MinFuture

Report on pilot studies

Deliverable 4.1

MinFuture is funded by the Horizon 2020 Framework Programme of the European Union under Grant Agreement no. 730330. The contents of this document are the sole responsibility of MinFuture and can in no way be taken to reflect the views of the European Union

Authors

Zhi Cao (SDU), Gang Liu (SDU), Maren Lundhaug (NTNU), Romain Billy (NTNU), Daniel Beat Müller (NTNU), Sébastien Soleille (Deloitte), Mariane Planchon (Deloitte), Chloé Devauze (Deloitte), Jonathan Cullen (UCAM), Gara Villalba (UAB), and Seiji Hashimoto (RU)

Manuscript completed in September, 2018

This document is available on the Internet at: October, 2018

Document title	Report on pilot studies
Work Package	WP4
Document Type	Deliverable, Internal Document
Date	30 September 2018
Document Status	Final version

Acknowledgments & Disclaimer

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No 730330.

Table of Contents

List of Tables

List of Figures

List of abbreviations

CA	Consortium Agreement
CC	Consortium Committee
DOA	Description of Action
GA	Grant Agreement
PCG	Project Coordination Group
PO	Project Office
SPBTT	Science-Policy-Business Think Tank
WP	Work Package

1 Executive Summary

MinFuture project aims to develop a common methodological framework for monitoring the physical economy and to deliver clarity on the different components of MFA needed for monitoring the physical economy.

WP2 identifies and assesses barriers for the implementation of global material flow analyses in the seven MFA-related components: i) Systems; ii) Data; iii) Models & Scenarios; iv) Uncertainty; v) Indicators; vi) Visualization; and vii) Strategy & Decision Support. WP3 investigates the state-of-the-art of global material flow analysis with foci on the component 3-6.

The main objective of this report (**D4.1**) is to illustrate the use of the framework developed in WP2 and WP3 by pilot studies of raw materials and how the seven components can be addressed for the selected raw materials. The illustration of the framework will start from a zoomed-in assessment of literature and on-going efforts regarding selected case raw materials. Based on the literature assessment, we conduct pilot studies to illustrate:

- How to define the system definition that can facilitate characterise stocks and flows of primary materials, secondary materials, international trade, and all the end-use sectors in the global cycles of selected materials in order to enable effective access to material information?
- How to solve/identify gaps and inconsistencies in data availability and quality of all relevant goods that contain the selected materials?
- How to choose proper model approaches, drivers, and scenario techniques in demand-supply forecasting modelling of selected materials?
- How to assess uncertainties in parameters and data and their impacts on the final results?
- How to select proper indicators in order to systematically monitor the physical economy and avoid skewed policy making?
- How to design a visualization tool that can best convey the key messages from MFA results to support decision and policy making?
- How to conceive and conduct a MFA that can enhance the system understanding and guide system interventions?

2 Introduction

2.1 Background

The MinFuture framework distinguishes four dimensions (i.e., stages, trade, layers, and time) and seven components (i.e., systems, data, model & scenarios, uncertainty, indicators, visualization, and strategy & decision support).

The “stages” dimension applies to all non-energy raw materials and integrates all processing steps along the entire cycle (from mining to final waste disposal back into the geosphere). It covers both primary (geological) resources as well as secondary (anthropogenic) resources, and includes in-use reserves (called stocks) as well as the materials that are currently ‘flowing’ though the economy via national and international production, processing, recycling, waste, or trade streams. The recycling flows occur at several of these stages, so do losses to the environment.

The "trade" dimension represents the exchange of all goods along the supply chain (between all stages) among countries or regions. Material cycles can be constructed by either showing the trade between a country and the rest of the world, or with individual other countries.

The "layers" dimension explore the interactions and changing characteristics of materials across their lifecycle. Material flow layers may explore for instance interlinkages between goods, components, materials, chemical elements, as well as energy or value.

The "time" dimension refers to the possibility to track material flows over time, for example the measurement of historical or future stocks and flows of materials by use of scenarios.

The conceptual framework of MinFuture is structured in a pyramid (see http://www.minfuture.eu/themes) with seven MFA-related components (Figure 1). The hierarchical structure of the components implies that the robustness of the components on the higher levels depends on the robustness of the components on the lower levels. The system and data form the foundation of the common methodological framework.

Figure 1 Hierarchical pyramid of MinFuture components

2.2 Objectives and structure of the report

The main objective of WP4 is divided into three sub-objectives:

- Task 4.1 — to select relevant case critical materials used in wind energy technology and define their flows and use through all relevant stages based on the system integration developed in WP2;
- Task 4.2 — to illustrate how the seven components identified in WP 2 and WP3 can be addressed for the selected critical materials;
- Task 4.3 — to discuss implications of the pilot case on methodology and policy recommendations and to support to align interests for collaboration among researchers, authorities, and industry that are relevant to selected critical materials.

This report draws upon findings of Task 4.2 and Task 4.3 and synergies from other WPs. In WP4, we select **neodymium** (Nd) as case critical raw material used in wind energy technology to illustrate the use of the common methodological framework to address the **first four components** (i.e., systems, data, model & scenarios, and uncertainty) in implementing material flow analysis at international level. The **other three components** (i.e., indicators, visualization, and strategy & decision support) are addressed by using case studies (i.e., phosphorus and aluminium) extracted from other WPs. The framework is illustrated by case studies to highlight its generality for different materials and to improve its acceptance among multiple stakeholders.

3 Systems

Systems define a group of physical components, the interaction between these components, and boundaries between these and other components in space and time. Mathematically, systems are defined through (mass or energy) balance equations, which include observed and unobserved flows (e.g., material dissipation). Systems can be defined using different levels of aggregation, depending on the objectives of an investigation. Good system definitions reflect the real world adequately at an aggregation level that satisfies the requirements of their models. Without good system understanding, the MFA will be of poor quality and may even lead to wrong conclusions. The development of systems requires substantial background research, as well as engagement with multiple stakeholders and industry to ensure that it aligns well with the real world. Ultimately, the system maps the stocks and flows along all stages.

3.1 Current knowledge

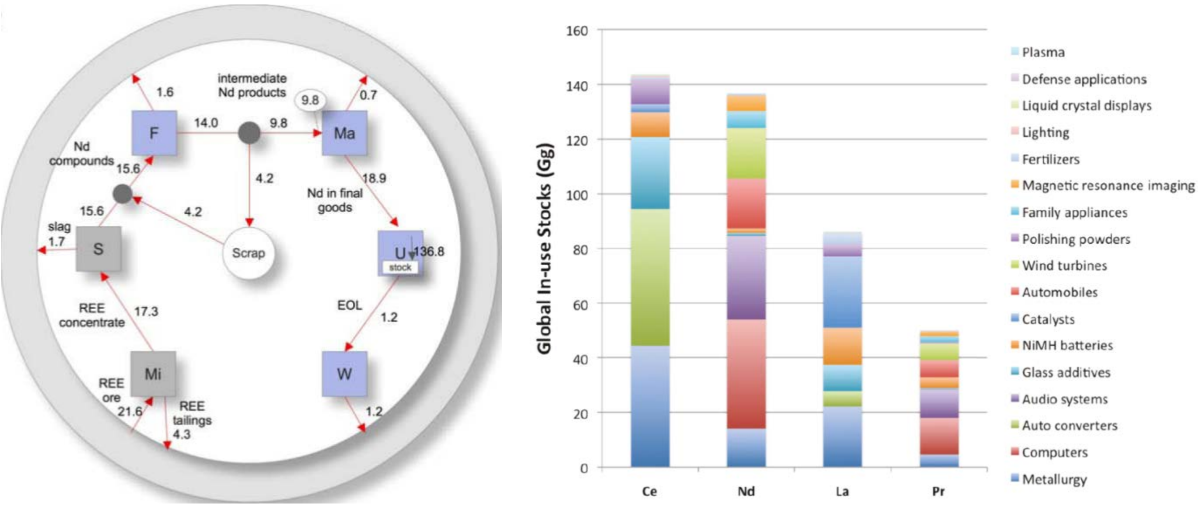
At each stage, mass balance must be respected, that is, the output flows must equal the input flows after adjustment for stocks (W.-Q. Chen and Graedel 2012). Failure to achieve mass balance is an indication that a deficiency exists in the description of the system or in the quantification. This means the system is of insufficient granularity: relevant stages are not completely covered; some flows are missing; and flows and stocks are not quantitatively understood enough.

Material flow data are normally drawn from a wide variety of sources pertaining to the four basic stages (i.e., geological mineral resources, fabrication & manufacturing, in-use stocks, and recycling potentials). Data are usually not systematically explored, classified, or inconsistently reported, and thus insufficiently integrated into national and international databases. Mineral raw materials that go through transformation stages (often outside the EU) are usually reported as aggregated data with limited per-substance resolution in national and international trade statistics. Available material flow data thus remain highly uncertain and have to be improved, harmonised, linked across the different dimensions, and integrated into information infrastructures to assist the development of reliable global material flow models.

A zoomed-in assessment of the state-of-the-art is conducted in Task 4.2 (detailed in Annex A). In summary, existing studies have described different parts of the neodymium cycle at different data aggregation levels.

The first attempt that characterises the global neodymium cycle was conducted by the top-down method based on production data and end use information from various sources (Du and Graedel 2011a, 2011c, 2011b, 2013). This study covered four stages (i.e., processing, fabrication & manufacturing, final products manufacturing, and waste management & recycling) and the in-use stage was divided into magnets, battery alloys, metallurgy, automobile catalysts, glass additives, ceramics, and others (Figure 1).

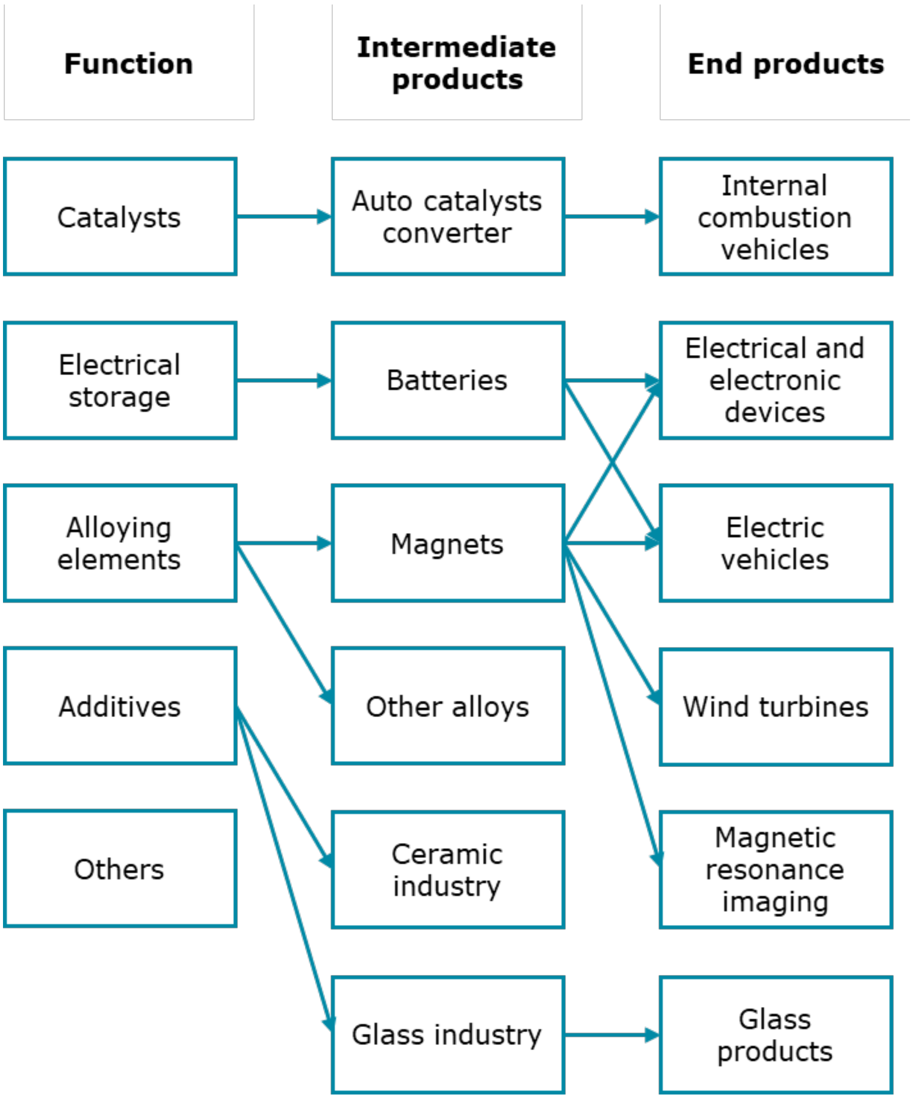
Figure 2 First estimate of global neodymium flow cycle



Sources: (Du and Graedel 2011b, 2011a)

The second attempt that traces the global neodymium cycle could be extracted from a material flow analysis of scarce metals (Peiró, Méndez, and Ayres 2013). This study presented a snapshot of by-product metals embodied in bulk metal ores and disaggregated intermediate product manufacturing stages into two stages (i.e., function and intermediate products) in year 2010 (as shown in Figure 2).

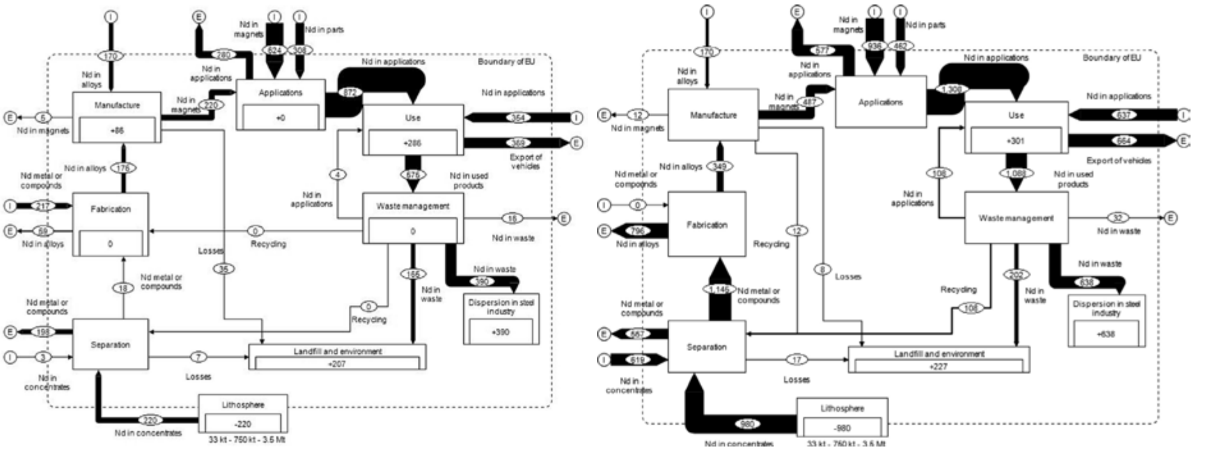
Figure 3 Neodymium-related stages (function, intermediate products, and end-use products)



Source: (Peiró, Méndez, and Ayres 2013)

At the regional level, a combination of top-down method and bottom-up data (e.g., production and trade of individual neodymium-contained products) was employed to map the European neodymium cycle (Figure 3). A forecast of European neodymium cycle in 2020 was then conducted based on a market outlook of intermediate products.

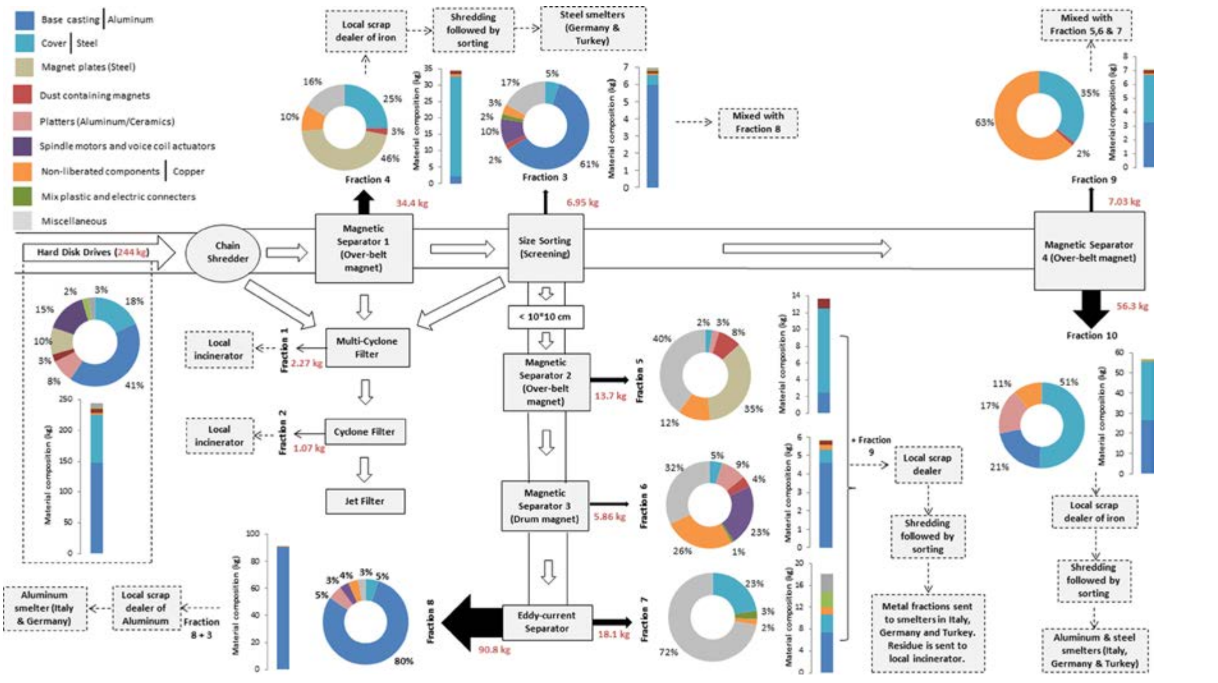
Figure 4 Historical and prospective neodymium flow cycle at regional level (A European case)



Sources: (Guyonnet et al. 2015; Rollat et al. 2016)

Most studies normally simplified the end-of-life stages. A case study on hard disk drives in Denmark gives a good example of how to track neodymium flows in end-of-life stages (Figure 4). Bottom-up data were collected from a local waste treatment centre. This study found that the shredding-based treatment processes resulted in almost 99% loss of neodymium in end-of-life hard disk drives.

Figure 5 Tacking neodymium flow in end-of-life products in Denmark: A case study on computer hard disk drive



Sources: (Habib, Parajuly, and Wenzel 2015)

The rest of literature was focused on different parts of the neodymium cycle. The permanent magnet is the biggest application of neodymium; thus, the final products that use permanent magnets were intensively investigated. Applications of neodymium were extensively found in different products, especially permanent magnets used in different end-use products (e.g., wind turbines, conventional vehicles, plug-in hybrid electric vehicles, hybrid electric vehicles, electric vehicles, hard disk drives, nickel metal hydride batteries, e-bikes, household appliances, IT & telecommunication, and medical devices).

3.2 Best practice

The generic design principles for systems are elaborated in MinFuture Deliverable 5.1.

Material flow analysis studies usually adapt the basic four-stage system into refined systems at different level of granularity, depending on data derived. A stage could be divided into several sub-stages. For example, the production stage of some metal could be divided into mining, smelting, and refining; the semi-product manufacturing stage could be divided into forging, extrusion, and sheeting; the in-use stage could be divided by major industrial sectors (buildings & construction, transportation, consumer durables, and so on and so forth); and the waste management & recycling stage can be divided into collecting, dismantling, cleaning, and re-melting (Liu, Bangs, and Müller 2012; Graedel et al. 2005; W. Chen, Wang, and Li 2016).

Material cycles can be static or dynamic, but the latter is preferable because it can provide useful information on the dynamics of reservoir stocks, anthropogenic stocks and flows over time. Neodymium, as one of the critical materials, is widely used in low-carbon technologies. A refined system is needed to translate low-carbon scenarios into technology/product demands. The number of necessary stages to describe the system depends on the objectives of the study and on the complexity of the system.

3.3 Illustration

A refined system (Annex A) focusing on wind energy system should include stages along the value chain of wind energy system: mining; refining & separation; NdFeB magnets production; generator production; wind turbine installation & commissioning; decommissioning; repowering; and dismantling & shredding. Table 1 exhaustively lists the sub-stages from mining to NdFeB magnets production (Sprecher et al. 2014).

