consultations with a leading NdFeB permanent magnet manufacturer in Japan + OEMs. Market share of robotic vacuums containing neodymium determined to be 50% for all robotic vacuums POM after 2003. Robotic vacuum market share of total vacuum market in Europe determined to be 15% as per Business Insider 2014. Therefore total market share of vacuums containing a NdFeB permanent magnet is 8% for all vacuums POM after 2003.

Personal care: Market share obtained from Habib et al. 2014 and is based on consultations with a leading NdFeB permanent magnet manufacturer in Japan + OEMs. Market share determined to be 30% for all personal care (electric toothbrushes and shavers) POM after 2007.

A11b Assumptions for 2010 neodymium MFA – automobiles

The table below denotes the necessary assumptions for modeling neodymium stocks and flows in the automotive sector in the Netherlands in 2010.

Automobiles			
Assumption	Item	Source	Note
Average product lifespan	20,2 years	Yano et al. 2015	
Neodymium composition per product	differs per auto type	This research, Chapter 7.2.1, Annex A10	Applied to calculate neodymium flow per ELV
Market share of PHEVs containing NiMH batteries in 2010	95%	Vikström et al. 2013 Schüler et al. 2011	
NiMH battery replacement	0	Habib & Wenzel 2014	NiMH batteries will have the same lifespan as PHEVs
NdFeB permanent magnet motor replacement	0	Habib & Wenzel 2014 Hoenderdaal et al. 2013	NdFeB permanent magnet motors will have the same lifespan as PHEVs
PHEVs in the ELV waste stream in 2010	0	ARN	Consultation with the ELV recycling compliance scheme in the Netherlands
Neodymium distribution per fuel type			
Fuel type	EEE	NdFeB permanent magnet motor	NiMH battery
Petrol	X		
Diesel	X		
Vehicles powered by propane (LPG)	X		
PHEV	X	X	X
EV	X	X	X
High pressure gas	X		
Compressed natural gas (CNG)	X		
Liquefied natural gas (LNG)	X		
Biofuel	X		

<u>Neodymium composition per product</u>: Differs for PHEVs and conventional vehicles with an ICE. The methodology for generating neodymium composition in the NiMH battery, NdFeB permanent motor and EEE is explained in detail in Chapter 7.2.1 and Annex A10 to this research

<u>NiMH market share</u>: Uncertainty about this figure going forward is pervasive in the literature although many industry experts predict the NiMH battery will be phased out and replaced with Li-ion batteries due to their high energy densities and low weight (Constantinides 2013; Hatch 2011; D. Kingsnorth 2013).

However PHEVs containing a NiMH battery since the introduction of the Li-ion battery is a recent development in the automotive sector. For example according to Constantinides 2013 the Toyota Prius used NiMH batteries from 1997 till at least 2012. Moreover it is estimated that the Toyota Prius market share of total PHEVs was 83% in 2008 and that the Li-ion battery market share was only 2%, further supporting the high NiMH battery market share claim (Schüler et al. 2011). For this reason a 100% NiMH battery market share will be assumed.

NdFeB permanent magnet motor market share: It was also assumed that 100% of all new registrations of PHEVs incorporated a NdFeB permanent magnet instead of an induction motor due to the operation efficiency of NdFeB permanent magnet motors. This assumption is supported and shared by scenario mapping assessments carried out by Hoenderdaal et al. 2013 and Habib and Wenzel 2014

PHEVs in the waste stream: According to a personal consultation with a consultant at the ELV compliance scheme in the Netherlands, ARN, only in the past year (2014) have PHEVs started to enter the ELV waste stream. Because the ELV waste stream was not disaggregated per fuel type combined with the information from ARN, it will be assumed no PHEVs entered the ELV waste stream in 2010.

EEE in automobiles: This research will assume that all vehicles that were newly registered, in the stock and reached EOL in 2010 in the Netherlands, had the same amount of neodymium in EEE.

A11c Assumptions for 2010 neodymium MFA – wind turbines

The table below describes the neodymium-wind turbines assumptions that are necessary for quantifying stocks and flows of neodymium in wind turbines in the Netherlands in 2010.

Wind turbines			
Assumption	Item	Source	Note
Average product lifespan	20 years	Rademaker, Kleijn & Yang 2013	
Average neodymium composition	196kg per MW	This research, Chapter 7.2.1, Annex A10	Applied to calculate neodymium flow per DDPM wind turbine; assumes all wind turbines are 1MW
Number of wind turbines in the Netherlands as per 2010	1700	www.thewindpower.net	Used to determine number of DDPM turbines based on DDPM market share
Market share of DDPM wind turbines in the Netherlands as per 2010	2% growth rate	Schüler et al. 2010 Habib & Wenzel 2014	Introduced in 2003 and market share of 14% in 2010; this research assumes 2% DDPM market share in 2004 with a 2% growth rate each year until 2010
DDPM wind turbines in EOL turbine waste stream in the Netherlands 2010	0	This research	Based on average lifespan + introduction to the market in 2003, not yet reached EOL

Average product lifespan: There was overwhelming consensus in the literature on 20 years from Rademaker, Kleijn, and Yang 2013, Habib and Wenzel 2014 and Zimmermann, Rehberger, and Gößling-reisemann 2010.

