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Rare earths supply chains: Current status, constraints and opportunities

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ABSTRACT

The unique properties of rare earth elements (REEs) and lack of alternatives for their application in modern technologies, especially electronics and fast growing green technologies such as renewable energy generation and storage, energy efficient lights, electric cars, and auto catalysts, as well as specific military and aerospace applications, underpin their strategic status.

The absolute domination of China in the production of REEs, aggravated by a significant reduction in export quotas since 2010, raised severe concerns of securing REE supply in the USA, Japan, European Union and other countries. In 2010–2012 it resulted in skyrocketing prices and supply deficit for most REEs, leading to numerous new REE start-up companies around the world, with allocation of large investments in additional geological explorations and technology development. At the same time, the supply difficulties enforced the downstream users of REEs to invest in the development of recycling technologies and reuse options for these elements.

The main focus of this paper is to overview existing and emerging REE supply chains outside of China up to date (end of 2013), define their environmental constraints and opportunities, as well as reflect on a broader range of technical, economic, and social challenges for both primary production and recycling of REEs. A better understanding of these factors could help to optimize the supply chain of virgin and recycled rare earths, minimise the environmental impacts arising from their processing, and be used as a prototype for a broader range of critical metals and commodities.

Introduction

The rare earth elements (REEs) represent a group of 17 chemical elements including 15 lanthanides, plus yttrium (Y) and scandium (Sc). All these elements have similar physical and chemical properties, providing superb characteristics for a variety of modern applications, from batteries in hybrid cars and phosphors for illuminated screens on electronic devices to permanent magnets used in computer hard drives and wind turbines. Depending on the application, they are used independently or as a mixture, or as an addition to other chemical compounds and/or metal alloys. Sometimes these elements are referred to as ‘vitamins’ because of their exclusive properties and the fact that only minor quantities are needed to boost the performance of the final products.

Despite the name ‘rare earth’, these elements are not particularly rare in their total crustal abundance, which exceeds such widely used elements as copper, zinc, nickel, and lead (Gupta and Krishnamurthy, 2005). However, REEs are scarce as a mineable resource. The limited availability of rare earth ores reflects a number of factors including the geological controls that affect not only their distribution but underlie technical mining and processing constraints.

The more abundant REEs are in the lighter spectrum of lanthanides group, the so-called light REEs (LREEs) that include lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), and samarium (Sm). The remaining REEs form the heavy REEs (HREEs) group, and include europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu), and yttrium.[1] Two elements are excluded from LREE/HREE classification: scandium, due to its unique properties and different occurrence, and light lanthanide promethium (Pm), due to its radioactivity.

Despite their similar basic chemical properties, each REE displays unique characteristics for specific applications and usually cannot be substituted one for another. This has resulted in a

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[1] There is no common classification for the light and heavy REEs, some authors also distinguish an intermediate group—medium REEs (e.g. see an overview in Gupta and Krishnamurthy, 2005). Most of the new REE mining projects use the classification presented.

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'criticality' classification which is based on a REE importance for specific applications (e.g. renewable energy), lack of comparable and reliable substitutes, and the monopolization of supply sources. According to the U.S. Department of Energy, the group of critical REEs comprises five elements: neodymium, europium, terbium, dysprosium, and yttrium (US DoE, 2011). This 'critical' status is often used as a reference point in project feasibility studies as ore bodies with higher percentages of 'critical' REEs are considered less at risk to market fluctuations.

New and existing REE sources outside of China are the main focus of this paper. An assessment of non-Chinese primary and secondary REE suppliers and the potential of recycling to circumvent supply constraints are initially reviewed. This information is then combined with known environmental issues and possible economic, technical and social factors to compare REE supply chains.

Rare earths primary supply

Individual stages of the full REE production chain – from mining to pure metals production – are often implemented by a number of different companies, in different countries. REEs are consumed in different chemical and physical forms, ranging from mixed and separated oxides (e.g. used in polishing powders, auto catalysts, and oxide ceramics) to metallic forms of specific elements (e.g. permanent magnets, and battery alloys). Consequently, it is important, when assessing the supply chain, to understand the geological basics and main processing steps, as well as existing industry statistics and market information.

Geology

The identified geological resources of REEs are significant, covering the current consumption level of these elements for several centuries (Chen, 2011). However, because of their geochemical properties they are not often found concentrated in economically exploitable ore deposits.[2] Furthermore, the mineralogy of some deposits is so complex that additional research into the development of appropriate processing technology will be required if they are to become commercially viable projects.

