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Materials flow analysis of neodymium, status of rare earth metal in the Republic of Korea

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ABSTRACT

Materials flow analysis of neodymium, status of rare earth elements (REEs) in the Republic of Korea has been investigated. Information from various resources like the Korean Ministry of Environment, Korea international trade association, United Nations Commodity Trade Statistics Database and from individual industry were collected and analyzed for materials flow analysis of neodymium. Demand of neodymium in the Republic of Korea for the year 2010 was 409.5 tons out of which the majority of neodymium, i.e., 68.41% was consumed by domestic electronics industry followed by medical appliances manufacturing (13.36%). The Republic Korea is one of the biggest consumer and leading exporter of these industrial products, absolutely depends on import of neodymium, as the country is lacking natural resources. The Republic of Korea has imported 325.9 tons of neodymium permanent magnet and 79.5 tons of neodymium containing equipment parts mainly for electronics, medical appliances, and heavy/light vehicles manufacturing industry. Out of which 95.4 tons of neodymium permanent magnet get exported as an intermediate product and 140.6 tons of neodymium in the form of consumable products get exported. Worldwide the neodymium is at the high end of supply chain critical metal because of increasing demand, scarcity and irreplaceable for technological application. To bring back the neodymium to supply stream the recycling of end of life neodymium-bearing waste can be a feasible option. Out of total domestic consumption, only 21.9 tons of neodymium have been collected and subsequently recycled. From material flow analysis, the requirement for an efficient recycling system and element-wise material flow management for these REEs in the Republic of Korea were realized and recommended.

1. Introduction

The Republic of Korea is totally depending on import for compounds or composites of rare earth elements (REEs). The domestic mining sector is not a significant contributor to the country's economic development, accounting for only a 0.2% of national GDP in 2012 (Korea, 2013; Shi, 2014). Whereas the value added product manufactured for worldwide exports from these imported compounds or composites of REEs has indispensable importance for the development of the industrial economy of the Republic of Korea. Lanthanides, yttrium, and scandium are commonly referred as REE, are vital commodities for various Korean industries like electronics and electrical equipment, heavy/light vehicle manufacturing, green energy production, battery, industrial catalyst, semi-conductor, alloy and abrasives. Because of unique physical and chemical properties of REE, and rare earth oxides (REO) have a wide range of hi-tech functional applications such as fluorescent materials, permanent magnets, superconductors, lasers, ceramics, semiconductors, catalysts, thermal neutron absorbents, abrasives, additives, semiconductor doping (Swain and Otu, 2011a, 2011b). Among REEs, neodymium (Nd) is a core element for various functional applications like a Nd permanent magnet, Nd-alloy, battery, rare earth catalyst, automotive catalyst, and semiconductor (Du and Graedel, 2011a). Mostly for these functions, intermediate products like rare earth permanent magnet (REPM), liquid crystal display (LCD), virtual channel memory (VCM), optical devices, audio devices, multi-layer ceramic capacitor (MLCC) and motors are manufactured. These intermediate products are technologically integrated manufacturing final products such as light/heavy (hybrid) electric vehicles, electronics and electrical devices, medical equipment, general machinery, and wind turbines. Basically Nd alloy along with minor contents of REE is used for various important applications, such as permanent magnet for wind-energy generation, heavy/light green-hybrid vehicle,

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electrical storage device (battery), electronics storage devices (hard drive), notepad/laptop/computer hard drive, mobile telephones, medical devices, scientific instruments (Peiró et al., 2011, 2013). The Nd has also other strategic important applications, like defense operating devices, jet fighter engines, missile guidance systems, antimissile for defense, and space applications like satellites-communication systems. The unique performance, strategic importance, limited resources, irreplaceable by other materials/metals, ever growing consumers' demand and potential to substantially increase in the future demands for REEs, trigger global competitions. China had monopolized more than 95% of REE supply (Stone, 2009; The U.S. Environmental Protection Agency, 2012) during several years. A recent report from USGS reported China continued to dominate REE supply, accounting for more than 90% of global mine production in 2012 (Gambogi, 2015).

The Nd is the core elements for high-performance permanent magnets, and these permanent magnets account for approximately 38% of the REE market by value and 21% by volume. REPMs' global demands expected to increases 43,000 tons (23%) if REE alloy included, the Nd demand estimated to reach 49% by 2015 (The British Geological Survey, 2011). Shaw et al. reported 86% of Nd was used for REPM worldwide in the year 2012. Demand for REPM estimated at 25.5 kt for the year 2012, whereas NdFeB magnet accounts for 98%. Over the next 7 years (following years 2012) demand for NdFeB magnets is forecasted to increase 9% per year. Even the same report represents after 2016 the world REPM market may grow at an accelerated rate beyond 9% (Shaw and Chegwidden, 2012). Almost all leading agencies of the world, like the US National Academy of Sciences (NAS), the European Commission, the US Department of Energy (DOE) and the American physical society and materials research society considered the Nd as a very critical metal in the supply chain for all terms, i.e., short, medium and long term (Bauer et al., 2010; Eggert et al., 2008; Hatch, 2011; Jaffe et al., 2011; Michel, 2010; Shaw and Chegwidden, 2012). Du et al. have investigated global rare earth in-use stocks in NdFeB permanent magnets and global in-use stocks of the REEs, and recommended for efficient recycling of these important industrial metals (Du and Graedel, 2011a, 2011c). Guyonnet et al. have studied material flow analysis of REE in the Europe (Guyonnet et al., 2015). Material flow analysis of Nd REPM Magnets for Denmark has been studied by Habib et al. (2014). All reports above have a common recommendation, i.e. development of recycling mechanism and technology of REE is absolutely essential to bring back consumed REE to MF stream.

