Estimates of global REE recycling potentials from NdFeB magnet material

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Abstract

Rare earth element (REE) containing neodymium-iron-boron (NdFeB) magnets play a major role in green technologies, including motor and generator applications. Recycling of REE from NdFeB magnets is expected to be beneficial from an environmental point of view compared to the production of magnets using primary REE currently practiced. This study gives a broad overview of global recycling potentials from end-of-life magnets from eleven different application groups and industrial scrap, quantified through dynamic material flow analysis. Data was obtained through a review of the literature, complemented by expert estimations. Recycling potentials achievable for REEs used in NdFeB magnets, namely neodymium (Nd), praseodymium (Pr), terbium (Tb) and dysprosium (Dy), were calculated for years 2020–2030, derived from two demand scenarios to reflect uncertainties in historic NdFeB demand figures and future demand development, taking into account the recent success in heavy REE reduction efforts. The most important NdFeB application groups in terms of recycling potentials are identified. The modelled scenarios show that between 18 and 22 percent of global light REE (Nd and Pr) and 20–23 percent of heavy (Dy and Tb) REE demand for use in NdFeB magnet production can be met by supply from secondary sources and scrap in years 2020, 25 and 30 (ranges of values for individual years and scenarios).

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1. Introduction: background to the research issue

Researchers in the EREAN project are working on the direct and indirect recycling of NdFeB (neodymium-iron-boron) magnets (EREAN, 2015). The direct recycling of magnetic material involves reprocessing into new magnets. Indirect recycling routes involve the chemical decomposition of the magnets and extraction of (individual) REEs. Current recycling rates are low for end-of-life (EOL) NdFeB magnets, but expected to increase in the near future (Binnemans et al., 2013). Originally motivated by the aim to help mitigate supply risks for the critical metals felt outside China, recycling of REE is also expected to be environmentally beneficial, not only from a resource conservation point of view, but also due to the environmental impacts associated with REE mining and processing. Environmental benefits of NdFeB recycling from EOL NdFeB magnets have been quantified for both indirect and direct magnets, when compared to magnet production from primary REE (Sprecher et al., 2014b; Walachowicz et al., 2014).

In recent years, a number of material- and substance flow analysis (MFA/SFA) studies have been conducted on REE magnets. Most of these studies have tried to answer the question of whether recycling can alleviate REE supply shortages. They were conducted against the background of REE supply uncertainties faced by companies outside China, the main producing country, with implications for green applications relying on NdFeB magnets in mind. A common finding in many studies was that recycling will not be able to meet a large fraction of REE supply in the near future, but that this fraction is increasing, with the delay due to the time lag associated with product lifetimes and the predicted growth of NdFeB applications—(see for example Alonso et al., 2012; Bradshaw et al., 2013; Buchert et al., 2011; Rademaker et al., 2013; Seo and Morimoto, 2014).

As a reaction to supply uncertainties, producers of NdFeB magnets and—components are making efforts in REE substitution and reduction. Depending on the speed of these developments, this will have implications for REE demand, especially dysprosium, and impact the fraction of the demand which can potentially be met by recycled REE in the short and medium term. NdFeB magnet produc-
tion technologies or appliance design modifications allowing for a reduction in heavy REE (HREE) use being or have been developed in an effort to minimize HREE supply risks—see e.g. Greenfield and Graedel (2013). Dy is the main HREE used in NdFeB magnets to ensure heat resistance of the magnets; Tb is used to a much lesser extent. Examples for NdFeB production technologies with less Dy which have already been implemented on an industrial scale include hot-pressed NdFeB magnets, and sintered NdFeB magnets produced with different heavy REE diffusion techniques. A recent paper reports on the feasibility of Dy replacement by cerium on a laboratory scale (Pathak et al., 2015). However, the new technologies sometimes imply higher production costs, which have to be weighed up against HREE material cost savings—(see for example VAC (2013)). Patent licenses associated with new technologies may also impede their use (Anon., 2015d) and/or increase production costs.

Whilst numerous authors have made efforts to quantify the HREE recycling potential from post-consumer (EOL) NdFeB magnets, the potential to recycle pre-consumer (industrial) magnet scraps has been given less attention. Recycling of magnet swarf is already being practiced (Anon., 2015c). The consideration of this material as an input material for the direct recycling process considered in this study is addressed in Section 4.3.

The objective of this work is to give an estimate of global annual REE recycling potentials from pre- and post-consumer magnet material in years 2020–30, considering eleven different application groups as sources for EOL magnets. We chose 2020 as a starting year for which recycling potentials are presented since the establishment of collection and recycling infrastructure is expected to take a few years. Effects of heavy REE content reduction efforts are taken into account to reflect both expected changes in REE demand for magnet applications and implications for the derived recycling potentials. Recycling potentials from post-consumer magnet material are derived from the demand for magnets for the respective application groups, expected product lifetimes, expected collection efficiencies and losses during disassembly. A direct recycling route was assumed for magnets from hard disk drives (recycling of magnet material), and an indirect recycling route for magnets from other applications (extraction of REEs from magnets). The findings will help inform a dialogue with strategic decision makers.

2. Methodology

A dynamic material flow analysis was applied to estimate the global REE recycling potential from NdFeB magnets. The focus is on sintered magnets which can be used as an input to the direct/indirect recycling routes described in Bast et al. (2015) and the direct route using hydrogen decrystallisation (Sprecher et al., 2014b; Walachowicz et al., 2014). Sintered NdFeB magnets account for approximately 92–95% of current NdFeB production by mass. The material flow quantities were derived from two NdFeB demand scenarios constructed to estimate the range of possible future demand in years 2020–30 and to depict uncertainties in literature data on historic demand for different NdFeB application groups. Further scenario assumptions were made to derive the corresponding REE material flows and recycling potential estimates.

The material flow model which forms the basis for the quantification of sintered NdFeB demand and recycling potentials is presented in Section 2.1. Equations for annual demand calculations of individual rare earth elements, expressed in rare earth metal (REM) quantities, and the annual recycling potentials for individual REM from magnets extracted from EOL appliances are presented in Section 2.2. The scenario approach taken to quantify the independent variables described in Section 2.2 is presented in Section 2.3. The numbers are derived from qualitative and quantitative information acquired through an extensive review of the literature, complemented by discussions with industry and own scenario assumptions (Section 3).

2.1. Modelling of material flows—quantification of recycling potentials

The focus of this work is on quantifying the recycling potentials for NdFeB magnet material and individual REEs contained in the magnet material through a dynamic material flow analysis. The annual global demand for NdFeB magnets is derived from the demand for different NdFeB application groups in the same year. Recycling potentials for NdFeB magnets are derived from the volumes of EOL appliances containing NdFeB magnets expected to become available in the respective year and production waste quantities derived from production of NdFeB magnets in the same time period (magnet material available for recycling, after subtration of losses from collection and disassembly). We define the recycling potential for individual REM as the amount (mass) of REM which can be supplied from secondary sources, including pre- and post-consumer magnet material, after subtration of losses during collection, disassembly and recycling (sum of flows 7 and 9, Fig. 1).