Table 1 Sub-stages along the value chain of permanent magnets

Process	Description
Mining & milling	Ore is recovered from the open pit mine using conventional surface mining techniques such as drilling and blasting. The second step after mining of the crude ore is milling. The ore is crushed and subsequently ground to fine powder in the mill with the aim of creating a high surface which is needed for the further separation.
Beneficiation/separation	The third step is the separation of the valuable metals from the rest of the ore by physical separation methods. The most commonly used method is flotation. The flotation requires a lot of water and chemicals (flotation agents) as well as a high amount of energy. The input into the flotation is the milled crude ore with usually low concentrations (grades) of REO (often between 1 and 10%). The product of the flotation is an enriched concentrate with a higher REE-percentage (in the range of 30 – 70%). The huge waste streams, called tailings, are a mixture of water, process chemicals and finely ground minerals. Usually, the tailings are led to impoundment areas,

	which can be either artificial reservoirs or even natural water bodies (e.g. lakes). They are surrounded by dams.
Acid roasting	Bastnaesite (RECO3F) is a carbonate that can be decomposed to REO and REOF, using high temperature oxidative roasting. Monazite (REPO4) is a highly stable phosphate mineral structure that requires roasting with the addition of strong acid or alkali agents. The goal of acid roasting is to remove the fluoride and carbonate so that only water-soluble rare earth sulphate remains, which is leached out of the ore in a later process.
Leaching	After acid roasting, the ore will contain RE2(SO4)3 and is mixed with cold water. A molar excess of caustic soda (NaOH) is added, causing the REO to precipitate in the form of double salts. These precipitates are then washed and dried. In the final step of the leaching process, a molar excess of HCl is added. This converts the salts into RECl3, which can be used as input for the following solvent extraction process.
Solvent extraction	After obtaining a relatively pure 92% RECl3 concentrate from leaching, the individual rare earths must be separated from each other. This is done using a process known as solvent extraction, which exploits the fact that different rare earths differ slightly in their basicity. The precipitate (mainly RE2(C2O4)3 or RE2(CO3)3) from leaching is heated, causing the formation of rare earth oxides with a purity of up to 99.99%.
Nd-Oxide molten salt electrolysis	The most common industrial process for the production of metallic neodymium involves dissolving Nd2O3 into fluoride based molten salt (e.g., NdF3–LiF) and electrolyzing to produce pure liquid Nd metal.
NdFeB alloying and strip casting	The most common casting process in industry is strip casting. In strip casting, a mixture of Nd, Fe, and B is molten in an induction furnace and then poured over a fast spinning copper wheel.
Jet milling	The NdFeB flakes are milled into 5–7 μm particles using a process known as jet milling, or fluid energy milling.
Aligning and pressing	The NdFeB particles need to be pressed before they can be sintered together. The NdFeB powder is poured into a mould. The particles are then aligned using a short 4–8 T magnetic pulse.
Vacuum sintering	The blocks of aligned and compressed NdFeB particles are vacuum-sintered at pressures of 2–10 mbar. The temperature (1000 °C) is chosen so that the neodymium-rich phase between the NdFeB particles will liquefy, while the particles themselves remain solid.
Grinding and slicing	The sintered block of NdFeB alloy is sliced into a rough shape and then ground and polished into its final form, most commonly using the centreless grinding method.
Electroplating	Magnets used in a sea based wind turbine are laser welded into stainless steel canisters. Magnets used in less demanding environments are coated with a nickel or nickel–copper–nickel layer.

Pulse magnetizing and testing	After coating, the NdFeB magnets are subjected to a strong (4–8 T) magnetic field in order to magnetize them.

Permanent magnet generator is one type of generators of which the excitation field is provided by a permanent magnet instead of a coil. Permanent magnet generators are commonly used to convert the mechanical power output of steam turbines, gas turbines, reciprocating engines and hydro turbines into electrical power for the grid. Some designs of wind turbines might use permanent magnets[1].

Wind turbines can be categorised into six types by their drive train configuration:

- Type A: Geared and high-speed SCIG (Squirrel Cage Induction Generator);
- Type B: Geared and high-speed WRIG (Wound-Rotor Induction Generator);
- Type C: Geared and high-speed DFIG (Doubly-Fed Induction Generator);
- Type D: Direct drive configuration and low-speed PMSG (Permanent Magnet Synchronous Generator) or EESG (Electrically Excited Synchronous Generator) with full power converter. Type D.PM has PMSG and Type D.EE has EESG;
- Type E: Geared and medium/high-speed PMSG (Type E.PM) or EESG (Type E.EE) with full power converter;
- Type F: Geared and high-speed SCIG with full power converter.

A wind farm is expected to have an operational life of approximately 20 to 30 years. When wind turbines reach their lifetime, the project owner will either decommission the site, restoring the area to its previous land use, or negotiate with landowners to repower or upgrade the equipment and extend the wind farm's operational lifespan.

4 Data

Data represent observations of either stocks (at a given point in time) or flows (over a given time period). A system should be able to reflect reference points of measurement where data are collected. Ideally, data collection should be based on system understanding to reflect the real situation, ensuring high quality and robust data that can be used to monitor material systems.

4.1 Current knowledge

Data for bulk metals are relatively more sufficient to characterise their material cycles. Quantitative characterisation of 'minor metal' cycles is mostly hindered by the scarceness and fragmentation of relevant data. A refined system can help position the available data, identify data gaps, assess data quality, and elucidate indicators relevant to neodymium cycle.

Typically, information about mass flows in a material cycle is usually taken from databases or measured directly or indirectly on site (Brunner and Rechberger 2016). Mapping a global material cycle normally either starts from the semi-production stage

[1] https://en.wikipedia.org/wiki/Permanent_magnet_synchronous_generator#cite_note-1

where domestic shipment data are available or the primary production stage where primary production data are available (Glöser, Soulier, and Tercero Espinoza 2013; Liu, Bangs, and Müller 2012; Pauliuk, Wang, and Müller 2013). The quality of material cycle mapping could be improved by using independent bottom-up data to calibrate and verify some of the material flows (Buchner et al. 2015). Similarly, the mapping of minor metals' cycle can be conducted in the same manner.

The neodymium cycle reported in literature is either too aggregate or too regional. To characterise the multiregional neodymium cycle, information on primary production, semi-production, manufacturing, waste management and trade with a global coverage are indispensable. For primary production, USGS and BGS are the two most important data reporters that provide worldwide data. For semi-products and final products, there is no database that could comprehensively cover all countries across the world; nevertheless, official data are reported in certain regions (e.g., EU's Prodcom). Some discrete data series with limited coverage are reported in Industrial Commodity Statistics Database, United Nations Statistics Division. Data on waste are normally unavailable and reliant on simulations with the lifetime model, meaning that the assumptions on lifetime are extremely critical for the material cycle.

In some cases, data of production outputs and trade are both available but needed to be harmonised. For example, the classification of commodities in Prodcom is more disaggregated than UNComtrade and their classification is not always consistent.

Moreover, material content and market penetration rate are equally important for mapping neodymium cycle. Information about neodymium contents in commodities is scarce and highly fragmented in different sources, e.g., industrial reports, publications, surveys, expert judgements, experimental analysis, and so forth (see Annex E). The fragmentation and inconsistency of data cause tremendous uncertainties in the material flows.

4.2 Best practice

The generic design principles for data are elaborated in MinFuture Deliverable 5.1.

A consistent data collection and reporting system is fundamental for compiling global material cycles. The data regarding material flows are collected by several governmental agencies for a variety of purposes, meaning that the data are not collected specifically for material flows. Data used in MFA are collected from a variety of sources, including national statistical offices, international trade statistics databases, data from geological surveys, trade associations and industry. Apparently, the data are also not reported within a system context, which might lead to misinterpretation. In this sense, a refined system could add information, identify data gaps, and eventually improve the robustness of reported data.

Regarding trade data, the following well-established method provides a potential solution. Different material-containing commodities are reported mainly by international statistical organizations, e.g., United Nations Commodity Trade Database (UN Comtrade) and Global Trade Analysis Project (GTAP). They both have two common problems: the missing of physical values for some commodities and the inconsistency of reported bilateral trade (Liu and Müller 2013). In their study, an algorithm was developed to address these physical data gaps and inconsistences, using the following steps:

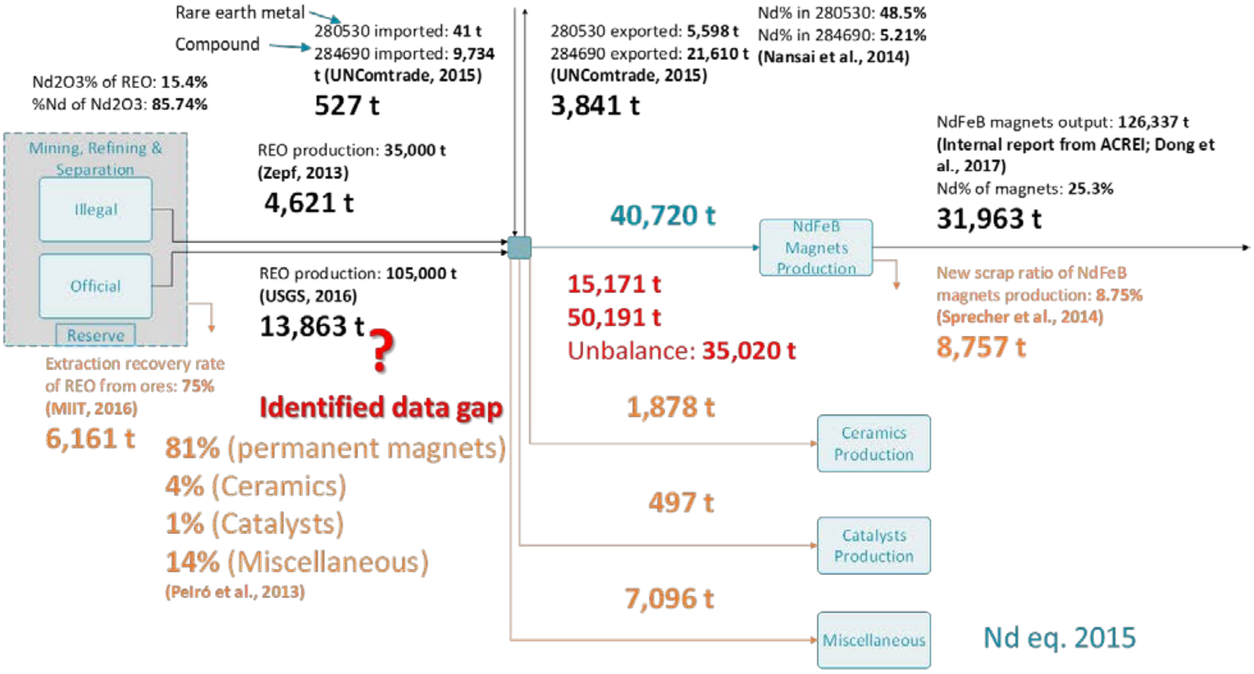
- A trade matrix was developed for each commodity, each year, and each trade direction (import and export);

- In the cases where only monetary values ($) but no physical values (kg) are reported, the physical data gaps were filled by converting monetary values into physical values through the approximation of "world average price";
- "Outliers" were identified by certain criteria (e.g., the ratio of the values in question relative to their neighbours) and then replaced by the arithmetic average of the neighbours;
- Imports and exports for each commodity and each year were derived from trade matrices;
- Materials equivalent embodied in imports and exports were derived by assigning market penetration rate and material concentrations to product categories.

4.3 Illustration

China is dominating the production of rare earth elements worldwide and thus the neodymium cycle in China is of great importance to trace the global value chain of neodymium. Based on the refined system definition, data from a variety of sources are gathered to map the first two stages of 2015 neodymium cycle in China (Figure 5). Because the statistics of semi-products are more trustful, we use the domestic shipment of NdFeB magnets taken from an industrial report as the starting point. Combined with the material composition of permanent magnets, the neodymium equivalent in the domestic shipment of NdFeB magnet is 31963 tonnes. The material efficiency in NdFeB magnet production is 91.25%, meaning that 8.75% (8757 tonnes) of neodymium is scrapped. According to the mass-balance principle, 40720 tonnes of neodymium were fed into the NdFeB magnets production processes in year 2015. The permanent magnets production uses 81% of the neodymium, meaning that China in total used 50191 tonnes of neodymium in year 2015. However, according to the production statistics of REOs and their ore grade, the reported 2015 production of neodymium is 13863 tonnes. Even if the unreported mining and trade are taken into account, the material flows between primary production stage and semi-production stage are tremendously imbalanced. Large uncertainties remain in neodymium production data and trade data, especially the production data from USGS. We also suspect that some uncertainties are from the illegal mining activities.

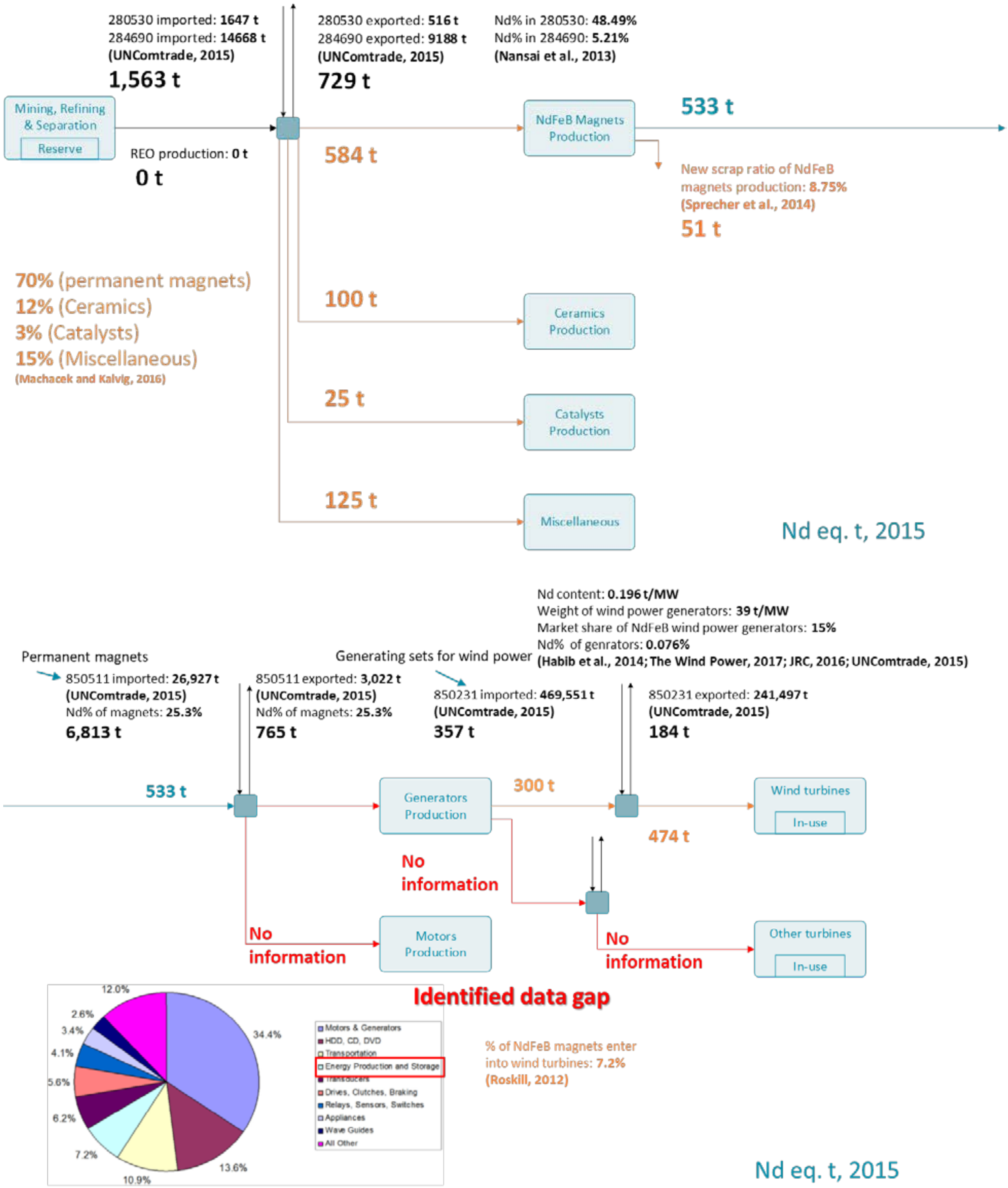
Figure 6 Neodymium flows from primary production stage to semi-production stage of 2015 neodymium cycle in China



Sources: i) UNcomtrade. (2015). https://comtrade.un.org/db/; ii) Ministry of Industry and Information Tech, MIIT. (2016). http://www.miit.gov.cn/n1146295/n1652858/n1652930/n4509607/c4981945/content.html; iii) U.S. Geological Survey, USGS. (2016). Mineral Commodity Summaries. Minerals information: rare earths; iv) Zepf, V. (2013). Rare earth elements: a new approach to the nexus of supply, demand and use: exemplified along the use of neodymium in permanent magnets. Springer Science & Business Media; v) Nansai et al. 2014; vi) Peiró, Méndez, and Ayres 2013 vii) Dong et al. 2017; viii) Sprecher et al. 2014

A similar analysis is conducted on EU28's value chain of neodymium in 2015. The starting point is the primary production of neodymium. The data gaps identified in Figure 6 indicate that the lack of information on market distribution of neodymium hinders the mapping of neodymium cycle.

Figure 7 2015 neodymium cycle in EU28



Sources: i) (Machacek and Kalvig 2016); ii) (Habib et al. 2014); iii) Rosklill: Shaw S, Constantinides S (2012) Permanent magnets: the demand for rare earths. Presentation in: 8th International Rare Earths Conference. 13–15 November 2012, Hong Kong. http://roskill.com/wp/wp-content/uploads/2014/11/download-roskillspaper-on-permanent-magnets-the-demand-for-rare-earths.attachment1.pdf; iv) JRC http://publications.jrc.ec.europa.eu/repository/bitstream/JRC105720/kjna28530enn.pdf; v) http://www.thewindpower.net

5 Models & Scenarios

Models are mathematical representations of material cycles and their drivers which are used to simulate historical changes in material cycles or to make forecasts for future changes through the use of scenarios. Scenarios are plausible developments for the material cycles that are consistent with the mass balance principle and the assumed drivers. Strong models and scenarios depend on robust system definition and data.

5.1 Current knowledge

This report undertook a literature assessment on 38 studies related to the neodymium cycle (Annex B). Roughly half of the assessed studies are focused on the retrospective neodymium cycle and most of them are conducted by a top-down approach. The top-down approach provides a holistic overview of the overall system but much more aggregate information, which is not capable of forecasting the neodymium demand on detailed technology level. Prospective studies are mostly using the inflow-driven approach to forecast the future neodymium demand.

The first attempt analysed the future development of wind technology and the metal demand using the inflow-driven model (Elshkaki and Graedel 2013). This analysis was carried out from 1980 through 2050, using two scenarios: Market First and Policy First. 57 countries are covered in this analysis and grouped into eleven global regions. The amounts of metals required for the wind technology were determined by metal contents.

Another prospective study used the inflow-driven model to estimate the annual recycling potential of neodymium from wind technology (Rademaker, Kleijn, and Yang 2013). The historic and forecast data of installed wind capacity are taken from energy agencies. The scenarios used in this study take account of the market share of wind capacities that contain permanent magnets, the mass of permanent magnets, the composition of permanent magnets.

A prospective study that has the most comprehensive scenarios was used to assess the material demand for U.S. wind generation system under various Clean Power Plan scenarios (Nassar, Wilburn, and Goonan 2016). The uncertainties considered in this study are electricity generation capacities, technology market shares, and material intensities.

Two studies have developed a technology-specific stock-driven model to assess the material demand of British automotive systems (Busch et al. 2014) and U.S. automotive systems (Fishman et al. 2018). The technology-specific stock-driven model has the advantages to assess materials in technologies embedded within infrastructure, where one technology relies on subcomponents, each with their own in-use dynamics and lifetime characteristics. Technology components and materials should be explicitly incorporated in the model, each with their own stock and flow dynamics.

5.2 Best practice

The generic design principles for systems are elaborated in MinFuture Deliverable 5.1.

To address the linkage of materials and environmental aspects, a multi-level approach would be desirable, in which environmental and economic aspects are included alongside the mass balance layer to provide different viewpoints and a holistic approach. At the "substance" layer it would be valuable to account the quality of the substance in addition to the quantity. This is especially relevant for critical raw materials, which otherwise would be negligible, and therefore dismissed, in a mass flow context.

Another important aspect of the model is to estimate inflows and outflows in a prospective modelling approach. Estimations of past and future flows can provide insights on factors influencing resource use and early warnings of environmental problems, or they can support investment planning in infrastructures for mining, production, and waste management (E. Müller et al. 2014). Various methods have become well-established to dynamically model past and future stocks and flows of metals, which provide information about the behaviour of the system as a function of time.

The dynamic material flow analysis (MFA) generally assumes that in the production, manufacturing, and waste management processes, no material is stored or the net flow during the sample time is zero, that is, that this part of the system can be treated as static. Hence, the dynamic modelling approaches focus on the use phase (which has nonzero net flows) and the resulting in-use stock changes. Outflows are quantified by assigning lifetime distribution functions to specific products or end-use sectors, with the relationship between inflows and outflows corresponding to a convolution.

The flow-driven model relies on extrapolation of inflow data. Inflows often fluctuate due to economic and technological developments, such as market crises or product substitutions, which are difficult to predict. Stocks, however, are less affected by short-term market fluctuations and thus provide a more robust basis for forecasts. Therefore, the stock-driven model is preferable to predicting the long-term material demand.

The metal content of stocks and flows is calculated either directly by computing metal stocks and flows from input data or indirectly by computing material stocks of end-use sectors or products and then calculating metal quantities based on the assumed metal share in an end-use sector or content in a product. In the indirect case, the metal share or content is usually considered time-variant.

A dynamic MFA study on aluminium shows that the historical evolution of product stocks and flows, as well as their aluminium contents, determines the patterns of the historical evolution of in-use aluminium stocks for products (W.-Q. Chen, n.d.). In-use stock at nebulous sector level provide only a rough picture of stock development patterns; while the in-use stock at product level uncovers the information hidden in aggregate sectoral results, which enables manufacturers, metal suppliers, recyclers, and governments to plan their material-related policies and actions with much increased precision (e.g., form of recyclable neodymium, technology substitution, material substitution, and so forth). Neodymium-contained products (e.g., electronic vehicles and wind turbines) are normally regarded as emerging technologies. These emerging technologies are rapidly replacing and foreseen to replace the conventional technologies because of societies' accelerated low-carbon transition.

