GSDR 2015 Brief

Rare Earth Elements; from Mineral to Magnet

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Related Sustainable Development Goals

Goal 07	Ensure access to affordable, reliable, sustainable and modern energy for all (7.2 – 7.3)
Goal 08	Promote sustained, inclusive and sustainable economic growth (8.4)
Goal 09	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation (9.4)
Goal 12	Ensure sustainable consumption and production patterns (12.2 – 12.4 – 12.5 – 12.6)

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Introduction

In recent years there has been an increasing focus on rare earth elements (REEs) as highly valuable ingredients for innovation, especially regarding the development of sustainable energy technologies.[1] Rare earth elements, also commonly referred to as rare earth metals, are defined by the International Union of Pure and Applied Chemistry (IUPAC) as a group of seventeen elements, consisting of the fifteen lanthanoids, along with scandium and yttrium.[2] Related to the chemical structure and purpose REE can be divided in Light REEs (LREEs) and Heavy REEs (HREEs) (see table 1).[3, 4] Their relative chemical similarity makes them hard to separate during the mining process, but their different physical properties make different REEs valuable for a range of various technological applications.[5] Several of these technologies support sustainable development, for instance through increased energy efficiency and renewable energy production. Examples include – but are not limited to – permanent magnets, batteries for e-mobility and energy-efficient lighting (for further applications see appendix). World-wide demand is expected to grow by 8 to 11% each year.[6] The increase in demand is intertwined with environmental implications of production and existing supply risks due to an intricate and complex market. This has led to the identification of REEs as critical raw materials,[7] which this science digest focus on.

FOOD FOR THOUGHT

- There is no single REE market, but each REE has its specific characteristics and its own value chain (including price, application and abundance).[i]
- Currently China is the only producer of HREEs worldwide.[ii]
- Hardly any REE recycling is applied yet, although the REE in-use stock was four times as much as the amount extracted in 2007.[iii]
- There is sparse knowledge and only a few studies about the life cycle of REEs.[iv]

The United Nations Environmental Programme, the United States (U.S.) National Research Council and the European Commission, amongst others, identify all REEs as critical.[8,9,10] Their classifications use similar approaches to evaluate mineral criticality, based on a methodology with three-pronged indicators that involve economic importance, supply risk and environmental implications.[11]

Due to their criticality we emphasize the need to address REEs with regard to sustainable development**,** because of both their vital role in sustainable energy applications and their environmental implications.[12,13] The main applications of REEs and their benefits seem to be in the developed world, whereas the majority of the environmental impact appears to occur in transition and developing countries. Instead, sustainable energy technology ought to be implemented on a more widespread and global scale so to benefit all. Simultaneously, the weight of the environmental implications of production should be carried worldwide. After all, if sustainable energy technologies are based upon unsustainably produced natural resources, how sustainable are they really? Therefore, the aim of this science digest is to analyze and illuminate the current REE market situation and to point out the most critical sustainability issues the international community should address.

Scientific Debate

The current scientific debate discusses both the REE life cycle and its value chain. The connections to environmental impact, recycling potential, industry distribution and development, as well as price trends will be explored. The REE life cycle, which should promote sustainable natural resource management, can be divided into three steps; production (mining and refining), consumption (manufacturing of end-user goods and use) and recovery (recycling and reuse at all steps of the lifecycle).[14]

REE production

Production includes extraction of the REE containing mineral, milling, flotation, purification and further processing of the ore.[15,16] The Chinese Ministry of Environmental Protection implemented pollution standards and monitoring options, and Australia and the United States supposedly apply the newest mining technologies.[17,18] However, environmental pollution due to radio-active waste and other chemicals still remains a critical issue for REE production.[19] Besides the environmental risks as a result of unregulated illegal mining,[20] flotation is most damaging for the surrounding environment.[21] Flotation entails chemical beneficiation in ponds, known as tailings.[22,23] The residues, such as radioactive thorium or uranium other chemicals, remain in the waste water. This water is exposed to natural environmental conditions (precipitation, run off, drainage etc.) or disruptions (dam collapse), and therefore poses high risks of environmental contamination (see appendix).[24,25] Purification is energy intensive and costly, but necessary, because a purity of 99% is often needed.[26]