Average neodymium composition: There was some variance in the literature depending on MW size. This research assumes all turbines erected until 2010 were 1MW turbines. For methodology and neodymium composition per 1MW, see Chapter 7.2.1 and Annex A10.

Number of turbines in the Netherlands as per 2010: This research referred to www.thewindpower.net and manually inventoried all wind turbines erected in the Netherlands since 1990. When it was indicated from thewindpower.net, the inventory in this research included province/municipality/MW/year of erection/whether it had a gearbox or DDPM per wind turbine. Of all 2700 wind turbines, the year of erection was denoted for 811 wind turbines and year of erection unknown for the remaining 889 wind turbines. Since this research uses 1990 as the first year, the 889 unknown wind turbines were evenly distributed over all 20 years until 2010, resulting in 44 extra turbines added per year. There is uncertainty in this approach but no other data was identified that could facilitate determining the year of the unknowns.

Market share of DDPM wind turbines in the Netherlands as per 2010: There is relatively stable consensus in the literature on the 2010 DDPM market share – 14% according to Schüler et al. 2011. The year DDPM turbines entered the market was 2003 according to Habib and Wenzel 2014. Because there was a lack of data from other sources on DDPM market shares without having to go through paywalls, this research will assume an annual 2% growth in market share, starting at 0% in 2003, 2% in 2004 and 14% in 2010.

DDPM wind turbines in EOL turbine waste stream in the Netherlands 2010: Based on wind turbine lifespan of 20 years from Rademaker, Kleijn, and Yang 2013 and introduction of DDPM wind turbines to the market only in 2003 according to Habib and Wenzel 2014, the first DDPM wind turbines will not reach EOL until 2024.

A12 WEEE collection in the Netherlands

Formal collection of WEEE in the Netherlands is managed by the Dutch compliance schemes – Wecycle and other small compliance schemes. The WEEE compliance schemes are responsible for the collection, logistics and ultimate recycling of WEEE as regulated by the EU WEEE Directive 2012/19/EU. Each municipality in the Netherlands has a contract with the compliance schemes that ensures EOL management of WEEE collected in the municipalities is handled by the compliance schemes. These WEEE are collected in containers or other types of collection points. A second channel of collection is through retailers with whom the compliance schemes also have contracts for managing any WEEE accepted at retailers. Collection as can also incorporate complementary WEEE streams that reach the recycling centres directly from local scrap dealers (Huisman et al. 2012).

Uncollected WEEE are those which enter municipal residual waste streams and end up treated with non-WEEE municipal waste; these can be quite high for some UNU key categories, such as small IT products and accessories as well as lamps and light bulbs. Uncollected figures also include unknown end-destinations, which are marginal compared to the known waste stream channels (Huisman et al. 2012).

Export includes both legal and illegal export of WEEE. Formally under the rules of the Basel Convention which regulates the transboundary movement of hazardous waste, OECD countries are prohibited from transporting hazardous waste, which includes WEEE, to non-OECD countries; it nonetheless is still taking place (Schluep et al. 2009; Kahhat et al. 2008). Legal export of functioning used-EEE (UEEE) to developing countries is allowed and is 9% of POM data from the previous three years of the *Future Flows* study.

A13 Methodology for determining waste stream per individual WEEE

WEEE Generated data was provided by the *Future Flows Report* for the individual WEEE appliances. However the waste stream characterizations – collected, uncollected, export – were aggregated into broader domains: large household appliances (LHA), cooling and freezing (CF), small household appliances (SHA) and information technology (IT).

The ratio of individual WEEE appliances was generated by dividing individual WEEE generated figure by the aggregated WEEE generated figure per domain. Corresponding ratios were calculated and applied to the waste streams to generate individual WEEE appliance figures per characterized waste stream.

