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ScienceDirect
Procedia Environmental Sciences 20 (2014) 280 – 287
Procedia Environmental Sciences

4th International Conference on Sustainable Future for Human Security, SustaiN 2013

# Sustainability of the Rare Earths Industry

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**Abstract**

Rare Earths have been of considerable interest in recent years for a variety of reasons, in particular due to concerns over the security of supply for modern high efficiency electronics and energy technologies. Such concerns have placed them among the list of “critical” or “strategic” elements in countries such as the United States of America, the European Union, Japan and even in the largest producer and holder of reserves, China. Focus has been given to the environmental impacts of production, and on the distribution of reserves and politico-economic conflict over supply, but international academic work quantifying these impacts is lacking. Moreover, broader consideration of sustainability impacts and benefits in a systematic manner – particularly in regard to the social impacts of RE extraction, processing and utilisation – is not yet apparent.
This paper undertakes a review of the literature and state-of-play of sustainability assessment of rare earth elements. Furthermore, the paper highlights areas of sustainability research considered by academic and industrial representatives to be essential for filling these gaps, and a pathway forward towards a more sustainable rare earths industry.


Selection and peer-review under responsibility of the SustaiN conference committee and supported by Kyoto University; (RISH), (OPIR), (GCOE-ARS) and (GSS) as co-hosts

*Keywords:* Rare earths; sustainability; social; environmental; energy

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doi:10.1016/j.proenv.2014.03.035

**Nomenclature**

| | |
|---|---|
| RE | rare earths |

## 1. Introduction

Rare Earths (RE) have been of considerable interest in recent years for a variety of reasons, in particular due to concerns over the security of supply for modern high efficiency electronics and energy technologies. Such concerns have placed them among the list of "critical" or "strategic" elements in countries such as the United States of America (USA) [1], the European Union (EU) [2], Japan [3] and even in China [4] - the largest producer and holder of reserves.

Amid this sudden peak in interest, focus has been given to the environmental impacts of production, and on the distribution of reserves globally and politico-economic conflict over supply, but international academic work quantifying these impacts is lacking. Moreover, broader consideration of sustainability impacts and benefits in a systematic manner – particularly in regard to the social impacts of RE extraction, processing and utilization – is largely lacking [5].

In response to the gap in knowledge, this paper presents a review of the literature and analysis of the state-of-play of sustainability assessment of RE. Furthermore, the paper highlights areas of sustainability research considered by academic and industrial representatives to be essential for filling these gaps, and a pathway forward towards a more sustainable rare earths industry.

Sustainability of minerals or specifically "sustainable mining" is a point that often sparks confusion and debate, due to the ultimate limits of extractable mineral resources. As a definition therefore, this paper considers sustainability within the frameworks of mineral resources as: "a state of dynamic interplay between environment and society (in a broad sense) that ultimately contributes positively to indefinite human development and universal wellbeing whilst not overdrawing on natural resources or over-burdening the environment in an irreversible manner. When we use the term sustainability in mining, for example, we do not mean mining that can be "sustained" but rather we mean a mine that is making its proper contribution to societal sustainability." [5].

## 2. Methodology

The literature relating to RE was extensively reviewed from both academic and industry sources. Due to the lack of literature specifically into sustainability of RE, focus was placed on examination of literature covering four associated categories: environmental, social, economic and technical aspects of RE supply chains. The first three of these categories follow the widely used approach of the triple-bottom-line (TBL) however, it is also acknowledged that more literature does not specifically examine any of these categories, but focuses on the technical (technological and scientific) aspects of RE. Without understanding these technical aspects, it is argued that it is impossible to examine RE sustainability. These four areas combined give a reasonable picture of the state-of-play in considering a variety of sustainability impacts of RE.

From the reviewed literature, key topics were drawn out, and in conjunction with recent discussions between academic and industry stakeholders, some important research themes for the future were identified.

## 3. Results

The results of the review are organized below under the thematic headings.

