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Uncovering the end uses of the rare earth elements

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HIGHLIGHTS

- We have derived the first quantitative end use information of the rare earths (REE).
- The results are for individual REE from 1995 to 2007.
- The end uses of REE in China, Japan, and the US changed dramatically in quantities and structure.
- This information can provide solid foundation for decision and strategy making.

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ABSTRACT

The rare earth elements (REE) are a group of fifteen elements with unique properties that make them indispensable for a wide variety of emerging and conventional established technologies. However, quantitative knowledge of REE remains sparse, despite the current heightened interest in future availability of the resources. Mining is heavily concentrated in China, whose monopoly position and potential restriction of exports render primary supply vulnerable to short term disruption. We have drawn upon the published literature and unpublished materials in different languages to derive the first quantitative annual domestic production by end use of individual rare earth elements from 1995 to 2007. The information is illustrated in Sankey diagrams for the years 1995 and 2007. Other years are available in the supporting information. Comparing 1995 and 2007, the production of the rare earth elements in China, Japan, and the US changed dramatically in quantities and structure. The information can provide a solid foundation for industries, academic institutions and governments to make decisions and develop strategies.

1. Introduction

The rare earth elements (REE) are a group of metals comprised of yttrium and fourteen lanthanide elements: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu). Promethium is absent from REE ores and generally excluded because all of its isotopes are radioactive with short half-lives. The REE are important in a growing number of critical technologies due to their unique physical and chemical properties. For example, neodymium and dysprosium are vital to high-performance permanent magnets, and yttrium is a promising raw material for superconductors and laser technology (Angerer et al., 2009). When these intermediate products are incorporated in final products such as wind turbines, hybrid electric vehicles, or defense applications, REE provide performance that is currently irreplaceable by other materials (Stone, 2009), at least without some decrease in performance. As modern technological innovations drive an increase in demand of the REE, these potential critical materials require special attention from the perspective of future availability and sustainability.

China has played a dominant role in REE mining and production for the past two decades; other countries such as Japan and the US are almost completely dependent upon imports from China with respect to REE resources. China also has been increasing REE consumption in its domestic manufacturing industries, an activity that has the potential to decrease exports to the rest of world. Because very little mining and production activities are ongoing outside China, some countries are gradually losing the capability of mining and processing these ores and of manufacturing REE products. A gap in the supply chain has thereby been created due to their diminished domestic manufacturing infrastructure, especially at the critical early life stages. For example, there is no facility producing NdFeB permanent magnet powders in the US, and Europe constituted only 2% of 2007 global production compared to 76% in China and 19% in Japan (Liu and Xie, 2008). The potential conflict between domestic consumption surpassing production in China, rapid increases in global REE demand, and difficulty in opening new mines and achieving permits come together to make future REE supply questionable for the global market, at least in the short term (Stone, 2009; Bradsher, 2009).

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REE resource issues have been drawing a great amount of attention, but the quantitative information is still sparse. To address this issue, we assembled and generated the end use information that provides the first quantitative view of REE end uses in the various application sectors during the past 13 years.

2. Methods

To estimate the end uses of individual REE in China, Japan, and the US, we collected information on average REE content distribution in the end uses, the annual percentage breakdown of the end uses in China, Japan, and the US, and the mass of the total end uses in China, Japan, and the US for the past 13 years. We derive the quantitative end use information by the equation:

$$\left(U_{i,j,k,l}\right) = \left(C_{i,j}\right) \times \left(P_{j,k,l}\right) \times M_{k,l}$$

where $U_{i,j,k,l}$ is the end use by weight in Gigagrams (Gg) for element *i* in end use *j* in country *k* in year *l*; $C_{i,j}$ is the REE *i* content in end use *j*, $P_{j,k,l}$ is the fraction of end use *j* by percentage in country *k* in year *l*, and $M_{k,l}$ is the total end use weight in Gg in country *k* in year *l*. For example, the Chinese end use of Nd by weight in magnets $U_{\text{Nd, magnet, china, 2007}}$, was derived by multiplying the magnet Nd content in magnets of 69.4% ($C_{\text{Nd, magnet}}$), the magnet percentage among all the end uses of 27.6% ($P_{\text{magnet, China, 2007}}$), and total end use of 62.1 Gg ($M_{\text{China, 2007}}$).

The approach involves ten major end use sectors: magnets, nickel metal hydride battery alloys, metallurgical additives and alloys (except battery alloys), automobile catalysts, fluid cracking catalysts (FCC), polishing powders, glass additives, phosphors, ceramics, and others (Lynas Corporation, 2010). The calculation is complicated by the fact that a number of product applications utilize more than one of the REE. For example, permanent magnets typically contain Nd, Pr, Dy, Gd and Tb in proportions of ~70%, ~25%, 5%, 2% and 0.2% (Lynas Corporation, 2010). Because the US, Japan, and China are the three major consumers in the rare earth market (constituting some 90% of world demand in 2006) (Liu and Xie, 2008) we present the end use structure of these three countries.

