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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

[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 [$(Ca,REE,Sr,Na,K)_3Ca_2(PO_4)_3(F,OH)$],
- 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

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

Fig. 1. Schematic of REE production technology.

and multiple magnetic and electrostatic separation stages progressively concentrate the monazite from the other heavy minerals—ilmenite, rutile, zircon and leucoxene. Due to their nature, ion-adsorption clays require no physical beneficiation and can be processed by direct hydrometallurgical techniques (Chi et al., 2001).

The mixed REE concentrate is chemically attacked by acid or alkali treatment before the individual elements are able to be separated. This is where the thorium waste stream is removed from the concentrate. Sulphuric acid and sodium hydroxide are the typical leach solutions used for digestion. Depending on the acid/ore ratio, temperature and concentration either thorium or the rare earths can be selectively solubilized by sulphuric acid (Gupta and Krishnamurthy, 2005). Treatment of monazite with caustic soda allows the recovery of a marketable by-product, trisodium phosphate and results in an insoluble hydroxide residue of rare earths and thorium which can be acid leached as preparation for solvent extraction (ibid).

Individual rare earths are inherently difficult to separate because of their similar chemical properties—this is reflected in their late and extended discovery (Gschneidner and Cappellen, 1987). REEs are separated by taking advantage of the differences in basicity resulting from their ionic radii. Although selective oxidation/reduction, fractional crystallisation/precipitation and ion-exchange can be used, the most common separation technique is solvent extraction. Solvent extraction relies on different reaction kinetics of the various elements with various commercially available extractants (e.g. TBP, HDEHP and EHEHPA), and includes multiple iterations to obtain high purity separated REO (Gupta and Krishnamurthy, 2005).

Production statistics

The most widely cited statistics on rare earths are based on British (Table 1) and US Geological Surveys' data that assess the production of REEs on the basis of mined minerals (BGS, 2013; USGS, 2013). These statistics however fail to accurately represent REEs actually produced due to such factors as different recovery rates for different mineral concentrates and companies, and significant potential delays between mining, processing and delivery of final products to the market. Furthermore, mining of complex mineral ores where REEs are not the primary ore sought may not result in any REE extraction (e.g. mining of heavy mineral sand deposits, with monazite being a minor constituent that is usually rejected or stockpiled). These facts are not always adequately recorded in the world mining statistics. Neither are instances where REEs are produced from old stockpiles and/or previously rejected low grade ore (e.g. production at Mountain Pass, USA in 2008–2010), and from tailings (e.g. Solvay's plant in France has processed old REE tailings since 2010). Perhaps most significant however is the fact that data on REE production is not always publically reported by producers.

The list of current non-Chinese primary producers and reported production levels over 2007–2012 are presented in Table 2. Two new companies – Lynas (Australia/Malaysia) and SARECO (Kazakhstan) – are expected to join this list delivering their first product to the market in 2013. Comparing information in Tables 1 and 2, it can be seen that there is a mismatch in figures from British Geological Survey and data reported by the

Table 1
World production of rare earths, tonnes (100% REO content).
Source: British Geological Survey (BGS, 2013).

Country	2007	2008	2009	2010	2011
China	120,800	124,500	129,400	118,900	105,000
Russia	2,711	2,470	2,500	2,500	2,500
Malaysia	440	150	20	471	498
Brazil	760	540	200	160	188
India	35	22	16	0	0
Australia	0	0	0	0	2,188
USA	0	0	0	0	0
Total	**124,746**	**127,682**	**132,136**	**122,031**	**110,374**
China, share	97%	98%	98%	97%	95%

companies, supporting the explained earlier lack of accuracy in the statistics on REEs.

Supply chains

The REE supply chains consist of relatively small number of mining and processing companies, while multiple actors are usually involved in the manufacturing of final products based on rare earths. An illustration of the existing and emerging REE supply chains outside of China across main production stages is presented in Table 3. Originating from different countries, they also rely on different hosting mineral and technology (Table 3).

