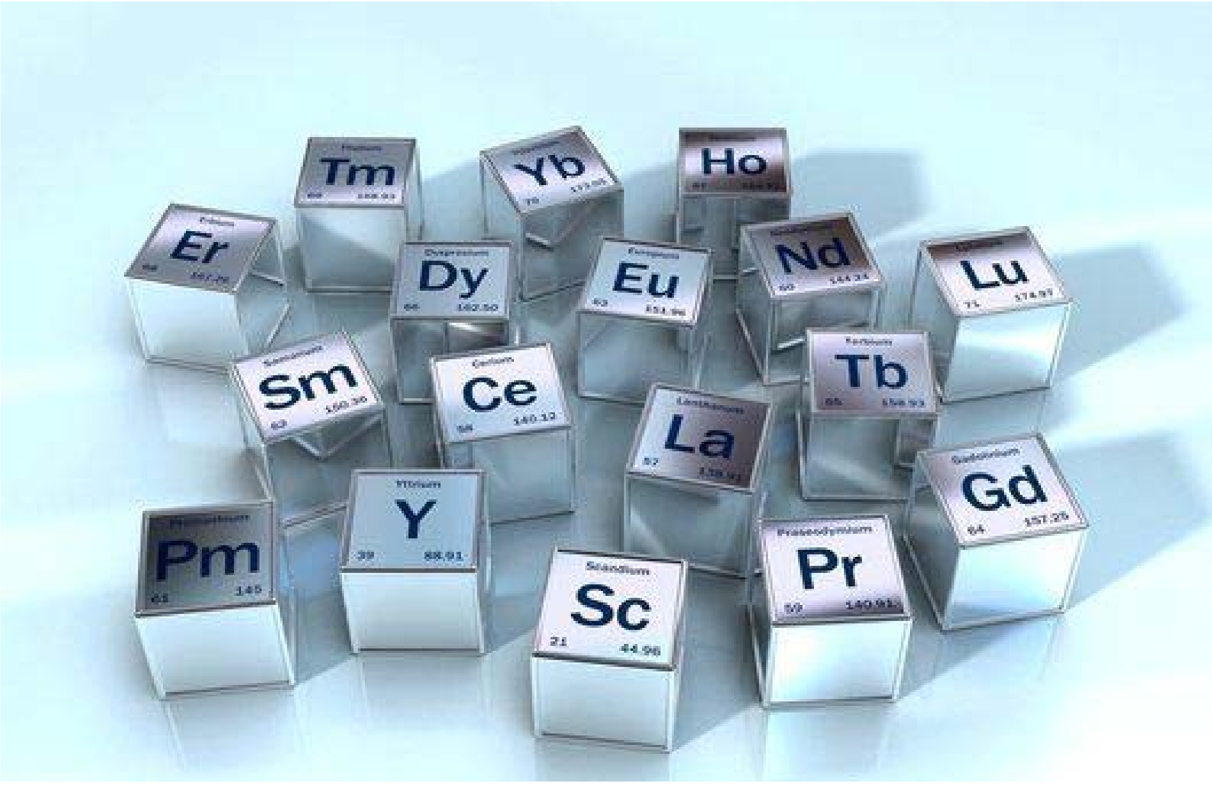
Scarcity of Rare Earth Elements



KNCV

a review commissioned by the
Royal Netherlands Chemical Society

The media have paid much attention to the scarcity of water and energy. Recently, scarcity of critical metals has become a matter of concern. This overview attempts to give a clear, unique, concise and objective analysis of all reports in the field of rare earth elements. It is commissioned by the Royal Netherlands Chemical Society (KNCV; the CMG section) to review the many recently published studies to give insight into the rare earth elements with respect to criticality, reserves, production, supply, application, urban mining and policy; with special attention to the Dutch policy strategies.

M.A. de Boer
Prof. dr. K.Lammertsma

24.06.2012

Samenvatting (Nederlands)

Schaarste van zeldzame aardmetalen

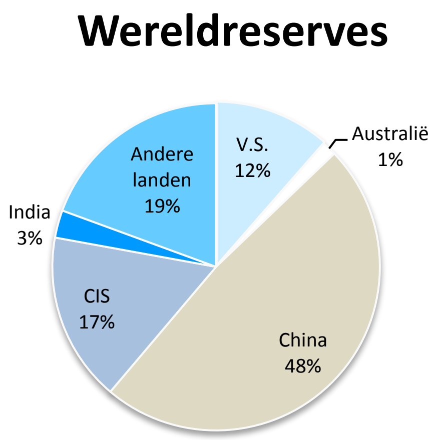
M.A. de Boer

K. Lammertsma

De zeldzame aardmetalen	
HREE's	
Holmium	Ho
Erbium	Er
Thulium	Tm
Ytterbium	Yb
Lutetium	Lu
Gadolinium	Gd
Yttrium	Y
Terbium	Tb
Dysprosium	Dy
LREE's	
Neodymium	Nd
Europium	Eu
Lanthanum	La
Cerium	Ce
Praseodymium	Pr
Promethium	Pm
Samarium	Sm
Scandium	Sc