Both the material and element level are investigated. The demand and secondary material supply figures are used as a basis to derive the flow of the REE elements contained in the magnet material. The consideration of individual REM content in the magnet material and the distinction between the different REM are relevant because of their unique properties, different mining routes, and different criticality levels. Furthermore, the REM composition in the magnets is related to their grade and suitability for use in different applications, with material cost implications. Assumptions are made for NdFeB/REE losses occurring during NdFeB magnet production, EOL collection, disassembly and recycling. An early representation of some exemplary scenario model results is shown in Fig. 1 to illustrate the model structure. REM quantities are expressed in tons of rare earth metals (REM). The model makes three assumptions for necessary simplification: (i) that for each year considered, the global supply (production) meets demand for REM in NdFeB magnets, through a combination of NdFeB magnets from primary REM, secondary REM or secondary NdFeB material; (ii), that magnets are demanded and supplied in the same year, and (iii), that NdFeB material is recycled and made available as secondary material in the year it arises (no stockpiling). The contribution to the supply mix from primary production is the difference between the REM demand and the secondary supply. The composition of the production mix is modelled in two demand scenarios to reflect demand level uncertainties. Details on scenario assumptions are provided in section 2.3.

REM contained in magnets extracted from EOL appliances entering the secondary REM supply route each year, illustrated in Fig. 1 (flow 1), is calculated from production quantities of NdFeB containing appliances, appliance lifetimes, magnet contents and compositions (see 2.2, Eq. (3)). (For simplification, it is assumed that the lifetime of the magnets is determined by the lifetime of the appliances containing them.) Losses then occur along the process route (Table 1). A collection rate is assumed for each magnet-containing appliance group to estimate which fraction of the appliances is collected for recycling (Fig. 1), flow 3). Losses during sorting and disassembly may occur if the magnets are deeply embedded in the devices and cannot be easily extracted, are too small or not suited as input material (flow 4). Once the magnets have been extracted, material losses occur at several processing stages during direct or indirect magnet recycling (flow 6).

The magnets which do not enter the recycling process (flows 2, 4 and 6) are lost to other waste management routes, which can
be other recycling routes not aimed at REE recovery. The distinction between alternative waste treatment routes (other than NdFeB recycling routes) is of interest for this study. After subtraction of those losses, the flow represents the secondary REE input from EOL magnets, at the point where it enters the NdFeB magnet production process (see 2.2, Eq. (2)).

According to our model assumptions, secondary REE from industrial waste are extracted from the wet scrap not suitable for direct internal material recycling, estimated as a percentage of input material to the magnet production process (flow 10, Fig. 1). This type of scrap arises largely from cutting and grinding of the sintered magnets to the desired shapes, but also at other stages in the magnet production process. More details on scrap from magnet production can be found in Section 3.1.12. It is assumed that the scrap material enters an indirect recycling process during which the REE are extracted from the material. Losses occur during this process (flow 11).

The REM quantity which needs to be supplied from primary sources is the difference between REM demand and supply from secondary sources (flow 8).

2.2. Demand calculation for REM used in NdFeB magnets, derived supply of REM from EOL NdFeB magnets and industrial scrap, potential recycling rates

NdFeB magnets are used in numerous applications with different specifications and magnet weights. The demand for individual REM used in NdFeB applications was calculated as the sum of the expected individual REM requirements for all magnet appli-
cation groups (Eq. (1)). The bottom-up calculation of REM demand is described by the following equation:

\[
D_{ij} = \sum_{k=1}^{n} g_{ij} \times p_{ij} \times m_{ij} \times c_{ij} \times l
\]  

(1)

- \(D_{ij}\): demand for REMi in year j (sum of demand from all groups k, in tonnes REM)
- \(g_{ij}\): demand quantities for appliances of groups k = 1 – n, (n number of appliance groups) in year j
- \(p_{ij}\): percentages of appliances in groups k using NdFeB magnets in year j
- \(m_{ij}\): average masses of magnets in groups k in year j (in tonnes)
- \(c_{ij}\): average weight percentages of REMi in year j in magnets of groups k
- \(l\): efficiency factor > 1 to account for average losses of REM in magnet production/fabrication of groups k

\(D_{ij}\) corresponds to the sum of flows 7, 8 and 9 illustrated in Fig. 1. For some application groups, insufficient information was available to determine all the independent variables specified in Eq. (1). Where this was the case, estimates for the total production of NdFeB magnets for use in this application group were taken from the literature and multiplied with \(l\) and \(g_{ij}\). Details are provided in Section 3.

The potential supply of secondary REM extracted from post-consumer magnet materials (neodymium and dysprosium, terbium and praseodymium) is derived from the REM demand figures, taking into account the product lifetimes for different NdFeB application groups and expected yields from collection, disassembly and recycling (Eq. (2)). The bottom-up REM supply from EOL (post-consumer) magnet recycling is calculated as follows:

\[
S_{\text{net},ij} = \sum_{k=1}^{n} S_{\text{gross},i,j,k} \times b \times d \times r
\]  

(2)

- \(S_{\text{net},ij}\): net supply of REMi in year j from EOL magnet recycling from magnets from all application groups k (losses occurring during recycling deducted, in tonnes REM)
- \(S_{\text{gross},i,j,k}\): gross supply of REMi in year j from EOL appliances from all groups k (in tonnes REM, see Eq. (3))
- \(b\): collection rates <1 for magnets for EOL appliances, constant for each group for all years considered (defined as “old scrap collection rate” in \(UNEP\) (2011))
- \(d\): efficiency rates of disassembly <1 for EOL appliances, constant rate for each group for all years considered
- \(r\): efficiencies of REM extraction from EOL magnet in recycling process, <1, same efficiency for different REM i assumed, constant over time period considered (defined as “recycling process efficiency rate” in \(UNEP\) (2011))

\(S_{\text{net},ij}\) is illustrated by flow 7; \(S_{\text{gross},i,j,k}\) by flow 5 in Fig. 1.

\[
S_{\text{gross},i,j,k} = \sum_{l=\text{baseyear}}^{j-1} D_{il} \times k \times p_{ij} \times k
\]  

(3)

The results from this equation for all groups k are used to form the vector \(S_{\text{gross},i,j}\) for all groups k, (see Eq. (2)).

\(S_{\text{gross},i,j,k}\) : gross supply of REMi from EOL magnets arising in year j produced for use in group k applications in years l, in tonnes REM

- \(D_{il,k}\): (historic) demand for REMi in all years l for applications in group k (in tonnes REM)
- \(p_{ij} \cdot l\): vector, probabilities of magnet containing appliances from groups k produced (demanded) in year l to become available for recycling in year j, assuming a Gaussian probability distribution of lifetimes with

\[
p = f(m) = \frac{1}{\alpha \sqrt{2\pi}} \times e^{-(m-u)^2 / (2\sigma^2)}
\]  

(4)

with p: probability of magnet produced in year l to reach EOL in year j (scalar), \(m – u\): (time appliance has been in use, age of the appliance) with average lifetime \(\mu\) and standard deviation \(\sigma\).

\[
l_{\text{net},ij} = D_{ij} \times 0 \times u
\]  

(5)

With \(l_{\text{net},ij}\): supply of REMi extracted from industrial scrap arising in year j with \(o\): factor > 0 < 1 to account for material losses during magnet production/fabrication (to calculate scrap quantities arising)

\(\text{potentialRIR}_{ij} = \left( S_{\text{net},ij} + l_{\text{net},ij} \right) / D_{ij}
\]  

(6)

with \(\text{potentialRIR}_{ij}\): (average) recycled content in the (global) production flow of REMi in year j, in line with the “Recycling Input Rate” defined in \(UNEP\) (2011). For this study, the equation refers specifically to the percentage of demand for REMi in year j for use in NdFeB magnet production which can be met by REMi supplied from secondary sources (according to scenario estimates).