There are three connections between mining companies and REE manufactures in Table 3. Magnequench, a neodymium–iron–boron (NdFeB) magnet powders producer, was acquired by Molycorp in 2012. Originally based in the USA, the company's current production facilities are located in China and Thailand (www.molycorp.com). Indian Rare Earth Ltd has a joint venture with Toyota, while Summit Atom Rare Earth Company LLP in Kazakhstan is a joint venture between Kazatomprom and Sumitomo. Both joint ventures are aiming to recover and produce rare earths for Japanese customers.

With large scale American-owned Molycorp and Australian-owned Lynas becoming fully operational at the end of 2013, it is likely that the Chinese monopoly for REE supply will be challenged. However, HREE processing capacities both at the mining and separation stages (Table 3) are bottlenecks to developing the increasing number of identified resources outside of China. The Solvay's facility in La Rochelle is the only large scale REE separation plant outside of China that is able to separate both light and heavy REEs. Currently relying on Chinese feedstock and having an excess capacity for REE separation (Rollat, 2012), Solvay could become a key component in the supply chain for some junior miners, providing separation services at the early stage of project development.

Rare earths secondary supply

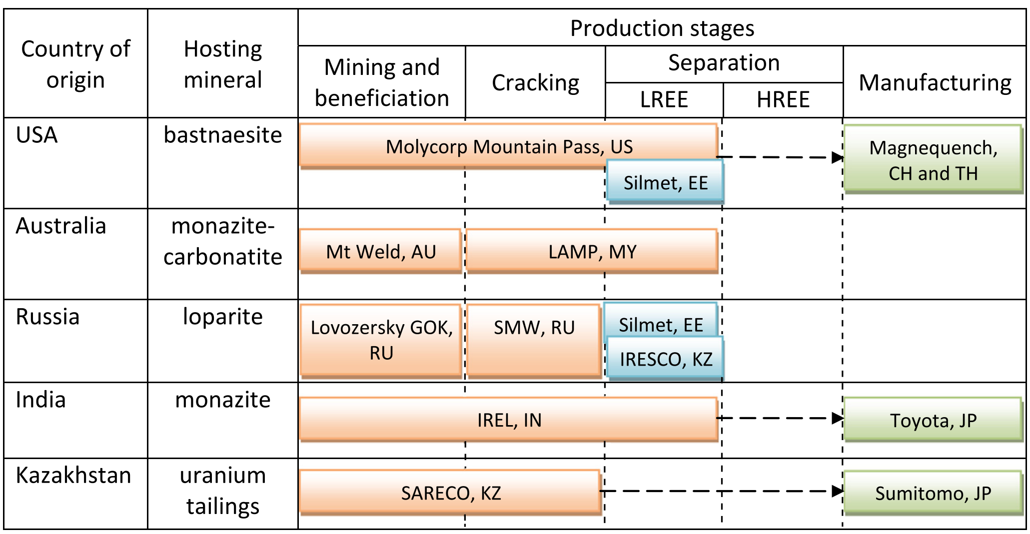
The combination of primary mining with recycling activities is often recognised as a cornerstone for sustainable development by satisfying the needs of modern society in metals and other elements (Legarth, 1996; Prior et al., 2012). The recycling of basic and precious metals is well established and recognised. However, this has been poorly developed for many commodities that are used in minor quantities due to economic, technical, social and

Table 2
Production of rare earths by non-Chinese mining companies, tonnes (100% REO content).
Source: Companies' annual reports and announcements.

Producer	Country	2007	2008	2009	2010	2011	2012
Mountain Pass (Molycorp)	USA	0	2000	2000	3062	3764	2661
SMW	Russia	2711	2470	1898	1496	1444	2131
Indian Rare Earths Ltd	India	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total		**2711**	**4470**	**3898**	**4558**	**5208**	**4792**

N.a.—Data is not available.

Table 3
Existing and emerging rare earths primary supply chains outside of China (2013).
Source: Companies' reports, announcements, and personal communication. Acronyms: LAMP—Lynas' Advanced Materials Plant, SMW—Solikamsk Magnesium Works, IRESCO—Irtysh Rare Earths Company Ltd, IREL—Indian Rare Earths Ltd, SARECO—Summit Atom Rare Earth Company.



regulatory issues (UNEP, 2013). Apart from the collection and separation system for the end-of-life consumer products, and technologies needed for the extraction of critical elements from scrap, the success of recycling also significantly depends on the involvement of different industries along the supply chain in the design of products suitable for recycling and in the design of industrial processes suitable to accept and reprocess the recycled material.