*Table 1 : An overview of rare earth elements, their chemical symbols and additional characteristics; N/A indicates not available data, *identifies free on board (FOB) prices (the price paid for the REE product from the moment and port of departure).*

REE	REO	Major deposits[v]		Price range (USD/kg)[vi]		Major application[vii]
		Average REO abundance per/mass(%)	*Largest deposit*	**minimum FOB China*		
				May 2014	*Nov 2014*	
LREE	Major mines: Bayan Obo, China; Mountain Path, USA ; Mount Weld, Australia					
Scandium (Sc)	Sc_2O_3	N/A	N/A	N/A	N/A	
Lanthanum (La)	La_2O_3	25,35%	China	10.50*	9.60*	*Lighting* (LEDs)
Cerium (Ce)	CeO_2	42,84%	China	13	10	*Lighting* (LEDs), *Batteries* (e-mobility)
Praseodymium (Pr)	Pr_6O_{11}	4,06%	China	155.00*	150.00*	*Permanent magnets* (wind turbines, e-mobility, electronics)
Neodymium (Nd)	Nd_2O_3	11,99%	Australia	87.50*	83.00*	*Permanent magnets* (wind turbines, e-mobility, electronics)
Promethium (Pm)	Pm_2O_3	N/A	N/A	N/A	N/A	
Samarium (Sm)	Sm_2O_3	1,35%	Australia	33.50*	25.00*	*Permanent magnets* (wind turbines, e-mobility, electronics)
Europium (Eu)	Eu_2O_3	0,24%	Australia	1250.00*	1000.00*	*Lighting* (LEDs)
HREE	Major mines: South of China (Jiangxi, Guangdong, Fuijian, Guangxi province)					
Gadolinium (Gd)	Gd_2O_3	1,28%	China	132.50*	132.50*	*Lighting* (LEDs)
Terbium (Tb)	Tb_4O_7	0,22%	China	975.00*	825.00*	*Lighting* (LEDs)
Dysprosium (Dy)	Dy_2O_3	1,24%	China	625.00*	475.00*	*Permanent magnets* (wind turbines, e-mobility, electronics)
Holmium (Ho)	Ho_2O_3	0,25%	China	N/A	N/A	
Erbium (Er)	Er_2O_3	0,66%	China	N/A	N/A	
Thulium (Tm)	Tm_2O_3	0,10%	China	N/A	N/A	
Ytterbium (Yb)	Yb_2O_3	0,55%	China	N/A	N/A	
Lutetium (Lu)	Lu_2O_3	0,08%	China	N/A	N/A	
Yttrium (Y)	Y_2O_3	9,71%	China	60.00*	60.00*	*Lighting* (LEDs)

Table 1 provides an overview of all light and heavy REEs and a number of relevant properties. It presents the rare earth oxide (REO) form in which they are mined, and their abundance in the ore relative to the other REEs. This shows cerium is relatively most abundant, while HREEs are generally scarce. What is important to mention is that the area of largest production does not necessarily mean the largest deposits are located in the same country. The price fluctuation for a period of 6 months was available, also showing a great range of difference in prices between elements.

REE consumption

In contrast to the negative impacts of mining and refining, REE consumption positively impacts sustainable development, when used for sustainable energy technologies. Increased sustainable energy production and consumption through improved efficiency is only possible with different REE dependent applications (see table 1).[27]

The intermediate product used for end-user applications are for example permanent magnets, fuel cell alloys and REE-phosphor combinations. REE-containing permanent magnets are mainly used in wind turbines, and electric motors for e-mobility. The advantages for wind turbines are principally reduced maintenance needs as usually no gearbox is required, the theoretical higher efficiency, [28] and a strong magnetic field with strong resistance of demagnetization.[29,30,31] Miniature permanent magnets are also used for small electronics (power tools, mobile phones, hard disks, displays, etc.). Additionally, hybrid vehicles often make use of fuel cell alloys containing REEs.[32] Furthermore, the combination of REE and phosphor is needed for energy efficient lighting, such as LEDs.[33,34]