2.3. Quantification of recycling potentials from EOL magnets and production waste via a scenario approach

2.3.1. EOL magnet quantities derived from NdFeB demand

To reflect uncertainties in the development of the NdFeB magnet market, derived from the demand of the respective applications, a scenario approach is adopted to illustrate possible future market developments. Since a complete and reliable dataset for historic NdFeB demand in different application groups was not available, the uncertainties of historic demand figures were also addressed by the same scenarios. The scenarios differ in their levels of NdFeB demand and resulting REM demand and in terms of derived NdFeB/REM recycling potentials. Based on the calculation method outlined in 2.2, Eq. (1), two NdFeB demand scenarios were constructed, starting from the respective base year and ending in 2030:

a Low NdFeB demand scenario, based on lower-end demand estimates for individual NdFeB magnet application groups, with derived demand scenarios for individual REEs Nd, Dy, Pr, Tb, considering only the fraction of the REM demanded for use in NdFeB magnets (i.e., Nd, Tb, Dy, Pr used in applications other than sintered NdFeB magnets are not taken into account). This scenario assumes moderate growth in demand for applications and components, and slower progress in heavy REM content reduction in the magnets.

b High NdFeB demand scenario, based on higher-end demand estimates for individual NdFeB magnet application groups, with derived demand scenarios for REEs Nd, Dy, Pr, Tb, considering the fraction of the REM demanded for use in NdFeB magnets. This scenario considers higher growth rates in demand for applications and components, and faster progress in heavy REM content reduction in the magnets.

\footnote{For the direct recycling process for the hard disk drives, the losses in the recycling process refer to the magnetic material recycling, rather than individual REE extraction. r then stands for efficiency of material recycling.}
The quantification of the material flows was based on a review of the literature conducted to obtain an understanding of the markets for the NdFeB containing application groups. Quantitative and qualitative information was obtained to model the market trends at product/component and magnet material level and derive NdFeB/REM demand scenarios.

Historic market information on NdFeB magnet containing appliances was included, starting from a “base year”, to determine quantities of material available for recycling from EOL magnets, based on the expected product lifetimes (and probability distribution) to account for all appliances reaching EOL in years 2020–30. The data obtained from scientific publications, company reports and other sources was complemented by discussions with experts from industry and research. For each demand scenario, NdFeB and REM recycling potentials (secondary supply from EOL magnets) were derived according to Eq. (2).

2.3.2. Production waste

Recycling potentials for pre-consumer magnet scrap were quantified in a top-down approach based on information on the process material efficiency in sintered NdFeB magnet production, and NdFeB production quantities. The recycling potential from industrial scrap was calculated for years 2020–2030, respectively. The information which formed the basis for the assumptions made was obtained from interviews with industry experts and literature data. The recycling potentials are presented for the respective years in which the material arises.

3. Overview of applications and key assumptions

3.1. NdFeB magnets used in different application groups, current technology trends

3.1.1. Electric two-wheelers

Electric two-wheelers are powered by a combination of manpower and electric power, or electric power only. E-bicycles (pedal-assisted or throttle controlled e-bikes), scooters and e-motorbikes are included in this application group. E-bicycles dominate in numbers in the electric two-wheeler group (around 86% of vehicles in 2015). According to one source, the distinction between throttle-controlled e-bikes and scooters is based on whether they can be pedaled by the rider (INSG, 2014). The largest market for e-bikes is China, with an approximate 90% market share by volume (INSG, 2014). The global market is expected to see substantial growth in the next years. E-bike motors constitute an important application of NdFeB magnets, currently accountable for around 8% of global NdFeB demand (Lucas et al., 2015). In accordance with the expectation of an expanding e-bike market, the demand for NdFeB magnets for use in e-bikes is expected to grow (Bast et al., 2015; Binnemans et al., 2013; Shaw and Constantinides, 2012b). REE free e-bike motors have been developed (Honkura, 2013), but details on or evidence of their current use could not be found. It is assumed that almost all e-bikes produced today use sintered NdFeB-magnet based motors—based on findings by Schuler et al. (2015), who conducted expert interviews to answer this question.

3.1.2. Air conditioners

Permanent magnet motors with NdFeB magnets are used in compressor motors of some air conditioners (AC) (Hitachi, 2011). Fan motors sometimes contain NdFeB magnets (Constantinides, 2014b; Grieb, 2014), but are mostly ferrite-based (Anon., 2015a). The global demand is growing for both commercial and residential ACs. Gloe et al. (2015) provide details on different air conditioner types. Growth rates around 5% are expected for the next years (PR Newswire, 2015a). Approximately 80% of ACs are manufactured in China (2013 figures) (Yu, 2014). The largest AC markets are China, Japan and USA, with largest growing markets in Asia, Africa and South America (Holley, 2014; Yu, 2014). Efficiency standards for air-conditioning units are being raised to achieve GHG emission targets (Mikami, 2012; Yu, 2014), with efficient NdFeB-based compressors expected to support this transition (Frontier Rare Earths, 2012; Minowa, 2008).

The global demand for NdFeB magnets used in air-conditioning systems is expected to increase (Benecki, 2013; Frontier Rare Earths, 2012; Shaw and Constantinides, 2012); and an increase in NdFeB demand associated with the growing market for inverter air conditioners in China is expected (Frontier Rare Earths, 2012; Kesheng Magnet, 2013; Research in China, 2011). However, based on the information found in the literature, it is difficult to derive assumptions for a bottom-up quantification of NdFeB magnets used in air conditioners. Apart from the lack of reliable information on the market share of NdFeB-based air-conditioning systems, the difficulties arise from the large variation in magnet weights per air-conditioning unit. Values for magnet weights of NdFeB magnets in air conditioners are between 100g–500g for domestic and 250–300g for industrial air conditioners, (Bast et al., 2015; Habib et al., 2014; Isatani et al., 2013). The collection and recycling of magnets from air conditioners is already being practiced in Japan (Hitachi Ltd., 2010; Mitsubishi Electric, 2014).

3.1.3. Traction motors hybrid and electric cars ((H)EVs)

The global demand for passenger cars is increasing, driven by the demand in new markets, e.g. India and China. Although they only contribute a small fraction of global passenger cars on the road today, sales of hybrid and electric vehicles have grown in the past years (EVI, 2015) and are expected to grow until 2030, with different levels of global electric vehicle uptake projected (Kühn et al., 2014; Siemens, 2014). It has been suggested that the shift towards electric and hybrid vehicles could make EV traction motors the main application for REE by 2050 (Habib and Wenzel, 2014). Hybrid cars are currently dominating the automotive hybrid and electric market (Kühn et al., 2014).

Direct current (DC) brushless REPM motors are standard for hybrids and plug-in hybrids (Burwell et al., 2013; Rippel, 2007). Electric cars use PM or induction motors. Mitsubishi, Toyota, Nissan and Chevrolet’s models run with permanent magnet motors (Chevrolet, 2015; Mitsubishi Electric, 2015; Nakada et al., 2014; Toyota Global, 2015), whereas Tesla BEVs use induction motors, based on copper rotors (Green Car Congress, 2013; Widmer et al., 2015). Traction motors for hybrid and electric vehicles are amongst the NdFeB applications which require the highest HREE contents (Binnemans et al., 2013), due to high operating temperatures. However, considerable research efforts are being conducted at material and component level.

