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Recycling and its effects on joint production systems and the environment – the case of rare earth magnet recycling – Part I — Production model

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ABSTRACT

The primary production of rare earth elements (REE) used in neodymium-iron-boron (Nd-Fe-B) magnets is associated with environmental impacts from both mining and processing. It has been suggested that recycling of scrap Nd-Fe-B magnets would reduce primary production of REE, and thus environmental impacts. However, existing studies on environmental effects of recycling based on the methodology of Life Cycle Assessment (LCA) do not take into account the so-called balance problem, which accounts for the fact that all elements co-occuring in the ore are jointly produced, resulting in either an excess or a shortage of individual elements. We develop a two-part approach to incorporate this issue into LCA. In the first part, we investigate the effects of introducing large-scale Nd-Fe-B recycling to the global rare earth market. A production model is presented that quantifies the potential market effects of secondary production (recycling) on the balance problem. Results show that primary production could partly be avoided when introducing a secondary production route to the rare earth market, whilst still meeting demand for joint (non-magnet) REE, only produced from the primary route. The production model will be used for a consequential life cycle assessment study which will be published as a separate paper (Part II). In addition, we show that our approach may also be interesting for other LCA studies, where effects of market changes on a co-production system are investigated.

1. Introduction to study objectives

1.1. Background to this case study

To date, rare earth elements (REE, i.e. Lanthanum to Lutetium plus Yttrium) are predominantly produced through primary mining and processing. Like other metals, rare earth elements (REE) generally occur in low concentrations in the ore, and large quantities of ore need to be processed per ton of REE extracted. In addition, in some deposits, REE are mined together with other metals that co-occur in the ore, e.g. iron. The primary production of REE is associated with environmental and social impacts (Schüler et al., 2011; Sprecher et al., 2014; Wulf et al., 2017). Ionizing radiation is often associated with rare earth mining and has to be adequately managed (ERECON, 2015; Schmidt, 2015, 2016). Furthermore, mining areas are affected by process emissions, deposition of tailings and land degradation. After extraction, REE then need to be brought into a concentrated and chemically accessible form and separated in an elaborate process, due to their chemical similarity.

In recent years, efforts are being made to develop recycling processes for some REE. Notably, processes for the recycling of rare earths contained in scrap Nd-Fe-B magnets (usually neodymium (Nd), praseodymium (Pr), dysprosium (Dy) and sometimes terbium (Tb)) are under development (Demeter, 2017; EREAN, 2015; Hitachi, 2014; Rare3, 2017; Walton et al., 2015; Yang et al., 2016; Zakotnik et al., 2009).[1] The production of these magnets is increasing due to their role in efficient motors and generators. Based on this market growth, the criticality of the REE contained in the magnets, the potential for economic viability of the recycling processes, and other factors, scrap Nd-Fe-B magnets have been identified as a priority material for REE recycling in Europe (ERECON, 2015). The provision of rare earths (Nd, Pr, Dy and Tb) through the recycling of Nd-Fe-B magnet material has already been shown to be beneficial from an environmental point of view. Life Cycle Assessment (LCA) studies found that process-specific impacts compared per metric ton of 'magnet REE' are lower from both direct and indirect recycling routes compared to primary production (direct recycling refers to Nd-Fe-B material recycling and indirect

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[1] Recycling processes for other rare-earth containing products, including batteries and phosphors, have also been developed ERECON (2015); Ruiz-Mercado et al. (2017).

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recycling to REE extraction from Nd-Fe-B material[2]) (Jin et al., 2016; Sprecher et al., 2014; Walachowicz et al., 2014).

In addition, the recycling of neodymium and dysprosium has been suggested as a strategy to overcome the so-called “balance problem”, a term used to describe the imbalance of demand and supply for some REE inherent to the current production system (Binnemans et al., 2013b; Binnemans et al., 2013a; Binnemans and Jones, 2015; ERECON, 2015; Falconnet, 1985). REE are produced according to the ratio at which they occur in the mined ore. The provision of some of those REE that determine production quantities through an alternative secondary route (recycling) could reduce excess production for those elements produced in oversupply, and lower overall production volumes. By bringing the supply mix more in line with the demand mix for individual REE, the efficiency of the global REE production system could be improved, and less storage of unintentionally overproduced elements would be required. Supply chains which use raw materials efficiently are less vulnerable to potential price fluctuations, and therefore more competitive (Witteveen and Klein, 2015). While also substitution of those REE for which potential supply shortages are anticipated, a diversification of deposits, or the development of new applications for overproduced REE have been suggested as possible strategies to overcome the balance problem (Binnemans and Jones, 2015; Jones, 2017b), this paper focusses on the recycling of REE from Nd-Fe-B magnets.