Main grounds for recycling

The general reasons for recycling and reuse of commodities include both economic and environmental factors, including concerns for the exhaustion of geological resources. The recycling of critical elements often adds another vital reason—the security of supply for a specific country or region. REEs have been ranked as critical elements in several countries (e.g. USA, Japan, South Korea, UK, and EU) considering their crucial importance for modern technologies and military applications, lack of supply sources, and concentration of the processing facilities and technical expertise mostly in China (Skirrow et al., 2013).

The minor quantity of REEs used in the final applications was previously the major barrier preventing their recycling. The technical difficulties to separate and extract REEs from scrap, relatively low prices, and the abundance of primary supply were among other factors. Recent extremely high volatility on the REE market (Table 4), as well as uncertainties in availability of REE supply from China (Hayes-Labruto et al., 2013; Wübbeke, 2013) have raised significant interest in REE recycling.

Table 4
The price dynamics for selected REO in 2007–2013 (US$/kg, FOB China).
Source: Lynas Corporation (2013), Metal-Pages (2013).

Element	2007	2008	2009	2010	2011	2012	2013
Lanthanum oxide	3.4	8.7	4.9	22.4	104.1	25.2	8.0
Cerium oxide	3.0	4.6	3.9	21.6	102.0	24.7	8.3
Praseodymium oxide	29.1	29.5	18.0	48.0	197.3	121.0	92.3
Neodymium oxide	30.2	31.9	19.1	49.5	234.4	123.2	70.7
Samarium oxide	3.6	5.2	3.4	14.4	103.4	64.3	15.6
Europium oxide	323.9	481.9	492.9	559.8	2842.9	2484.8	1161.4
Terbium oxide	590.4	720.8	361.7	557.8	2334.2	2030.8	974.0
Dysprosium oxide	89.1	118.5	115.7	231.6	1449.8	1035.6	550.4

It is a well-known fact that relatively abundant elements, such as lanthanum and cerium, are usually underpriced and supplied to the market significantly below the average production costs. Higher prices for other elements (Table 4) compensate for this difference to keep a positive overall return for REE producers. From the production point of view, however, most REEs have similar processing costs as they all are extracted together. Thus, the variation in prices is mostly due to the market conditions, i.e. the demand-supply balance for individual elements, overall efficiency benefits that REEs can provide for specific applications, and expenses associated with the replacement of REEs by alternative materials. This has a direct application to the attractiveness of recycling for some of the REEs. There is little to no interest in recovering relatively cheap elements that are unlikely to cover processing costs, while the recycling of high valued REEs can make a good business case.

The REE prices have been quite volatile in the past both in absolute terms (i.e. price for a specific element) and in relative terms (i.e. price as a ratio in relation to the price of a base element, e.g. cerium oxide). An increase in demand for specific REEs may cause overproduction of less demanded elements, followed by repricing of all REEs to balance the market. This is the so-called "balance problem", or a need to match the production structure with the demand (Falconnet, 1985). There is still no real solution to this problem. Some adaptive measures may include temporary stockpiling of overproduced elements, and/or allowing for excess capacities in the mining operations for ore bodies with different REE distribution. Higher level of recycling is also considered as an important strategy to overcome both supply limitations and the "balance problem" (Binnemans et al., 2013a).

Current recycling activities

The recycling of REEs, being investigated at the laboratory scale for several decades, is still a relatively novel activity (Tanaka et al., 2013). Up to 2012, the amount of recycled rare earths is estimated to be as low as 1% for the end-of-life products (Binnemans et al., 2013b; UNEP, 2013), which is drastically lower than other recyclable elements. The recent activities are mostly concentrated in the areas where a relatively REE rich scrap can be obtained and at the same time the rare earths in the scrap are mainly represented by highly valued critical REEs. These include the recycling of permanent magnets, lamp phosphors, and nickel metal hydride batteries (Binnemans et al., 2013b; EPA, 2012; Schüler et al., 2011; Tanaka et al., 2013).

Several companies in Japan, the largest consumer of rare earths outside of China, have announced REE recycling initiatives, including Toyota, Honda, Hitachi, and Mitsubishi. Some companies target to cover as much as 10% of their REE needs by recycled materials in the near future (Clenfield et al., 2010).