Operating temperatures around 150 °C, which might be reached in today’s traction motors of hybrid or electric cars (Galioto et al., 2015), require HREE contents higher than those of other NdFeB applications to prevent demagnetization. To some extent, the operating temperatures can be altered by changing the motor design: a few years ago, specifications for NdFeB magnets in hybrid cars were designed for operating temperatures of 180 °C—see Gutleisch et al. (2011). REE free motors for hybrid cars are currently at research stage—see e.g. Chiba et al. (2015). Research regarding new magnet production methods focuses on microstructural changes, with the aim to enhance magnetic properties and reduce HREE content; e.g. via a more even distribution of the Nd-rich phase or a reduction in grain size (Brown et al., 2014; Goto et al., 2012). Different grain boundary diffusion methods are already being successfully implemented, allowing for a significant reduction in HREE content. Some electric/hybrid car manufacturers report HREE reduction efforts for the magnets used in their traction motors (Chevrolet, 2015;
Molycorp, 2013; Nakada et al., 2014). The adoption of the grain boundary diffusion technologies is likely to spread in coming years (Anon., 2015d), allowing a further reduction in global heavy REE use.

3.1.4. MRI scanners

MRI scanners can be based on permanent magnets, superconducting magnets or electromagnets, with superconducting magnets being the most popular technology in use today. The market is currently dominated by high-field MRI scanners which use superconducting magnet technology (Markets and Markets, 2015). Permanent magnet based MRI constitute the second most popular technology (Gupta and Kumar, 2014). They are used in smaller, open MRI scanners and generate lower field strengths than superconducting MRI scanners (up to 0.35 T) (Cosmus and Parizh, 2011; Zepf, 2015). Today, Hitachi is the global market leader in open MRI systems, with two thirds of their installed capacity based on permanent magnet technology (Hitachi, 2015b, 2015c). In their latest business report, they report declining sales for permanent magnet MRIs (Hitachi Medical Corporation, 2013). Values for magnet weights of NdFeB magnets in MRI scanners found in the literature are between 700 and 3000 kg per device (Bast et al., 2015; Talens Peiró et al., 2013), making MRI scanners an interesting material source for recycling in principle.

Overall, the information on NdFeB containing MRI scanners or low-field MRI scanners found in the literature was non-conclusive. Details on the estimates found in the literature are provided in the supporting information. The uncertainties regarding the numbers of MRI scanners based on NdFeB magnets are reflected in different low- and high NdFeB demand scenarios.

3.1.5. Generators used in wind turbines

Geared doubly-fed induction generators are currently the most common wind turbine generator type on the market (Blaabjerg and Ma, 2013). Larger difficult-to-access offshore turbines benefit from the gearless permanent magnet (gearless PM) drives since they require less maintenance. Lower speed turbines suitable for use in areas with lower wind speeds also rely on PM direct drive technology (Lacal-Arántegui, 2014; USDOE, 2015).

Global annual installations of wind power capacity are expected to grow until 2030 (Lacal-Arántegui, 2014). PM (NdFeB) generators and high temperature superconductor generators are seen as the two promising future technologies for higher performance generators (Lacal-Arántegui, 2015); with the latter not as advanced in their development. As with magnets used in (H)EV traction motors, manufacturers are reducing the Dy content in the magnets in an effort to reduce risks associated with REE price volatility. Siemens are aiming to completely eliminate Dy from the magnets used in their wind turbines by 2017 (DERA, 2014; Metaevents, 2014). Furthermore, future development aims at the reduction of magnet weights per MW installed via the improvement of magnetic densities (Lacal-Arántegui, 2015).

Uncertainties regarding the recycling potentials from EOL NdFeB magnets used in wind turbine applications arise from projections regarding the share of new installations with REPM magnets in the next 15 years and from lack of knowledge on the actual lifetimes of the turbines (extent of generator/turbine reuse at EOL). Whilst the reuse of magnets from wind turbines is considered unlikely (Zero Waste Scotland, 2014), the reuse of decommissioned turbines is practiced for wind turbines from the EU, which are generally sold on the international market (Lacal-Arántegui, 2014). The composition of the magnets is being changed to contain less dysprosium, with implication for HREE recycling potentials. However, this has been reported by a single turbine manufacturer. Chinese manufacturers may not be equally motivated to reduce REE contents. The global average will significantly shift if the new designs are adopted by other manufacturers.

3.1.6. Hard disk drives

NdFeB magnets are used in hard disk drive (HDD) motors (voice coil actuators) to move read/write heads (Constantinides, 2012). The global demand for data storage is rapidly increasing. Presently, HDDs are the most common storage solution, but the use of NdFeB-free solid state disks (SSDs) has seen an exponential increase since 2010 (Sprecher et al., 2014a). HDDs applications for traditional consumer applications (desktops, laptops) are in decline, but the decline could be compensated to some degree by the increased use in the expanding segments, namely enterprise and gaming applications (Businesswire, 2015; Toshiba, 2014; Western Digital, 2014). Besides a small compositional variety, HDDs offer the benefit of being available in larger quantities than newer NdFeB applications, and could serve as a secondary REE source in the near future.

3.1.7. Acoustic transducers

Electro-acoustic transducers either convert electricity to sound, or sound into electric signals. Common applications include speakers, headphones and microphones. Other applications include material property characterization tools and echo sound tools used in fishing or for the detection of pipe leaks. 35% of NdFeB demand was for use in audio systems in 2009, with lower percentages around 7% in developed countries (Du and Graedel, 2011). Speakers are found in PCs, notebooks, TVs, cars, and other audio systems. In larger speakers, NdFeB magnet weights are around 100–300 g, based on information taken from a product specification (Eminence, 2015). NdFeB magnets used in small speakers used in mobile phones and mobile phone headphones weigh around 0.3 g (Zepf, 2013). 2.3 g of NdFeB magnet material are used in speakers of notebooks (Buchert et al., 2012).

According to a Chinese magnet manufacturer, ferrite is the most common magnet type used in speakers (EukeMag, 2014). It is likely that NdFeB magnets are widely used in small speakers for mobile phones and notebooks, tablets and headphones, but detailed information on the percentages of speakers with NdFeB magnets was not available in the literature. According to Lucas et al. (2015), the market is not expected to grow significantly in future due to the replacements of magnets by piezoelectric transducers. Piezoelectric speakers can be built even smaller than REPM based speakers, and consume around half the power (BeStar Acoustics, 2012; ECN, 2012; Onishi et al., 2010). They are being mass-produced for the use in mobile phones, tablets and other mobile devices (Murata, 2011). Details on market penetration could not be found.