### *3.1. Environmental*

Environmental aspects of sustainability are considered to be highly important along the whole supply chain of RE. Discussions of environmental sustainability of RE may be classified broadly into a number of categories: geological reserves and availability; environmental impacts or comparative benefits of production processes (including recycling); and environmental benefits of utilization.

With regards to the first category (perhaps a tenuous use of the "environmental" term), discussion and data are relatively open. It is important to note that rare earths are not necessarily rare, but that the particular geological conditions that promote their concentration to levels warranting economic extraction are rare. Therefore, most rare earths have been extracted as by-products of other mined materials – iron ore or phosphorus, for example.

With regards to the second category, the environmental impacts are less readily accessible if available at all. Despite much discussion of the environmental damage caused by RE extraction in China, only broad estimates – generally from government sources – are available. For example, the emissions of dust, sulfur compounds and fluoride [6] or the usage rates of reagents [4]. Moreover, the associated radioactive thorium and uranium waste may also be of concern [7]. Some new technology developers have provided a breakdown of water and reagent consumption in order to prove the benefits of their own products over existing techniques [8], but these lacks a clear datum to compare the status quo, due to the lack of reliable, independent data sources.

In the utilization category, the technological advantages of alternatives versus RE-containing products are readily translatable into energy savings or emissions reductions at the point of usage, but this does not include the full life cycle impacts. Standard values for emissions and energy embodied in RE are not commonly available due to the large range of elements considered (14-17 elements) and the highly complex, interconnected flow sheets required. Likewise, each deposit is unique in its specific balance of RE, making the allocation to each element additionally challenging. The review identified one lifecycle assessment of RE, which concluded that mining and beneficiation have much lower energy and material consumption compared to the other downstream stages – separation of rare earth oxides and reduction to rare earth elements [9]. Furthermore, the life cycle assessment results showed that the high environmental impact of rare earth elements (on a per kg basis) coupled with low yield and low abundance provided a sound incentive to investigate recycling and recovery of rare earths or minerals that contain rare earths. However, there is as yet insufficient data available to verify the study or to apply it to different techniques and deposits. Even conventional RE processing environmental impacts are far from clear, so the recycling and extraction from other unconventional deposits need significant research to be completed.

Therefore, the environmental aspects of RE research are still very limited- especially on the production processes. It is to be expected that the emergence of new RE producers globally and the focus on environmental improvement in China will help to expand the available data and knowledge in this area.

### *3.2. Social*

The social and human components of sustainability are generally the least developed in regards to their implementation and assessment across all industries, and in the RE industry, this is no exception. Recently socio-environmental issues of the health impacts of RE processing in areas of China have been raised as a major concern[6]. Moreover, the potential for such impacts has been one of the key drivers behind protests at the Lynas Corporation plant in Malaysia [10].

Social resistance to rare earths mining stems from arguments about environmental justice and how processing sites are often more difficult to get permitted in developed countries - leading to their construction in developing countries. Indeed, environmental regulation was one key reason for the closure of RE operation in the USA and the resistance to the Lynas plant in Malaysia over Australia has been controversial due to suspicions of this type of reasoning.

On the other hand, RE contribution towards developing a "green economy" can be cited as a potential positive impact [11]. Social perceptions of risk at the site level thus need to be balanced against broader national priorities towards sustainable technology development. Recycling and service sector opportunities for this sector have much potential for development as retrieval technologies improve, and there is likely to be less social resistance to efforts towards a circular economy for rare earths develop alongside their green economic uses in products.

### 3.3. Economic

Research on the economic pillar of sustainability in RE has been focused on three key elements – the price of RE in the market (and its implication for technology costs), the restriction of supply by China (and its implications for price of RE and ability to roll-out new technology), and the availability of non-Chinese deposits. These elements reflect the concerns of governments and companies that rely on RE in their production lines.