As the share of these technologies is expected to grow, REE demand is assumed to be of a higher importance in the future as well. For example, since the market introduction of the neodymium-based permanent magnets in wind turbines in 2003, they already gained a market share of 14%.[35] Due to the advantages, several wind turbine producers state that this will be their first choice technology. [36] Furthermore, if in the near future the electric car market expands as expected; several REEs will also become increasingly important.[37]

REE Recovery

Losses of REEs occur at each stage of the REE life cycle.[38] Therefore, the potentials of REE recycling, including collection systems, waste handling and processing have to be considered for a sustainable natural resource management.[39] Several authors stress the importance of recycling in order to support supply security, however, at present this is still under research.[40] Recycling during the manufacturing phase hardly exists, but not at all in the end-of-life phase.[41,42] [43] In this regard several aspects have to be taken into account. First, because full recovery is not feasible and a growing demand is expected, recycling should be done for the sake of environmental concerns, rather than to reduce the dependency on foreign supply.[44] In that regard recycling can reduce the negative impact of mining on the environment, especially concerning radioactive waste.[45] [46] Second, the relatively small amounts of REEs in electronics and rather low prices makes recovery economically and technologically inefficient.[47] Hence, it is suggested to focus on the

FACTS & FIGURES

- A REE is never minded alone, either with other REEs or other materials, such as iron or uranium.[viii]
- Since 2003 neodymium-based permanent magnets have gained a market share of 14%, which is expected to increase in the future.[ix]
- It can be assumed that at least 1000t of neodymium is globally required in total in the next 40 years regarding the various permanent magnet applications.[x]
- From February 2011 to December 2011 the price for dyprsoiumoxide increased by almost a factor ten from 375$/kg to 3500$/kg.[xi]

recycling of applications in which REEs are used in relative large quantities, such as neodymium and dysprosium in permanent magnets for wind turbines and automobiles.[48] [49]

REE market

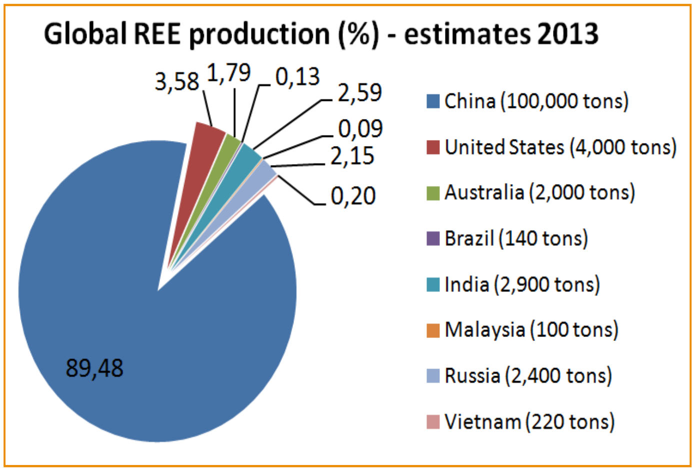
In order to identify potential supply risks it is necessary to take a look at the value chain of REEs as a whole. So far this has rarely been done in scientific literature.[50]

From the time China entered the REE market in the 1980's their market share rapidly increased to 89% in 2013,[51] based on U.S. Geological Survey estimates (see figure 1).[52] The small number of producers outside China is connected to the high economic risk of investing in REEs, which is connected to the very small tonnages that are actually produced.[53,54] Still, there are additional mining projects in various countries at an early planning stage, such as Canada, Greenland, Kazakhstan, Kirghizia, Malawi6. However, due the time lag between initiation and actual REE production (five to twelve years), the market is slow in responding to sudden demand increases.[55] Therefore, short-term shortages can occur[6, 23]. This applies especially be critical for HREEs, as they are generally less abundant than LREEs[4] and only mined in the South of China.[56,57,58] A shortage could for instance happen for dysprosium towards 2020, potentially resulting in a hampered development of the e-mobility market.[59]