This paper presents the first comprehensive quantification of the uses of REE, comparing them over time and with the industrial end uses for the three countries that constitute most global REE production and use.

The information of average REE content distribution in the end uses is information provided by the Lynas Corporation (2010). The annual percentage breakdown of the end uses and the mass of the total end uses in the US, Japan and China are from the US Geological Survey (2004), the Japan Oil, Gas and Metals National Corporation (JOGMEC) (2007), the Metal Economics Research Institute in Japan (Metal Economics Research Institute, 2003), and the Chinese Society of Rare Earths (2008), as well as industry contacts. Relevant literature published in Chinese or Japanese was also extremely helpful. Together, these constitute the most comprehensive publicly available data and information on domestic end uses from the national institutes from China, Japan, and the US. There is no single source that provides data from all these countries or for all the end uses. We have verified the information by cross-checking if data of the production and end uses meet each other quantitatively in terms of the flows and stocks (Du and Graedel, 2011a, 2011b). The results show satisfactory data continuity and reliability. “Phantom flows,” i.e., cycle closing discrepancies, were shown to be small (Du and Graedel, 2011a).

3. Results

Drawing upon the available information, the end use distributions of the REE in 1995 and 2007 are illustrated at the right of Figs. 1 and 2. The countries in which those end uses occur appear at the left of the diagram, with the use sectors in the center. The years between 1995 and 2007 are not shown in the interest of brevity, but can be found in the Supplementary Information.

The total amount of the REE among all the end uses in three countries doubled as a whole from 40.2 Gg in 1995 to 83.5 Gg in 2007 as a

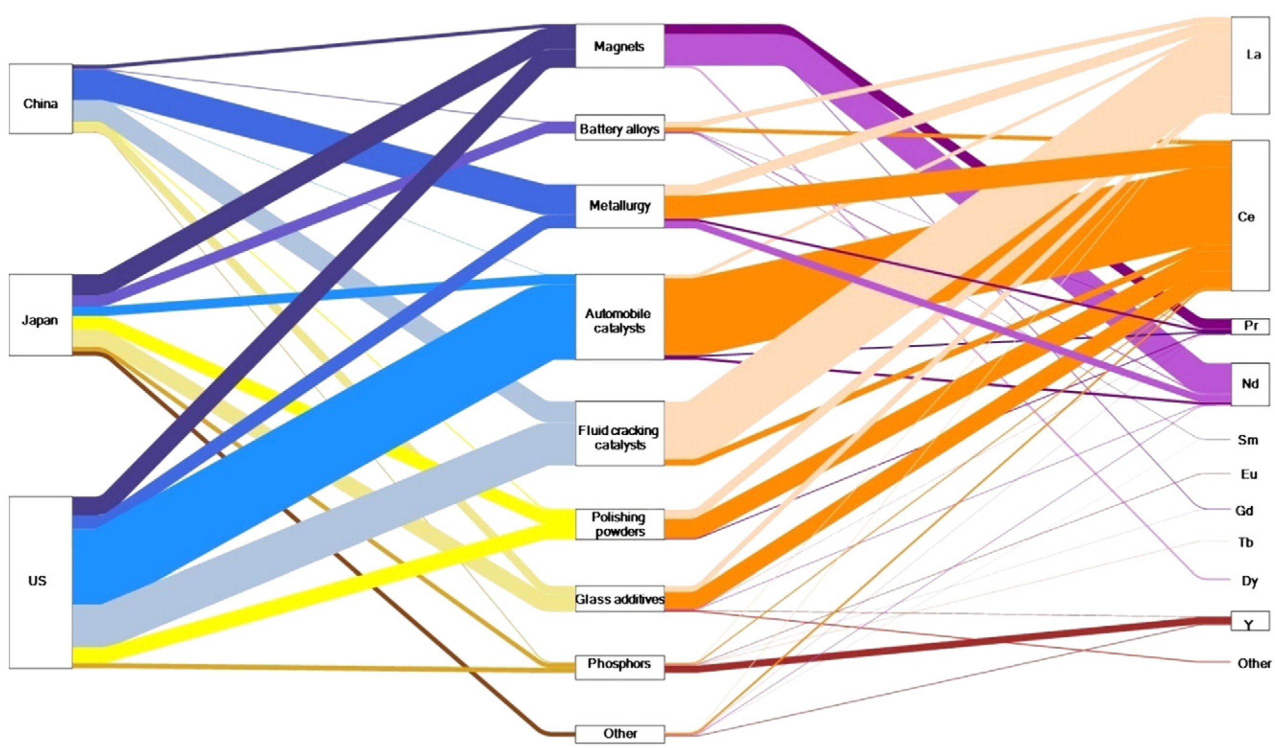

Fig. 1. The end uses of the rare earth elements in 1995. The total use of REE in that year was 40.2 Gg (for interpretation of the references to color in this figure legend, the reader is referred to the web version of the article).

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