3.1.8. Magnetic separators

Magnetic separators allow for effective removal of metal contamination from agricultural products, coal, and chemicals, during mineral processing, manufacturing and recycling processes (Lucas et al., 2015). Apart from ensuring a clean material, they help protect the equipment (conveyor belts etc.) from being damaged by metal pieces (Wei, 2009). Rare-earth permanent magnet separators became popular in the 1990s (Fuerstenau and Han, 2003). NdFeB magnets are used for the separation of wet and dry materials, normally for the extraction of smaller particles, while larger ferrous pieces are extracted with electromagnets. The demand for NdFeB magnets used in magnetic separation is expected to “increase steadily” (Prysmag, 2015). Growth is expected for the moderate field strength separators used in mining, and mainly driven by the development of the mining industries in the Asia-Pacific region (FMI, 2015; Transparency Market Research, 2015). Average weights for NdFeB magnets used in separators or numbers
for units produced could not be obtained. Large magnetic separators are manufactured based on the bespoke needs of the clients.

3.1.9. Other generators (excl. wind turbine generators)

NdFeB applications related to power generation include power generators other than wind turbines. NdFeB magnets are used in automotive alternators (Constantinides, 2015) and bicycle dynamos (Molycorp, 2013). REPM generators are used in small hydropower plants, tidal or wave power plants and other renewable energy applications (Alibaba, 2015; Binder and Schneider, 2005; Ikäheimo, 2009; Shaw and Constantinides, 2012; Smith Stegen, 2015). High-speed permanent magnet generators are used in microturbines—small gearless combustion turbines which are suited to generate the energy off-grid, or as part of a power network (Huynh et al., 2009). REPM are also used in portable generators, which are enjoying increasing popularity in the Asian-Pacific region, and for which an annual growth of 8% is predicted until 2019 (TechNavio, 2015). Constantinides (2012) estimated the demand for NdFeB magnets for use in generators to roughly halve between 2010 and 2015. The weights of magnets used in generator applications vary greatly. A 300 kW turbine for a small hydropower plant uses 72 kg of REE magnets (Binder and Schneider, 2005), whilst the total weight of rare-earth magnet based dynamos can be as low as 52 g (Velogical Engineering, 2015).

3.1.10. Other motors

Motors used in industry, cars and other applications now constitute the largest application group for NdFeB magnets at around 25% by volume (Constantinides, 2014b). The demand for magnets in this group is growing exponentially and has been the cause for the rapid increase in dysprosium demand in years 2000–10 (Mikami, 2012). Electric motors are responsible for around 45% of the global power consumption (Waide and Brunner, 2011), which illustrates the need for efficient motors such as rare-earth permanent magnet (REPM) motors. New energy performance standards and rising electricity prices are expected to drive the production of energy efficient motors (Buchert et al., 2013; GlobeNewswire, 2015).

Industrial applications for which PM motors are suitable include adjustable speed pumps, fans, extruders, conveyers, crane and hoist systems, winders and printing presses (USDOE, 2014). Factory automation, including robotics and material handling, is currently the largest sector by revenue for PM motors (PR Newswire, 2015b). The majority of PM electrical machines (motors, generators) is NdFeB-based (DrivesNControls, 2015; Eriksson, 2014). Globally, the use of NdFeB magnets in PM motor applications is predicted to grow at an annual rate of 10.8% from 2014 until 2020 (PR Newswire, 2015b).

Automotive applications of sintered NdFeB magnets other than traction motors in electric/hybrid cars include motors for electric power steering (EPS), automated manual transmission motors, starter motors etc. and other small automotive motors (Constantinides, 2014a; Hitachi, 2015a; Shin-Etsu, 2015). There is a tendency towards “electrification”, resulting in an increasing number of electric motors, especially in high-end cars. Belt-driven components (connected to the main drive motors via a belt), for example, are being replaced by electronically driven ones to increase energy efficiency (Arnold Magnetic Technologies, 2014). EPS and automotive transmission motors are increasingly adopted in new vehicles due to fuel efficiency improvements associated with the automation. There can be up to 100 motors in high-end cars, most of which, however, are DC brush motors with ferrite magnets (Hitachi, 2015a), with an estimated average 250 g of NdFeB magnets per standard car, mainly used in motors and sensors (Shaw and Constantinides, 2012). Some ferrite-based automotive accessory motors are being replaced with bonded NdFeB magnet motors which are smaller and lighter (Honkura, 2013; Magnequench, 2009; Sheth, 2011). The use of bonded magnets for automotive applications, such as fuel pumps and ABS motors, is increasing (Pati et al., 2013). Research efforts undertaken to reduce the use of (heavy) REEs include the development of bonded magnets motors with no dysprosium content (Honkura, 2013).

Other NdFeB motor applications include motors used in buildings and other infrastructure (e.g. pumps, fans, office automation, elevators and escalators and home appliances). Home appliances like refrigerators, vacuum cleaners and washing machines are available with efficient rare earth permanent magnet (REPM) motors. The motors are advantageous in terms of noise and energy efficiency. 250,000 elevators and escalators are globally installed per year (Zepf, 2015) citing (IMU-Institut, 2007). In Europe, PM synchronous motors are becoming the leading technology in this application field, with an increased share of rare-earth magnet based motors (ISR, 2010).

Pumps used in central heating systems offer large energy saving opportunities, with inverter PM motors constituting one of the key factors driving this improvement (Waide and Brunner, 2011). The use of efficient pumps in heating systems is now mandatory in the EU, and pump manufacturers are increasingly building pumps with efficient REPM motors (Anon., 2015f, Sims, 2015). Both sintered and bonded NdFeB magnets are used in pump motors, with typical magnet weights of 30–200 g per pump, depending on pump motor size (Anon., 2015f). Around 32 million circulation pumps are produced worldwide annually for use in private homes, commercial buildings and industry etc. (Grundfos, 2014). Not all of these pumps contain PM motors, see e.g. (Meza, 2014).

3.1.11. Other NdFeB applications

Due to the tremendous diversity of NdFeB uses, many applications could not be investigated in detail for the purpose of this study. They include sensors, torque coupled drives, hysteresis clutches, energy storage systems, gauges, brakes, relays and switches, other transport applications (trains, magnetic levitation), etc.

3.1.12. Pre-consumer scrap

Pre-consumer magnet scrap arises at various stages in the manufacturing process (Anon., 2015d; Lyman and Palmer, 1993). The most relevant waste streams in terms of mass are dry magnet material arising from cutting block magnets into shape or off-quality magnets, which can be suitable as an input for direct recycling processes (e.g. remelting), and wet swirl from magnet finishing processes, only suitable for indirect recycling processes, since the material is contaminated and partly oxidized (Bast et al., 2015; Tanaka et al., 2013). Around 20–30% of the starting material is lost during the magnet production process as wet swirl from magnet finishing processes (Anon., 2015b; Constantinides, 2015; Tanaka et al., 2013). Losses are lower for magnets pressed to shape before sintering and higher for block magnets which are cut to shape. For magnets cut to shape, the percentage of the material lost in this process depends on the surface-to-mass ratio of the magnets, and is hence larger for smaller magnets. An additional (gross) 10% of

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2 This percentage excludes the motor applications which are addressed as separate categories in this paper (HDD, Electric Two-Wheelers, HEV/EV and air conditioners) in this paper – if included, motors account for more than half of NdFeB applications by mass.

3 In bonded/hot-pressed magnet production, scrap arises from alloy melting, discarded ribbon material or discarded finished magnets. Powder metallurgy processes produce waste from grinding, discarded sintered and unsintered (green compact) magnet pieces.
the initial alloy material becomes solid magnet waste, arising from block cutting and off-quality magnets (i.e. magnets which do not pass the quality tests). Expert opinions differed on the extent of recycling for manufacturing scrap, and information on the specific processes currently employed for the recycling of the production waste were not available.