This methodology contains some uncertainty due to disproportionate distribution of particular products across different waste streams, for example the export of particular products, such as fridges. However due to data unavailability, this research will assume the ratio of individual WEEE appliance to WEEE category is uniform for each product across all WEEE waste streams.

unit	*kt*	*%*	*kt*	*kt*	*kt*
	WEEE GEN	**WEEE GEN Ratio**	**Collected**	**Uncollected**	**Export**
LHA	105,92		77,41	24,20	4,31
washers	43,77	41%	31,99	10,00	1,78
dryers	13,15	12%	9,61	3,01	0,54
CF	49,06		31,83	7,29	9,95
fridges	31,83	65%	20,64	4,73	6,45
freezers	9,81	20%	6,36	1,46	1,99
aircons	2,08	4%	1,35	0,31	0,42
SHA	106,75		77,74	25,03	3,98
microwaves	8,62	8%	6,28	2,02	0,32
vaccuums	6,79	6%	4,95	1,59	0,25
personal care	2,11	2%	1,54	0,50	0,08
video	10,07	9%	7,33	2,36	0,38
speakers	5,44	5%	3,96	1,27	0,20
IT	49,73		30,50	9,28	9,95
desktop pc	11,74	24%	7,20	2,19	2,35
laptop	2,86	6%	1,76	0,53	0,57
smartphone	0,36	1%	0,22	0,07	0,07

A14a Assumptions for 2030 neodymium MFA – electronics

The inventory of assumptions for the electronics sector below provided the necessary parameters for modeling all neodymium flows in EEE in the Netherlands in 2030.

Electronics			
Assumption	**Item**	**Source**	**Note**
Average product weight	varies per product	Balde et al. 2015	
Average product lifespan	varies per product	Balde et al. 2015	
Gross World Product	2,5%	IPCC	IPCC report on Emissions Scenarios, Chapter 2.4.5, with the median Gross World Product value at 2,5%
Growth Cohort 1	2,5%	based on IPCC	EEE growth proportionate to projected median Gross World Product from the IPCC
Growth Cohort 2	4,5%	based on IPCC	EEE growth proportionate to projected median Gross World Product from the IPCC at 2,5% + an additional 2% due to the importance of these EEE
Market share containing neodymium			
washers	25%	Habib et al. 2014	Consultations with a leading NdFeB permanent magnet manufacturer in Japan as well as OEMs
dryers	25%	Habib et al. 2014	
refrigerators	30%	Habib et al. 2014	
freezers	30%	Habib et al. 2014	
airconditioners	30%	Habib et al. 2014	
microwaves	30%	Habib et al. 2014	
vaccuums	8%	Habib et al. 2014 & Business Insider 2014	
personal care	25%	Habib et al. 2014	
video	100%	assumption	
speakers	100%	assumption	
desktop pc	95%	Statista 2015	Shipments of HDDs v SSDs
laptop	95%	Statista 2015	Shipments of HDDs v SSDs
smartphone	100%	Buchert 2012	Market share data in Germany

<u>Average product weights</u>: Ascertained from Annex 3 of the report from Balde, K., Kuehr, R., Blumenthal, K., Fondeur Gill, S., Kern, M., Micheli, P., Huisman 2015 on e-waste statistics. The average product weights for 2030 will remain the same as 2010.

<u>Average product lifespans</u>: Determined by UNU and will also remain the same for 2030 modeling.

Gross World Product (GWP): Although forecasting economic growth is inherently uncertain due to many external, unknown forces such as financial crises and war, this research will peg growth of individual electronics to the median GWP figure, 2,5%, from Chapter 2.4.5 of the report on Emissions Scenarios from the IPCC 2000. This figure synthesises potential growth rates from 148 scenarios for the years 1990-2050.

Growth Cohort 1: This group of electronics comprises washing machines, dryers, refrigerators and freezers and will grow proportionately to GWP at 2,5%. It must however be noted that it was extremely difficult to obtain growth forecasts on individual electronics as such due to the high levels of uncertainty. Moreover there were expensive paywalls in the cases where growth forecasts were made.

Growth Cohort 2: This group of electronics comprises all remaining electronics, air conditioners, microwaves, vacuums, personal care items, video, speakers, PCs, laptops and smartphones. These electronic products will be pegged to IPCC GWP median growth with an additional 2% due to their economic importance, totaling a 4,5% growth rate. This figure falls in line with the average growth rate in the electronics sector at 5% between 2010-2013 according to the industry research group, RNCOS (Schüler et al. 2011)

Market share of electronic products containing neodymium: This research will use the same market share figures per individual electronics as for 2010. Determination of market share of electronics comprising neodymium is explained in detail in Annex A11a

A14b Assumptions for 2030 neodymium MFA – automobiles

The inventory of assumptions for the automotive sector below provided the necessary parameters for modeling all neodymium flows in automobiles in the Netherlands in 2030. Contrary to 2010 results, the 2030 assessment will only model PHEV flows.