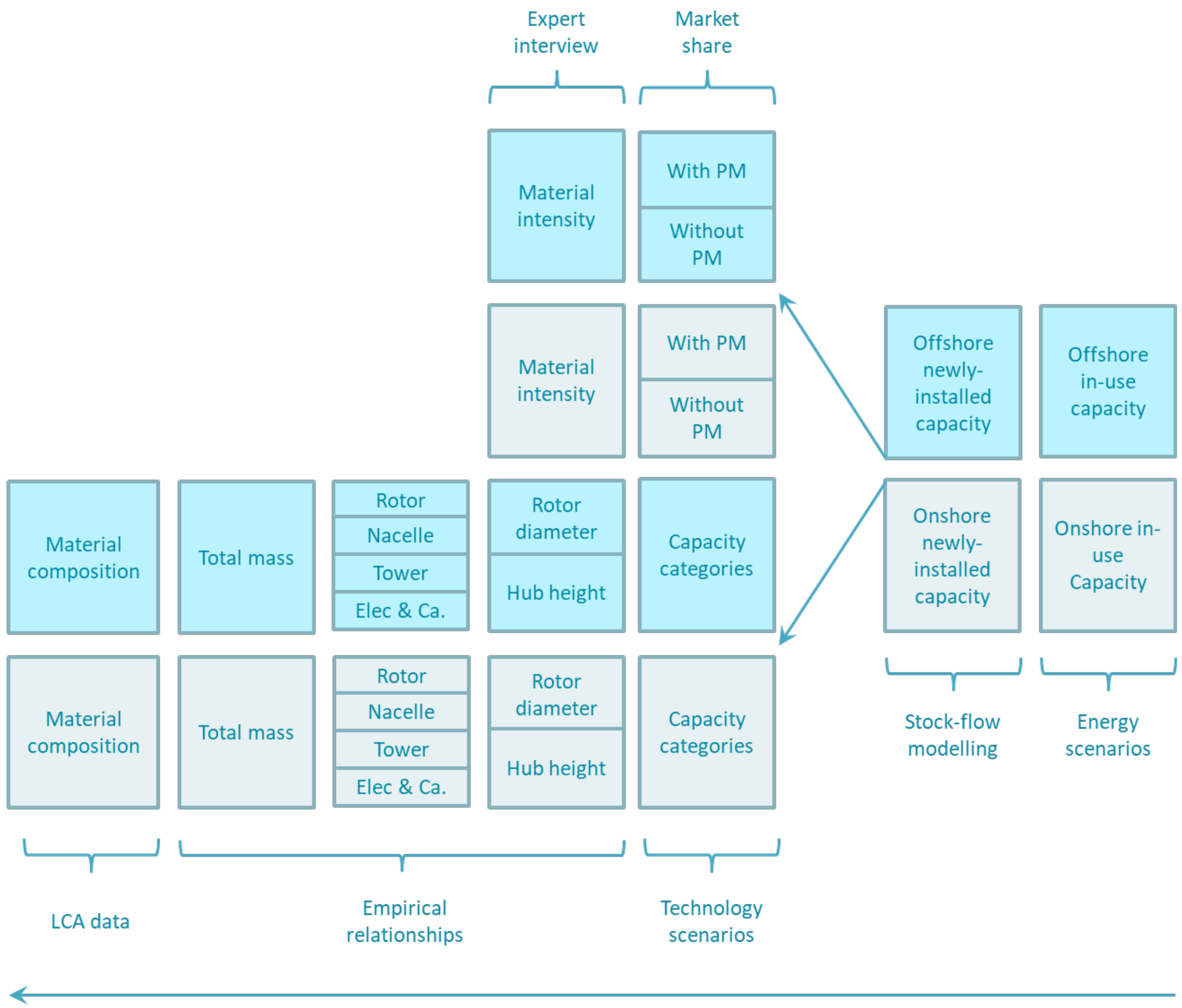
Several key drivers and scenario techniques (i.e., energy technology capacity, lifetime, technical parameters, market share of final products, and material content variations) should be considered in the stock-driven model.

5.3 Illustration

Stock/capacity-driven model

A stock-driven model with bottom-up technology-specific information is developed to forecast the demand and potential secondary supply of materials in Danish wind energy system (Figure 7). Energy scenarios are served as the major driver of the stock-driven model. Empirical data (e.g., wind turbine design specification and LCA inventory) are used to transform the capacity of wind turbines to material demands. For minor and bulk materials, different approaches are employed to estimate their demand and secondary supply.

Figure 8 Forecasting the material demands of future Danish wind energy system

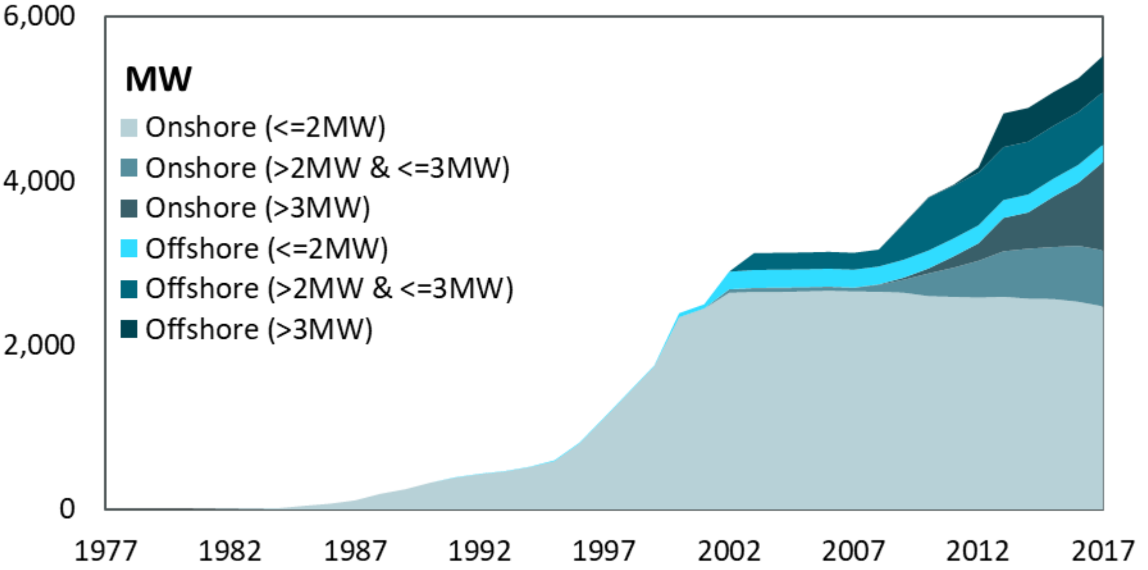


Source: developed by the authors

Denmark was a pioneer in developing commercial wind power during the 1970s due to the oil crisis. Around 40% of electricity in Denmark's energy system comes from wind. Denmark has relatively abundant wind resources, with more onshore wind resource in western part of the country and more offshore wind resource in the eastern islands coastline facing south or west. The long-term governmental goal for Denmark is to fundamentally transform the Danish energy system into a 100% renewable one by 2050.

Denmark has to decide between a biomass-reliant and wind-reliant energy system. The in-use capacities of wind turbines have kept increasing from 1977 to 2017 and reach 5619 MW in 2017 (Figure 8); simultaneously, the average size of wind turbines keeps growing since around 2007.

Figure 9 Historical development of Danish wind energy



Source: https://ens.dk/sites/ens.dk/files/Vindenergi/anlaegprodtilnettet.xls

The Danish Energy Agency (DEA) has developed four different fossil free scenarios[2] for the future Danish energy system: a wind scenario, a biomass scenario, a Bio+ scenario, and a hydrogen scenario. The four scenarios are constructed from a biomass perspective. The wind scenario is developed through a massive electrification of the transport and the heating sectors, thereby reducing the biomass demand to 250 PJ. Some of this biomass is used for biofuel production that is integrated into the electricity and heating supply, while wind power will be the dominant technology for electricity production. In the hydrogen scenario, surplus wind energy will be converted into methane gas by electro-catalysis and stored in the natural gas grid. The wind-gas process could eliminate CO2 emissions.

A fossil scenario has been developed neglecting all national targets and therefore continuing the consumption of fossil fuels. This scenario consumes a large share of coal due to its low price, but also oil and natural gas for transport and electricity and heat production. In the future, wind power and electric vehicles are also assumed to be economical and therefore these technologies are also part of the fossil scenario, but on a lower level than in the wind scenario.

Based on the DEA wind scenario, the Danish Society of Engineers (IDA) developed an energy scenario[3] up to 2050 with updated data. The IDA scenario therefore assumed that the onshore wind capacity would expand to 5000 MW in 2050. An expansion potential for onshore wind turbines exists, but is restricted by planning regulations that require wind turbines to be placed at a distance of 4 times the height of the wind turbine from buildings, as well as outside protected areas. However, recently Energinet.dk released a

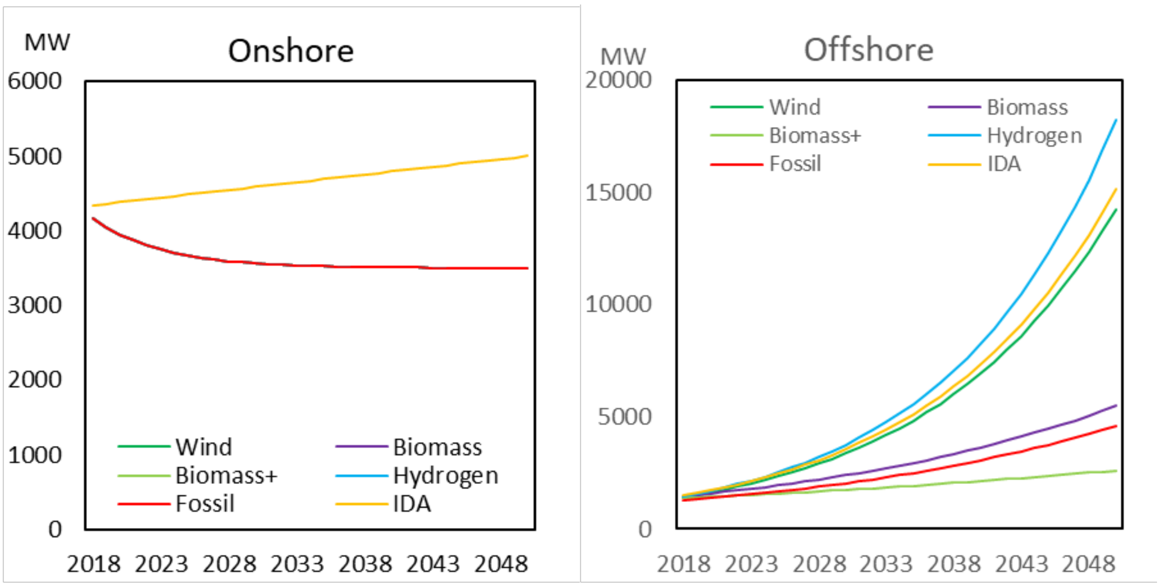
---

[2] https://ens.dk/sites/ens.dk/files/Basisfremskrivning/energiscenarier_-_analyse_2014_web.pdf

[3] http://vbn.aau.dk/files/222230514/Main_Report_IDAs_Energy_Vision_2050.pdf

report examining the onshore potential with the possibility of buying up buildings to create more space for onshore wind turbines. The report concludes that a total onshore potential of 12 GW wind capacity is socio-economically more attractive than building offshore wind capacity. Figure 9 plots the smooth transition of the future Danish wind energy systems under different scenarios.

Figure 10 Prospects on Danish wind energy development under different energy scenarios



Source:

DEA, https://ens.dk/sites/ens.dk/files/Basisfremskrivning/energiscenarier_-_analyse_2014_web.pdf;

IDA, http://vbn.aau.dk/files/222230514/Main_Report_IDAs_Energy_Vision_2050.pdf

A stock-driven model is developed to determine the annual new capacity and decommissioned capacity of wind turbines, based on the well-established stock-flow methodological framework (D. B. Müller 2006). The stock refers to the in-use capacity of wind turbines and is analogous to a time buffer, meaning that the decommissioned capacities are the previously installed capacities that reach their end-of-life with corresponding lifetime characteristics. Mathematically, the relationship between the new and decommissioned capacities can be expressed as a convolution, respecting the mass-balance principle. Thus, the new and decommissioned capacities are calculated backwards from the assumed development of in-use capacities, according to the equations below.

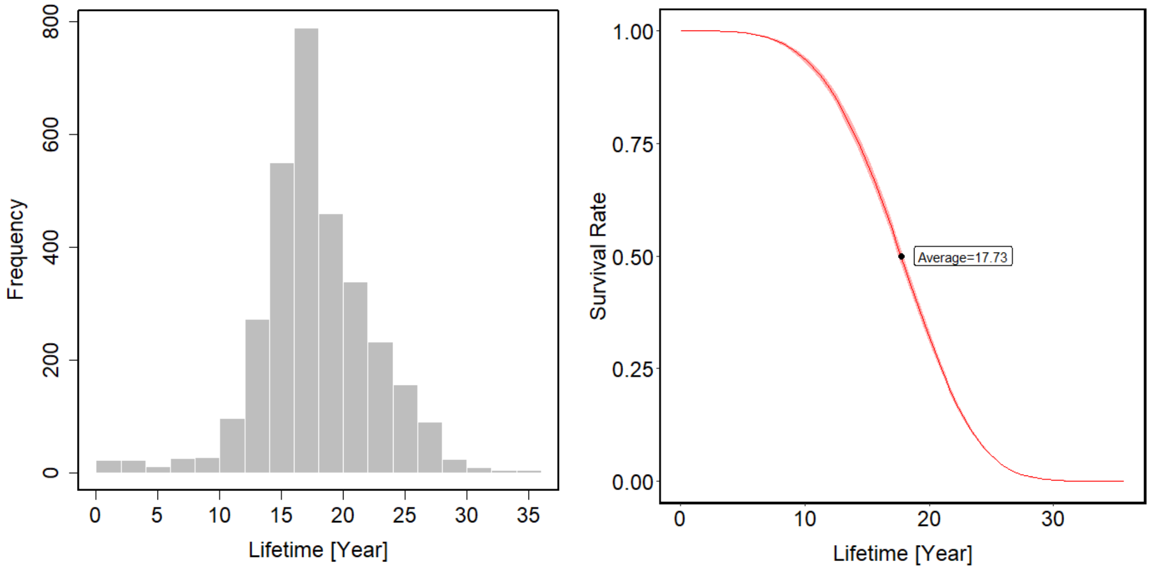
$$Inflow_t = Stock_t - Stock_{t-1} + Outflow_t$$

$$Outflow_t = \sum_{t'=t0}^{t'=t-1} Inflow_{t'} \times (1 - S_{t-t'})$$

where $Inflow_t$ or $Inflow_{t'}$ refers to the new capacities at year t or t'; $Stock_t$ or $Stock_{t-1}$ refers to the in-use capacities of wind turbines at year t or $t-1$; $Outflow_t$ refers to the decommissioned capacities at year t; and $S_{t-t'}$ refers to the probability that the previously installed capacities reach their end-of-life after $t-t'$ years.

A Weibull distribution is used to determine the lifetime distribution of wind turbines and corresponding survival function. The average lifetime of wind turbines in Danish energy system is slightly lower than assumptions used in previous studies, due to the fact that Denmark is one of leading wind turbine R&D countries in the world and thus certain amounts of wind turbines installed in Denmark are pilot projects (Figure 10).

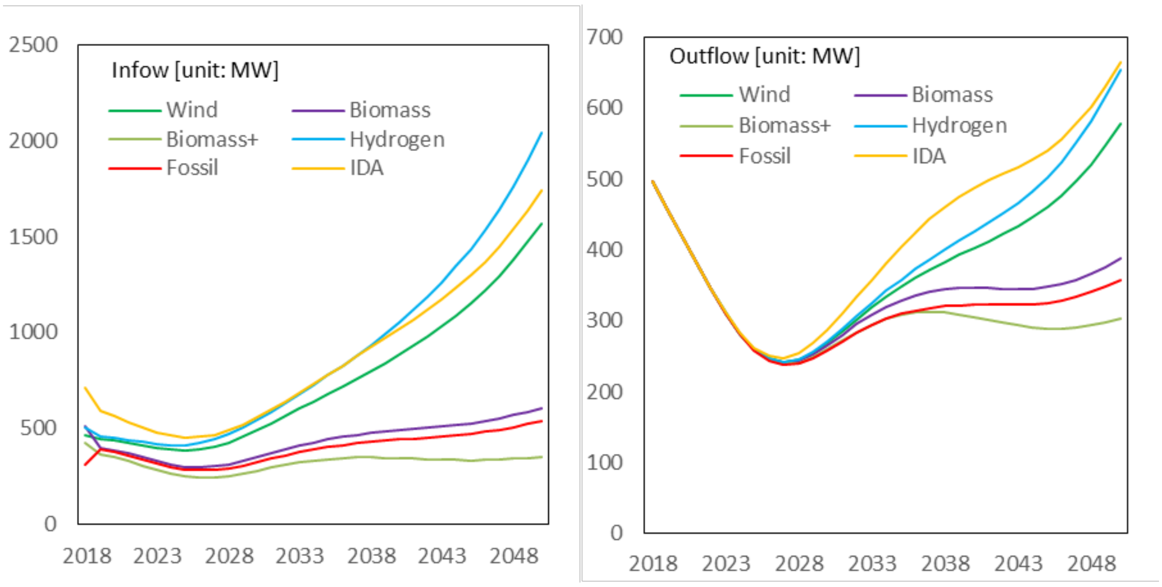
Figure 11 Lifetime and survival function of Danish wind turbines



Source: plotted by the authors

Based on the two drivers (in-use stock and lifetime), the future new and decommissioned capacities are simulated and plotted in Figure 11.

Figure 12 Estimated new and decommissioned capacities of wind turbines



Source: plotted by the authors

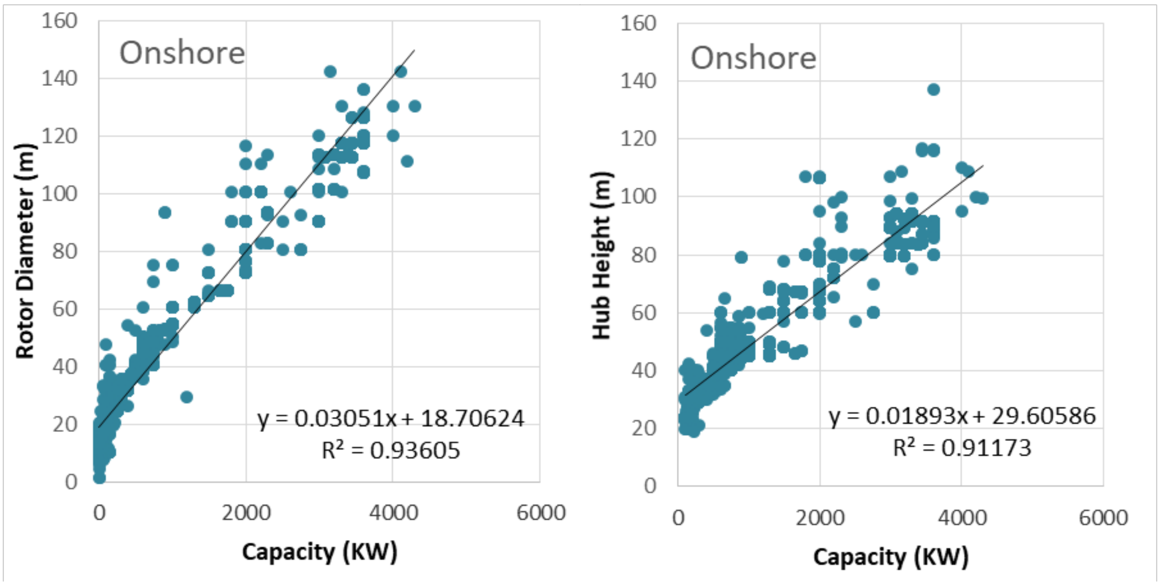
To be more economically competitive with fossil fuel and nuclear power generation technologies, the current trend shows that the size of wind turbines is continuously scaled up (Lacal-Arántegui 2015), which has considerable impacts on the mass of wind turbines with different sizes. The technological trend of turbine size predicted by DEA[4] is used to translate the capacities to the mass of wind turbines. The average size of onshore wind turbines will increase to 4 MW by 2030 and 5 MW by 2050; meanwhile, the average size of offshore wind turbines will increase to 12 MW by 2030 and 15 MW by 2050.