The balance problem was initially discussed as an issue for light rare earth elements (LREE; Lanthanum to Samarium) (Binnemans et al., 2013a,b), where the supply ratio for individual REE does not match the demand ratio. For heavy rare earth elements (HREE) (Europium to Lutetium plus Yttrium), supply has only recently equaled demand for dysprosium, europium, yttrium and erbium, according to the European Commission (EC) (EC, 2014). The market for heavy rare earths, however, has been changing in recent years because REE are losing their importance in lighting applications (Binnemans and Jones, 2015), while global REE demand for use in Nd-Fe-B magnets is growing rapidly (Du and Graedel, 2013; Habib et al., 2014; Rademaker et al., 2013; Schulze and Buchert, 2016; Sprecher, 2016; Zepf, 2015). According to a recent market forecast, the REE market imbalance is expected to worsen in years to come due to the increasing NdFeB demand (Castilloux, 2017) − hence, the issue is highly topical. Furthermore, market imbalances are not unique to rare earths: Co-production and by-production of metals and market imbalances are common in other metal markets (Gauß et al., 2016; Nuss et al., 2014; Reuter, 2005; USGS, 2010).

1.2. Brief summary of findings from a previously conducted material flow analysis study

Whilst progress has been made in recent years regarding the recycling of industrial Nd-Fe-B scrap, recycling of end-of-life magnet scrap is still a negligible production route for REE to date (ERECON, 2015; Jones, 2017a; Sprecher et al., 2017). Low REE prices and, especially for some REE used in magnets, long use phases, are seen as two key barriers to implementing recycling (Jones, 2017a,b). To answer the question what could be feasible if recycling was politically incentivized, a recent study by Schulze and Buchert (2016) quantified global REE recycling potentials from end-of-life magnets from eleven different Nd-Fe-B application groups and industrial scrap through dynamic material flow analysis. Data on past, current, and predicted future production volumes for Nd-Fe-B magnets in different applications were collected through a detailed review of the literature, and complemented by expert estimations from industry representatives. Typical weights and compositions of Nd-Fe-B magnets in different applications were considered, as well as industry efforts to improve the magnet compositions and microstructure. To give an example, the recent HREE reduction efforts for magnets used in motors were taken into account in the scenario estimations. Factors influencing the ease of collection, disassembly of the appliances, extraction of the magnets from the components, etc. were considered to derive estimates for potential recycling rates for magnets from the different Nd-Fe-B application groups. Process efficiency data was adopted from previous LCA studies to estimate the material losses during the recycling process. Recycling potentials achievable for REE used in Nd-Fe-B 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 both historic Nd-Fe-B demand figures and future demand development. The most important Nd-Fe-B application groups in terms of recycling potentials were identified. According to the scenario results, globally, between 18 and 22 percent of light REE (Nd and Pr) and 20–23 percent of heavy REE (Dy and Tb) demand for use in Nd-Fe-B magnet production could be met by supply from secondary sources from end-of-life magnets and industrial scrap in years 2020, 25 and 30.

1.3. Aims and objectives of this study, relation to other work

The mitigation of the balance problem has been predominantly presented as an opportunity for economic benefit, but there are also potential environmental implications (Binnemans et al., 2013b; Binnemans and Jones, 2015). Elshkaki and Graedel (2014) have highlighted the need to take into account the issue of overproduction when analyzing environmental impacts of REE production. However, as has been pointed out before, existing LCA studies on scrap Nd-Fe-B recycling have focused on impacts associated directly with the recycling process chains (Jin et al., 2016; Sprecher et al., 2014; Walachowicz et al., 2014). The authors of those recent attributional LCA studies applied economic or mass allocation to divide the impact of primary rare earth production between individual elements. Economic allocation distributes the impact amongst the joint products, based on market value and output ratio, but does not take market dynamics into account.

One study used the avoided burden method; i.e. impacts of the recycling process were analyzed, and credits given for the avoided primary production of those elements (Walachowicz et al., 2014). The credits correspond to a share of the impact from the primary production system, determined either by mass or value. However, due to the joint occurrence of REE in the ores, it is generally not possible in practice to partially avoid the production for some REE and not for others. In other words, REE primary production is generally a joint production situation, which means that the co-products cannot be varied independently in terms of output quantity (Weidema et al., 2013). This is true for most processing stages in the REE supply chain, whose output contains a mix of REE. Hence, replacing some of the primary production mix by secondary production would have an impact on joint REE. However, there are some exceptions: in solvent extraction, the last separation stages between individual REE can be omitted and semi-finished products temporarily stored, if supply exceeds demand for selected output groups − (see Schulze et al., 2017).

Thus, we developed a novel approach to incorporate the possible market effects of recycling on the 'balance problem' into LCA. Our approach is based on the methodology of consequential LCA (CLCA) which generally is employed to assess the possible effects of a decision on the flows of a system (Finnveden et al., 2009). CLCA studies do so by taking into account market dynamics, i.e. changes which are likely to occur as a consequence of a decision, but may be outside the system being studied (see e.g. Zamagni et al., 2012). The introduction of a recycling scheme is expected to mitigate the balance problem by reducing the oversupply of some rare earths (Binnemans and Jones, 2015), so changes in market dynamics are foreseen and intended. Hence, a consequential modelling approach is appropriate to assess the environmental effects of NdFeB recycling in light of its expected effects on the balance problem (Binnemans et al., 2013b; Jones, 2017a).

[2] A detailed review of direct and indirect recycling processes is given in two review papers Binnemans et al. (2013a), Yang et al. (2016).