Automobiles			
Assumption	Item	Source	Note
Average product lifespan	20,2 years	Yano et al. (2015)	
PHEV target 2020	200.000	Dutch National Action Plan for Electric Driving	To achieve the goal, a 6% growth rate for PHEVs and 35% growth rate for EVs is needed until 2025
Neodymium composition per EEE	0,002 kg per automobile	Chapter 7.2.1, Annex A10	
Neodymium composition per NdFeB permanent magnet motor	0,63 kg per automobile	Chapter 7.2.1, Annex A10	
Neodymium composition per NiMH battery	0,25 kg per automobile	Chapter 7.2.1, Annex A10	
Market share of PHEVs containing NiMH batteries in 2010	65%	Schüler et al. 2011	
Market share of PHEVs containing a NdFeB permanent magnet motor	100%	Habib & Wenzel 2014	
Collection at EOL	43%	Results from this research, Chapter 8.2.2	EOL will be modeled to reflect ELV waste stream from 2010
Uncollected at EOL	7%		
Export at EOL	50%		

<u>Average product lifespan</u>: This research will use the same lifespan figure of 20,2 years for 2030 as 2010 from Yano, Muroi, and Sakai 2015.

<u>PHEV targets for 2020 and 2025</u>: With a 200.000 PHEV target by 2020 set by the Dutch National Action Plan for Electric Driving under the Dutch Government, a linear 6% growth rate for PHEVs and a linear 35% growth rate for full electric vehicles was applied to achieve these targets. The same linear growth rates are applied after 2020 until 2030.

<u>Neodymium composition in EEE / NdFeB permanent magnet motor / NiMH battery</u>: 2030 modeling will use the same neodymium compositions as 2010 at 0,002kg, 0,63kg and 0,25kg per automobile, respectively. Sources and methodology can be found in Chapter 7.2.1 and Annex A10.

Market share of PHEVs containing NiMH batteries in 2010: With Li-ion battery market share for PHEVs forecasted to reach 35% by 2020, the remaining 65% will come from neodymium-containing NiMH batteries according to Schüler et al. 2011. This research will assume the same market share until 2030.

Market share of PHEVs containing a NdFeB permanent magnet motor: The 100% market share from 2010 will remain in the 2030 modeling assessment due to the higher-performance and increased efficiencies of the NdFeB motor over the ferrite-magnet induction motors. This assumption was also used in the scenario mapping assessments carried out by Habib and Wenzel 2014 and Hoenderdaal et al. 2013.

EOL waste stream characterization: The 2030 waste stream characterization will reflect the ratio of ELVs in each waste stream in 2010. Of total 499.253 ELVs in the Netherlands in 2010, 43% were collected, 7% uncollected and 50% exported.

A14c Assumptions for 2030 neodymium MFA – wind turbines

The inventory of assumptions for the renewable energy sector below provided the necessary parameters for modeling all neodymium flows in DDPM wind turbines in the Netherlands in 2030.

Wind turbines			
Assumption	Item	Source	Note
Average product lifespan	20 years	Rademaker, Kleijn & Yang 2013	
Neodymium composition per DDPM wind turbine	196 kg per MW	Habib & Wenzel 2014 Hoenderdaal et al 2013	
Market share of wind energy to total renewable energy by 2020	27,8%	CBS Energie Verkenning 2014	
Market share of wind energy to total renewable energy by 2030	34,4%		
DDPM wind turbine market share in 2020	20%	Habib & Wenzel 2014	
DDPM wind turbine market share in 2030	30%		
Collection at EOL	100%	Twidell 2009 www.government.nl (WRO Act)	

<u>Average product lifespan</u>: As with all other sectors, this research will use the same lifespan at 20 years for modeling neodymium flows in 2030 as 2010 according to Rademaker, Kleijn, and Yang 2013.

<u>Neodymium composition per DDPM wind turbine</u>: The neodymium composition will remain the same at 196kg per MW calculated by Habib and Wenzel 2014 and Hoenderdaal et al. 2013. Methodology for determining composition can be found in Chapter 7.2.1 and Annex A10 to this research.

<u>Market share of wind energy to total renewable energy by 2020 and 2030</u>: To achieve the 27,8% wind energy of total renewable energy target, CBS denoted the amount of accumulated PJ that must come from wind energy for 2020 and 2030 in its 2014 Energie Verkenning.

For 2020 wind energy installed capacity is targeted to be 63,8 PJ which totals 17 x 10^6 MWh. Using $MW_{2020} = \frac{MWh_{2020}}{hours\ x\ turbine\ efficiency}$ where 8760 hours per year at 25% efficiency, total installed MW in 2020 is 8092 MW. According to the www.thewindpower.net the total installed wind energy capacity in the Netherlands in 2015 was 2955 MW from 1577 wind turbines. This research will assume that the delta between the 2020 target of 8092 MW and 2015 figure at 2955 MW from 1577 turbines will be added evenly over 5 years. This amounts to 1027 MW and 863 turbines will be added per year from 2015-2020.
For 2030 wind energy installed capacity is targeted at 148 PJ which totals 41 x 10^6 MWh. Using the same formula to calculate MW, total targeted installed MW in the Netherlands in 2030 equals 18 x 10^3 MW. Applying the same approach, the 10,7 x 10^3 MW and 1367 wind turbines are added evenly over 10 years between 2020 and 2030.