In Europe, the Solvay Group has recently developed the process for extracting REEs from on-site monazite/xenotime processing tailings to reduce its reliance on Chinese feedstock (Binnemans et al., 2013c). Recognising the supply constraints with critical REEs, Solvay has also started recycling REEs from three major sources: lamp phosphors (La, Ce, Eu, Y, Tb), NiMH batteries (La, Ce, Pr, Nd), and magnets (Pr, Nd, Dy, Tb) (Binnemans et al., 2013b; Rollat, 2012). There has been no data released on the volume of recycling, yet the company's target is to process 3000 t of waste materials a year (Solvay-Rhodia, 2013). This would secure Solvay's needs for critical rare earths to manufacture new lamp phosphors, while relying on primary mining feedstock only for less critical elements used to produce polishing powders and auto catalysts (Table 5).

There is no doubt that recycling could offset some of the rare earths primary supply, however the ecological footprint and economic costs for REE recycling still can be significant. The most costly processes for rare earths primary production are chemical cracking and separation (EPA, 2012), similar processes are also required for many recycling schemes (Tanaka et al., 2013). However, the recycling can offer an opportunity to reprocess the most desired elements, specifically targeting products with high concentration of certain valuable REEs, in contrast with the processing of virgin ores where all the elements have to be extracted. Another benefit of REE recycling versus mining is likely to be associated with the treatment and disposal of radioactive wastes arising from the processing of virgin raw materials. Even though there have been minimal investigation to assess the real significance of radioactive pollution arisen from REE processing (Schmidt, 2013), it is evident that taking into account this issue would position recycling as more advantageous (Binnemans et al., 2013b; EPA, 2012).

Environmental concerns

The mining and processing of REEs usually result in significant environmental impacts. Many deposits are associated with high concentrations of the radioactive elements such as uranium and thorium, which requires separate treatment and disposal. The REE processing is characterised by high levels of water consumption, energy inputs, and chemicals use (EPA, 2012). The land allocation can be also significant for both mining and processing operations, as well as for the tailings dams, and long-term storages of the radioactive waste materials.

There are multiple examples of negative past experience and incidences associated with the rare earth processing. The Asian Rare Earth company in Malaysia (1982–1992) probably is one of the most cited examples of the radioactive pollution from the processing of monazite rare earths (Ichihara and Harding, 1995). The past negligence of environmental impacts in China caused severe contamination of the surface and underground waters, and soils with heavy metals, toxic chemicals, and radioactive elements (Hurst, 2010).

Radioactivity issues

Most of the rare earth deposits have the presence of radioactive thorium and in some cases uranium. The concentration of radioactive elements, usually being relatively benign for human health in the ore body, rises significantly during beneficiation. This could be of serious concern for the waste by-product, emissions or tailings after the cracking stage in the processing of rare earths bearing minerals (EPA, 2012).

Table 5
Rare earths secondary (recycling) supply chain for Solvay.
Source: Companies' reports, announcements, and personal communication.

<table>
<tr><th rowspan="3">Recycled material</th><th colspan="6">Process stage</th></tr>
<tr><th rowspan="2">Collection</th><th rowspan="2" colspan="2">Pre-treatment</th><th colspan="2">Separation</th><th rowspan="2">Manufacturing</th></tr>
<tr><th>LREE</th><th>HREE</th></tr>
<tr><td>Batteries</td><td></td><td colspan="2">Umicore, BE</td><td rowspan="4" colspan="3">Solvay (La Rochelle), FR</td></tr>
<tr><td>Lamp phosphors</td><td></td><td>Lamp recyclers</td><td>Solvay (Saint Fons), FR</td></tr>
<tr><td>Industrial scrap (magnets)</td><td>Magnets producers</td><td colspan="2">→</td></tr>
<tr><td>Tailings</td><td></td><td colspan="2">Solvay (La Rochelle), FR</td></tr>
</table>

Table 6
Processing of radioactive materials in the REE primary production.
Source: Companies' reports and announcements.