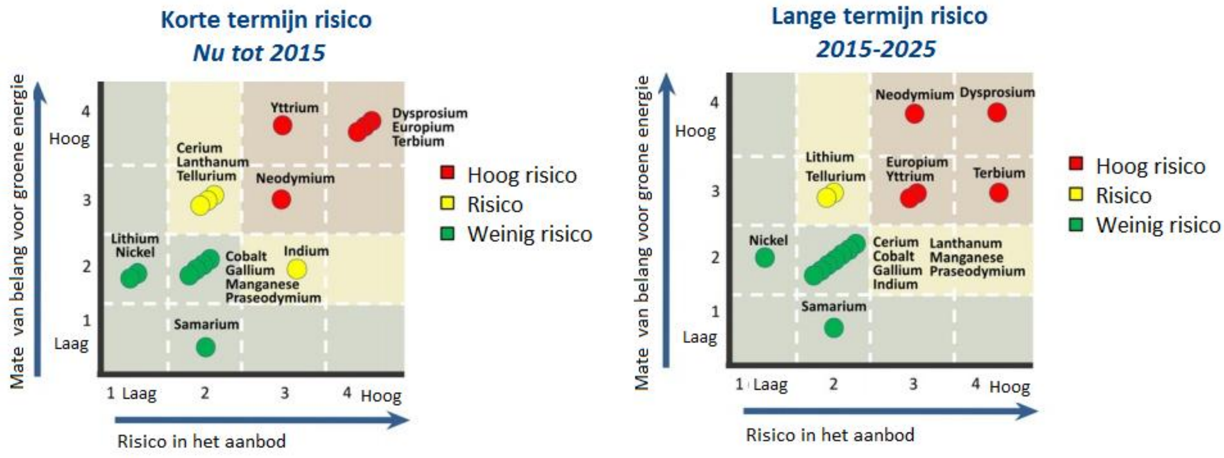
Materiaalschaarste staat volop in de aandacht vanwege de beperkte beschikbaarheid van zeldzame aardmetalen, ook wel REEs genoemd. De 17 REEs zijn cruciaal voor hightech technologieën in magneten, elektronica, efficiënte belichting, katalysatoren, keramiek en polishing materialen. De vraag naar REEs overtreft het aanbod door de bevolkingsgroei en de stijgende consumptie.

Ondanks de grote hoeveelheid REEs in de aardkorst (de bronnen), is maar een klein deel economisch mijnbaar (de reserve). De wereldwijde winbare reserve wordt geschat op 114 miljoen ton en bevindt zich in China (48%), de CIS (de vroegere Sovjet Unie), de Verenigde Staten en Australië. De Europese hoeveelheden zijn buitengewoon klein.



De 17 REEs zijn ingedeeld in twee groepen, de zware (HREEs) en lichte (LREEs) zeldzame aardmetalen zoals aangegeven in de tabel waarbij de vijf meest schaarse onderstreept zijn. Ook andere metalen naast REEs zijn schaars. De Europese Commissie heeft 14 elementen gedefinieerd als 'kritieke metalen' waarvan twee zeldzame aardmetalen zijn.

De wereldproductie van 134 kiloton REEs lag in 2010 voor 97% in handen van China. Tot 2007 was deze sterk gestegen waarna China de focus richtte op de duurzaamheid van de mijnen om de impact op het milieu te verkleinen, waaronder het sluiten van illegale mijnbouw. Om het binnenlandse aanbod van REEs veilig te stellen, hanteert China export quota's en belastingen die zullen stijgen tot in 2015. Hiermee ondermijnt China de wereldwijde vrije exportregels.



De 2011 DOE korte en lange termijn risico matrix (USGS)

De stijgende vraag naar REEs (een stijging van 8–11%), de dalende export van China en de geopolitieke afhankelijkheid hebben gezorgd voor het (her)openen van mijnen zoals Mountain Pass in Californië en Mt Weld in Australië. Het openen van een mijn vergt minimaal 10 jaar door de hoge investeringskosten, de strenge mijnbouw eisen aan mijnen, de moeilijkheidsgraad van het extraheren van de REEs uit de erts (0.1-10%) en de milieuaspecten, waaronder de radioactieve contaminatie bij het mijnen. Door de trage marktreactie wordt verwacht dat het aanbod van Terbium, Dysprosium, Praseodymium, Europium, Yttrium en Neodymium niet aan de korte termijn vraag zal voldoen; zie de figuur voor de DOE risico matrixes. Deze zeldzame aardmetalen worden vooral gebruikt voor wind- en zonne-energie en in permanente magneten (elektrische auto’s).