Bottom-up technical parameters at a component-by-component level

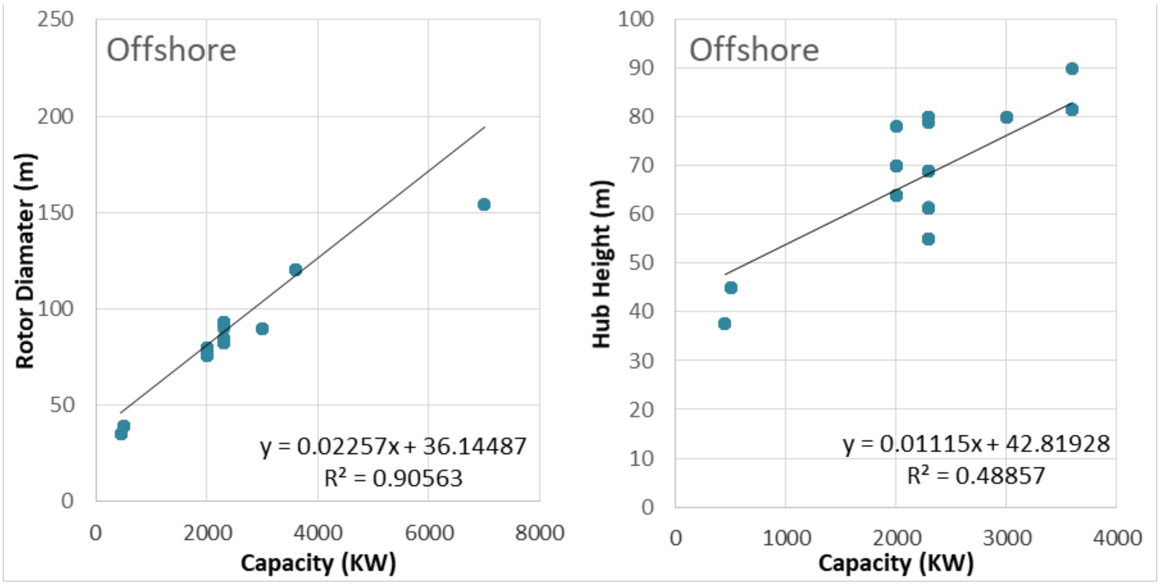
To translate the capacity into mass, the empirical relationships between different technical parameters of wind turbines are derived from a large sample of wind turbines. The "translation" takes two steps:

- Determine the empirical relationships between the capacity and the hub height, and the capacity and the rotor diameter (Figure 12)

Figure 13 Relationships between capacity and rotor diameter or hub height



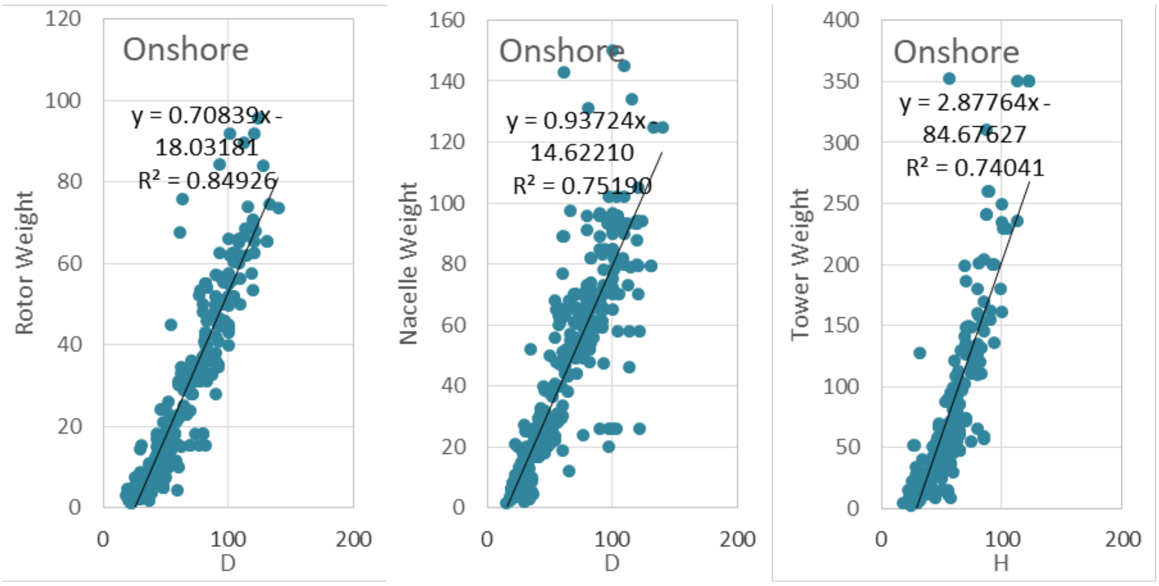
[4] https://ens.dk/sites/ens.dk/files/Analyser/technology_data_catalogue_for_energy_plants_el_and_dh_-_aug_2016_update_juli2018.pdf

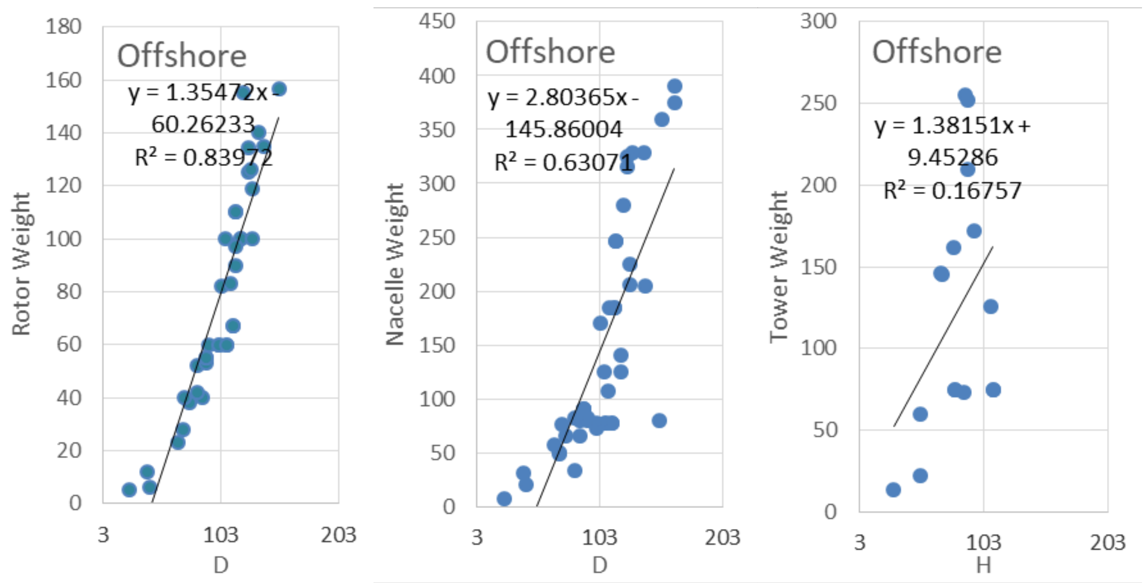


Source: plotted by the authors

- Determine the empirical relationship between the rotor diameter and the rotor weight, the rotor diameter and the nacelle weight, and the product of rotor diameter and hub height and the tower weight (Figure 13)

Figure 14 Regression analysis of technical parameters



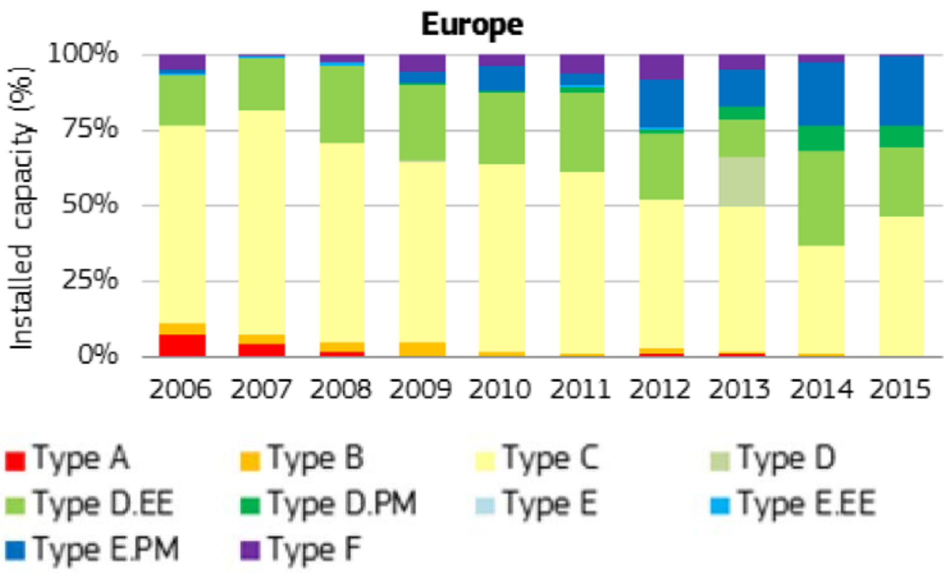


Source: plotted by the authors; data retrieved from http://www.thewindpower.net

Prospect on market share of final products and material compositions

Due to data availability, the market share for European wind energy system (see Figure 14) is applied to the Danish wind energy system. In Europe, the onshore wind market is mainly dominated by type C configuration and to a lesser extent type D. In Europe, type D configuration was mainly dominated by EESGs versus PMSGs, representing 35 % and 10 % respectively. The hybrid arrangements type E-PM and type F only represented 8 % and 1 %, respectively.

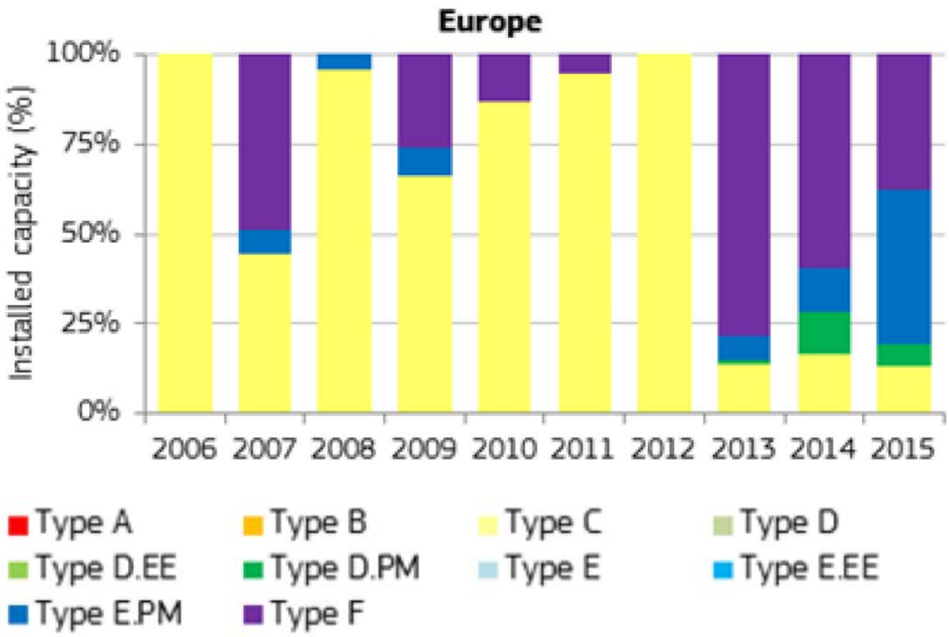
Figure 15 Historical market development of onshore wind turbines



Source: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC105720/kjna28530enn.pdf

The offshore wind market has evolved from a dominant type C configuration (geared high-speed DFIG) towards both direct drive (type D) and hybrid arrangements (types E and F). In the European market, the hybrid configurations type F and type E-PM have reached a prominent role in recent years (Figure 15).

Figure 16 Historical market development of offshore wind turbines



Source: http://publications.jrc.ec.europa.eu/repository/bitstream/JRC105720/kjna28530enn.pdf

The mass of the magnet depends on the generator's speed and its size, suggesting that the permanent magnet mass in low-speed, direct-drive turbines ranges from approximately 500-1000 kg per MW with the median value being around 600 kg per MW (Nassar, Wilburn, and Goonan 2016). In general, hybrid-drive generators use permanent magnets that are approximately one-third the mass of their direct-drive counterparts or about 200 kg per MW. The Nd content in permanent magnets adopted in wind turbines typically ranges from 28% to 31%.

In order to demonstrate MFA's capacity on exploring the demand for other materials, the stock-driven model also includes six bulk materials: stainless steel, copper, aluminium, cast iron, concrete, and fibre glass. The selected six bulk materials represent the majority of materials used in wind energy system. Material compositions are extracted from LCA inventory data (Table 2). Concrete is mainly used in the foundation of wind turbines. Because the foundation of wind turbines is not included in the bottom-up technical data, the mass ratio of concrete is calculated separately.

Table 2 Material compositions of wind turbines with different sizes

	<=2MW	>2MW&<=3MW	>3MW
Stainless steel	70.1%	83.6%	69.0%
Aluminium	1.4%	1.0%	1.1%
Copper	0.8%	0.9%	0.9%

Cast iron	13.5%	16.9%	15.8%
Fibre glass	6.0%	7.2%	5.8%
Concrete	369.4%	339.7%	278.0%

6 Uncertainty

Uncertainty is inherent in all MFAs due to errors in system definitions and the data used. Approaches to uncertainty analysis aim at making uncertainties transparent and reducing them. They enable the users to make more robust assumptions and to become aware of the model's strengths and limitations. A good uncertainty analysis addresses both systematic errors (e.g., system definition) as well as random errors (e.g. data).

6.1 Current knowledge

Most of the MFA studies used a symmetric approach to deal with uncertainty using standard statistics to estimate standard deviations and using Gauss's Law of error propagation. Some additionally include Monte Carlo Simulation and STAN for their analysis. Sensitivity analysis is applied to quantify the range of possible output outcomes (e.g. indicators), given a set of uncertain inputs.

Due to the data scarceness, a few of neodymium-related studies considered uncertainties. A Danish case study collected a large amount of samples from the waste flow to estimate uncertainties in individual neodymium flows (Habib et al. 2014). Five levels (1-5) depending on the data source are assigned to the material flows. A Japanese case study considered uncertainties in Nd composition, magnet weight, and lifetime (Sekine, Daigo, and Goto 2016). A Swiss case study defined levels of uncertainty and assigned a corresponding relative uncertainty to all parameters used in the calculation depending on: i) reliability of data source, ii) data quality, and iii) representativeness of the experiment's sample (Restrepo et al. 2017). An American case study on vehicles took account of uncertainties in scenario variables and other model parameters (Fishman et al. 2018).

6.2 Best practice

The generic design principles for uncertainty are elaborated in MinFuture Deliverable 5.1.

For system, the first step for handling uncertainty in MFA is to define the elements of the system and the mathematical relationships between them in consideration of the mass balance principle.

For data, to deal with uncertain data appropriately, functions need to be characterised. If sufficient empirical evidence is available, statistical parameter estimation techniques or goodness-of-fit tests can be applied.

For model, model equations are usually solved numerically and therefore associated uncertainty is low. For exploratory MFA, sensitivity analysis is used to evaluate the effects of parameter variation on the model outputs. It forms the basis to identify critical model parameters, which can influence the material flows in the system and therefore the final outcomes. Indictors and their associated uncertainty can be calculated from the model outputs.

6.3 Illustration

The statistical parameter estimation technique is employed to assess uncertainties in parameters generated by regression. A sensitivity analysis is conducted to assess the impact of uncertainties in each individual parameter on simulation outputs (taking glass fibre [5] as an illustration). For parameters of which statistical uncertainties are not available, a sensitivity analysis is conducted to assess the impact of parameter variation on simulation results (taking neodymium as an illustration).

The maximum likelihood estimation method is employed to fit the distribution of wind turbines' lifetime function (see Table 3). The lower and upper limits of the 95% confidence level are used to assess how uncertainties of parameters would affect the results.

Table 3 Uncertainties in regressions of technical data

	Onshore (±2σ)	Offshore (±2σ)
Scale	19.48 (±0.18)	19.48 (±0.18)
Shape	4.07 (±0.11)	4.07 (±0.11)
Slope of regression equation for Capacity → Rotor Diameter	0.03051021 (±0.0001728673)	0.02256912 (±0.0006396086)
Intercept of regression equation for Capacity → Rotor Diameter	18.7062434 (±0.173165)	36.14487 (±1.680013)
Slope of regression equation for Capacity → Hub Height	0.01892778 (±0.0001558885)	0.01114527 (±0.001004959)
Intercept of regression equation for Capacity → Hub Height	29.60586 (±0.1905436)	42.81928 (±2.576586)
Slope of regression equation for Rotor Diameter → Rotor Weight	0.7083895 (±0.03176943)	1.354724 (±0.1972863)
Intercept of regression equation for Rotor Diameter → Rotor Weight	-18.03181 (±2.19336)	-60.26233 (±20.79415)
Slope of regression	0.9372353	2.803648

[5] Glass fibre is a low-value material and its recycling requires high investment and processing costs. Commercial applications of recovered glass fibre are extremely limited, meaning that the majority of end-of-life glass fibre is sent to landfill.

equation for Rotor Diameter → Nacelle Weight	(±0.05180454)	(±0.6543103)
Intercept of regression equation for Rotor Diameter → Nacelle Weight	-14.6221 (±3.410971)	-145.86 (±71.26413)
Slope of regression equation for Hub Height → Tower Weight	2.877635 (±0.1997686)	1.381508 (±1.645867)
Intercept of regression equation for Hub Height → Tower Weight	-84.67627 (±11.51322)	9.452863 (±137.5672)

The model is run again using the lower and upper limits of each parameter. Results of the 2050 demand for glass fibre in Denmark are selected to demonstrate how significant uncertainties in each parameter are propagated into simulated results. Table 4 shows that uncertainties in two parameters (i.e., the slope coefficient in the regression relationship between the hub height and tower weight, and the slope coefficient in the regression relationship between the rotor diameter and nacelle weight) affect the simulated results the most.

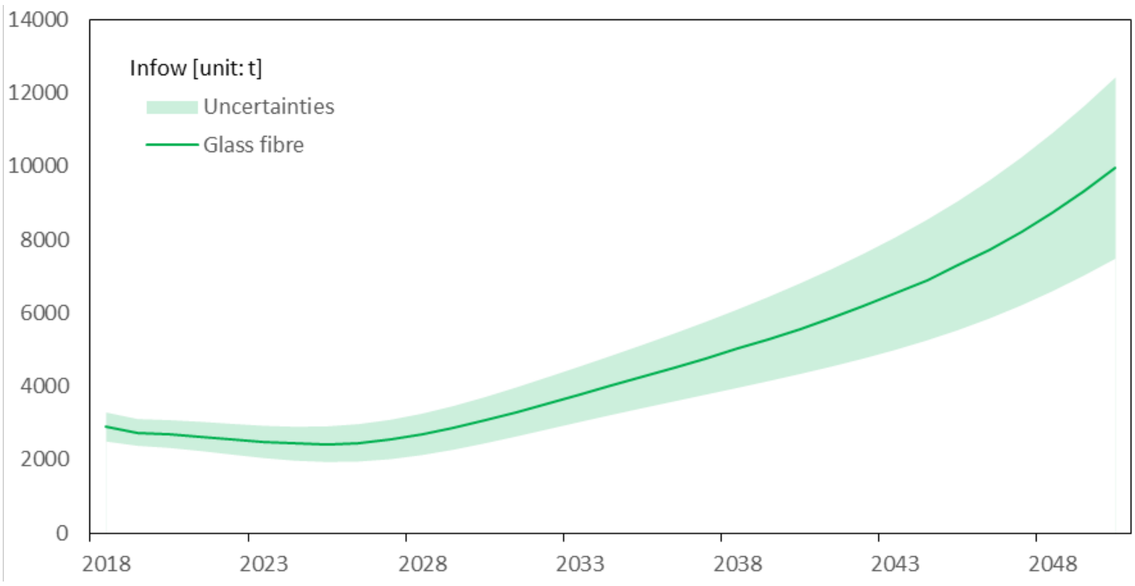
Table 4 Sensitivity of 2050 demand for glass fibre in Denmark to each parameter in the Wind scenario

	Onshore	Offshore
Scale	[-0.50%, +0.52%]	
Shape	[-0.20%, +0.22%]	
Slope of regression equation for Capacity → Rotor Diameter	[-0.03%, 0.03%]	[-2.15%, 2.15%]
Intercept of regression equation for Capacity → Rotor Diameter	[-0.01%, 0.01%]	[-0.38%, 0.38%]
Slope of regression equation for Capacity → Hub Height	[-0.05%, 0.05%]	[-1.12%, 1.12%]
Intercept of regression equation for Capacity → Hub Height	[-0.01%, 0.01%]	[-0.19%, 0.19%]
Slope of regression equation for Rotor	[-0.11%, 0.11%]	[-3.98%, 3.98%]

Diameter → Rotor Weight		
Intercept of regression equation for Rotor Diameter → Rotor Weight	[-0.05%, 0.05%]	[-1.12%, 1.12%]
Slope of regression equation for Rotor Diameter → Nacelle Weight	[-0.19%, 0.19%]	[-13.21%, 13.21%]
Intercept of regression equation for Rotor Diameter → Nacelle Weight	[-0.07%, 0.07%]	[-3.84%, 3.84%]
Slope of regression equation for Hub Height → Tower Weight	[-0.52%, 0.52%]	[-18.63%, 18.63%]
Intercept of regression equation for Hub Height → Tower Weight	[-0.24%, 0.24%]	[-7.41%, 7.41%]

The total uncertainty is calculated by the propagation of errors, assuming that the lifetime data and technical data are independent. Taking glass fibre as an example, Figure 16 shows uncertainties in the 2018-2050 demand for glass fibre in Denmark. From 2018 to 2050, the uncertainty in demand increases from 13.65% to 24.81%, due to the assumption that uncertainties of model variables are amplified by the increasing average capacity.

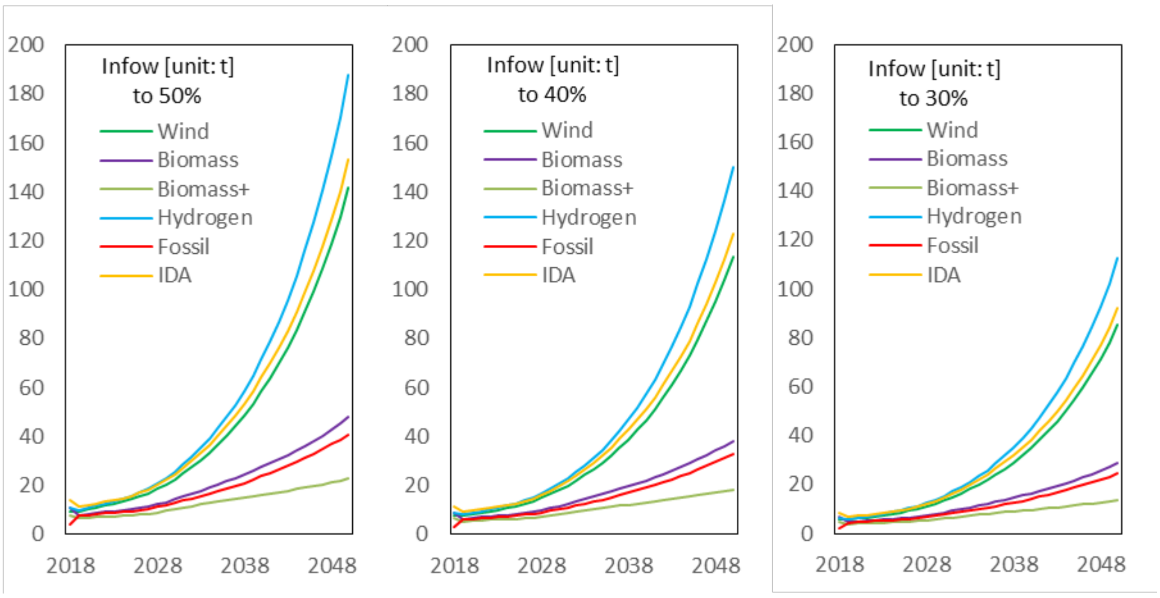
Figure 17 Uncertainties in the 2018-2050 demand for glass fibre in Denmark



Source: plotted by the authors

The neodymium demand during 2018-2050 shows an upward trend under various energy scenarios (Figure 17). The market share of wind turbines containing permanent magnet would systematically change the neodymium demand, suggesting that the market share is a crucial factor determining the neodymium demand.