Rare earth ores are the result of the concentration of REEs either in igneous rocks or in sediments such as sand or clay. Primary rare earth ores contain REEs concentrated in minerals through magmatic processes such as partial melting, fractional crystallisation and metasomatism, while secondary rare earth ores are formed from weathering and transportation, sedimentary processes (Long et al., 2010). There are about 200 known minerals containing REEs (Kanazawa and Kamitani, 2006), however, known production of rare earths is primarily from six sources:

- Bastnaesite [(Ce,La)(CO_3)F],
- Monazite [(Ce,La)PO_4)],
- Xenotime (YPO_4),
- Loparite [(Ce,Na,Ca)(Ti,Nb)O_3],
- Apatite [(Ca,REE,Sr,Na,K)$_3$Ca$_2$(PO_4)$_3$(F,OH)],
- Ion-adsorption clays.

Of these, the first three minerals – bastnaesite, monazite, and xenotime – are by far the most important source of rare earths (Jordens et al., 2013), forming about 95% of the world's known reserves for rare earths (Gupta and Krishnamurthy, 2005). Loparite is used for REE extraction in Russia only (Vereschagin et al., 2006), while REEs sourced from apatite are a by-product of some phosphate fertiliser production operations (Chi et al., 2001).

As for ion-adsorption clay deposits, they are a unique source of rare earths located in the southern provinces of China (Chi et al., 2001). These deposits represent highly weathered REE-rich rocks, or laterites, developed as residuum from chemical weathering under very specific climatic conditions. The weathering process both enriches the REEs by intensive leaching of igneous and other rocks, and enables the REEs to be 'adsorbed' as ions on the surface of clay minerals (Kanazawa and Kamitani, 2006). Despite the enrichment of REE in this process, the ore grades remain low, typically 0.05–0.2% of rare earth oxides (REO). However ion-adsorption clay deposits are one of the most economic sources of REEs because of the simple processing required (as the mineral is already "cracked").

The concentration and association of individual REEs varies greatly by mineral and deposit. Bastnaesite, monazite, loparite and apatite are the main sources of LREEs, while xenotime and ion-adsorption clays are associated with a higher proportion of HREEs. These minerals occur variously in primary or secondary ores and in varying abundance in a wide range of geological settings (Kanazawa and Kamitani, 2006; Orris and Grauch, 2002). The richest deposits operating currently are the monazite–carbonatite deposit at Mount Weld in Western Australia (operated by Lynas) which has an average head grade of 14.8% total REO, and the bastnaesite–carbonatite deposit at Mountain Pass in California, USA (operated by Molycorp)—which ranges from 8% to 12% total REO.

The co-extraction of REEs along with other metals (e.g. iron ore, niobium, titanium, zirconium, uranium, and thorium) is also possible (Gupta and Krishnamurthy, 2005). The current largest REE producer, the Chinese Baotou Steel Rare-Earth Group, extracts REEs from iron ore production tailings (Jordens et al., 2013). However, this practice is not more widespread because of the increased sophistication of technology required, and some limitations on the scale of production. An associated practice is that of extracting REEs from waste such as bauxite residue (red mud), phosphogypsum, uranium industry tailings, and some metallurgical wastes. The concentration of REEs in stockpile and tailing waste streams whilst typically below 1%, does present a very large, ever growing and readily accessible source of REEs (Binnemans et al., 2013c).

Processing

The concentration of pure REEs from mined rock is complex, involves many stages, and impacts the economic decisions of the industry. First, the rare earth containing minerals are recovered from the host rock via comminution and physical separation. The concentrated minerals are subsequently chemically leached into a solution in a process commonly referred to as cracking. The individual elements are selectively removed from the mixed REE solution via hydrometallurgical techniques such as solvent extraction and ion exchange. The precipitated products can either be sold as pure metal oxides or reduced to pure metal products depending on the required end purpose (Fig. 1).

The method of physical beneficiation of rare earth bearing minerals depends on the mineralogy of the deposit. In most cases, the deposits are presented as hard rock, requiring the ore to be initially comminuted to liberate the valuable mineral grains. Conventional physical separation methods such as gravity separation, magnetic separation, electrostatic separation and froth flotation are employed to concentrate rare earth bearing minerals (Jordens et al., 2013). In placer, mineral sands deposits, gravity separation (spirals) is typically used to remove the silicate gangue

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[2] Mineral resources that are potentially valuable, and for which reasonable prospects exist for eventual economic extraction.