Except for the short REE price peak in 2011,[60] prices are relatively low considering the costly production technology and the connected environmental risk (see table 1).[61] Externalities, such as the impact of radioactive waste, are not incorporated in the current price. In literature the peak price developments in 2011 are related especially to the sharpening of Chinese export quotas in 2010. For 2013 these quotas were 93,800 tons (t) for production and 31,000t for export, which caused tensions between REE exporting and importing countries.[62] It is supposed that the decision for the export quota was not primarily guided by geopolitical motivation. Instead, the restrictions are supposed to focus on environmental protection and industry development, as export allowance for exporting companies is only given when an environmental assessment is passed.[63] Another aspect of the REE value chain is illegal mining, which is said to be driven by the export quotas[64] and has an influence on REE prices. In 2009 for example, 20,000t of illegally mined rare earth oxides were exported from China,[65] which was expected to amount to a market share of 20% of global REE demand.[66]

In summary, the REE market is relatively small and opaque, with low, volatile prices, embraces mining and separation technologies, which are costly, complicated and highly detrimental to the environment.[67]

Figure 1: Global REE production (%) per country[xii].



Overview

The different aspects mentioned above have to be taken into account when identifying REE specific indicators for criticality. First, in connection to environmental implications, the avoidance of negative environmental impacts during production remains an enormous challenge, especially with regard to the radioactive tailings and other environmental contamination. In regard to recycling, technologies are being developed, but under current price conditions it remains a challenge to implement this on an industrial scale required for sustainable natural resource management. Second, REEs are of great economic importance in connection with sustainable energy technologies, both for sustainable energy production and increased energy efficiency. Third, the opaque market remains a bottleneck for providing supply security, resulting in supply risks.

Taking the REE life cycle and value chain into consideration, there are several additional critical points, which should be taken into consideration. It should be noted that while this science digest considers REEs as a whole, in reality they cannot be generalized due to their individual element characteristics. As a result, there is no single REE market.[68]

While the REEs debated in this report comprise both LREEs and HREEs, HREEs are considered the most critical, especially with regard to their limited production sites. The value chain remains nearly impossible to track, for several major reasons. There is a lack of quantitative scenarios for possible supply,[69] and no monitoring systems on production exist. Furthermore, predictions on supply are very uncertain[70] and it was found that data often varies or even contradicts. In order to ensure sustainable development – keeping in mind the possibilities REE applications offer and the necessary environmental protection – these critical points should be accounted for while addressing the major issues presented.

Goals & targets

The REE issue is strongly linked to the production and consumption of renewable energy (SDG 7, 7.2) and energy efficiency (SDG 7.3). However, to support and increase sustainable energy production, the supply of REE should be ensured. In order to do so, considerations mentioned in the scientific debate should be taken into account, which mainly link to resource efficiency (SDG 8.4, 9.4), sustainable consumption (SDG 12, 12.2) and minimizing environmental impact (SDG 12.4). These considerations have led to the following recommendations.

Recommendations

- Consideration of REEs on a more individual basis is recommended, due to the varying importance in application, production and or abundance. Thus a primary focus can be put on a number of elements of major importance, for example the HREEs.

- The creation of an international platform is recommended, in order to promote dialogue between nations, encourage international co-operation and increase transparency.[71]

- To overcome the major constraints of lack of transparency and data gaps, we suggest this platform takes up responsibility for the initiation and funding of a database for the collection of statistics and other data on REEs.[72]

- To support this database we recommend to strengthen scientific research through funding, in two major fields; (1) quantitative scenarios for REE future supply and deposits,[73] and (2) REE recovery, including related material flows, collection schemes, financial risks and possible legal frameworks.[74,75]