Figure 18 Neodymium demand in Denmark (2018-2050) under various market shares (to 50%, 40%, and 30%) and energy scenarios (Wind, Biomass, Biomass+, Hydrogen, Fossil, and IDA)



Source: plotted by the authors

7 Indicators

Indicators stand for quantitative measures that aim to reflect the status of complex systems. They are used to analyse and compare performance of businesses, sectors or economies across countries and to determine policy priorities. A careful selection of indicators or indicator sets is therefore of uttermost importance for transforming the socio-economic metabolism in a desired direction. If indicators are poorly selected, there is a risk that policies based on indicators have unintended side effects that impede rather than facilitate the overall goals. A typical example is EU's ELV Directive sets targets for "reuse & recycling" and "reuse & recovery". These targets are focused on bulk materials and neglecting critical materials that are used in small amounts. In addition, the quality of recycled materials and criticality of materials are entirely omitted.

7.1 Current knowledge

A comprehensive evaluation on indicators is elaborated in D3.2. Evaluated indicators are grouped into the following categories:

- Material flows and stocks indicators, including indicators for the production stage, indicators for the use stage, indicators for the end-of-life stage, and indicators for the losses and dissipation;

- Environmental and social sustainability indicators, including life cycle assessment indicators, air emissions indicators, water indicators, extractive waste management indicators, occupational safety indicators, and sustainability reporting indicators;
- Criticality indicators, including EC criticality indicators, three-dimension indicators, and thermodynamic rarity indicators;
- Policy indicators, including mining activity and minerals exploration indicators, national minerals policy framework indicators, public acceptance indicators;
- Competitiveness and innovation indicators, including value added and employment indicators, corporate R&D investment indicators, patent applications indicators, knowledge and skills indicators, Eurostat raw material use indicators;
- Statistical entropy analysis indicators;
- Circularity index;
- By-product indicators, including by-product fraction, value ratio of by-product/carrier, price elasticity of supply/demand, Gibb free energy of mineral and ore grade, supply potential;

7.2 Best practice

Indicators are needed to represent both the goal and the means to achieve goals. Therefore, there is a need to differentiate between goals (e.g. increase resource efficiency, reduce environmental impact) and the means to reach that goal (i.e. increase recycling, use renewable energy).

In general, there is a trend for a service-oriented economy and indicators should reflect this shift from owning to using. For example, people are not interested in having natural gas to heat their house, but they are interested in having a warm house. Consequently, materials are not in focus but the service these materials provide.

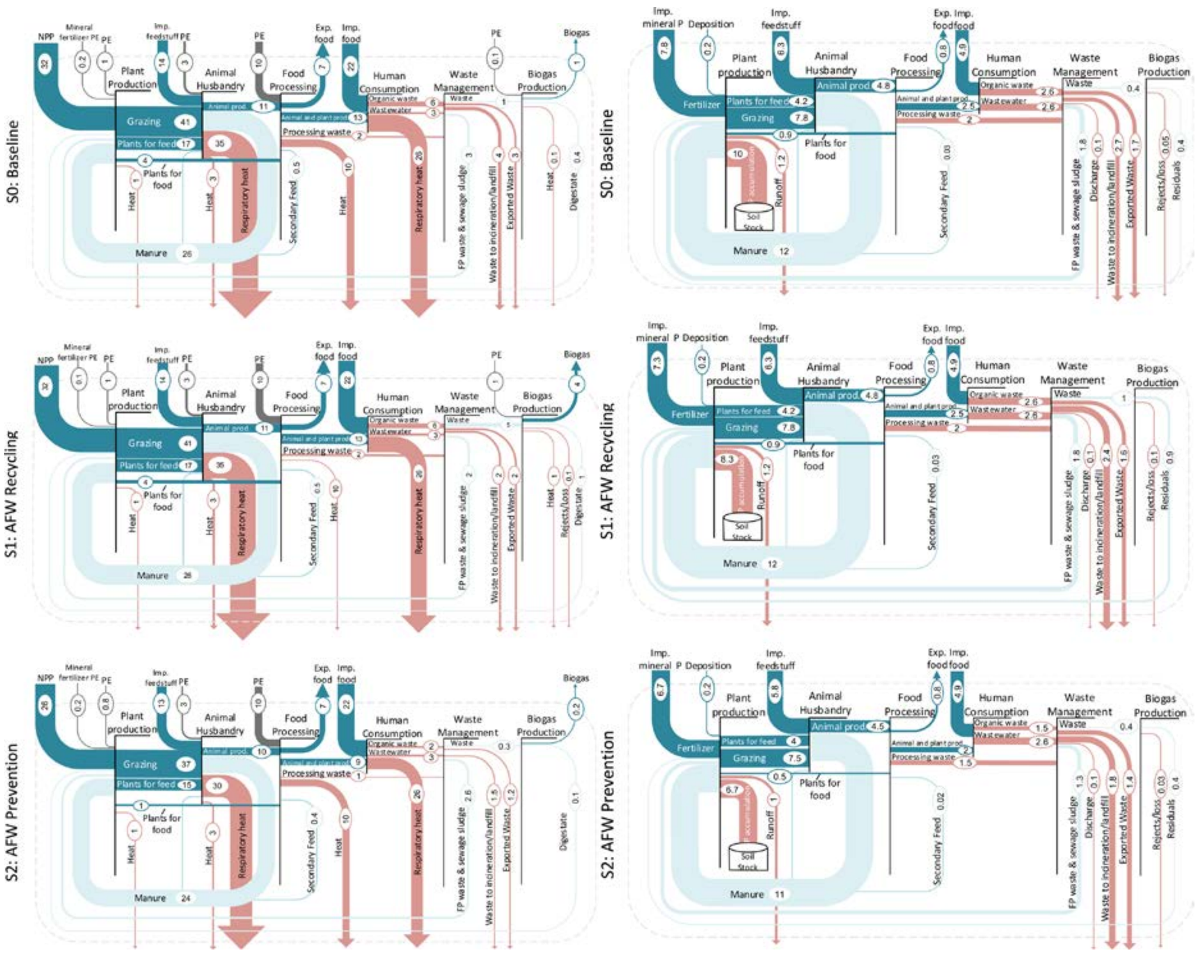
Quantitative physical indicators need to be complemented by a set of different indicators, used for different purposes to provide a holistic approach, for example environmental, financial, social indicators.

The use of indicators in policy making can be quite challenging. On the one hand, the indicators should provide a basis to control a complex system, but on the other hand, few well-intended but poorly selected indicators may not be able to capture the relevant parts of the system. Based on the MinFuture framework (see http://www.minfuture.eu/themes), indicators are placed towards the top of the pyramid. This implies that a robust system, data, models and uncertainty should form the basis, based on which a set of indicators reflecting the system as a whole should be used.

7.3 Illustration

A multi-indicator, multi-layer analytical framework was developed to assess the system-wide impacts of food waste prevention and recycling strategies in Norwegian food system. The energy balance and phosphorus balance are characterised on top of the biomass layer of the food system in Norway (see Figure 18). The analysis results from the systematic framework found that overall phosphorus and energy use can be reduced more effectively with prevention strategies. The recycling strategies mainly look at end-of-life (EOL) measures, leading to a risk that if EOL measures are prioritized developed infrastructure would create a lock-in effect. Usually, the infrastructure of EOL measures are reliant on the production of food waste to operate. This points out that even policies meant to increase sustainability get skewed with narrow system boundaries, which necessitates a multi-indicator framework in order to help avoid such situations.

Figure 19 Energy balance (left) and phosphorus balance (right) of Norwegian food system under Baseline scenario (S0), Food waste recycling scenario (S1), and Food waste prevention scenario (S2)



Source: (Hamilton et al. 2015)

8 Visualisation

Visualisation is an essential part of the way how MFA results are presented and portrayed. MinFuture sees the visualisation as a visual story-telling tool that provides an interactive data environment, structures the MFA data, creates data stories, and communicates these stories to decision makers.

8.1 Current knowledge

A comprehensive evaluation on MFA's visualization is elaborated in D3.4.

Most MFA studies include multidimensional variables, with heightened complexity, resulting in a broad range of diagrams being adopted. Many different visual forms are employed across the MFA studies, ranging from Sankey diagrams through to Bubble charts. Sankey diagrams, in different forms, are popular in providing a holistic overview of material systems, particularly for single year MFA studies. However, Sankey diagrams are less effective for visualising MFAs conducted over multiple years; traditional Line Charts, Bar Charts and Area Plots are more likely to be used to visualise the change in variables over time.

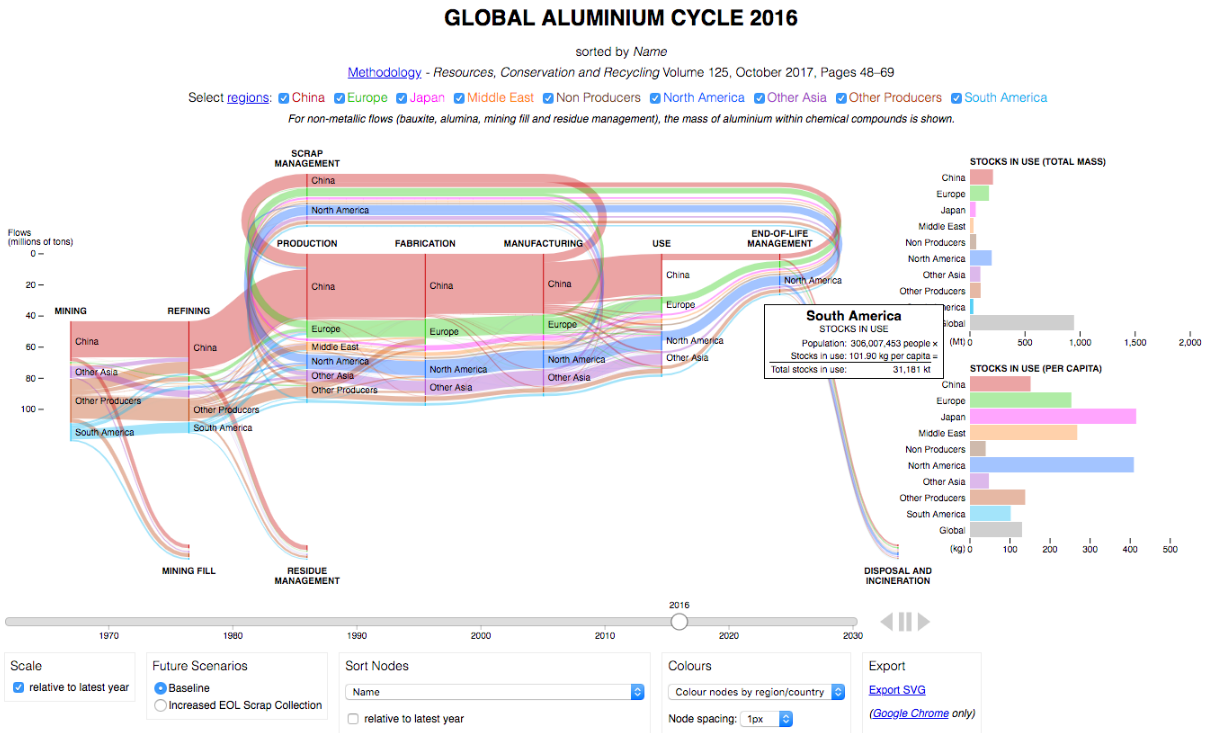
8.2 Best practice

Sankey diagrams are judged as the preferred primary visualisation tool used in MFA, because they perceivably convey both the material system structure and the quantitative values of material flows. To communicate more dimensions, more optional visual aids are needed: bar chart, table, flow diagram, line chart, area plot, and pie chart. Sankey diagrams are capable of displaying multivariate data—a common requirement in MFA studies. They provide a holistic view of the entire material system and the relative importance of individual material flows. Supplementary visualisations should be used to support the primary Sankey visualisation. An interactive online MFA model is ideal, because it allows the user to interrogate the primary Sankey visualisation, present more detailed multivariate data as 'meta data' labels, and provide a link to a secondary 'pop-up' visual.

8.3 Illustration

Taking the global aluminium cycle as an illustration (http://www.world-aluminium.org/statistics/massflow/), the visualization developed by Norwegian University of Science and Technology (NTNU), International Aluminum Institute (IAI) and Truth Studio shows the interactive Sankey diagram's capability on displaying MFA results and allowing the reader to interrogate and manipulate the MFA data to create their own data stories. The online interactive Sankey diagram allows users to scroll through several years of data and see the Sankey Diagram updating in real time. A short animation can also be viewed which traverses the years of data updating the Sankey in chronological sequence. This visualization can be a powerful strategy or decision supporting tool for government and industry.

Figure 20 Interactive visualization of global aluminium cycle



Source: http://www.world-aluminium.org/statistics/massflow/

9 Strategy & Decision Support

MFAs are developed to facilitate the reflection about material (and energy) systems. They are typically developed to address two fundamental questions: i) How well do we understand the physical system, and how can we improve our understanding of the system most effectively? ii) What are challenges related to the real world system analysed, and how can we control the system most effectively to reach certain goals? While the first question addresses the understanding of the system (methodology), the second question aims at changing the system (interventions).

a) Strategies for enhancing system understanding

Following the logic of the framework presented here, the interpretation of an MFA should include interpretations of the results that answer the following methodological questions:

- How robust is our understanding of the system? Do we consider all of the relevant stocks and flows at an adequate granularity?
- How well is our quantitative understanding of the system? Do we have relevant data gaps?
- Where do we have major uncertainties that need to be considered when drawing policy-relevant conclusions?
- How good and useful are the models and scenarios for addressing the specific questions at hand?
- Are the indicators developed sufficient to adequately reflect the performance of the system?
- Are the visualisations suitable to communicate the main findings?
- How well is our overall understanding in order to support policy-relevant conclusions? Where can we be confident, and where do we need to be cautious?

Carefully answering these methodological questions is considered best practice in MFA. Ensuring transparency and reproducibility in the MFA research community involves pointing out the strengths and limitations of the approach and data used. It is a prerequisite for developing **research strategies** of individual research groups, research institutions, as well as research foundations.

However, the relevance of these methodological findings is not restricted to the research community. Also governments, NGOs, and industry associations have started to monitor various aspects of the physical economy. Answers to the questions laid out above are therefore highly relevant for informing the development of **monitoring strategies**. For example, the findings of MFAs can be used to identify relevant *data gaps* and effective ways to address them, either by using the mass balance principle, by making informed estimates, or by proposing new measurements or proposing amendments to existing measurement programmes. Another important aspect of monitoring strategies is *data harmonisation*. MFAs can facilitate the reflection about the *scope of monitoring programmes*, including the identification of relevant aspects that should be monitored at different levels of granularity.

b) Strategies for system interventions (governance and business models)

MFAs are designed with many different purposes in mind, but most commonly to identify or describe problems related to the physical economy, to test alternative strategies for mitigating these problems, or to identify potential business opportunities. The relevance of MFA results is always limited by the system definition chosen. It is therefore critical that the purpose of the model is stated explicitly and upfront, and that it is aligned with the system definition. The MFA component at the top of the pyramid ("strategy and decision support") should therefore not be considered the last one, but rather the first and the last, with the first one (purpose, scope) informing the base of the pyramid (system definition).

MFA results cannot provide policy makers and industry representatives with meaningful strategies. The problems typically analysed in MFAs are too complex, and cannot be solved by one scientific discipline alone. Policy-prescriptive interpretations of the results are therefore not consistent with the scientific principles. Nevertheless, MFAs can inform decisions and strategies with relevant findings. The art of interpreting MFA findings is therefore to be policy- (and business-) relevant while avoiding to be policy-prescriptive.

MFAs are also poorly suited to distinguish between "good" and "bad" solutions or outcomes or to blame specific actors for certain phenomena. Changes in the physical economy may involve aspects that are desired by some actors and undesired by others. What we perceive as problems is usually generated by the entire system involving many stakeholders that are all linked with each other through the physical economy. On the other side, MFAs are well suited to facilitate the reflection about complex multi-stakeholder problems (how different processes and stakeholders are linked with each other through the physical economy) and how they can be addressed most effectively through multi-stakeholder interventions.

MFAs can inform government and industry strategies in many ways:

- MFAs can demonstrate where materials are "lost" or ineffectively used along the supply chain, and thereby point out the largest potentials for resource recovery and recycling. This information is highly relevant for informing strategies related to resource management, circular economy, or (critical) raw materials supply. Whether or not governments or businesses should focus on the recovery of these resources, however, may be determined by many other factors that are out of scope.

- MFAs have been developed to forecast future scrap availability. This information can be relevant for informing investments in new recycling facilities or the development of new sorting technologies needed to separate different fractions of the scrap.
- Other MFAs have been developed to forecast demand for certain materials. This information is relevant for investments into mining and production of these materials.
- Some MFAs for individual materials have been linked to models of energy use and greenhouse gas emissions, which allowed the model developers to develop scenarios for greenhouse gas emission in these sectors, and to test the effectiveness of alternative intervention options for overall reduction of greenhouse gas emissions.

These examples illustrate that MFAs have a potential for informing strategies, among others for resource management and circular economy, critical raw material supply, climate change, and investments. Since many of the great problems of humanity today are linked with each other through the physical economy, MFA has also a great potential to inform strategies that aim at simultaneously addressing several sustainable development goals.

10 References

Alonso, Elisa, Andrew M. Sherman, Timothy J. Wallington, Mark P. Everson, Frank R. Field, Richard Roth, and Randolph E. Kirchain. 2012. 'Evaluating Rare Earth Element Availability: A Case with Revolutionary Demand from Clean Technologies'. *Environmental Science & Technology* 46 (6): 3406–14. https://doi.org/10.1021/es203518d.

Bandara, H. M. Dhammika, Julia W. Darcy, Diran Apelian, and Marion H. Emmert. 2014. 'Value Analysis of Neodymium Content in Shredder Feed: Toward Enabling the Feasibility of Rare Earth Magnet Recycling'. *Environmental Science & Technology* 48 (12): 6553–60. https://doi.org/10.1021/es405104k.

Brunner, Paul H, and Helmut Rechberger. 2016. *Handbook of Material Flow Analysis: For Environmental, Resource, and Waste Engineers*. CRC press.

Buchner, Hanno, David Laner, Helmut Rechberger, and Johann Fellner. 2015. 'Dynamic Material Flow Modeling: An Effort to Calibrate and Validate Aluminum Stocks and Flows in Austria'. *Environmental Science & Technology* 49 (9): 5546–54. https://doi.org/10.1021/acs.est.5b00408.

Busch, Jonathan, Julia K. Steinberger, David A. Dawson, Phil Purnell, and Katy Roelich. 2014. 'Managing Critical Materials with a Technology-Specific Stocks and Flows Model'. *Environmental Science & Technology* 48 (2): 1298–1305. https://doi.org/10.1021/es404877u.

Chancerel, Perrine, Max Marwede, Nils F. Nissen, and Klaus-Dieter Lang. 2015. 'Estimating the Quantities of Critical Metals Embedded in ICT and Consumer Equipment'. *Resources, Conservation and Recycling* 98 (Supplement C): 9–18. https://doi.org/10.1016/j.resconrec.2015.03.003.

Chen, Wei-Qiang. n.d. 'Dynamic Product-Level Analysis of In-Use Aluminum Stocks in the United States'. *Journal of Industrial Ecology*, n/a-n/a. https://doi.org/10.1111/jiec.12710.

Chen, Wei-Qiang, and T. E. Graedel. 2012. 'Anthropogenic Cycles of the Elements: A Critical Review'. *Environmental Science & Technology* 46 (16): 8574–86. https://doi.org/10.1021/es3010333.

Chen, Wu, Minxi Wang, and Xin Li. 2016. 'Analysis of Copper Flows in the United States: 1975–2012'. *Resources, Conservation and Recycling* 111 (August): 67–76. https://doi.org/10.1016/j.resconrec.2016.04.014.

Cucchiella, Federica, Idiano D'Adamo, S. C. Lenny Koh, and Paolo Rosa. 2015. 'Recycling of WEEEs: An Economic Assessment of Present and Future e-Waste Streams'. *Renewable and Sustainable Energy Reviews* 51 (November): 263–72. https://doi.org/10.1016/j.rser.2015.06.010.

Dong, Shengzhi, Wei Li, Hongsheng Chen, and Rui Han. 2017. 'The Status of Chinese Permanent Magnet Industry and R&D Activities'. *AIP Advances* 7 (5): 056237. https://doi.org/10.1063/1.4978699.

Du, Xiaoyue, and T. E. Graedel. 2011a. 'Global In-Use Stocks of the Rare Earth Elements: A First Estimate'. *Environmental Science & Technology* 45 (9): 4096–4101. https://doi.org/10.1021/es102836s.

———. 2011b. 'Uncovering the Global Life Cycles of the Rare Earth Elements'. *Scientific Reports* 1 (November). https://doi.org/10.1038/srep00145.

———. 2011c. 'Global Rare Earth In-Use Stocks in NdFeB Permanent Magnets'. *Journal of Industrial Ecology* 15 (6): 836–43. https://doi.org/10.1111/j.1530-9290.2011.00362.x.