Company	Processed material	Content			ThO_2/REO ratio (g/kg)	Processing/treatment of radioactive materials
		REO (%)	ThO_2	U_3O_8		
IREL, India	Monazite concentrate	57	9.2%	0.35%	161	Co-production of thorium and uranium
SMW, Russia	Loparite concentrate	30.5–36	0.5–0.7%	200 ppm	18	Concentrated radioactive cake is disposed at the permanent storage facility
LAMP (Lynas), Malaysia	Monazite–carbonatite concentrate	40	0.16%	29 ppm	4	Low radioactive phosphogypsum is temporarily disposed for possible reuse in road building
Mountain Pass (Molycorp), USA	Bastnaesite (ore)	8–12	200 ppm	20 ppm	2	Permanent disposal at the mine site (as paste) with further land rehabilitation

The concentration of thorium and uranium varies significantly for different ore bodies. Intermediate concentrates and final waste products contain radioactive elements depending on the processing route and potential co-extraction of Th/U. Information about processing and treatment of radioactive materials at the existing REE primary producers is summarised in Table 6, and also illustrated by the ThO_2/REO ratio which likely defines the feasibility of different treatment options and/or co-production schemes.

A higher concentration of thorium/uranium in the ore body makes the co-production of radioactive elements more feasible. However the current market for thorium is very limited (Gambogi, 2013), and most of it has to end up either at the long-term storage or permanent disposal. The separation, treatment and disposal of radioactive materials in the latter case would result in significant additional costs, as well as high human health and environmental risks. The low radioactive ore bodies are highly preferable for the new REE projects, but even in this case there are environmental issues that have to be carefully addressed.

Lynas' Advanced Materials Plant in Malaysia, which started REE production early 2013, still has uncertainties around disposal/reuse options for the low radioactive phosphogypsum. Despite the company's announcement to reuse most of phosphogypsum in road building, there are concerns about associated environmental and human health risks. For example, the USA Environmental Protection Agency (EPA) has banned the reuse of phosphogypsum (currently coming from phosphate fertiliser production) with radium 226 content (daughter product for Th-232 decay chain) more than 10 pCi/g (0.37 kBq/kg), as it can cause significant radiation exposure if used in the building industry (EPA, 1999). This has led to massive waste piles of phosphogypsum in the USA, with only a minor part of it being able to pass the legislative requirement, and with no current or potential future solution.

It is likely that the radioactivity aspect is overlooked in many new REE project proposals, both from the environmental and human health risk perspectives, and from the economic point of view (i.e. costs associated with treatment, disposal, and future land rehabilitation). Nevertheless, China has banned mining of pure monazite due to high-level radioactive elements and recently revised emission guidelines for the rare earths industry, setting standards that are in some cases more stringent than industrial nations (Schüler et al., 2011). Global awareness of these developments suggests that new REE projects in other jurisdictions may require revision of radioactive waste management before they can successfully go into production.

Assessing other environmental impacts

Future decisions concerning the development of new rare earth mines will undoubtedly be based upon target REE concentrations and/or the ability to economically co-extract other minerals from these deposits. However, if these deposits are to be developed sustainably there is a need to assess their impacts on the ecosystems and landscapes in which they occur. As most REE mines are developed using open cut techniques, existing ecosystems are either removed to access the ore, covered over by waste rock, tailings dams and processing plants, and fragmented by service infrastructure (EPA, 2012), thus there is a need to reduce the incursion of REE mining into intact ecosystems.

Global datasets from US Geological Survey detail 577 rare earths deposits worldwide (Orris and Grauch, 2002). These datasets can be coupled with critical ecosystems locations identified by the World Resources Institute (Miranda et al., 2003) in order to define a list of future mines with potentially lower environmental impacts, or that are able to meet the ecosystem barrier criteria. The latter has to be coupled with the existing standardised assessments of environmental impacts associated with rare earths mining and processing, including:

- Energy, water, and chemicals consumption rates for different production stages and operations;
- The amount of emissions, effluents, and solid wastes generation;
- Land allocation for the mine site, landscape position of processing plant(s), additional infrastructural facilities, waste disposals, and tailings dams;
- Land allocation for the permanent storage of the radioactive waste materials;
- Transportation distances and routes (for separately located processing facilities).