Clean hard scrap is internally recycled. The uncoated dry magnet material waste is collected according to composition and recirculated via direct recycling route, ideally to be used internally in products of the same composition. Most of the solid waste (ca. 90%) can be used for internal recycling (Anon., 2015d). It is mixed with the alloy material (Tanaka et al., 2013). Off-quality magnets which have already been coated are usually processed in indirect recycling routes (Anon., 2015b). Nickel coatings, for example, are detrimental to magnetic properties (Liu and Chinnasamy, 2012). Direct internal recycling of solid magnet material has the advantage of a known composition of the material for recycling; both the sources of contamination and quantities arising are predictable, and the material is promptly available for internal reprocessing. However, some property losses are experienced, limiting the percentage of hard scrap in the material (Anon., 2015d; Walachowicz et al., 2014).

It is likely that indirect recycling routes are used to extract the REEs from the wet scrap. Based on the information obtained, there is a market for sintered NdFeB manufacturing scrap, and it is possible that the recycling potential from sintered NdFeB manufacturing scrap is already being utilized to a large degree, and will be utilized in the time period 2020–30. Indirect recycling is more complex than direct recycling, but can produce pure REE, which can be sold on the market. It is expected that the processes applied for indirect recycling of REEs from magnet scrap are similar to that starting from the (concentrated) ore; however, the REE concentration in the starting material is higher. Some magnet manufacturers export the wet scrap (Bast et al., 2015) and other material not suitable for direct internal recycling. Information on the specific processes conducted is usually undisclosed (Anon., 2015b; Anon., 2015c; Tanaka et al., 2013). Indirect recycling of magnet scrap is already practiced in China and economically viable (Anon., 2015b; ERECON, 2015). According to one expert opinion, the potential for material efficiency optimization in magnet production is already well utilized, implying that NdFeB process waste is not commonly landfilled. Hitachi recycle 95% of the scrap from their magnet manufacturing process (Hitachi, 2014a). Kingsnorth (2014) state that pre-consumer magnet scrap recycling is now starting to become economically viable. Swarf stockpiles are estimated to contain 10–50 kt REM, depending on the consulted source (ERECON, 2015; Kingsnorth, 2014).

It has been suggested that wet processing waste could be used as a base load for indirect recycling processes to be set up for EOL material magnets to alleviate the current problem of small quantities of EOL magnets available for recycling and insufficient feedstock in the near future (Bast et al., 2015). This type of waste is suitable as an input material to the indirect recycling route investigated by Bast et al. (2015), and constitutes the most relevant input in terms of feedstock quantities arising in the near future (see Section 4.3). This suggests that the scrap should be considered in the quantification of recycling potentials for material inputs to the indirect recycling route. There is some indication that the recycling processes currently employed may involve a large number of processing steps, and may therefore be associated with higher environmental impacts than other (more optimized) indirect recycling routes. However, due to the lack of information on the exact processing routes which are currently applied, the differences between the suggested and the currently practiced routes cannot be detailed in this paper.

3.2. Key assumptions

An overview of key scenario assumptions is provided in this section. Background information compiled to derive these assumptions can be found in the supporting information. The grouping of NdFeB magnet applications was based on Constantinides (2014b), who provided an estimate for NdFeB demand by application group for the years 2010 and 2015.

3.2.1. Assumptions for demand calculations

Demand for individual REM was calculated according to Eq. (1).

\[ \text{Demand} = \text{Production} \times \text{REM rate} \times \text{Quality factor} \]

(Section 2.2). The variables in the equation were estimated by compiling information on current use and demand growth rates for NdFeB used in different application groups, and historic production rates relevant to the quantification of EOL quantities arising. Furthermore, for each group, information on the fraction of applications which contains NdFeB magnets, size and composition of magnets was used to come up with the values for the variables. This information was compiled from qualitative and quantitative information found in the literature—see Annex A for details and literature References.

The demand growth rates for years 2020–2030 have been grouped into 5 categories from “declining” to “very high growth” (Fig. 2).

As discussed in 2.1, it is assumed that the production and sale of NdFeB magnets happen in the same year, i.e. the demand quantities for NdFeB applications in the respective year are directly linked to the REM demand figures, with no time delay. The demand for REM for use in NdFeB magnet production was derived from the content of REM in the NdFeB magnet material demanded in the respective year. A percentage was added to account for REM losses during magnet production (20% of REM in starting material).

A total REM content of 31% by weight is assumed. Nd and Pr are the two light REE (LREE) presently used in NdFeB magnet production. Up to 25% of Nd required can be replaced by Pr without significant magnetic property losses in some magnets. Regarding HREE, Dy can be replaced by Tb, which allows for better magnetic properties. This is currently uncommon because the additional cost of Tb exceeds the additional “benefit” of using the more effective HREE (Anon., 2015b; Anon., 2015e). Tb is used in compact fluorescent lightbulbs, which may be gradually replaced by light emitting diodes in future, and for which a recycling process is now available—see e.g. Machacek (2015). It has been suggested that the increased use of LEDs could free up some terbium for the use in NdFeB magnets in future (Binnemans and Jones, 2015). We assume an average LREE mix of 17% Pr, 83% Nd, and an average HREE mix of 92% Dy, 8% Tb, based on the demand for the elements for use in NdFeB magnets reported in EC (2014). The average HREE content in the NdFeB magnet material varies between application groups and is assumed to decrease from an average content of 4%/3.7% by weight in 2015–2.5%/1.4% by weight in 2030 for the low and high NdFeB demand scenario, respectively.

3.2.2. Assumptions for recycling routes and secondary supply calculations

In order to estimate recycling potentials from both EOL magnets and industrial scrap from NdFeB production, assumptions for the supply of secondary materials were necessary.

3.2.2.1. Assumptions regarding recycling routes. Direct and indirect NdFeB recycling routes are distinguished. In direct recycling, the magnet material is recovered. In indirect recycling routes, rare earths are extracted. Direct recycling is feasible for sintered magnets from hard disk drives due to small compositional changes over the years for those magnets (Binnemans et al., 2013). For example, this can be achieved through a hydrogen decrepitation, milling and
resintering route (Sprecher et al., 2014b; Walton et al., 2015). Sintered NdFeB magnets from voice coil motors (VCM) are used as input material for this route. Direct recycling avoids the complex extraction of REEs from the magnet material. Small percentages of Nd hydride additions are necessary to avoid downsizing, i.e. losses in magnet performance caused by Nd oxidation and evaporation (Zakotnik et al., 2005). VCM magnets from HDD are already being collected, extracted and recycled in Japan (Hitachi, 2014b), albeit through an indirect recycling route (Hitachi Ltd., 2013). For our scenarios, we assume that hard disk drives, contrary to EOL magnets from other appliances and industrial scrap, are processed in a direct recycling route (hydrogen decrepitation and resintering).

Indirect recycling for rare earths from magnets has been trialed, e.g. for EOL NdFeB magnets from motors of hybrid cars, and is transferrable to other magnet applications (Bast et al., 2015; Walachowicz et al., 2014). We assume that EOL magnets from all application groups presented in 3.1, as well as pre-consumer scrap, will be processed in an indirect recycling route (route 3, described in Walachowicz et al. (2014). Magnets are extracted from motors, demagnetized and milled. The powder is leached, exogens are precipitated and rare earths are separated in a solvent extraction process.