Du, Xiaoyue, and T.E. Graedel. 2013. 'Uncovering the End Uses of the Rare Earth Elements'. *Science of The Total Environment* 461–462 (September): 781–84. https://doi.org/10.1016/j.scitotenv.2013.02.099.

Du, Xiaoyue, Eliette Restrepo, Rolf Widmer, and Patrick Wäger. 2015. 'Quantifying the Distribution of Critical Metals in Conventional Passenger Vehicles Using Input-Driven and Output-Driven Approaches: A Comparative Study'. *The Journal of Material Cycles and Waste Management; Dordrecht* 17 (2): 218–28. http://dx.doi.org.proxy1-bib.sdu.dk:2048/10.1007/s10163-015-0353-3.

Elshkaki, Ayman, and T. E. Graedel. 2014. 'Dysprosium, the Balance Problem, and Wind Power Technology'. *Applied Energy* 136 (December): 548–59. https://doi.org/10.1016/j.apenergy.2014.09.064.

Elshkaki, Ayman, and T.E. Graedel. 2013. 'Dynamic Analysis of the Global Metals Flows and Stocks in Electricity Generation Technologies'. *Journal of Cleaner Production* 59 (November): 260–73. https://doi.org/10.1016/j.jclepro.2013.07.003.

Fishman, Tomer, Rupert J. Myers, Orlando Rios, and T. E. Graedel. 2018. 'Implications of Emerging Vehicle Technologies on Rare Earth Supply and Demand in the United States'. *Resources* 7 (1): 9. https://doi.org/10.3390/resources7010009.

Gemechu, Eskinder D., Guido Sonnemann, and Steven B. Young. 2017. 'Geopolitical-Related Supply Risk Assessment as a Complement to Environmental Impact Assessment: The Case of Electric Vehicles'. *The International Journal of Life Cycle Assessment* 22 (1): 31–39. https://doi.org/10.1007/s11367-015-0917-4.

Glöser, Simon, Marcel Soulier, and Luis A. Tercero Espinoza. 2013. 'Dynamic Analysis of Global Copper Flows. Global Stocks, Postconsumer Material Flows, Recycling Indicators, and Uncertainty Evaluation'. *Environmental Science & Technology* 47 (12): 6564–72. https://doi.org/10.1021/es400069b.

Graedel, T. E., Dick Beers, Marlen Bertram, Kensuke Fuse, Robert B. Gordon, Alexander Gritsinin, Ermelinda M. Harper, et al. 2005. 'The Multilevel Cycle of Anthropogenic Zinc'. *Journal of Industrial Ecology* 9 (3): 67–90. https://doi.org/10.1162/1088198054821573.

Gutfleisch, Oliver, Matthew A. Willard, Ekkes Brück, Christina H. Chen, S. G. Sankar, and J. Ping Liu. 2010. 'Magnetic Materials and Devices for the 21st Century: Stronger, Lighter, and More Energy Efficient'. *Advanced Materials* 23 (7): 821–42. https://doi.org/10.1002/adma.201002180.

Guyonnet, Dominique, Mariane Planchon, Alain Rollat, Victoire Escalon, Johann Tuduri, Nicolas Charles, Stéphane Vaxelaire, Didier Dubois, and Hélène Fargier. 2015. 'Material Flow Analysis Applied to Rare Earth Elements in Europe'. *Journal of Cleaner Production* 107 (November): 215–28. https://doi.org/10.1016/j.jclepro.2015.04.123.

Habib, Komal, Keshav Parajuly, and Henrik Wenzel. 2015. 'Tracking the Flow of Resources in Electronic Waste - The Case of End-of-Life Computer Hard Disk Drives'. *Environmental Science & Technology* 49 (20): 12441–49. https://doi.org/10.1021/acs.est.5b02264.

Habib, Komal, Peter Klausen Schibye, Andreas Peter Vestbø, Ole Dall, and Henrik Wenzel. 2014. 'Material Flow Analysis of NdFeB Magnets for Denmark: A Comprehensive Waste Flow Sampling and Analysis Approach'. *Environmental Science & Technology* 48 (20): 12229–37. https://doi.org/10.1021/es501975y.

Habib, Komal, and Henrik Wenzel. 2014. 'Exploring Rare Earths Supply Constraints for the Emerging Clean Energy Technologies and the Role of Recycling'. *Journal of Cleaner Production*, Special Volume: The sustainability agenda of the minerals and energy supply and demand network: an integrative analysis of ecological, ethical, economic, and technological dimensions, 84 (December): 348–59. https://doi.org/10.1016/j.jclepro.2014.04.035.

———. 2016. 'Reviewing Resource Criticality Assessment from a Dynamic and Technology Specific Perspective – Using the Case of Direct-Drive Wind Turbines'. *Journal of Cleaner Production* 112, Part 5 (January): 3852–63. https://doi.org/10.1016/j.jclepro.2015.07.064.

Hamilton, Helen A., M. Samantha Peverill, Daniel B. Müller, and Helge Brattebø. 2015. 'Assessment of Food Waste Prevention and Recycling Strategies Using a Multilayer Systems Approach'. *Environmental Science & Technology* 49 (24): 13937–45. https://doi.org/10.1021/acs.est.5b03781.

Hoenderdaal, Sander, Luis Tercero Espinoza, Frank Marscheider-Weidemann, and Wina Graus. 2013. 'Can a Dysprosium Shortage Threaten Green Energy Technologies?' *Energy* 49 (January): 344–55. https://doi.org/10.1016/j.energy.2012.10.043.

Imholte, D. D., R. T. Nguyen, A. Vedantam, M. Brown, A. Iyer, B. J. Smith, J. W. Collins, C. G. Anderson, and B. O'Kelley. 2018. 'An Assessment of U.S. Rare Earth Availability for Supporting U.S. Wind Energy Growth Targets'. *Energy Policy* 113 (February): 294–305. https://doi.org/10.1016/j.enpol.2017.11.001.

Kleijn, René, Ester van der Voet, Gert Jan Kramer, Lauran van Oers, and Coen van der Giesen. 2011. 'Metal Requirements of Low-Carbon Power Generation'. *Energy* 36 (9): 5640–48. https://doi.org/10.1016/j.energy.2011.07.003.

Koning, Arjan de, René Kleijn, Gjalt Huppes, Benjamin Sprecher, Guus van Engelen, and Arnold Tukker. 2018. 'Metal Supply Constraints for a Low-Carbon Economy?' *Resources, Conservation and Recycling* 129 (February): 202–8. https://doi.org/10.1016/j.resconrec.2017.10.040.

Lacal-Arántegui, Roberto. 2015. 'Materials Use in Electricity Generators in Wind Turbines – State-of-the-Art and Future Specifications'. *Journal of Cleaner Production* 87 (January): 275–83. https://doi.org/10.1016/j.jclepro.2014.09.047.

Liu, Gang, Colton E. Bangs, and Daniel B. Müller. 2012. 'Stock Dynamics and Emission Pathways of the Global Aluminium Cycle'. *Nature Climate Change* 3 (4): 338–42. https://doi.org/10.1038/nclimate1698.

Liu, Gang, and Daniel B. Müller. 2013. 'Mapping the Global Journey of Anthropogenic Aluminum: A Trade-Linked Multilevel Material Flow Analysis'. *Environmental Science & Technology* 47 (20): 11873–81. https://doi.org/10.1021/es4024404.

Machacek, Erika, and Per Kalvig. 2016. ‘Assessing Advanced Rare Earth Element-Bearing Deposits for Industrial Demand in the EU’. *Resources Policy* 49 (September): 186–203. https://doi.org/10.1016/j.resourpol.2016.05.004.

Müller, Daniel B. 2006. ‘Stock Dynamics for Forecasting Material Flows—Case Study for Housing in The Netherlands’. *Ecological Economics* 59 (1): 142–56. https://doi.org/10.1016/j.ecolecon.2005.09.025.

Müller, Esther, Lorenz M. Hilty, Rolf Widmer, Mathias Schluep, and Martin Faulstich. 2014. ‘Modeling Metal Stocks and Flows: A Review of Dynamic Material Flow Analysis Methods’. *Environmental Science & Technology* 48 (4): 2102–13. https://doi.org/10.1021/es403506a.

München, Daniel Dotto, and Hugo Marcelo Veit. 2017. ‘Neodymium as the Main Feature of Permanent Magnets from Hard Disk Drives (HDDs)’. *Waste Management* 61 (Supplement C): 372–76. https://doi.org/10.1016/j.wasman.2017.01.032.

Nansai, Keisuke, Kenichi Nakajima, Shigemi Kagawa, Yasushi Kondo, Sangwon Suh, Yosuke Shigetomi, and Yuko Oshita. 2014. ‘Global Flows of Critical Metals Necessary for Low-Carbon Technologies: The Case of Neodymium, Cobalt, and Platinum’. *Environmental Science & Technology* 48 (3): 1391–1400. https://doi.org/10.1021/es4033452.

Nassar, Nedal T., David R. Wilburn, and Thomas G. Goonan. 2016. ‘Byproduct Metal Requirements for U.S. Wind and Solar Photovoltaic Electricity Generation up to the Year 2040 under Various Clean Power Plan Scenarios’. *Applied Energy* 183 (December): 1209–26. https://doi.org/10.1016/j.apenergy.2016.08.062.

Pauliuk, Stefan, Tao Wang, and Daniel B. Müller. 2013. ‘Steel All over the World: Estimating in-Use Stocks of Iron for 200 Countries’. *Resources, Conservation and Recycling* 71 (February): 22–30. https://doi.org/10.1016/j.resconrec.2012.11.008.

Pavel, Claudiu C., Roberto Lacal-Arántegui, Alain Marmier, Doris Schüler, Evangelos Tzimas, Matthias Buchert, Wolfgang Jenseit, and Darina Blagoeva. 2017. ‘Substitution Strategies for Reducing the Use of Rare Earths in Wind Turbines’. *Resources Policy* 52 (June): 349–57. https://doi.org/10.1016/j.resourpol.2017.04.010.

Pavel, Claudiu C., Christian Thiel, Stefanie Degreif, Darina Blagoeva, Matthias Buchert, Doris Schüler, and Evangelos Tzimas. 2017. ‘Role of Substitution in Mitigating the Supply Pressure of Rare Earths in Electric Road Transport Applications’. *Sustainable Materials and Technologies* 12 (July): 62–72. https://doi.org/10.1016/j.susmat.2017.01.003.

Peiró, Laura Talens, Gara Villalba Méndez, and Robert U. Ayres. 2013. ‘Material Flow Analysis of Scarce Metals: Sources, Functions, End-Uses and Aspects for Future Supply’. *Environmental Science & Technology* 47 (6): 2939–47. https://doi.org/10.1021/es301519c.

Rademaker, Jelle H., René Kleijn, and Yongxiang Yang. 2013. ‘Recycling as a Strategy against Rare Earth Element Criticality: A Systemic Evaluation of the Potential Yield of NdFeB Magnet Recycling’. *Environmental Science & Technology*, September, 130903123155005. https://doi.org/10.1021/es305007w.

Restrepo, Eliette, Amund N. Løvik, Patrick Wäger, Rolf Widmer, Radek Lonka, and Daniel B. Müller. 2017. ‘Stocks, Flows, and Distribution of Critical Metals in Embedded Electronics in Passenger Vehicles’. *Environmental Science & Technology* 51 (3): 1129–39. https://doi.org/10.1021/acs.est.6b05743.

Rollat, Alain, Dominique Guyonnet, Mariane Planchon, and Johann Tuduri. 2016. ‘Prospective Analysis of the Flows of Certain Rare Earths in Europe at the 2020 Horizon’. *Waste Management* 49 (March): 427–36. https://doi.org/10.1016/j.wasman.2016.01.011.

Schulze, Rita, and Matthias Buchert. 2016. 'Estimates of Global REE Recycling Potentials from NdFeB Magnet Material'. *Resources, Conservation and Recycling* 113 (October): 12–27. https://doi.org/10.1016/j.resconrec.2016.05.004.

Sekine, Nobuo, Ichiro Daigo, and Yoshikazu Goto. 2016. 'Dynamic Substance Flow Analysis of Neodymium and Dysprosium Associated with Neodymium Magnets in Japan: RESEARCH AND ANALYSIS'. *Journal of Industrial Ecology*, July. https://doi.org/10.1111/jiec.12458.

Smith, Braeton J., and Roderick G. Eggert. 2018. 'Costs, Substitution, and Material Use: The Case of Rare Earth Magnets'. *Environmental Science & Technology*, March. https://doi.org/10.1021/acs.est.7b05495.

Sommer, P., V. S. Rotter, and M. Ueberschaar. 2015. 'Battery Related Cobalt and REE Flows in WEEE Treatment'. *Waste Management*, Urban Mining, 45 (November): 298–305. https://doi.org/10.1016/j.wasman.2015.05.009.

Sprecher, Benjamin, Rene Kleijn, and Gert Jan Kramer. 2014. 'Recycling Potential of Neodymium: The Case of Computer Hard Disk Drives'. *Environmental Science & Technology* 48 (16): 9506–13. https://doi.org/10.1021/es501572z.

Sprecher, Benjamin, Yanping Xiao, Allan Walton, John Speight, Rex Harris, Rene Kleijn, Geert Visser, and Gert Jan Kramer. 2014. 'Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets'. *Environmental Science & Technology* 48 (7): 3951–58. https://doi.org/10.1021/es404596q.

Swain, Basudev, Leeseung Kang, Chinmayee Mishra, JoongWoo Ahn, and Hyun Seon Hong. 2015. 'Materials Flow Analysis of Neodymium, Status of Rare Earth Metal in the Republic of Korea'. *Waste Management* 45 (November): 351–60. https://doi.org/10.1016/j.wasman.2015.07.020.

Ueberschaar, Maximilian, and Vera Susanne Rotter. 2015. 'Enabling the Recycling of Rare Earth Elements through Product Design and Trend Analyses of Hard Disk Drives'. *Journal of Material Cycles and Waste Management* 17 (2): 266–81. https://doi.org/10.1007/s10163-014-0347-6.

Widmer, Rolf, Xiaoyue Du, Olaf Haag, Eliette Restrepo, and Patrick A. Wäger. 2015. 'Scarce Metals in Conventional Passenger Vehicles and End-of-Life Vehicle Shredder Output'. *Environmental Science & Technology* 49 (7): 4591–99. https://doi.org/10.1021/es505415d.

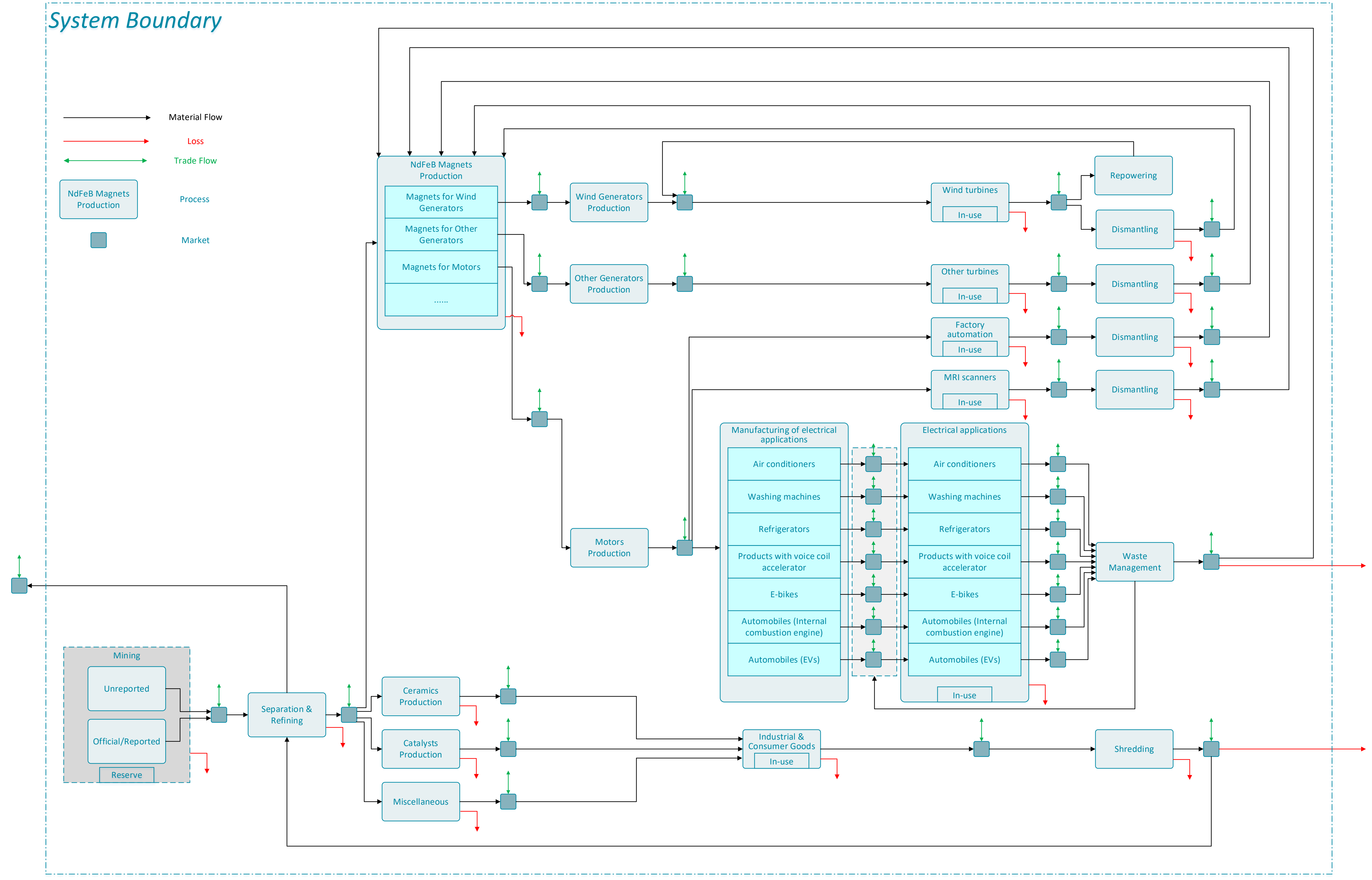
Wilburn, David R. 2011. 'Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010 Through 2030'. Reston, Virginia: U.S. Geological Survey. https://pubs.usgs.gov/sir/2011/5036/sir2011-5036.pdf.

Winterstetter, A., D. Laner, H. Rechberger, and J. Fellner. 2016. 'Evaluation and Classification of Different Types of Anthropogenic Resources: The Cases of Old Landfills, Obsolete Computers and in-Use Wind Turbines'. *Journal of Cleaner Production* 133 (October): 599–615. https://doi.org/10.1016/j.jclepro.2016.05.083.

Zhang, Yiying. 2013. 'Peak Neodymium: Material Constraints for Future Wind Power Development'. http://www.diva-portal.org/smash/record.jsf?pid=diva2:668091.