DDPM wind turbine market share: Building on the 14% DDPM market share in 2010, this research will use the forecasted 20% and 30% DDPM market share in 2020 and 2030, respectively, from Habib and Wenzel 2014. From 2010-2020, each year will have a linear 0,6% increase; from 2020-2030, DDPM market share will increase linearly per annum from 20%-30%, i.e. an increase of 1% per annum.

Collection at EOL: According to Twidell 2009 of the Cleaner Energy Council in Australia, it is up to the owner of the wind farm to decommission all EOL wind turbines once they become waste. Currently there is no legislation addressing EOL wind turbines, although this is being discussed nationally in Denmark. However due to the strict land planning regulations in the Spatial Planning Act (WRO) in the Netherlands (www.government.nl), this research will assume that all redundant wind turbines will be responsibly decommissioned and disposed of accordingly.

A15a Theoretical total neodymium demand in the Netherlands – 2010

In order to calculate the estimated neodymium demand for the neodymium products and applications not modeled in this research, this research determined the percentage of products per neodymium application that were modeled based on the Neodymium Sector-Product Portfolio in Chapter 7.1

	Permanent magnets	Alloys	Batteries	Ceramics	Other	Glass	Catalysts
Neodymium demand distribution percentages from Goonan 2011	76%	8%	5%	4%	4%	2%	1%
Total products in the Neodymium Sector-Product Portfolio	27	2	2	2	1	1	1
Total products modeled	19	0	1	0	0	0	0
Total products not modeled	8	2	1	2	1	1	1
Percentage modeled per neodymium application	70%	0%	50%	0%	0%	0%	0%
TOTAL PERCENTAGE MODELED	53%	0%	3%	0%	0%	0%	0%

70% of products with a permanent magnet were modeled in 2010, totaling 135t. The remaining products, 30% were not modeled, totaling 58t. Together, the modeled and not modeled figures amount to 193t. At 76% of total neodymium demand, total neodymium demand amounts to 253t.

	POM	**EOL**
Permanent magnets (modeled)	135,0	127,7
Batteries (modeled)	3,9	0,0
Permanent magnet	58,0	
Alloys	20,2	
Batteries	8,8	
Ceramics	10,1	
Other	10,1	
Glass	5,1	
Catalysts	2,5	
Total neodymium demand NL 2010	**252,6**	**127,7**

A15b Theoretical total neodymium demand in the Netherlands – 2030

In order to calculate the estimated neodymium demand for the neodymium products and applications not modeled in this research, this research determined the percentage of products per neodymium application that were modeled based on the Neodymium Sector-Product Portfolio in Chapter 7.1

	Permanent magnets	Alloys	Batteries	Ceramics	Other	Glass	Catalysts
Neodymium demand distribution percentages from Goonan 2011	76%	8%	5%	4%	4%	2%	1%
Total products in the Neodymium Sector-Product Portfolio	27	2	2	2	1	1	1
Total products modeled	19	0	1	0	0	0	0
Total products not modeled	8	2	1	2	1	1	1
Percentage modeled per neodymium application	70%	0%	50%	0%	0%	0%	0%
TOTAL PERCENTAGE MODELED	53%	0%	3%	0%	0%	0%	0%

70% of products with a permanent magnet were modeled in 2030, totaling 390t. The remaining products, 30% were not modeled, totaling 167t Together, the modeled and not modeled figures amount to 557t. At 76% of total neodymium demand, total neodymium demand amounts to 733t.

	POM [t]	**EOL [t]**
Modeled		
Permanent magnets (modeled)	390,1	171,5
Batteries (modeled)	16,4	4,0
Not modeled		
Permanent magnets	167,2	
Alloys	58,7	
Batteries	20,3	
Ceramics	29,3	
Other	29,3	
Glass	14,7	
Catalysts	7,3	
Total neodymium demand NL 2030	**733,3**	**175,6**

A16 Data quality

Methodology for determining the data quality of the compositions per product was carried out on one dimension, quantity of peer-reviewed publications containing neodymium compositions per product using the scale below.

Rating	Description	Designation	Quantity	Quality
1	poor		no sources	Assessed based on peer-review, uncertainty analysis, sensitivity analysis, age of source
2	fair		1 sources	
3	good		2 sources	
4	excellent		3 sources	

The qualitative results are found below:

Laptops	Average score: 3				
	Überschaar & Rotter (2015)	Habib et al (2014)	Rademaker, Kleijn & Yang (2013)	Sprecher et al (2014)	Buchert (2012)
Peer review?	yes	yes	yes	yes	no
Uncertainty analysis?	no	yes	no	no	no
Sensitivity analysis?	no	yes	yes	yes	no
Age?	2014	2014	2013	2014	2012
Description	>only HDDs (voice coil actuator and spindle motor) addressed and not the optical drives >sample size: 6 >manual dismantled >chemical composition of magnets carried out using an ICP-OES or ICP-MS followed by x-ray fluorescence >magnets crushed and sent to third party for analysis	>MFA in Denmark >only HDDs (voice coil actuator and spindle motor) addressed and not the optical drives >sample size: 31, magnets found in all laptops >chemical composition carried out using electron microscope with EDX spectroscopy; further chemical analysis carried out after magnets removed >Uncertainty analysis determined laptops to have the lowest level of uncertainty on a scale of 1-5	>global MFA >only HDDs (voice coil actuator and spindle motor) addressed and not the optical drives >no chemical analyses or sampling undertaken; neodymium content at 29% used for all magnets; uncertain where the size of the magnets was obtained >magnet mass from 2008	>detailed description of the primary production process >refers to the estimates on REE primary production from Du >different Nd concentrations per magnets coming from Zepf (2013) while average weight of HDDs are assumed to have decreased based on results from Zepf from 1990-2006; they dismantled 10 HDDs manufactured between 2007-2010 and found that the trend was generally HDDs decreasing in weight >90% efficiency >3 different collection scenarios	>4 different magnets in laptops - HDD (VCA and spindle), optical drive, loudspeaker; most researchers only looked at HDDs >neodymium concentration per each of the four magnets obtained from VAC (2011)
Score	3	4	3	3	2

PCs	Average score: 4	
	Überschaar & Rotter (2015)	Habib et al (2014)
Peer review?	yes	yes
Uncertainty analysis?	no	yes
Sensitivity analysis?	no	yes
Age?	2014	2014

Description	>only HDDs (voice coil actuator and spindle motor) addressed and not the optical drives >sample size: 6 >manual dismantled >chemical composition of magnets carried out using an ICP-OES or ICP-MS followed by x-ray fluorescence >magnets crushed and sent to third party for analysis	>MFA in Denmark >only HDDs (voice coil actuator and spindle motor) addressed and not the optical drives >sample size: 61, magnets found in all IPCs >chemical composition carried out using electron microscope with EDX spectroscopy; further chemical analysis carried out after magnets removed >Uncertainty analysis determined PCs to have the lowest level of uncertainty on a scale of 1-5
Score	3	4

Tablet	Average score: 2
	Habib et al (2014)
Peer review?	yes
Uncertainty analysis?	yes
Sensitivity analysis?	yes
Age?	2014
Description	>MFA in Denmark >sample size: 0, magnet composition determined based on consultation with leading magnet supplier >chemical composition determined based on consultation with a leading NdFeB permanent magnet supplier and a leading home appliance OEM >Uncertainty analysis determined tablet to have the second lowest level of uncertainty on a scale of 1-5
Score	2

Smartphone	Average score: 2,5	
	Habib et al (2014)	Buchert (2012)
Peer review?	yes	no
Uncertainty analysis?	yes	no
Sensitivity analysis?	yes	no
Age?	2014	2012
Description	>MFA in Denmark >sample size: 0, magnet composition determined based on consultation with leading magnet supplier >chemical composition carried out using electron microscope with EDX spectroscopy; further chemical analysis	>Oeko-institut measured weighed one magnet from one smartphone and applied the same neodymium concentration in laptop loudspeakers

	carried out after magnets removed >Uncertainty analysis determined smartphoness to have the second lowest level of uncertainty on a scale of 1-5	
Score	3	2

Loudspeakers	Average score: 2
	Habib et al (2014)
Peer review?	yes
Uncertainty analysis?	yes
Sensitivity analysis?	yes
Age?	2014
Description	>MFA in Denmark >sample size: 6, magnet found in 4, uncertain if it was a NdFeB permanent magnet >chemical composition determined based on consultation with a leading NdFeB permanent magnet supplier and a leading home appliance OEM >Uncertainty analysis determined loudspeakers to have the second lowest level of uncertainty on a scale of 1-5
Score	2

CD/DVD	Average score: 3
	Habib et al (2014)
Peer review?	yes
Uncertainty analysis?	yes
Sensitivity analysis?	yes
Age?	2014
Description	>MFA in Denmark >sample size: 6, 5 had a NdFeB permanent magnet >chemical composition carried out using electron microscope with EDX spectroscopy; further chemical analysis carried out after magnets removed >Uncertainty analysis determined smartphoness to have the lowest level of uncertainty on a scale of 1-5
Score	3

Fridge, Aircon, Freezer, Dryer, Washer, Average score: 2	
	Habib et al (2014)
Peer review?	yes
Uncertainty analysis?	yes
Sensitivity analysis?	yes
Age?	2014
Description	>MFA in Denmark >sample size: 0 >chemical composition determined based on consultation with a leading NdFeB permanent magnet supplier and a leading home appliance OEM >Uncertainty analysis determined smartphoness to have the second lowest level of uncertainty on a scale of 1-5
Score	2