The environmental impact assessment reports should cover most of the parameters listed above; however they are not publicly available for every company and/or project. A comprehensive academic literature overview, special research investigations, as well as industrial site visits are other sources of information.

The development of recycling and reuse of REEs from waste materials or mine tailings is generally recognised as a more environmentally friendly activity than establishing a new REE mine (Binnemans et al., 2013b). However, recycling techniques for REEs have a number of environmental consequences including high energy use, consumption of large amounts of chemicals and the generation of waste chemicals and water. For example, the removal of mercury from lamp phosphors which contain the HREEs europium, terbium and yttrium, requires complicated, energy intensive equipment and there have been no studies on recovery of rare earths from LCD backlights which also contain mercury (Buchert et al., 2012). Hydrometallurgical methods to recycle REE magnets require large amounts of strong mineral acids and non-recyclable reagents such as H_2SO_4, NaOH and HF, and generate large quantities of waste water (Binnemans et al., 2013b).

Table 7
Relative values of different rare earths supply chains.

REE supply chain	Product value	Technical feasibility and expertise	Environmental impacts and radioactivity risks	Social risks and community pressure	Comment on process
	(Higher is better)		(Lower is better)		
1. Solvay, recycling of lamp phosphors	High	High	Low	Low	Waste reduction, high content of critical REEs
2. SARECO, reprocessing of uranium tailings	Medium	Medium	Medium	Low	Waste reduction, low population impact
3. SMW, loparite processing	Low	High	Medium	Medium	Underground mining, diversification of market risks due to co-extraction of several metals
4. Molycorp, bastnaesite processing	Low	Medium	Medium	Medium	Localised impact of mining and processing operations, cost benefits
5. Lynas, monazite–carbonatite processing	Low	Medium	Medium	High	Thorium storage concerns at the processing plant (Malaysian site)
6. IREL, monazite processing	Low	Medium	High	Medium	High thorium content and high opportunity costs may limit the production

Comparing supply chains

Comparing mining and resource recovery projects requires consideration of a range of complex parameters, including the geological profile and in-situ value of resources, technical feasibility of the project, ecosystem's sensitivity and environmental impacts from main operations, potential social risks and local community confrontation. The ranking of REE projects, however, is not a straight forward task, and would require expert opinion for assessing most parameters.

Four main categories representing economic, technical, environmental, and social factors have been used to compare the REE supply chains described earlier. Solvay's lamp phosphors recycling project and the joint Kazakh–Japanese venture (SARECO) for the reprocessing of uranium tailings (Table 7) have a high to medium product value and low environmental and social impacts. The existing primary producers mainly supply less economically attractive light rare earths, generate higher environmental impacts, and potentially raise community concerns in the processing plant locations.

The technical feasibility and expertise are marked as high for Solvay in France and SMW in Russia, where the existing processing facilities have already been in operation for several decades. The same parameter for other companies in Table 7 has been assessed as medium, due to the still ongoing commissioning operations and/or capacity expansions.

The recycling and waste reuse projects usually result in minimal additional land allocation and influence on the local ecosystem, while primary production can cause significant environmental damage. The mining of loparite in Russia is carried out by underground methods, partly alleviating the environmental impacts (Hedrick et al., 1997). Molycorp's and Lynas' REE deposits are located in the desert arid zones, which meet the ecosystem barrier criteria and have lower impact compared with other locations. The beach and inland placer deposits exploited for monazite and other minerals extraction in India are situated within relatively sensitive ecosystems, and also associated with the highest content of the radioactive elements. IREL's rare earths processing operations thus appears to have the most difficult REE production condition.

A similar process could be performed for other potential REE projects around the world in order to assess their risks and viability. This would be especially relevant at the early stage of project development, and could be used to support the decision-making for a wide range of stakeholders, including government authorities and local community groups, as well as partners from the downstream industries.

Conclusion

There is no lack of geological resources for rare earths, with proven reserves covering the current demand for several centuries. The supply risks for rare earths, however, exist with the monopoly of one country (China) over several stages of REE processing—from mining to separation into individual elements. Diversity in the supply sources is a key element for the current and future application of REEs, including the development of green technologies.