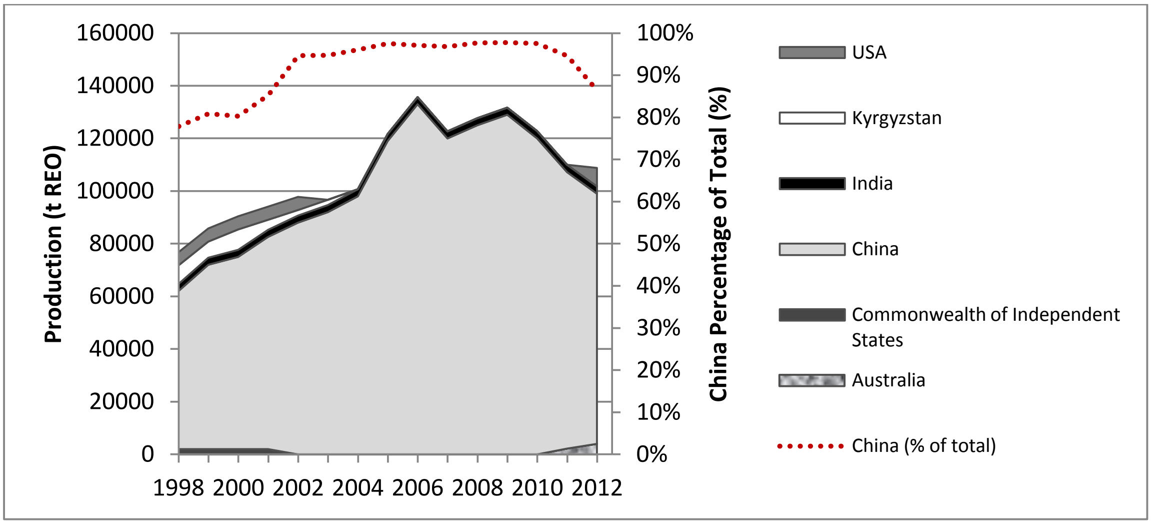


Fig. 1. World production of rare earths (omitting two producers with <1000tpa) (Data source: USGS [12])

The recent export quota reductions by China (as the majority producer of RE) [13] sent a shock through the international community – with those especially concerned being the countries and companies that relied heavily on RE for economic production and security (Japan, USA and Europe). These quota reductions were the key driver behind dramatic increases in prices [14] which in turn led to the labeling as "critical" or "strategic", and the furthering of concerns that supply had become too centralized in China. Subsequently both nations and companies have made significant efforts to bring new non-Chinese resources into production – for example, reviving the Mountain Pass mine in the USA and the Lynas Corporation deposits in Australia. Fig. 1 shows the relative dominance of China over the past 15 years as well as the re-emergence of alternative producers.

Conventional resources have not been the only source of interest however, with unconventional resources such as expanded recycling [15], coal and coal ash [16] and deep sea deposits [17]. These unconventional resources are still largely or entirely undeveloped – although some recycling is being undertaken commercially and there is a significant research drive in this area. Japan hopes to enable production from deep sea deposits from 2018 [18].

While this may alleviate the issue of reserves centralization and security of supply, there remain various unanswered questions, such as: "Will such resources be economically viable?", "Will the environmental impacts be acceptable?" Despite positive claims [19], there is no reliable estimate on the cost of such operations, which provides a significant gap in knowledge.

### 3.4. Technical

The majority of RE research is devoted to the technical aspects of its extraction, processing, utilization and reprocessing or recovery. In regards to the technical elements of RE sustainability, the utilization in high efficiency and clean energy technologies, and the improvement of recycling and waste reclamation are areas of clear importance. The improvement of extraction and processing or the discovery of low-impact alternatives are also of key importance for the future.

A recent review of RE-bearing minerals summarized the main beneficiation methods as gravity, magnetic, electrostatic and flotation separation techniques [20]. The authors note that the existing literature on the physical beneficiation of rare earth minerals mainly concentrates on two major rare earth element mineral deposits, Bayan Obo in China and Mountain Pass in USA – both of which have been the largest producing deposits at different periods of time. They note that there was a lack of requisite background information (proper chemical names of collector molecules, detailed descriptions of processes etc.) to provide significant insights into the development of separation processes for alternative rare earth minerals from much existing literature. This is one reason why there has been recent increasing interest in researching new methods for the extraction and processing of rare earths.