Microwave	Average score: 2
	Habib et al (2014)
Peer review?	yes
Uncertainty analysis?	yes
Sensitivity analysis?	yes
Age?	2014
Description	>MFA in Denmark >sample size: 2, 2 had a magnet, unknown if it was a NdFeB permanent magnet >chemical composition determined based on consultation with a leading NdFeB permanent magnet supplier and a leading home appliance OEM >Uncertainty analysis determined smartphoness to have the second lowest level of uncertainty on a scale of 1-5
Score	2

Vacuum	Average score: 2
	Habib et al (2014)
Peer review?	yes
Uncertainty analysis?	yes
Sensitivity analysis?	yes
Age?	2014

Description	>MFA in Denmark >sample size: 5, no magnet found (likely not robotic vacuum) >chemical composition determined based on consultation with a leading NdFeB permanent magnet supplier and a leading home appliance OEM >Uncertainty analysis determined smartphoness to have the second lowest level of uncertainty on a scale of 1-5
Score	2

Shaver	Average score: 3
	Habib et al (2014)
Peer review?	yes
Uncertainty analysis?	yes
Sensitivity analysis?	yes
Age?	2014
Description	>MFA in Denmark >sample size: 5, 5 NdFeB permanent magnets found >chemical composition carried out using electron microscope with EDX spectroscopy; further chemical analysis carried out after magnets removed >Uncertainty analysis determined smartphoness to have the second lowest level of uncertainty on a scale of 1-5
Score	3

Electric toothbrush, Average score: 2	
	Habib et al (2014)
Peer review?	yes
Uncertainty analysis?	yes
Sensitivity analysis?	yes
Age?	2014
Description	>MFA in Denmark >sample size: 5, 3 NdFeB permanent magnets found >chemical composition determined based on consultation with a leading NdFeB permanent magnet supplier and a leading home appliance OEM >Uncertainty analysis determined smartphoness to have the second lowest level of uncertainty on a scale of 1-5
Score	2

PHEV Permanent magnet motor	Average score:3	
	Habib et al (2014)	Hoenderdaal et al (2013)
Peer review?	yes	yes
Uncertainty analysis?	yes	no
Sensitivity analysis?	yes	yes
Age?	2014	2013
Description	>MFA in Denmark >sample size: 0 >chemical composition determined based on consultation with a leading car manufacturer and a major REE mining company as well as from three other literature sources >Uncertainty analysis determined smartphoness to have the second lowest level of uncertainty on a scale of 1-5	>dynamic MFA, dysprosium focused >assumptions were made on the size of the magnet and neodymium content - basis of assumptions are unclear >does include lower, middle and upper bound scenarios
Score	3	2

PHEV NiMH battery	Average score: 3	
	Habib & Wenzel (2014)	USDOE (2011)
Peer review?	yes	yes
Uncertainty analysis?	no	no
Sensitivity analysis?	yes	no
Age?	2014	2011
Description	>dynamic MFA, neodymium focused >sample size: 0 >chemical composition determined based on another literature source >does include 4 different scenarios based on BAU, BlueMAP, Blue hi REN, 100% REN	>critical raw materials strategy for the US >sample size: 0 >chemical composition determined based on another literature source
Score	3	2

EEE in Automobiles	Average score: 4
	Widmer et al (2015)
Peer review?	yes
Uncertainty analysis?	yes
Sensitivity analysis?	no

Age?	2015
Description	>Identification of strategic materials and 17 EEE hotspots was based on assessments carried out by Blaser et al (2011), Blaser, Widmer & Wäger (2012) and Wäger, Widmer & Müller (2011) + consultations with the Swiss Federal Office for the Environment >31 strategic materials were identified and two separate measurements were conducted to quantify strategic metal amounts in EEE in the shredder output >Sample composition was four-door, mid-size vehicles manufactured between 2003 and 2008 >Project strategic metal content was subsequently compared to the strategic metal content in the shredder fractions >Sample was prepared, all EEE parts were comminutized to >0,5 mm and final chemical analysis was carried out with an X-ray fluorescence spectrometer
Score	4

A17 Updated neodymium supply risk – 2010 and 2030

Under the following assumptions and applying the results of the neodymium MFA carried out in Chapter 8 and Chapter to the supply risk formula used by the European Commission Ad-hoc working group on defining critical raw materials, explained in depth in the report from Oakdene Hollins and Faunhofer ISI 2014, the updated neodymium supply risk score was generated in Chapter 8.

i. Supply=demand;
ii. China is the only source of virgin neodymium in 2010
iii. The neodymium stocks and flows modeled in the Netherlands in 2010 is representative of global neodymium stocks and flows;
iv. All neodymium entering the waste stream in products collected in the Netherlands is recycled using the hydrometallurgical process cited by Sprecher, Kleijn, and Kramer 2014 with a 95% recovery rate.