For this study, the assumptions regarding the chosen recycling routes are relevant regarding the process-specific material losses during recycling, which are detailed in the following paragraph.

3.2.2. Scenario assumptions secondary supply. Supply of REM from EOL magnet recycling was estimated from (historic) NdFeB use in different application groups, average product lifetimes, with normal distribution of lifetime probabilities, and material losses occurring during collection, disassembly and recycling operations assumed (Table 1). The losses occur when material is landfilled or incinerated, or collected for other recycling routes, which do not recover REE or NdFeB material (e.g. steel recycling). Estimates on product lifetimes and collection rates were taken from literature sources or communicated during expert interviews—see Annex A for details. Losses during disassembly are mainly based on own estimates. Estimates take into account factors such as magnet weights per appliance, the fraction of bonded magnets not suitable as an input to the recycling processes, and information from existing collection schemes, disassembly or recycling trials where available. For the calculation of potential secondary REM supply, as a rough estimate, it is assumed that 10% of NdFeB material/REM is lost in the direct recycling route applied for HDD recycling, and 8% of the REM material is lost in the indirect recycling routes applied to EOL NdFeB material from other applications (Bast et al., 2015; Sprecher et al., 2014b), starting from the point at which the magnets have been extracted from the appliances. The distinction between alternative waste treatment routes (other than NdFeB recycling routes) is not of interest for this study. Post-consumer magnets are expected to become available and to be recycled in the year the appliance reaches EOL, i.e. stockpiling of EOL material is not considered.

The data quality differed between application groups. A bottom-up calculation was not possible for all application groups – see supporting information for details.

Quantities of secondary REM supply were estimated in a top-down approach, assuming that 20% of input material in magnet production becomes scrap not suitable for direct internal recycling. The composition of the scrap is in accordance with that of the production mix in the respective year. The efficiency of REM extraction Eq. (5) is estimated at 60%.

4. Scenario results

4.1. Demand for NdFeB magnets and derived REE demand

NdFeB demand for magnets used in different application groups was calculated, based on the key assumptions set out in 3.2. According to the scenario results, the overall demand for NdFeB could increase by factor 3 (low NdFeB demand scenario) to 6 (high NdFeB demand scenario) from current (2015) levels to 2030, from around 80–112 kt in 2015–240-633kt in 2030 for the low and high NdFeB demand scenario, respectively (Fig. 3). Motors for use in small automotive and industrial applications remain the most important group in terms of absolute NdFeB volumes. The demand for NdFeB in wind generators is expected to increase until 2030, both in terms of relative importance and in absolute volumes. Furthermore, the demand for NdFeB in electric two-wheelers, air conditioners, hybrid and electric vehicles and magnetic separators is expected to grow in absolute terms; NdFeB use for MRI and HDD is stable or declining, generators stable or slowly increasing, acoustic transducers increasing or slowly decreasing.

REM demand for use in NdFeB magnets has been derived from the composition of the NdFeB material and tonnes demanded, with a percentage added to account for REM losses during NdFeB production. For both the high and the low NdFeB demand scenario, HREM demand for use in NdFeB magnets is growing slower than the demand for NdFeB and contained LREM, and LREM demand for use in NdFeB grows slightly faster than NdFeB demand. Our assumption regarding the level of HREM reduction in the magnets was more optimistic for the high NdFeB demand scenario. As a consequence, the estimates for HREM demand do not differ as much
between the two scenarios as our LREM estimates. According to our scenario assumptions, around 7–11 kt of HREE and 86–234 kt of LREM will be required for NdFeB production in 2030. Detailed figures for NdFeB and derived REM demand can be found in the supporting information.

### 4.2. Recycling potentials from EOL magnets, global scope, low and high NdFeB demand scenario, and derived REE supply

The estimated net availability of secondary NdFeB supply from EOL magnets in years 2020–2030 is shown in Fig. 3. The underlying data can be found in the supporting information. Material losses expected to occur from the collection and disassembly stages have been deducted from the gross supply figures of magnets from EOL appliances. Net potentials for secondary HREM and LREM production were then calculated, based on the average composition of the net EOL NdFeB material arising in the respective year (Fig. 4, Fig. 5). REM losses expected during the recycling process have been deducted.

Currently, (2015 estimates) electric two-wheelers, acoustic transducers, magnetic separators, HDD and ‘other motors’ (see 3.1.10) constitute interesting sources of NdFeB material from EOL appliances in terms of global recycling potentials expected. The percentage contribution of magnets from “other motors” roughly doubles in both scenarios between 2015 and 2020. Air conditioners could constitute an important source, but with larger differences between the two scenarios. By 2030, “other motors” (see 3.1.10), traction motors from hybrid and electric vehicles and electric two-wheelers are likely to dominate as potential sources for EOL NdFeB magnets, in different orders of importance for the low and the high NdFeB demand scenario. Compressor motors from air conditioners and separators constitute other potentially interesting sources of post-consumer NdFeB.

### Table 2
Industrial processing waste not suitable for direct (material) recycling route.

<table>
<thead>
<tr>
<th>Scrap estimates—wet scrap suitable for indirect recycling routes</th>
<th>2020</th>
<th>2025</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>kt NdFeB—low demand scenario</td>
<td>28</td>
<td>40</td>
<td>60</td>
</tr>
<tr>
<td>kt NdFeB—high demand scenario</td>
<td>45</td>
<td>88</td>
<td>158</td>
</tr>
</tbody>
</table>

The supply for LREM from EOL magnets follows a similar trend to that of NdFeB material in general. For HREM, electric two-wheelers, separators, other motors and air conditioners are important post-consumer sources in the near future. By 2030, (H)EVs, electric two-wheelers and other motors are most significant. The supply quantities are subject to HREM content reduction assumptions made for the demand scenarios.

### 4.3. Recycling potentials from pre-consumer magnet scrap

Recycling potentials from pre-consumer scrap for indirect recycling routes were derived from overall NdFeB production figures, assuming that 20% of starting alloy for magnet production becomes scrap destined for the indirect recycling route (same assumption as in Section 3.2), (Table 2). The clean processing waste suitable for direct recycling is not included in these estimates; we assume that this fraction is processed in a direct internal recycling route. Indirect recycling of processing scrap is already being practiced, but details on the recycling processes are not available.

### 4.4. Overall potential of secondary REM to meet REM demand for NdFeB

We provide estimates for the percentages of the LREM and HREM supply mixes for use in NdFeB production which can be met by secondary sources in years 2020, 2025 and 2030, according
Fig. 4. LREE demand for use in NdFeB magnets (gross demand, including expected losses during magnet production), and potential LREE supply from recycled EOL magnets, low and high NdFeB demand scenario, years 2020-30, tonnes REM (sum Pr and Nd).

to scenario assumptions made in this study (Fig. 6). The modelled scenarios show that 18–22 percent of global light (Nd and Pr) and 20–23 percent of heavy (Dy and Tb) REE demand for use in NdFeB magnet production can be met by supply from secondary sources from end-of-life magnets and industrial scrap in years 2020, 25 and 30 (range of RIR values for individual years and scenarios). Results show a decline in the relative contribution of secondary REM to the potential LREM supply mix, and a small increase for HREM.
The overall decline in the percentage LREM supply from secondary sources is due to the declining relative contribution from EOL magnets. It shows that according to our scenario estimates, the demand for LREM used in NdFeB magnets grows faster than the LREM supply from EOL magnets. For LREM, the rate of the decline differs between the low and the high NdFeB scenario. For HREM, there are only small differences between the low and the high NdFeB demand scenarios in this percentage contribution trend, due to the mitigating effect of faster HREM reduction assumed for the high NdFeB demand scenario.