As the Nd is a very important metal for clean energy, low CO_2 footprint, critical metal in supply chain and at the high end of scarcity, understanding of material flow is very important. To keep industrial growth in a competitive edge, securing a steady-stable supply of REE and the Nd is the utmost important for the Republic of Korea. To handle supply–demand vulnerability, the import–export economy, fate of end-of-life (EOL) consumer products, and to support environmental regulations, the material flow of the Nd must be understood. The information on supply–demand, material recycling and resources management are very limited and unorganized in the Republic of Korea for REEs and Nd. To organize all this information, material flow analyses (MFAs) and substance flow analyses (SFAs) are performed for the ministry of knowledge, economy, universities and research institutes, the Republic of Korea.

The MFA/SFA is a major, most accurate and internationally acknowledged research tool for identifying and controlling materials/substance flows (Habuer et al., 2014; Lau et al., 2013; Sommer et al., 2015; Steubing et al., 2010; Tasaki et al., 2004; Yoshida et al., 2009). Globally, the material flow chain of REE includes six stages; i.e. (i) mining, (ii) separation of REO, (iii) metal refining, (iv) preparation of intermediate and final products, (v) collecting the EOL products and (vi) recovery of REEs from REE-bearing waste (Humphries, 2012; Jung et al., 2006; Schüler et al., 2011). Neither mining resources exist, nor recycling technology ever been developed for REEs in the Republic of Korea, hence, these two categories are eliminated from our MFA. In our current investigation, MFA for the Nd has been analyzed. The purpose of this study is to identify the relevant issues for developing an efficient recycling system for Nd and REEs, to understand supply–demand, export–import scenario of the Nd used in Korean manufacturing industries, through an SFA/MFA. For this purpose, the MFA has been carried out to perform the detailed mapping of flows of Nd in the Republic of Korea. A novel element of this study is that, to the traditionally practiced MFAs at national and/or global levels is complemented with a comprehensive sampling and an element wise analysis of Nd, taken from the sample out of 403 classifications and 53 industries.

2. Material flow analysis method and data

2.1. Material flow analysis methodology

The flow diagram in Fig. 1 shows the strategic method applied to data collection in various stages for MFA of the Nd. Essentially the MFA analysis for the Nd is divided two categories, i.e. (I) first, the material flow of raw materials to final product (consumer goods) through intermediate products, and (II) second, the material flow of EOL products to waste disposal and possible recycling. As shown in Fig. 1, for the first category the MFA was investigated as follows: (a) raw materials export, import and their domestic uses, (b) primarily processed, their import, export and domestic uses, (c) identification of intermediate product, their import, export and domestic uses, and (d) final consumer product export, import and domestic use, were categorically analyzed. For the second category, MFA was investigated for waste flow through the following stages: (a) collection of waste, (b) recycling of waste and (c) disposal of waste. Finally, the critical concerns for resources, environment, and recycling were identified.

For a detailed understanding of the MFA, (i) procurement, manufacturing, and production chain, and (ii) various individuals, industries, and entities associated with Nd were surveyed in the year 2010. Field survey, online survey, and direct telephone inquiry methods were adopted for the data collection from the manufacturers, entities, institutes and universities. Quantities of the Nd which are used for various industries like electrical storage (battery) industry, electronics industry, audio equipment industry, optical equipment industry, MLCC, ceramic, alloy and catalyst were surveyed for MFA. Consumption, collection of scraps, recycling, and disposal was tracked to understand MFA of the Nd. Simultaneously a look on REE recycling was considered and reviewed. Based on the guidelines of Republic of Korea national resources management system, bottom-up estimation was used to assess intermediate products for MFA. If bottom-up estimation was inappropriate, MFA, were analyzed by input–output (IO) analysis of intermediate. The export–import and supply–demand pairs of the intermediate products were comprehensively investigated. Lastly, the input of secondary flow of raw materials to produce intermediate products were assessed along with an estimation of REE contents in the intermediate products (Peiró et al., 2011, 2013). To estimate the Nd bearing waste being generated, extensive data collected from the existing waste disposal units, waste collectors, and statistical data of the Korean Ministry of Environment. Secondary material flow for reuse of pre-used intermediate products or pre-owned final products were also examined. Material flow for post-collection and recycling (including refining process to