11 Annex

Annex A: System definition



Annex B: Assessment of literature

Index	Reference	Reference	Stages	International trade	Linkages	Time	Note
1	Global in-use stocks of the rare earth elements: a first estimate	(Du and Graedel 2011a)	Production, fabrication & manufacturing, use, end-of-life	A global model; no international trade	15 rare earth elements (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y) identified; no explicit linkage	Retrospective (1995-2007); top-down stock estimation	This study explored the global flows into use for rare earth metals from 1995 to 2007, and the in-use stocks in 2007. The top-down method was employed based on production data from China, the U.S., and elsewhere, and end use information from various sources.
2	Global Rare Earth In-Use Stocks in NdFeB Permanent Magnets	(Du and Graedel 2011c)	Production, fabrication & manufacturing, use, waste management and recycling; only stages along the value chain of NdFeB permanent magnets	A global model; sum total of regional outputs	Four rare earth elements (Nd, Pr, Dy, Tb)	Retrospective (1983-2007); top-down stock estimation	This study explored the global in-use stocks of NdFeB permanent magnets as of 2007, using the top-down method, production data in China, the United States, Japan, and Europe, and estimated global end-use information from different sources.
3	Uncovering the Global Life Cycles of the Rare Earth Elements	(Du and Graedel 2011b)	Mining, separation, fabrication, manufacturing, use, end-of-life, waste management	A global model; no international trade	Ten rare earth elements (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Y); no explicit linkage	Retrospective (2007); top-down stock estimation	This study presents global cycles of rare earth elements in 2007 in an aggregate way.
4	Evaluating Rare Earth Element Availability: A Case with Revolutionary Demand from Clean Technologies	(Alonso et al. 2012)	No description of stages	A global model; no international trade	Ten rare earth elements (Tb, Eu, Dy, Gd, Sm, Pr, Y, Nd, La, Ce)	Prospective (2010-2035); no stock-flow	This study presents an evaluation of potential future demand scenarios for REEs with a focus on the issue of co-mining. Future demand is estimated for a range of scenarios including one developed by the International Energy Agency (IEA) with adoption of electric vehicles and wind turbines at a rate consistent with stabilization of CO2 in the atmosphere at a level of 450 ppm.
5	Uncovering the end uses of the rare earth elements	(Du and Graedel 2013)	Manufacturing (e.g., magnets, metallurgy, and so on)	Regional use of rare earth elements in different intermediate products; no international trade	Ten rare earth elements (La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Y); no explicit linkage	Retrospective (1995-2007); no stock-flow	We estimated annual domestic production by end use of individual rare earth elements from 1995 to 2007.
6	Dynamic analysis of the global metals flows and stocks in electricity generation technologies	(Elshkaki and Graedel 2013)	Use (permanent magnets used in wind power technologies)	A global model; no international trade	Metals (steel, aluminium, copper, nickel, lead, neodymium, dysprosium) used in onshore and offshore wind turbines	Prospective (2010-2035); stock-flow	The analysis is carried out from 1980 through 2050, using two scenarios, termed Market First and Policy First, combined with specific scenarios for the technologies.
7	Material Flow Analysis of Scarce Metals: Sources, Functions, End-Uses and Aspects for Future Supply	(Peiró, Méndez, and Ayres 2013)	Mineral products, intermediate products, final products	A global model; no international trade	Linkages between different hitch-hiker metals (by-products) and attractor metals (important industrial metals)	Retrospective (2010); no stock-flow	This article presents a material flow analysis (MFA) of the complex inter-relationships between these groups of metals. First, it surveys the main sources of geologically scarce (by-product) metals currently considered critical. This is followed by a detailed survey of their major functions and the quantities contained in intermediate and end-products.
8	Recycling as a Strategy against Rare Earth Element Criticality: A	(Rademaker, Kleijn, and Yang	Use (permanent magnets in wind turbines, PHEV, EV, desktop HDDs,	Global and EU-27; no international trade	Nd and Dy used in permanent magnets	Prospective (2010-2030);	This paper estimates the annual waste flows of neodymium and dysprosium from permanent

	Systemic Evaluation of the Potential Yield of NdFeB Magnet Recycling	2013)	portable HDDs), waste management (recollection, recycling)			flow-driven	magnets during the 2011-2030 period.
9	Peak Neodymium : Material Constraints for Future Wind Power Development	(Zhang 2013)	Use (permanent magnets used in wind power technologies and NiMH batteries used in EV/PHEV)	A global model; no international trade	Nd; no explicit linkage	Prospective (2013-2035); no stock-flow	By fitting historic production data with three curve models (logistic, Gompertz, and Richards) and designing future demand based on IEA's scenarios, the projections of future supply and demand trends of neodymium was obtained.
10	Value Analysis of Neodymium Content in Shredder Feed: Toward Enabling the Feasibility of Rare Earth Magnet Recycling	(Bandara et al. 2014)	Use (NdFeB magnets used in light duty vehicles, household appliances and construction steel), waste management (shredding and separation)	USA; no international trade	Nd, Pr, Dy, Tb in shredder scrap	Retrospective (2013); no stock-flow	This paper presents an analysis of the neodymium (Nd) content in shredder scrap, based on three variables (composition of shredder feed, weight percentage of ferrous materials in each source of shredder feed, and the average weight of Nd in each source).
11	Managing Critical Materials with a Technology-Specific Stocks and Flows Model	(Busch et al. 2014)	Use (NdFeB motor used in vehicles), waste management (collection and recycling)	UK; no international trade	Nd; no explicit linkage	Prospective (2010-2050); stock-driven	This article developed a technology-specific stocks and flows model. The model's potential is demonstrated on a case study on the roll-out of electric vehicles in the UK forecast by UK Department of Energy and Climate Change scenarios.
12	Dysprosium, the balance problem, and wind power technology	(Elshkaki and Graedel 2014)	Use (permanent magnets used in wind power technologies)	A global model; no international trade	Ni, Cu, Al, Pb, Fe, Dy, Nd used in offshore wind power technology; REE as co-products of Fe, Ti, Zr, U, Th ores	Prospective (2010-2050); stock-flow	The demand for the metals in wind power technologies and other traditional technologies is based on the Policy First scenario of GEO-3. The supply of the metals has three scenarios.
13	Material Flow Analysis of NdFeB Magnets for Denmark: A Comprehensive Waste Flow Sampling and Analysis Approach	(Habib et al. 2014)	Use (NdFeB magnets in power, medical devices, home appliances, body care appliances, IT and telecommunication, miscellaneous)	Denmark; trade considered	Nd and Dy used in products containing NdFeB magnets	Retrospective and prospective (2006-2035); flow-driven	This study provides detailed mapping of stocks and flows of NdFeB magnets in Denmark. A comprehensive sampling and elemental analysis of NdFeB magnets were taken out from a sample of 157 different products representing 18 various product types.
14	Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling	(Habib and Wenzel 2014)	Use (wind turbines, vehicles, internal combustion engine vehicles, EVs/HVs/PHEVs, e-bikes, other end-use sectors), mining, waste management	A global model; no international trade	Nd and Dy used in all end-use sectors	Retrospective and prospective (2000-2050); no stock-flow	This study forecasts demand of Nd and Dy in four scenarios (Baseline, Blue Map, Blue hi REN, and 100% REN). This study projects primary and secondary supply.
15	Global Flows of Critical Metals Necessary for Low-Carbon Technologies: The Case of Neodymium, Cobalt, and Platinum	(Nansai et al. 2014)	No explicit stages	A global model; four types of trade commodities (ore, material, products, and waste & scrap)	Neodymium, cobalt, and platinum in trade commodities	Retrospective (2005); no stock-flow	This study traces the global flows of critical metals (Nd, Pt, and Co) based on trade data (BACI) and their metal contents.
16	Recycling Potential of Neodymium: The Case of Computer Hard Disk Drives	(Sprecher, Kleijn, and Kramer 2014)	Production, use, end-of-life, recycling of HDDs	A global model; no international trade	All elements in NdFeB magnets used in HDDs	Retrospective and prospective (2000-2023); flow-driven	This study uses a combination of dynamic modelling and empirical experiments to simulate recycling potential of NdFeB magnets from end-of-life HDDs.

17	Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets	(Sprecher et al. 2014)	Mining, production, recycling of NdFeB magnets	LCA of 1 kg NdFeB magnets; no international trade	Nd; no explicit linkage	No time definition	Three scenarios are constructed: baseline (the current state of industry), high-tech (the best available technology), and low-tech (more polluting processing technologies).
18	Estimating the quantities of critical metals embedded in ICT and consumer equipment	(Chancerel et al. 2015)	Use (information & communications technology, consumer equipment)	Germany; sales; no international trade	Only aggregate REEs content; no explicit linkage	Retrospective (2007-2012); no stock-flow	The estimation is based on sales volumes of 126 products, the mass or surface of the assemblies containing the target metals, and the mass or surface of the assemblies containing the target metals.
19	Material flow analysis applied to rare earth elements in Europe	(Guyonnet et al. 2015)	Separation, fabrication, manufacture, use, waste management	Continental Europe; trade considered	Nd, Pr and Dy in permanent magnets; Nd and Pr in NiMH batteries	Retrospective (2005-2010); bottom-up stock and flow estimation	This paper explores flows and stocks, at the scale of the European Union, of certain rare earth elements (REEs; Pr, Nd, Eu, Tb, Dy and Y) which are associated with products that are important for the decarbonisation of the energy sector and that also have strong recycling potential.
20	Tracking the Flow of Resources in Electronic Waste - The Case of End-of-Life Computer Hard Disk Drives	(Habib, Parajuly, and Wenzel 2015)	Waste management of HDDs	Denmark; no international trade	NdFeB magnets in in shredder scrap; no explicit linkage	No time definition	This study shows materials in the waste flows in a conventional WEEE treatment plant in Denmark.
21	Battery related cobalt and REE flows in WEEE treatment	(Sommer, Rotter, and Ueberschaar 2015)	Waste management of WEEE-batteries	Germany; no international trade	REEs in WEEE-batteries; no explicit linkage	Retrospective (2011); no stock-flow	Generated amount of WEEE is the average of the EEE sold in the market during the past three years.
22	Materials flow analysis of neodymium, status of rare earth metal in the Republic of Korea	(Swain et al. 2015)	Raw materials, primary process, intermediate products, final products, waste generated	Republic of Korea; trade considered	Nd; no explicit linkage	Retrospective (2010); no stock-flow	This study doesn't consider the in-use stage.
23	Scarce Metals in Conventional Passenger Vehicles and End-of-Life Vehicle Shredder Output	(Widmer et al. 2015)	Manufacture, use, waste management (dismantling, shredding, recycling) of neodymium in passenger cars' electrical and electronic equipment	Switzerland; no international trade	31 scarce metals	Retrospective (2012); bottom-up flow estimation	This study investigates the distribution of 31 SMs in selected electrical and electronic (EE) components of conventional passenger vehicles and in the end-of-life vehicle shredder fractions from a shredder plant in Switzerland.
24	Reviewing resource criticality assessment from a dynamic and technology specific perspective – using the case of direct-drive wind turbines	(Habib and Wenzel 2016)	Use (wind turbines)	A global model; no international trade	Nd, Dy, Fe, Cu, Sr	Retrospective and prospective (1994-2050); no stock-flow	This study assesses the resource criticality using a product design tree approach in a dynamic perspective using the case of direct-drive wind turbine technology, which has a permanent magnet generator with NdFeB magnet.
25	Assessing advanced rare earth element-bearing deposits for industrial demand in the EU	(Machacek and Kalvig 2016)	Use (auto catalyst, glass additives, fluid cracking catalyst, batteries, ceramics, metallurgy,	EU-28; no international trade	LREEs and HREEs	Retrospective (2014); no stock-flow	The Kvanefjeld project would significantly exceed REE demand of EU-28 countries in 2014 except for Eu, on which it would undersupply. In contrast, Kringlerne would under supply on La, Ce and Pr,

			phosphors, magnets, polishing				oversupply on Nd and Y, and on all HREO with the exception of Eu.
26	Byproduct metal requirements for U.S. wind and solar photovoltaic electricity generation up to the year 2040 under various Clean Power Plan scenarios	(Nassar, Wilburn, and Goonan 2016)	Use (wind turbines)	US; no international trade	Nd, Pr, Dy, Tb	Prospective (2016-2040); inflow-driven	Three key uncertainties (electricity generation capacities, technology market shares, and material intensities) are varied to develop 42 scenarios for each by-product metal.
27	Prospective analysis of the flows of certain rare earths in Europe at the 2020 horizon	(Rollat et al. 2016)	Separation, fabrication, manufacture, use (NdFeB magnets, NiMH batteries), waste management	European Union; trade considered	Nd, Pr, Dy, Tb	Prospective (2010-2020); inflow-driven	The scenario in this study considered an increase of the production of NdFeB magnets close to 80% over the 2010–2020 decade and a decrease of the proportion of Dy in the magnets to 1.9% around 2020.
28	Estimates of global REE recycling potentials from NdFeB magnet material	(Schulze and Buchert 2016)	Production and fabrication, use (NdFeB magnets), waste management	A global model; no international trade	Nd, Pr, Dy, Tb	Prospective (2020-2030); inflow-driven	Historic demand of different NdFeB application groups is estimated by back-casting.
29	Dynamic Substance Flow Analysis of Neodymium and Dysprosium Associated with Neodymium Magnets in Japan	(Sekine, Daigo, and Goto 2016)	Production and fabrication, use (NdFeB magnets), waste management	Japan; international trade considered	Nd, Dy	Retrospective (1985-2012); stock-flow	A bottom-up approach was employed in the analysis to estimate annual consumption by end use. Factors used in the analysis were the amounts of rare earth contents, weight of a magnet used for each product, adoption ratios of neodymium magnet usage in each product, and lifetime of products.
30	Geopolitical-related supply risk assessment as a complement to environmental impact assessment: the case of electric vehicles	(Gemechu, Sonnemann, and Young 2017)	Use (electric vehicles)	Australia, Canada, China, EU, France, Germany, Greece, India, Italy, Japan, Norway, UK, and USA; no international trade	Al, Au, Brass, Cu, Mg, Nd, Ni, Pb, PGMs, Sn, Steel, Zn	No time definition	The study draws on the structure and inventory data for a European representative first-generation battery small EV.
31	Substitution strategies for reducing the use of rare earths in wind turbines	(Pavel, Lacal-Arántegui, et al. 2017)	Use (per wind turbine)	no international trade	Nd, Dy	Prospective (2015-2020); no stock-flow	This study evaluates up-to-date substitution possibilities of rare earths in wind turbines and analyses the potential impact of substitution on short-term demand for rare earths in the wind sector.
32	Role of substitution in mitigating the supply pressure of rare earths in electric road transport applications	(Pavel, Thiel, et al. 2017)	Use (permanent magnets in EVs)	A global model; no international trade	Nd, Dy, Pr	Prospective (2015-2020); no stock-flow	This study estimated the short-term demand for high-performing NdFeB magnets in EVs, HEVs, and E-bikes, and their constituent rare earths: neodymium, praseodymium and dysprosium.
33	Stocks, Flows, and Distribution of Critical Metals in Embedded Electronics in Passenger Vehicles	(Restrepo et al. 2017)	Use, waste management (passenger vehicles)	Switzerland; trade considered	Ag, Au, Pd, Ru, Dy, La, Nd, Co, Ag	Retrospective (2014)	The cohort, brand and model of vehicles imported and in stock were obtained from the MOFIS database. The mass of components in devices was obtained from studies analysing CM mass in automotive electronics. The mass of ELV D&D output flows was calculated with transfer coefficients determined by Dix in an experiment at a Swiss ELV dismantling plant in 2014, as well as by interviews at

							the same facility and by mass balance.
34	Metal supply constraints for a low-carbon economy?	(de Koning et al. 2018)	Use (electricity generation, transport, construction work)	A global model	Fe, Al, Cu, Ni, Cr, In, Nd, Dy, Li, Zn, Pb	Prospective (2010-2050); no stock-flow	This study calculated metal requirements for these sectors using detailed Life Cycle Inventory (LCI) data, combined with global annual capital goods production in these sectors, for instance for PV cells, wind energy, nuclear power plants, and electric cars.
35	Implications of Emerging Vehicle Technologies on Rare Earth Supply and Demand in the United States	(Fishman et al. 2018)	Use (alternative energy passenger vehicles)	US; no international trade	Al, Mn, Fe, Cu, Pr, Nd, Dy, Pb used in electric motors; Li, Cr, Ni, La, Pr, Nd, Gd, Tb, Dy, Er in NiMH battery	Retrospective and prospective (2000-2050); stock-driven	This study explores the long-term demand and supply potentials of rare earth elements in alternative energy vehicles (AEVs) in the United States until 2050. This study compares a baseline scenario with scenarios that incorporate an exemplary technological innovation: a novel aluminium–cerium–magnesium alloy.
36	An assessment of U.S. rare earth availability for supporting U.S. wind energy growth targets	(Imholte et al. 2018)	Use (wind turbines)	US; international trade considered	Nd; no explicit linkage	Prospective (2010-2030); no stock-flow	Onshore wind energy demand of gearbox and DDPMG designs was evaluated with a profit maximization model that determined optimal capacity addition decisions based on various constraints, including LREE supply. Due to the predominance of DDPMG designs in offshore wind energy, exogenous demand was assumed for offshore wind energy.
37	Costs, Substitution, and Material Use: The Case of Rare Earth Magnets	(Smith and Eggert 2018)	Use (permanent magnets)	no international trade	Nd, Tb, Dy, Pr	Retrospective (2010 and 2016); no stock-flow	This paper uses an expert survey to determine the relative importance of eight specific industry responses taken by magnet and wind turbine manufacturers in response to the 2010/2011 rare-earth price spike through 2016.
38	Wind Energy in the United States and Materials Required for the Land-Based Wind Turbine Industry From 2010 Through 2030	(Wilburn 2011)	Use (wind turbines)	US; no international trade	Steel, concrete, fiberglass, copper, Nd, cast iron	Prospective (2010-2030); no stock-flow	

Annex C: Neodymium-contained commodities in Pordcom database (EU-28)

Prodcom code	Description
26201100	Laptop PCs and palm-top organisers
26201300	Desk top PCs
26302200	Telephones for cellular networks or for other wireless networks
26302320	Machines for the reception, conversion and transmission or regeneration of voice, images or other data, including switching and routing apparatus
26403300	Video camera recorders

26404100	Microphones and their stands (excluding cordless microphones with a transmitter)
26404235	Single loudspeakers mounted in their enclosures (including frames or cabinets mainly designed for mounting loudspeakers)
26404237	Multiple loudspeakers mounted in the same enclosure (including frames or cabinets mainly designed for mounting loudspeakers)
26404239	Loudspeakers (including speaker drive units, frames or cabinets mainly designed for mounting loudspeakers) (excluding those mounted in their enclosures)
26404270	Headphones and earphones, even with microphone, and sets consisting of microphone and one or more loudspeakers (excluding airmen's headgear with headphones, telephone sets, cordless microphones with transmitter, hearing aids)
26404359	Audio-frequency electric amplifiers (including hi-fi amplifiers) (excluding high or intermediate frequency amplifiers, telephonic and measurement amplifiers)
26404370	Electric sound amplifier sets (including public address systems with microphone and speaker)
26601280	Electro-diagnostic, apparatus (excluding electro-cardiographs), n.e.c.
26701300	Digital cameras
27511110	Combined refrigerators-freezers, with separate external doors
27511133	Household-type refrigerators (including compression-type, electrical absorption-type) (excluding built-in)
27511135	Compression-type built-in refrigerators
27511150	Chest freezers of a capacity ≤ 800 litres
27511170	Upright freezers of a capacity ≤ 900 litres
27511200	Household dishwashing machines
27511300	Cloth washing and drying machines, of the household type
28221513	Self-propelled works trucks fitted with lifting or handling equipment, powered by an electric motor, with a lifting height ≥ 1 m
28221515	Self-propelled works trucks fitted with lifting or handling equipment, powered by an electric motor, with a lifting height < 1 m
28221630	Electrically operated lifts and skip hoists
28251220	Window or wall air conditioning systems, self-contained or split-systems
28251333	Refrigerated show-cases and counters incorporating a refrigerating unit or evaporator for frozen food storage
28251335	Refrigerated show-cases and counters incorporating a refrigerating unit or evaporator (excluding for frozen food storage)
28251390	Other refrigerating or freezing equipment
28294330	Automatic goods-vending machines incorporating heating or refrigerating devices
28295000	Non-domestic dish-washing machines
28411150	Machine tools for working any material by removal of material, operated by electro-discharge processes
28411220	Horizontal machining centres for working metal

28411240	Vertical machining centres for working metal (including combined horizontal and vertical machining centres)
28924030	Sorting, screening, separating, washing machines; crushing, grinding, mixing, kneading machines excluding concrete/mortar mixers, machines for mixing mineral substances with bitumen
28942150	Washing, bleaching or dyeing machines (including wringers and mangles, shaker-tumblers; excluding household or laundry-type washing machines)
28942230	Household or laundry-type washing machines of a dry linen capacity > 10 kg (including machines that both wash and dry)
28992020	Machines and apparatus used solely or principally for the manufacture of semiconductor boules or wafers
28992040	Machines and apparatus for the manufacture of semiconductor devices or of electronic integrated circuits (excluding machine tools for working any material by removal of material operated by ultrasonic processes)
28992060	Machines and apparatus used solely or principally for the manufacture of flat panel displays
28993920	Machines for assembling electric or electronic lamps, tubes, valves or flashbulbs, in glass envelopes
28993935	Industrial robots for multiple uses (excluding robots designed to perform a specific function (e.g. lifting, handling, loading or unloading))
28993945	Machines and apparatus used solely or principally for (a) the manufacture or repair of masks and reticles, (b) assembling semiconductor devices or electronic integrated circuits, and (c) lifting, handling, loading or unloading of boules, wafers, semiconductor devices, electronic integrated circuits and flat panel displays
29101300	Vehicle compression-ignition internal combustion piston engines (diesel or semi-diesel) (excluding for railway or tramway rolling stock)
29102100	Vehicles with spark-ignition engine of a cylinder capacity ≤ 1 500 cm^3, new
29102230	Motor vehicles with a petrol engine > 1 500 cm^3 (including motor caravans of a capacity > 3 000 cm^3) (excluding vehicles for transporting ≥ 10 persons, snowmobiles, golf cars and similar vehicles)
29102250	Motor caravans with a spark-ignition internal combustion reciprocating piston engine of a cylinder capacity > 1 500 cm^3 but ≤ 3 000 cm^3
29102310	Motor vehicles with a diesel or semi-diesel engine ≤ 1 500 cm^3 (excluding vehicles for transporting ≥ 10 persons, snowmobiles, golf cars and similar vehicles)
29102330	Motor vehicles with a diesel or semi-diesel engine > 1 500 cm^3 but ≤ 2 500 cm^3 (excluding vehicles for transporting ≥ 10 persons, motor caravans, snowmobiles, golf cars and similar vehicles)
29102340	Motor vehicles with a diesel or semi-diesel engine > 2 500 cm^3 (excluding vehicles for transporting ≥ 10 persons, motor caravans, snowmobiles, golf cars and similar vehicles)
29102353	Motor caravans with a compression-ignition internal combustion piston engine (diesel or semi-diesel) of a cylinder capacity > 1 500 cm^3 but ≤ 2 500 cm^3
29102355	Motor caravans with a compression-ignition internal combustion piston engine (diesel or semi-diesel) of a cylinder capacity > 2 500 cm^3
29102400	Other motor vehicles for the transport of persons (excluding vehicles for transporting ≥ 10 persons, snowmobiles, golf cars and similar vehicles)
29103000	Motor vehicles for the transport of ≥ 10 persons
29105200	Motor vehicles specially designed for travelling on snow, golf cars and similar vehicles
30921000	Bicycles and other cycles (including delivery tricycles), non-motorised
24201150	Line pipe, of a kind used for oil or gas pipelines, seamless, of steel other than stainless steel
24201250	Casing, tubing and drill pipe, of a kind used in the drilling for oil or gas, seamless, of steel other than stainless steel