According to our estimates, the supply potential for LREM from EOL magnets is lower than the potential of LREM from wet processing scrap. The gap widens due to the assumed high annual growth rates of LREM for use in NdFeB magnets. The supply potential for HREM from EOL magnets is of similar magnitude as the potential from the processing waste in years 2020–30, as a result of the HREM content reduction efforts.

5. Discussion and conclusions

The modelled scenarios show that between 18 and 22 percent of global light (Nd and Pr) and 20–23 percent of heavy (Dy and Tb) REE demand for use in NdFeB magnet production can be met by supply from secondary sources from end-of-life magnets and industrial scrap in years 2020, 25 and 30 (range of RIR values for individual years and scenarios), a significant potential from a resource conservation and environmental impact point of view. The fraction of HREM demand which can be met by secondary sources is increasing over time in both scenarios. The results also indicate that the importance of different EOL NdFeB applications changes over the time period considered, resulting in a changing mix of components to be handled by disassemblers, and a variability of the magnet material input to be handled in NdFeB recycling processes. Estimates for absolute volumes of HREM available for recycling are lower if the ongoing HREM reduction efforts are considered in the quantification of recycling potentials, with a time delay in the order of magnitude of the weighted average product lifetime. Lower demand growth rates for HREM also mean that a larger percentage of the HREM demand can come from secondary sources over time. Substitution efforts can help reduce the criticality of heavy REEs as recycling can, but substitution and recycling are also competing strategies, since the alleviated supply shortage achieved by reduction or substitution can make recycling less economically viable, and vice versa. Despite that, it has been suggested that recycling and dysprosium reduction make good complementing strategies to avoid dysprosium supply shortages (Seo and Morimoto, 2014). Substitution and REE reduction efforts could help stabilize the market for REE used in NdFeB magnets, which would facilitate planning for NdFeB recyclers.

The “European Rare Earths Competency Network” (ERECON) put together list of priority products for which NdFeB recycling is most likely to become economically viable—see ERECON (2015). The list includes HDD, automotive applications, motors in industrial applications, acoustic transducers, air conditioners, mixed electronics, electric bikes and wind turbines. In terms of global EOL magnets available for recycling quantified in this study for 2015 and 2020, electric two-wheelers and magnetic separators should appear higher up on this list; however, the differences could be explained by the European focus of the ERECON network, since at least for electric two-wheelers, the majority of EOL products arises outside Europe.
Scenario estimates of future NdFeB demand are inherently uncertain, but the uncertainties are further enhanced by the speed of market developments at both magnet material and component levels (motors, generators) and the diversity of applications. Uncertainties associated with data quality issues regarding REE content in EOL applications/magnets have previously been highlighted (Chancerel et al., 2015; Guyonnet et al., 2015). We found that different levels of details of qualitative information and data quality were available for different application groups, depending on the information which could be obtained from the literature or from communication with industry representatives. For example, historical production data was not available for some application groups and had to be estimated, but the figures were required to estimate recycling potentials. Losses during collection, disassembly and recycling were assumed for each application group, but were kept constant during the time period considered for simplification. In reality, the overall material recovery rates are currently low, but could increase over time as collection and recycling schemes are being established. The result should be interpreted as an estimate of what could be feasible from 2020 onwards.

The global focus of this study meant that issues related to the practical implementation of recycling, such as the level of (de-)centralization required for NdFeB recycling of global scrap quantities, were not addressed. A local quantification of REE recycling potentials from NdFeB would be suited to address the potential of recycling to alleviate the supply risks of individual REEs, which are not a uniform global issue. It has been suggested that the recycling of EOL NdFeB magnet material arising in Europe could meet the demand of the local magnet producers (ERECON, 2015). The results of this study can serve as a starting point for more detailed investigations, if particular application groups or the secondary REE potentials obtainable in a specific country or region are investigated.

The quantification of REE recycling potentials was undertaken against the background of environmental impacts associated with REE production, and supply risks outside China, yet with a global perspective. Since most NdFeB magnet production happens in China, it would be interesting and relevant to see if substitution, rare-earth magnet free technology alternatives and REE recycling efforts driven by policy makers and industry outside China will find followers within China, if for reasons other than supply risk alleviation. This would help improve global HREE demand projections. Furthermore, the Chinese market drives demand for many NdFeB applications (electric two-wheelers, rare-earth compressor motors for air conditioners, wind turbines…), so both EOL magnets and production scrap are likely to arise in China in large quantities. Recycling collaborations with China should therefore be investigated when following a sustainable resource strategy for REEs with maximized global impact.

Due to current low rare earth prices, economic incentives to introduce recycling schemes for NdFeB magnets are low, and incentives need to be created if recycling potentials are to be utilized. Labour costs pose a challenge, at least in high-income countries – see also (Habib et al., 2015). Economic incentives for recycling have been recommended to attain economic viability of REE recycling processes (see e.g. Chancerel et al. (2015)), and government subsidies have been used to kick-start REE recycling from NdFeB magnets in Japan. Alternatively, critical metal recycling could be incentivised by regulatory policy. Currently, policies for handling of electronic waste and end-of-life vehicles focus on recycling targets by mass and do not provide specific incentives for the extraction of magnet material containing critical metals such as REEs, which only make up a small fraction of the product weight. Competition between recyclers of individual material streams has been raised as an issue for EOL NdFeB collection, with implications for quantities available for recycling, and should be investigated further.

To complement the initially low quantities of EOL magnets, the use of industrial scrap as a feedstock to the same process has been suggested (Bast et al., 2015). Our findings support this view: Global supply of secondary NdFeB material from pre-consumer sources is likely to exceed the potential supply from EOL magnets in the time period considered. Its utilization could help recyclers reduce the risk of not obtaining enough input material for recycling. The scenario results illustrate a dynamic market, a large variety of NdFeB containing products reaching EOL, and a changing composition of NdFeB manufacturing scrap and EOL magnets, expected due to different demand growth rates of different magnet application groups, and changes to the engineering of the magnet materials. This suggests that a focus on recycling processes which are capable of handling changing input compositions could be a beneficial future strategy.

Despite economic challenges, extraction of REE from NdFeB magnets offers many benefits. REE recycling is beneficial over primary REE production from an environmental and resource conservation perspective (Schüler et al., 2011; Sprecher et al., 2014b; Walachowicz et al., 2014). Recycling as a supply risk mitigation strategy is associated with lower investment cost than the establishment of new mines, and the decentralized “urban mine” offers some flexibility. Despite the challenges associated with the compositional variation of the magnets, the REE composition of the EOL magnets/industrial processing scrap is closer to the desired REE ratio required in the production of new magnets than the ores, which allows for more efficient, shorter processing, beneficial from both an environmental and an economic perspective.

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This paper is dedicated to Dr. Wolfgang Jenseit (1958–2015).

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.resconrec.2016.05.004.

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