The new supply risk will be generated for 2010 and 2030 against three different neodymium collection rates signified by the lower bound, business as usual (BAU) and upper bound scenarios based on assumptions for 2010 and 2030 below.

Sector	**Lower Bound**		**BAU**		**Upper bound**	
	Collection rate	Note	Collection rate	Note	Collection rate	Note
2010						
WEEE	35%	Arbitrarily chosen	65%	Collection rate of neodymium-containing WEEE in the NL 2010 from Chapter 8	100%	Highest maximum collection rate to demonstrate potential
ELVs	76%	Lowest ELV collection rate in EU27 in 2010 (Liechtenstein)	83%	Collection rate of ELVs in the NL 2010 according to Eurostat	95%	2015 recycling rate stipulated by the EU Directive on ELVs, 2000/53/EC
Wind	0%	No DDPM turbines entered the waste stream	0%	No DDPM turbines entered the waste stream	0%	No DDPM turbines entered the waste stream
2030						
WEEE	45%	2016 collection target under WEEE Directive 2012/19/EU	65%	2019 collection target under WEEE Directive 2012/19/EU	100%	Highest maximum collection rate to demonstrate potential
ELVs	76%	Lowest ELV collection rate in EU27 in 2010 (Liechtenstein), applied to 2030	83%	Collection rate of ELVs in the NL 2010 according to Eurostat, applied to 2030	95%	2015 recycling rate stipulated by the EU Directive on ELVs, 2000/53/EC
Wind	100%	Maximum collection due to massive size	100%	Maximum collection due to massive size	100%	Maximum collection due to massive size

Supply risk formula: $SR = \sigma(1-\rho)HHI_{WGI}$

Overall supply risk score is a composite score between 0-10. This is determined by the equation above where SR is supply risk, σ is the substitutability, ρ refers to the secondary material:virgin material demand percentage and HHI_{WGI} aggregates virgin extraction concentration and the country's governance into one value. A SR>1 results in a supply risk designated as critical.

The remaining data come directly from Oakdene Hollins and Faunhofer ISI 2014.

HHI_{WGI} is calculated as follows:

- WGI_{scaled} for China = 6,2
- Fractional share of total neodymium produced by China = 1
- In order to convert the fractional share based on the HHI, the square of the shares is needed, $(\text{fractional share x } 100)^2 = (1 \text{ x } 100)^2 = 10000$.
- HHH_{WGI} = 6,2 x 10000 = 62000

σ or substitutability for neodymium = 0,67 as determined by Oakdene Hollins and Faunhofer ISI 2014.

Then, using the three total neodymium recovered values generated for lower bound, BAU and upper bound scenarios, $(1 - \rho)$ can be determined by dividing each recovered value by total neodymium demand in the Netherlands in 2010 and 2030, 253t and 733t.

Item	**Lower Bound**				**BAU**				**Upper Bound**			
	WEEE	ELV	Wind	Total	WEEE	ELV	Wind	Total	WEEE	ELV	Wind	Total
2010												
EOL total [t]	127	1,2	0	128,2	127	1,2	0	128,2	127	1,2	0	128,2
Collection rate [%]	35%	76%	100%		65%	83%	100%		100%	95%	100%	
Recovery rate [%]	95%				95%				95%			
Total recovered [t]	42,2	0,9	0,0	**43,1**	78,4	0,9	0,0	**79,4**	120,7	1,1	0,0	**121,7**
2030												
EOL total [t]	160	14,2	1,4	175,6	160	14,2	1,4	175,6	160	14,2	1,4	175,6
Collection rate [%]	45%	76%	100%		65%	83%	100%		100%	95%	100%	
Recovery rate [%]	95%				95%				95%			
Total recovered [t]	68,4	10,3	1,3	**80,0**	98,8	11,2	1,3	**111,3**	152,0	12,8	1,3	**166,1**

<u>2010</u>

Lower bound = 43,1t / 253t = 17%
BAU = 79,4t / 253t = 31%
Upper bound = 121,7t / 253t = 48%

Finally, all needed variables are known for completing the new neodymium supply risk.

Lower bound: 62000 x (1-0,17) x 0,67 / 10000 = 3,45
BAU: 62000 x (1-,31) x 0,67 / 10000 = 2,86

Upper bound: 62000 x (1-0,48) x 0,67 /10000 = 2,16

2030

Lower bound = 80t / 733t = 11%
BAU = 111,3t / 733t = 15%
Upper bound = 166,1t / 733t = 23%

Finally, all needed variables are known for completing the new neodymium supply risk.

Lower bound: 62000 x (1-0,11) x 0,67 / 10000 = 3,7
BAU: 62000 x (1-,15) x 0,67 / 10000 = 3,53
Upper bound: 62000 x (1-0,23) x 0,67 /10000 = 3,2