Alternative processes using supercritical fluids such as $CO_2$ have also been examined [21]. Moreover, interest in the extraction of RE using microbial [22] or other biological or enzymatic processes is growing, due to its potential for lower intensity processing and reduced environmental emissions.

With rises in RE market price and concerns over environmental impact and supply security, a number of major studies have been completed into the recovery of RE via recycling of low value waste streams such as bauxite residue, phosphogypsum, waste water, slag and mine tailings [23, 15]. Other authors have focused specifically on the waste from RE operations, which can hold significant amounts of unrecovered RE – especially in tailings from older, less efficient operations [24]. Ongoing interest in recycling of end-of-life batteries [25], computer monitors [26] and magnets [27] has shown some promise at the laboratory scale, with recoveries up to 96% of RE [28] and significant industrial investment in Japan and Europe has been made into new recycling plants. The techniques for extraction and purification of RE in waste streams are largely the same as those utilized in processing primary ore.

At the consumer end of the supply chain, end-use applications of RE are indeed the key underlying reason for the heightened interest – particularly the linkage with energy technologies such as wind power (magnets in generators), in batteries useful for electric vehicles and renewable energy storage, in energy efficient light emitting diodes and fuel cells – all are considered to be important for low carbon futures. Alternative technologies that reduce RE usage have also been of particular interest due to concerns over security of supply.

## 4. Discussion

When considering the sustainability of RE, it is important to consider the full lifecycle of the material, from extraction through to waste disposal and recycling. An example of the relationships between the sustainability categories is shown in Fig. 2 – inputs and outputs occur between each of the realms at every stage, however it is apparent the fundamental sourcing of raw materials from the environment, and return of waste to the environment are major streams, whilst the usage by society and disposal of end-of life goods are also highly important determinants.

As with most eco-design, the demand from society for products with functionality provided by RE is a pull-factor in the drive to increase production. This is leading to research into methods to minimize RE content or utilize alternative technologies to obtain the same functionality. However, the environmental impacts of production (largely limited to China over recent years) have been acknowledged as important, and have historically caused the limitation of production – in Malaysia, USA and now China. It is recognized that new techniques, processes and governance systems are required to ensure more environmentally benign RE operations, but the quantification of the current environmental burden – essential to identifying lifecycle impacts – is not currently evident. Thus, from an eco-design or lifecycle assessment perspective, it is difficult to justify to a reasonable degree of certainty whether the end-use benefits outweigh the production-side impacts.