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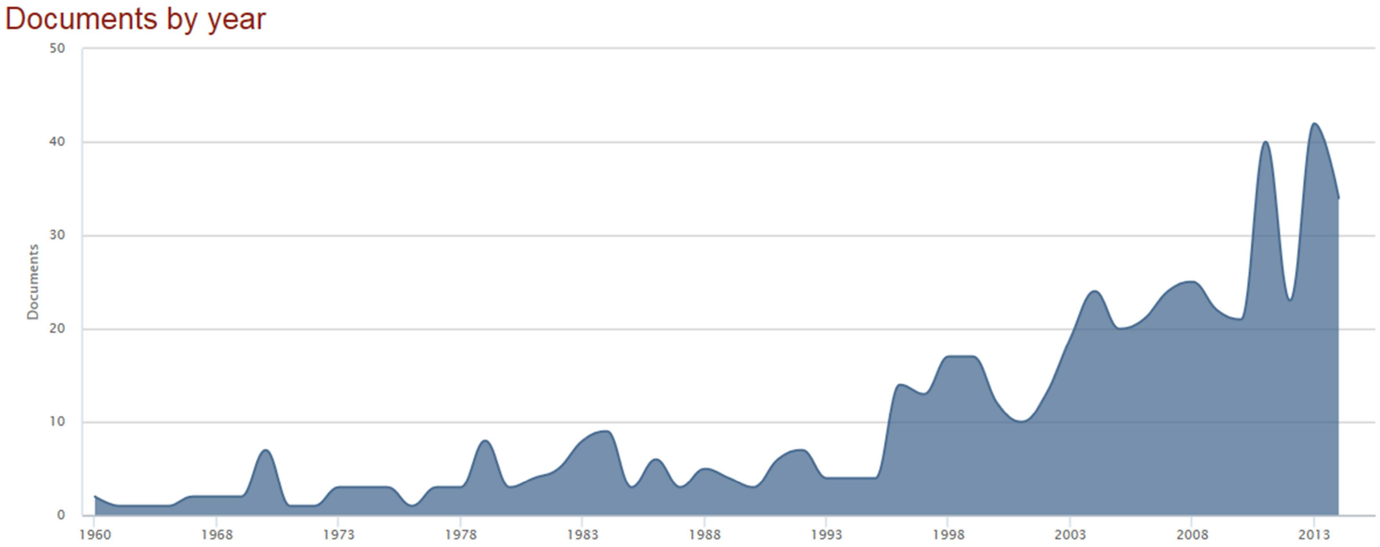
Appendix: Research methodology

Rare earth elements as a topic for the Global Sustainable Development Report was selected on the one hand as a result of personal interest in the topic and on the other hand on the assumption of its increasing importance for sustainable energy technologies. Throughout the process it became clear that this topic would be best described in the form of a science digest, instead of the intended financial mechanisms brief.

The same general methodology was used as stated in the general methodology chapter. For this topic literature research and interviews were used to investigate rare earth elements and their connection to sustainable development.

Initially the scientific search engine Scopus was used with the keywords *rare earth elements* and *rare earth metals*. By limiting the search on the subject areas social sciences and humanities, articles about chemical engineering or computer science were avoided, as this was not our focus. Therefore we narrowed down the search from 33,628 results to 533 results, containing of documents published the year 1960 onwards.

The keyword *Rare earth metals* gave 21,856 and 202 results respectively, from which 68 documents were from the last four years (2010). This interest peak in 2010 and 2013 also holds true for *rare earth elements*, as shown in graph below.