Annex D: Neodymium-contained commodities in UNComtrade database

UNComtrade code (HS as reported)	Description
280530	Rare-earth metals, scandium and yttrium
284690	Compds of rare-earth met nes,of yttrium/scandium/mx of these metals
720299	Ferro-alloys, nes
381511	Supportd catalysts,with nickel/nickel compounds as the active subst
381512	Supportd catalysts,w precious metal/compds thereof as the activ subs
381590	Reaction initiators,reaction accelerator&catalytic preparations,nes
381600	Refractory cements,mortars,concretes and similar compositions, nes
711510	Catalysts in the form of wire cloth or grill, of platinum
722530	Flat rolled prod,as,o/t stainless,in coils,nfw thn hr,w>/=600mm,nes
722540	Flat rolled prod,as,o/t stainless,nic nfw thn hr,>/=600mm wide, nes
722550	Flat rolld prod,as,o/t stainless,nfw thn cold rolld,>/=600mm wide,nes
722691	Flat rolled prod,as,o/t stainless,nfw than hot rolled,<600mm wide,nes
722692	Flat rolled prod, as, o/t stainless, nfw than cold rolled, <600mm wide
722790	Bars&rods,alloy steel,o/t stainless hr,in irregularly wound coils,nes
722830	Bars&rods,alloy steel,o/t stainless nfw thn hot rolld/drawn/extrud,nes
722850	Bars&rods,as,o/t stainless,not further workd than cold formed/finishd
722990	Wire of alloy steel, o/t stainless
850110	Electric motors of an output not exceeding 37.5 W
850511	Permanent magnets&art intendd to become permanent magnets,of metal
850650	Lithium primary cells and batteries
850780	Electric accumulators, nes
851810	Microphones and stands therefor
851821	Single loudspeakers, mounted in the same enclosure
851822	Multiple loudspeakers, mounted in the same enclosure
851829	Loudspeakers, nes
851830	Headphones, earphones and combined microphone/speaker sets

851840	Audio-frequency electric amplifiers
851850	Electric sound amplifier sets
851890	Parts of microphones,loudspeakrs,headphones,earphones&elec sound ampli
852311	Unrecorded magnetic tapes, of a width not exceeding 4 mm
852312	Unrecordd magnetic tapes,of a width exceedg 4 mm but nt exceedg 6.5 mm
852313	Unrecorded magnetic tapes, of a width exceeding 6.5 mm
852320	Unrecorded magnetic discs
852330	Cards incorporating a magnetic recording stripe
852390	Prepared unrecorded media for sound recording or other phenomena nes
711100	Base metals,silver o gold clad with platinum in semi-manufacturd forms
820900	Plates,tips & the like for tools of sintered metal carbides or cermets
841410	Vacuum pumps
841420	Hand or foot-operated air pumps
841430	Compressors of a kind used in refrigerating equipment
841440	Air compressors mounted on a wheeled chassis for towing
841451	Fans: table,roof etc w a self-cont elec mtr of an output nt excdg 125W
841459	Fans nes
841460	Hoods having a maximum horizontal side not exceeding 120 cm
841480	Air or gas compressors, hoods
841490	Parts of vacuum pumps, compressors, fans, blowers, hoods
841810	Combined refrigerator-freezers, fitted with separate external doors
841821	Refrigerators, household type, compression-type
841829	Refrigerators, household type, nes
841830	Freezers of the chest type, not exceeding 800 l capacity
841840	Freezers of the upright type, not exceeding 900 l capacity
841850	Refrigerating or freezing display counters, cabinets, show-cases, etc
841861	Compression type refrigeratg/freez equip whose condensrs are heat exch
841869	Refrigerating or freezing equipment nes

841891	Furniture designed to receive refrigerating or freezing equipment
841899	Parts of refrigerating or freezing equipment, nes
842810	Lifts and skip hoists
842820	Pneumatic elevators and conveyors
842831	Cont-action elevators/conveyors f goods/mat spec design f u/grd nes
842832	Cont-action elevators/conveyors for goods/mat, bucket types nes
842833	Cont-action elevators/conveyors for goods/mat, belt type nes
842839	Cont-action elevators/conveyors for goods/mat nes
842840	Escalators and moving walkways
842860	Teleferics,chair-lifts,ski-draglines;traction mechanisms f funiculars
842890	Lifting, handling, loading or unloading machinery nes
844351	Ink-jet printing machines
844359	Printing machinery nes
844400	Machines for extruding, drawing, text or cutting m-m textile materials
844511	Textile carding machines
844512	Textile combing machines
844513	Textile drawing or roving machines
844519	Textile preparing machines nes
844520	Textile spinning machines
844530	Textile doubling or twisting machines
844540	Textile winding (including weft-winding) or reeling machines
844590	Machinery for producing or preparing textile yarn nes
844610	Machines for weaving fabrics of a width not exceeding 30 cm
844621	Machines f weavg fabrics of a width exc 30 cm,shuttle type,power loom
844629	Machines for weavg fabrics of a width exceedg 30 cm shuttle type nes
844630	Machines for weavg fabrics of a width exceedg 30 cm shuttleless type
844711	Circular knitting machines with cylinder diameter not exceeding 165 mm
844712	Circular knitting machines with cylinder diameter exceeding 165 mm

844720	Flat knitting machines; stitch-bonding machines
844790	Mach f makg gimpd yarn/tulle/lace/embroidery/trimmgs/braid/net/tuftg
845011	Automatic washing machines,of a dry linen capacity not exceeding 10 kg
845012	Washg mach of a dry linen capacity </=10 kg,with built-in dryer,nes
845019	Household/laundry-type washg mach of a dry linen capa </=10 kg,nes
845020	Household/laundry-type washg mach of a dry linen capacity exceedg 10kg
845090	Parts of household or laundry-type washg machines,includg comb machy
845710	Machining centres, for working metal
845720	Unit construction machines (single sta) for working metal
845730	Multi-station transfer machines for working metal
845811	Horizontal lathes numerically controlled for removing metal
845819	Horizontal lathes nes for removing metal
845891	Lathes nes numerically controlled for removing metal
845899	Lathes nes for removing metal
845910	Way-type unit head mches for removing metal
845921	Drilling mches nes; numerically controlled for removing metal
845929	Drilling mches nes, for removing metal
845931	Boring-milling mches nes, numerically controlled for removing metal
845939	Boring-milling mches nes for removing metal
845940	Boring machines nes for removing metal
845951	Milling mach, knee-type numerically controlled for removing metal
845959	Milling mach, knee-type nes for removing metal
845961	Milling machines nes, numerically controlled for removing metal
845969	Milling machines nes, for removing metal
845970	Threading or tapping machines nes for removing metal
846011	Fl-surf grindg mach in which pos of 1 axis acc to 0.01 mm n/c rem met
846019	Fl-surf grindg mach in which pos of 1 axis acc to 0.01 mm nes rem met
846021	Grindg mach in which pos of 1 axis to an acc to 0.01mm n/c f rem met

846029	Grindg mach in which pos of 1 axis to an acc to 0.01mm nes f rem met
846031	Sharpening (tool or cutter grinding) mach n/c for removing metal
846039	Sharpening (tool or cutter grinding) mach nes for removing metal
846040	Honing or lapping machines for removing metal
846090	Mach-tools for deburring polishing etc for fin met nes o/t hdg 84.61
846120	Shaping or slotting machines by removing metal
846130	Broaching machines by removing metal
846140	Gear cutting, gear grindg or gear finishg machines by removg metal
846150	Sawing or cutting-off machines by removing metal
846190	Filg o engravg mach(o/t those of hdg 84.59 o 84.60) etc nes by rem met
847130	Portable digital computers <10kg
847141	Non-portable digital edp machines w processor & i/o
847149	Digital data processing systems, nes
847150	Digital processing units not sold as complete systems
847160	Computer input/outputs, with/without storage
847170	Computer data storage units
847180	Units of automatic data processing equipment nes
847190	Automatic data processing equipment nes
850910	Domestic vacuum cleaners
851650	Microwave ovens
852520	Transmission apparatus, for radioteleph incorporatg reception apparatus
851721	Facsimiles machines
851921	Record-players without loudspeaker, nes
851929	Record-players, nes
851931	Turntables with automatic record changing mechanism
851939	Turntables, nes
851940	Transcribing machines
852032	Magnetic digital audio tape recorders

852530	Television cameras
852540	Still image and other video cameras
870310	Snowmobiles, golf cars and similar vehicles
870321	Automobiles w reciprocatg piston engine displacg not more than 1000 cc
870322	Automobiles w reciprocatg piston engine displacg > 1000 cc to 1500 cc
870323	Automobiles w reciprocatg piston engine displacg > 1500 cc to 3000 cc
870324	Automobiles with reciprocating piston engine displacing > 3000 cc
870331	Automobiles with diesel engine displacing not more than 1500 cc
870332	Automobiles with diesel engine displacing more than 1500 cc to 2500 cc
870333	Automobiles with diesel engine displacing more than 2500 cc
870390	Automobiles nes including gas turbine powered
901813	Magnetic resonance imaging apparatus
852431	Recorded laser discs (other than sound/image discs)
852432	Recorded laser discs, sound only
852439	Recorded laser discs, nes
850231	Other generating sets :-- Wind-powered

Annex E: Neodymium content and penetration rate of magnets-contained products

Source	Products	Unit for NdFeB/device	NdFeB/device	Nd/magnet (%, w/w)	Share of products with NdFeB magnets
(Habib et al. 2014)	HDDs (3.5 in.)	%, w/w	2.2 ± 1.0	30.8 ± 4.1	100%
(Habib et al. 2014)	HDDs (2.5 in.)	%, w/w	2.9 ± 0.5	30.4 ± 3.1	100%
(Habib et al. 2014)	Mobile phones	%, w/w	0.6 ± 0.1	27.5 ± 1.6	100%
(Habib et al. 2014)	DVD players	%, w/w	0.04 ± 0.02	35.1 ± 3.2	100%
(Habib et al. 2014)	Wind turbine	kg/MW	660	30	100%
(Habib et al. 2014)	MRI	kg/unit	860	21	100%
(Habib et al. 2014)	Conventional vehicles	kg/unit	1.14 until 2011 1.72 from 2012	29	25% until 2005; increased to 50% by 2012; increased to 75% from

					2013 onwards
(Habib et al. 2014)	Electric and hybrid vehicles	kg/unit	same as a conventional vehicle +2 kg of magnet for the motor/generator system	same as a conventional vehicle +31% Nd for the motor/generator system	25% until 2005; increased to 50% by 2012; increased to 75% from 2013 onwards
(Habib et al. 2014)	Washing machine	kg/unit	1.04	29	25% from 2003
(Habib et al. 2014)	Dryer	kg/unit	0.54	29	25% from 2003
(Habib et al. 2014)	Refrigerator (freezer)	kg/unit	0.49	29	30% from 2003
(Habib et al. 2014)	Refrigerator (fridge)	kg/unit	0.26	29	30% from 2003
(Habib et al. 2014)	Air conditioner	kg/unit	0.5	29	30% from 2003
(Habib et al. 2014)	Vacuum cleaner (standard)	kg/unit	0.09	29	30% from 2013
(Habib et al. 2014)	Vacuum cleaner (robotic)	kg/unit	0.08	29	50% from 2003
(Habib et al. 2014)	Microwave oven	kg/unit	0.11	29	30% from 2013
(Habib et al. 2014)	Electric toothbrush	kg/unit	0.001	30	25% from 2007
(Habib et al. 2014)	Body shavers	kg/unit	0.001	30	25% from 2007
(Habib et al. 2014)	Desktop computer	kg/unit	0.0125	30.8	100%
(Habib et al. 2014)	Laptops	kg/unit	0.0034	30.4	100%
(Habib et al. 2014)	Notebook	kg/unit	0.0034	30.4	100%
(Habib et al. 2014)	Tablet	kg/unit	0.0034	30.4	100%
(Habib et al. 2014)	DVD players	kg/unit	0.0014	35.1	100%
(Habib et al. 2014)	Speakers	kg/unit	0.0015	29	100%
(Habib et al. 2014)	Mobile phones	kg/unit	0.0007	27.5	100%
(Habib et al. 2014)	Circulator pumps	kg/unit	0.055	25	100%
(Alonso et al. 2012)	Wind turbine	kg/MW	171 (REE)	69.4	100%
(Alonso et al. 2012)	HEV with NiMH	kg/unit	+0.684	31	100%
(Alonso et al. 2012)	HEV with Li-ion	kg/unit	+0.374	31	100%
(Alonso et al. 2012)	PHEV	kg/unit	+0.374	31	100%
(Alonso et al. 2012)	BEV	kg/unit	+0.561	31	100%

(Alonso et al. 2012)	FCEV	kg/unit	+0. 374	31	100%
(Peiró, Méndez, and Ayres 2013)	Auto catalysts	kg/unit	204/7050 (neodymium)		
(Peiró, Méndez, and Ayres 2013)	NiMH batteries for HEV	kg/unit	805/533 (neodymium)		
(Peiró, Méndez, and Ayres 2013)	Wind turbine	kg/unit	860	21	14%
(Peiró, Méndez, and Ayres 2013)	EV	kg/unit	6.3 (neodymium)		
(Peiró, Méndez, and Ayres 2013)	MRI	kg/unit	860	21	100%
(Rademaker, Kleijn, and Yang 2013)	Wind turbine	kg/MW	700	29	2010: 10% 2020: 15% 2030: 20%
(Rademaker, Kleijn, and Yang 2013)	HEV	kg/KW	0.01182	29	
(Rademaker, Kleijn, and Yang 2013)	EV	kg/unit	1.5	29	
(Rademaker, Kleijn, and Yang 2013)	HDD for desktop	kg/unit	0.015	29	100%
(Rademaker, Kleijn, and Yang 2013)	HDD for portable	kg/unit	0.002	29	From 100% in 2010 to 58% in 2020 and 14% in 2030
(Gutfleisch et al. 2010)	Wind turbine (direct-drive)	kg/MW	500		
(Gutfleisch et al. 2010)	HEV Motor/generator	kg/unit	1.3		
(Bandara et al. 2014)	Refrigerator	kg/unit	0.05	29	13%
(Bandara et al. 2014)	Washing machine	kg/unit	0.13	29	24%
(Bandara et al. 2014)	Air conditioner	kg/unit	0.23	29	80%
(Bandara et al. 2014)	Desktop computer (hard disk drive, optical drive and speakers)	kg/unit	0.0021 (neodymium)		100%

(Bandara et al. 2014)	Laptop computer (hard disk drive, optical drive and speakers)	kg/unit	0.0021 (neodymium)		100%
(Bandara et al. 2014)	Mobile phone (speaker)	kg/unit	0.28	29	100%
(Bandara et al. 2014)	Mobile phone (vibration unit)	kg/unit	0.3	29	100%
(Kleijn et al. 2011)	Wind turbine (direct-drive)	kg/MW	150 (neodymium)		
(Wilburn 2011)	Wind turbine (onshore)	kg/MW	216 (neodymium)	27	20% during 2010-2030
(Elshkaki and Graedel 2013)	Wind turbine	kg/MW	124 (neodymium)	31	25% of onshore 75% of offshore
(Hoenderdaal et al. 2013)	Wind turbine (direct-driive)	kg/MW	600	30	Low: 10% (2010-2015); 20% (2015-2020); 25% (2020-2030); 30% (2030-2040); 35% (2040-2050) High: 15% (2010-2015); 20% (2015-2020); 30% (2020-2030); 40% (2030-2040); 50% (2040-2050)
(Hoenderdaal et al. 2013)	HEV	kg/unit	2	29	
(Hoenderdaal et al. 2013)	E-bike	kg/unit	0.3	30%	
(Busch et al. 2014)	EV motors	kg/unit	1-2	31%	
(Elshkaki and Graedel 2013)	Wind turbine (offshore)	kg/MW	124 (neodymium)		20% (2020); 40% (2030); 50% (2050)
(Sprecher, Kleijn, and Kramer 2014)	2.5’’ HDDs	kg/unit	0.0025		
(Sprecher, Kleijn, and Kramer 2014)	3.5’’ HDDs	kg/unit	0.01787-0.00035*t (t=0@1990)		
(Du et al. 2015)	Conventional vehicles	kg/unit	0.00131-0.297 (neodymium)		
(Lacal-Arántegui 2015)	Low-speed direct-drive	kg/MW	650		
(Lacal-Arántegui 2015)	Medium-speed with 1- or 2-stage gearbox	kg/MW	160		

(Lacal-Arántegui 2015)	High-speed with 3-stage gearbox	kg/MW	80		
(Ueberschaar and Rotter 2015)	HDDs	kg/unit	0.016	22.93	
(Widmer et al. 2015)	High-end car	kg/unit	0.0031 (neodymium)		
(Widmer et al. 2015)	Low-end car	kg/unit	0.0016 (neodymium)		
(Widmer et al. 2015)	Mid-range car	kg/unit	0.0024 (neodymium)		
(Widmer et al. 2015)	Coupé high-end	kg/unit	0.003 (neodymium)		
(Widmer et al. 2015)	Coupé low-end	kg/unit	0.0016 (neodymium)		
(Nassar, Wilburn, and Goonan 2016)	Wind turbine	kg/MW	600 (conservative), 400 (neutral), and 200 (optimistic) @2010 550 (conservative), 350 (neutral), and 150 (optimistic) @2020 450 (conservative), 285 (neutral), and 120 (optimistic) @2040	31 (conservative), 29 (neutral), and 22.5 (optimistic)	5% (BAU) 5% (2016) to 50% (2040)
(Sekine, Daigo, and Goto 2016)	Driving motors of HEVs	kg/unit	1-2	23-24	100%
(Sekine, Daigo, and Goto 2016)	EPS motors	kg/unit	0.02-0.05	26	68% (@2010)
(Sekine, Daigo, and Goto 2016)	Other motors	kg/unit	0.034 (@2004)	26-27	100%
(Sekine, Daigo, and Goto 2016)	Air conditioners	kg/unit	0.1-0.25	28	75% (@2010)
(Sekine, Daigo, and Goto 2016)	Washing machines	kg/unit	0.1-0.2	28	24% (@2010)
(Sekine, Daigo, and Goto 2016)	Refrigerators	kg/unit	0.1-0.25	28	14% (@2010)
(Sekine, Daigo, and Goto 2016)	Single axis unit	kg/unit	0.56	26-28	100% (@2010)
(Sekine, Daigo, and Goto 2016)	Manipulator	kg/unit	1.12	26-28	100% (@2010)

(Sekine, Daigo, and Goto 2016)	Manipulating robots	kg/unit	1.68	26-28	100% (@2010)
(Sekine, Daigo, and Goto 2016)	Perpendicular articulated robots and parallel robots	kg/unit	3.36	26-28	100% (@2010)
(Sekine, Daigo, and Goto 2016)	Electronic component mounting machines	kg/unit	2.45	26-28	100% (@2010)
(Sekine, Daigo, and Goto 2016)	Semiconductor manufacturing equipment	kg/unit	1.53	26-28	100% (@2010)
(Sekine, Daigo, and Goto 2016)	Flat panel display manufacturing equipment	kg/unit	2.46	26-28	100% (@2010)
(Sekine, Daigo, and Goto 2016)	Main shaft motors (ordinary machine tools)	kg/unit	7	26-28	100% (@2010)
(Sekine, Daigo, and Goto 2016)	Feed shaft motors (ordinary machine tools)	kg/unit	3.06	26-28	6.7% (@2010)
(Sekine, Daigo, and Goto 2016)	Main shaft motors (electric discharge machine)	kg/unit	6	26-28	100% (@2010)
(Sekine, Daigo, and Goto 2016)	Feed shaft motors (electric discharge machine)	kg/unit	3.06	26-28	6.7% (@2010)
(Sekine, Daigo, and Goto 2016)	MRI machines	kg/unit	1500	31	100%
(Sekine, Daigo, and Goto 2016)	Desktop computers	kg/unit	0.01	29.5–30	100%
(Sekine, Daigo, and Goto 2016)	Laptop computers	kg/unit	0.002	29.5–30	100%
(Sekine, Daigo, and Goto 2016)	Laser pickup	kg/unit	0.001	29.5–30	100%
(Winterstetter et al. 2016)	Wind turbine	kg/MW	600		
(München and Veit 2017)	HDDs (laptop)	kg/unit	0.00309	21.48	
(München and Veit 2017)	HDDs (desktop)	kg/unit	0.00789	21.48	
(Pavel, Thiel, et al. 2017)	EVs	kg/unit	1-2		
(Restrepo et al. 2017)	New vehicles	kg/unit	0.04 (neodymium)		

(Restrepo et al. 2017)	Vehicles in stock	kg/unit	0.02 (neodymium)		
(Restrepo et al. 2017)	End-of-life vehicles	kg/unit	0.003 (neodymium)		
(Fishman et al. 2018)	HEV NiMH	kg/unit	0.73 (neodymium)		
(Fishman et al. 2018)	HEV Li-ion	kg/unit	0.5 (neodymium)		
(Fishman et al. 2018)	HEV Li-polymer	kg/unit	0.5 (neodymium)		
(Fishman et al. 2018)	PHEV Li-ion	kg/unit	1 (neodymium)		
(Fishman et al. 2018)	BEV Li-ion	kg/unit	0.5 (neodymium)		
(Fishman et al. 2018)	FCV NiMH	kg/unit	0.73 (neodymium)		
(Fishman et al. 2018)	FCV Li-ion	kg/unit	0.5 (neodymium)		
(Fishman et al. 2018)	FCV Li-polymer	kg/unit	0.5 (neodymium)		
(Fishman et al. 2018)	ICEV	kg/unit	0.12 (neodymium)		
(Fishman et al. 2018)	HEV NiMH	kg/unit	0.98 (neodymium)		
(Fishman et al. 2018)	HEV Li-ion	kg/unit	0.52 (neodymium)		
(Fishman et al. 2018)	PHEV Li-ion	kg/unit	0.49 (neodymium)		
(Fishman et al. 2018)	BEV Li-ion	kg/unit	0.79 (neodymium)		
(Cucchiella et al. 2015)	LCD notebooks	kg/unit	0.0021 (neodymium)		
(Cucchiella et al. 2015)	LED notebooks	kg/unit	0.0021 (neodymium)		
(Cucchiella et al. 2015)	Smart phones	kg/unit	0.000005 (neodymium)		

(Cucchiella et al. 2015)	HDDs	kg/unit	0.001 (neodymium)		
(Cucchiella et al. 2015)	Tablets	kg/unit	0.000427 (neodymium)		