The existing and emerging alternative supply chains include mining operations in the USA, Australia, Russia, India, and Kazakhstan, as well as processing plants in France, Malaysia, and Estonia. All together they can significantly alleviate the Chinese domination in the REE sector. The new large scale REE mining companies such as Molycorp and Lynas will help to overcome the general bottlenecks in the supply of LREEs, while the recycling operations similar to those introduced at Solvay's plant in France can partly offset the primary supply for heavy and critical REEs. Recycling and waste mining are new potentially significant sources for rare earths. The reprocessing of existing industrial waste tailings and recycling of end-of-life consumer products would not only provide a more diverse and secure supply chain, but also could contribute to minimizing the environmental impacts arising from REE production.

A better understanding of the risks associated with rare earths mining and possessing including radioactivity issues, as well as fair communications with stakeholder groups are critical success factors. It is equally important for the minimisation of environmental impacts arising from new mining projects, and for defining a comprehensive base to compare REE recycling with primary production. The values of the existing and emerging REE supply chains, based on the economic, technical, environmental, and social factors, suggest that recycling projects are the most advantageous, followed by the reprocessing of industrial waste streams for REE extraction. In addition, new rare earths mining and processing facilities should be developed outside of sensitive natural ecosystems, preferably targeting low radioactive ore bodies with higher content of critical REEs.

References

BGS, 2013. World Mineral Statistics Data. British Geological Survey.
Binnemans, K., Jones, P.T., Acker, K., Blanpain, B., Mishra, B., Apelian, D., 2013a. Rare-earth economics: the balance problem. J. Manage. 65, 846–848.
Binnemans, K., Jones, P.T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., Buchert, M., 2013b. Recycling of rare earths: a critical review. J. Cleaner Prod. 51, 1–22.

Binnemans, K., Pontikes, Y., Jones, P.T., Van Gerven, T., Blanpain, B., 2013c. Recovery of rare earths from industrial waste residues: a concise review. In: Proceedings of the Third International Slag Valorisation Symposium: The Transition to Sustainable Materials Management, pp. 191-205.

Buchert, M., Manhart, A., Bleher, D., Pingel, D., 2012. Recycling Critical Raw Materials from Waste Electronic Equipment. Öko-Institut e.V, Darmstadt, Germany.

Chen, Z., 2011. Global rare earth resources and scenarios of future rare earth industry. J. Rare Earths 29, 1–6.

Chi, R., Xu, S., Zhu, G., Xu, J., Qiu, X., 2001. Beneficiation of Rare Earth ore in China, Light Metals 2001 as Held at the 130th TMS Annual Meeting, pp. 1159–1165.

Clenfield, J., Yasu, M., Biggs, S., 2010. Hitachi leads rare earth recycling efforts as China cuts access to supply. Bloomberg.

EPA, 1999. National Emission Standards for Hazardous Air Pollutants: Rad NESHAPs: Subpart R Rule: Sec. 61.207 Radium-226 Sampling and Measurement Procedures. US Environmental Protection Agency

EPA, 2012. Rare earth elements: a review of production, processing, Recycling, and Associated Environmental Issues. US Environmental Protection Agency, Cincinnati, OH.

Falconnet, P., 1985. The economics of rare earths. J. Less-Common Met. 111, 9–15.

Gambogi, J., 2013. Thorium [Advance Release]. 2011 Minerals Yearbook U.S. Geological Survey.

Gschneidner, K.A., Cappellen, J., 1987. 1787–1987 Two Hundred Years of Rare Earths. Rare Earth Information Center, North-Holland.

Gupta, C.K., Krishnamurthy, N., 2005. Extractive Metallurgy of Rare Earths. CRC Press.

Hayes-Labruto, L., Schillebeeckx, S.J.D., Workman, M., Shah, N., 2013. Contrasting perspectives on China's rare earths policies: reframing the debate through a stakeholder lens. Energy Policy.

Hedrick, J.B., Sinha, S.P., Kosynkin, V.D., 1997. Loparite, a rare-earth ore (Ce, Na, Sr, Ca) (Ti, Nb, Ta, Fe^{+3})O_3. J. Alloys Compd. 250, 467–470.

Hurst, C., 2010. China's Rare Earth Elements Industry: What Can the West Learn? DTIC Document.