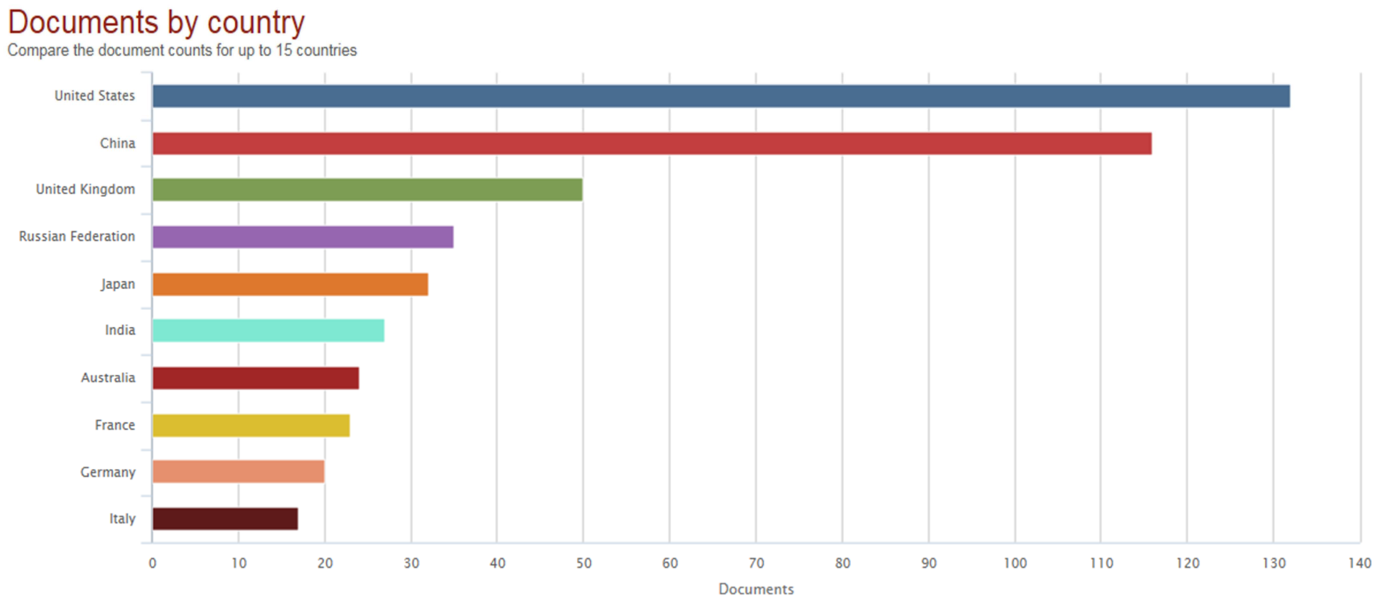


By analyzing the results in the documents-by-country graph below, it can be observed that most of the literature comes from the United States, followed by literature originating in China. In the broad search for all subject areas, this order changes with most Chinese results and United Stated as second.

To further find literature relevant for sustainable development, especially for renewable energy technologies, a combination of keywords was used. The search for *rare earth elements* and *renewable energy* resulted in 29 articles starting from 2000 with a major increase in articles published in 2011. Key articles used in this research were mainly found with this search option.

Besides Scopus, the global search engine and the library catalogue of the Wageningen University library was used to find additional literature, such as books ("Material for a sustainable future" and "Rare Earth Elements: A New Approach to the Nexus of Supply, Demand and Use: Exemplified along the Use of Neodymium in Permanent Magnets") and other peer-reviewed articles.

Furthermore, Google scholar was used as a search engine for a first literature research and to look for specific articles. These articles were especially chosen, because of their high frequency cited in other literature found. The literature research gave an good overview of the current research state of REEs, but also an insight in critical issues.



In addition to the literature research, interviews were conducted as a primary source of information on REEs. We started to look for potential experts, which were reachable in the Netherlands. Furthermore, by going through the literature we identified authors, who were often cited, published recent findings or statistical information, such as the British Geological Survey. Additional experts were found through the recommendation of already interviewed experts. Except from the interviews that were conduced in The Netherlands, most interviews were executed via Skype or phone. In total, five experts were interviewed, as listed in the table below. The information gained from these primary sources was very valuable and positively contributed to the content of this science digest. Through the direct contact with experts, some detailed issues could be clarified and different opinions were gathered.

Code	Expert
REE-1	Prof. Koop Lammertsma: Professor of Organic Chemistry; Faculty of Science at University Amsterdam; Netherlands Marissa de Boer: Post-doctoral researcher at the Faculty of Science (organic chemistry) at University Amsterdam; Netherlands *Interviewed on November 12, 2014, 10:00 (GMT+1)*
REE-2	Dr. Volker Zepf: Research fellow at the chair of Resource Strategies; Institute for Physics at Augsburg University; Germany *Interviewed on November 17, 2014, 10:00 (GMT+1)*
REE-3	Andrew Bloodworth: Science Director for Minerals and Waste; British Geological Survey (BGS); United Kingdom *Interviewed on November 21, 2014, 10:30 (GMT+1)*
REE-4	Dr. Patrick Wäger: Research fellow at the Organisational unit of Technology and Society at Empa research institute – Material Science and Technology , Austria *Interviewed on December 8, 2014, 10:00 (GMT+1)*
REE-5	Prof. Thomas E. Graedel: Professor of Industrial Ecology, Professor of Chemical Engineering, Professor of Geology and Geophysics, Director of the Center for Industrial Ecology at Yale University, United States Chair of Global Metal Flows Group, International Panel on Resource Sustainability, United Nations Environment Programme (UNEP) *Interviewed at December 9, 2014, 17:00 (GMT+1)*

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