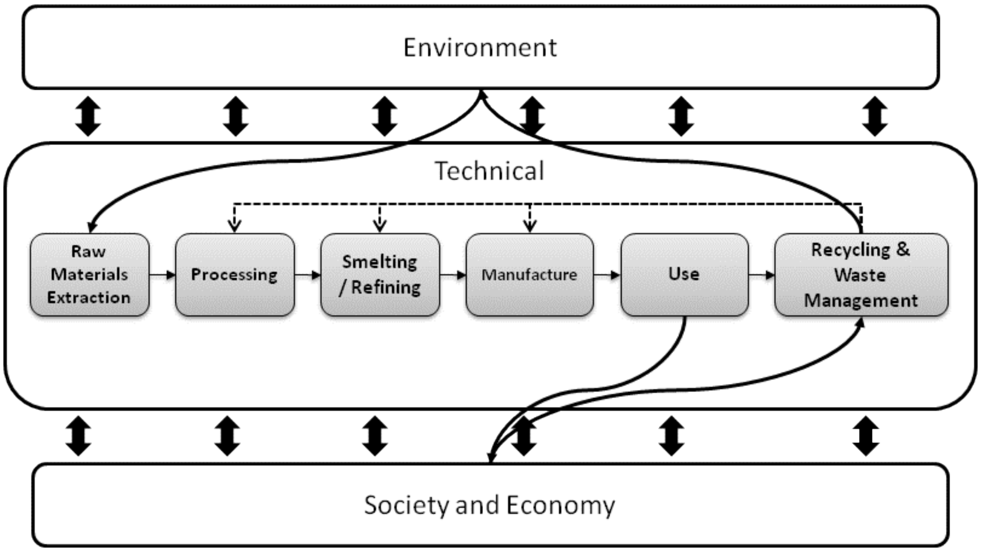


Fig. 2. Schematic representation of the relationship between the sustainability categories across the lifecycle

From the perspective of securing supply, it is apparent that geologically RE are relatively abundant, albeit not necessarily in concentrations that make economic extraction possible. Moreover, with the expectation and policy drive to utilize energy efficient and low carbon energy technologies, and with growing demand for electronics from developing countries, it is expected that demand will likely outstrip production. Until recently, there has been little need or apparent benefit in recycling RE from the economic perspective, due to the small quantities and concentrations contained in consumer products and the difficulty in collection and processing[15]. However, as demand-supply balance shifts, increasing the price of RE in the market, recycling becomes more attractive. From the environmental perspective however, even given the lack of quantitative information on primary production process impacts, the fact that the same techniques are used for recycling may make many of the recycling process impacts at least similar to primary materials.

Particularly interesting is the new consideration of non-conventional deposits of RE – both in waste streams such as coal ash, bauxite residue or slag, and in deep ocean deposits. In the latter case, the push by the Japanese government to exploit deposits that lie in the country's exclusive economic zone, but very distant from the mainland, very deep in the ocean and relatively close to international waters (as compared to the mainland) will be closely watched. Technology for the extraction of similar resources has been developed for shallower deposits [29] however, sub-sea mining has been a source of controversy due to the uncertainty of impacts on the environment. Moreover, the potential for associated radioactive compounds to be released during the mining process would undoubtedly raise concern from environmentalists. Moreover, due to the location of these resources, it is as yet unclear who the stakeholders of interest might be, and if an environmental impact assessment was undertaken, who would be consulted.

With regards to rolling-out renewable technologies, Ytterbium and Neodymium are two key RE that could limit the ultimate potential of photovoltaics and wind respectively with demand ratios in the order of 2000 – 3000% of 2008 production if the entire electricity fleet were to be replaced with these technologies (after Ashby [30]_ENREF_17). Whilst this is an unlikely scenario, and the replacement period out to 2050 is more than reasonable, it is important to keep in mind that rapid expansion would currently be limited on the materials supply side.

From the social element of sustainability, the supply of RE to meet demand is important, but the potential impacts on health at the site of production must be considered alongside the potential to create employment and economic benefit along the supply chain. The development of appropriate waste processing regimes – and particularly the opportunity to advance industrial ecology opportunities that may extract more valuable (and potentially harmful) components from the ore are vital issues overlapping the technical, social and environmental realms.

## 5. Conclusions

From the review and analysis presented in this article, the following topics of research that would benefit the rare earth industry in the short to mid-term are:

- Quantification of the environmental and social externalities of extraction and processing of RE - firstly from conventional sources as a baseline, but also from the unconventional sources under consideration (this should include a widely-based and rigorous life cycle assessment)
- Consideration of policies to enhance the closing of the material cycle, enabling more cost effective recycling
- Effective policies and methods for waste valorization, treatment and storage in the RE industry
- Better integration of community stakeholder concerns along the supply chain.

A number of emerging initiatives to link industry and academia are being funded globally, with research into the sustainability impacts and implications of these key materials as important elements of the research agenda.

## Acknowledgements

Funding for some of the authors' involvement in this work has been provided through the NextMine™ Initiative of the University of Queensland's Sustainable Minerals Institute through the UQ Rare Earths Consortium.

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