Ichihara, M., Harding, A., 1995. Human rights, the environment and radioactive waste: a study of the Asian rare earth case in Malaysia. Rev. Eur. Commun. Int. Environ. Law 4, 1–14.

Jordens, A., Cheng, Y.P., Waters, K.E., 2013. A review of the beneficiation of rare earth element bearing minerals. Miner. Eng. 41, 97–114.

Kanazawa, Y., Kamitani, M., 2006. Rare earth minerals and resources in the world. J. Alloys Compd. 408–412, 1339–1343.

Legarth, J.B., 1996. Sustainable metal resource management—the need for industrial development: efficiency improvement demands on metal resource management to enable a (sustainable) supply until 2050. J. Cleaner Prod. 4, 97–104.

Long, K.R., Van Gosen, B.S., Foley, N.K., Cordier, D., 2010. The Principal Rare Earth Elements Deposits of the United States—A Summary of Domestic Deposits and a Global Perspective: U.S. Geological Survey Scientific Investigations Report 2010–5220, 96 p. Available at 〈http://pubs.usgs.gov/sir/2010/5220/〉.

Lynas Corporation, 2013. What are their Prices? [Online]. Available: 〈http://www.lynascorp.com〉 (accessed 20 November 2013).

Metal-Pages, 2013. Metal Prices—Rare Earths.

Miranda, M., Burris, P., Bincang, J.F., Shearman, P., J.O., B., La Vina, A., Menard, S., 2003. Mining and Critical Ecosystems: Mapping the Risks. World Resources Institute, Washington DC.

Orris, G.J., Grauch, R.I., 2002. Rare Earth Element Mines, Deposits and Occurrences. US Department of the Interior, US Geological Survey.

Prior, T., Giurco, D., Mudd, G., Mason, L., Behrisch, J., 2012. Resource depletion, peak minerals and the implications for sustainable resource management. Global Environ. Change 22, 577–587.

Rollat, A., 2012. How to Satisfy the Rare Earths Demand Rhodia Rare Earth Systems Initiatives. SEII 2012/09/28. European Society for Engineers and Industrialists.

Schmidt, G., 2013. Description and Critical Environmental Evaluation of the REE Refining Plant LAMP Near Kuantan/Malaysia: Radiological and Non-radiological Environmental Consequences of the Plant's Operation and its Wastes. Öko-Institut eV Darmstadt. Prepared on behalf of NGO "Save Malaysia, Stop Lynas" (SMSL), Kuantan/Malaysia.

Schüler, D., Buchert, M., Liu, D.-I.R., Dittrich, D.-G.S., Merz, D.-I.C., 2011. Study on Rare Earths and Their Recycling. Öko-Institut eV Darmstadt.

Skirrow, R.G., Huston, D.L., Mernagh, T.P., Thorne, J.P., Dulfer, H., Senior, A.B., 2013. Critical Metals for a High-tech World: Australia's Potential to Supply Global Demand. Geoscience Australia, Canberra.

Solvay-Rhodia, 2013. Loop Life Project objectives [Online]. Available: 〈http://www.rhodia.com〉 (accessed 26 September 2013).

Tanaka, M., Oki, T., Koyama, K., Narita, H., Oishi, T., 2013. Chapter 255—recycling of rare earths from scrap. In: Jean-Claude, G.B., Vitalij, K.P. (Eds.), Handbook on the Physics and Chemistry of Rare Earths. Elsevier, pp. 159–211.

UNEP, 2013. Metal Recycling: Opportunities, Limits, Infrastructure. A Report of the Working Group on the Global Metal Flows to the International Resource Panel. Reuter, M.A.; Hudson, C.; van Schaik, A.; Heiskanen, K.; Meskers, C.; Hagelüken, C.

US DoE, 2011. Critical Materials Strategy. U.S. Department of Energy.

USGS, 2013. Rare Earths Statistics and Information. U.S. Geological Survey.

Vereschagin, Y.A., Kudrevatykh, N.V., Malygin, M.A., Emelina, T.N., 2006. Rare-earth magnets in Russia: raw materials, processing, properties control and output issues. J. Iron Steel Res. Int. 13 (Supplement 1), 23–32.

Wübbeke, J., 2013. Rare earth elements in China: policies and narratives of reinventing an industry. Resour. Policy 38, 384–394.