Door de complexiteit en de energiekosten zijn er (bijna) geen economisch rendabele recycle methodes (urban mining). De knelpunten zijn de inzamelmethodes, de hoge fluctuatie in prijzen, de lange levensduur van de producten en de niet optimale designs daarvan. Zo is het moeilijk om zeer kleine hoeveelheden te recyclen uit steeds kleiner wordende elektronische apparatuur. Recyclen verlaagt de onafhankelijkheid van geïmporteerde REEs. De stappen nodig voor het inzamelen en recyclen van zeldzame aardmetalen in Europa zijn een competentie netwerk, basisonderzoek, materiaalstroom analyses, het identificeren van afvalstromen, het integreren van huidige inzamelingsregelingen, meerdere pilots en financiële risico analyses, alles in een wettelijk kader. Naast recyclen is substitutie van de metalen van belang. Zolang die een lagere prestatie hebben zal de vraag naar REEs inelastisch zijn.

De prijzen voor zeldzame aardmetalen stijgen de laatste jaren extreem, soms met een factor 10. De grote vraag naar hightech en groene technologieën draagt bij aan deze prijsverhoging. De meest afhankelijke sectoren in Nederland zijn fabrikanten van transportmiddelen, metalen en metaalproducten, en machines. Nederland, als kleine afhankelijke speler, zou internationale politieke en economische samenwerking moeten omarmen, aangezien de onzekerheid van materiaalbeschikbaarheid een negatieve invloed kan hebben op de Nederlandse economie. Directe effecten zijn bijvoorbeeld stijgende kosten van Nederlandse producten door hogere materiaal import prijzen uit China. Nederland hanteert geen nationale restricties op het gebied van handel in grondstoffen, maar er zijn zorgen dat de beperkte beschikbaarheid van REEs een negatief effect kan hebben. Vooralsnog is er geen consensus over de aanpak tussen de verschillende Europese landen.

Zeldzame aardmetalen	Markt factoren		Politieke factoren		
	Kans dat de vraag snel stijgt	Beperkingen uitbreiding productie-capaciteit	Concentratie van het aanbod	Politieke risico's	Totale risico
Dysprosium	Hoog	Hoog	Hoog	Hoog	
Neodymium	Hoog	Medium	Hoog	Hoog	Hoog
Tellurium	Hoog	Hoog	Laag	Medium	
Gallium	Hoog	Medium	Medium	Medium	
Indium	Medium	Hoog	Medium	Medium	
Niobium	Hoog	Laag	Hoog	Medium	
Vanadium	Hoog	Laag	Medium	Hoog	Medium
Tin	Laag	Medium	Medium	Hoog	
Selenium	Medium	Medium	Medium	Laag	
Silver	Laag	Medium	Laag	Hoog	
Molybdenum	Medium	Laag	Medium	Medium	Laag
Hafnium	Laag	Medium	Medium	Laag	
Nickel	Medium	Laag	Laag	Medium	
Cadmium	Laag	Laag	Laag	Medium	

Het risiconiveau van de door de Europese commissie kritisch bestempelde metalen [23]

Summary

Rare earth elements (REEs) are important for green and high-tech technologies. They are used in magnets, automotive and industrial catalysts, energy efficient lighting, batteries for e-mobility, metal alloys, glass additives, electronics, ceramics and polishing materials. In varying degrees REEs are subject to supply disruptions in the short to medium term. The growing demand for REEs that result from the increasing world population and a rising world economy exceeds the current supply.

The 17 rare earth elements are divided into heavy REE and light REE (see insert; the most endangered ones are underscored). Some elements besides REEs are also becoming critical. The 14 elements identified as critical by the European Commission are tellurium, indium, tin, hafnium, silver, Dy, gallium, Nd, cadmium, nickel, molybdenum, vanadium, niobium and selenium.

The REE's

HREE's	
Holmium	Ho
Erbium	Er
Thulium	Tm
Ytterbium	Yb
Lutetium	Lu
<u>Gadolinium</u>	Gd
<u>Yttrium</u>	Y
<u>Terbium</u>	Tb
<u>Dysprosium</u>	Dy
LREE's	
<u>Neodymium</u>	Nd
Europium	Eu
Lanthanum	La
Cerium	Ce
Praseodymium	Pr
Promethium	Pm
Samarium	Sm
Scandium	Sc

Whereas there is no deficiency in the earth's crust of rare earth oxide (REO), the economic accessibility is limited. The global mineable REO reserves are estimated at 114 million tons which resides mainly in China (50%) the CIS (former Soviet Union), the United States and Australia. Of the current world supply of 124 kilo tons of REO a year China produces 97%. The production was increased until 2007, when China started to focus on the sustainability of mining and on reducing the environmental impact. Meanwhile, China has terminated issuing new mining licenses till 2015 and imposed export quotas and taxes, thereby undermining free trade rules.

The increased demand for REEs, the decreasing export from China, and geo-political concerns on availability contributed to the (re-)opening of Mountain Pass in California and Mt Weld in Australia. Other mines are slow to follow, because of the huge investment, the long lead time (ca. 10 years), and the environmental burden of mining and extracting REEs from the ore. As a result, the misbalance of particularly terbium, dysprosium, praseodymium and neodymium is expected to be a problem for at least the short term, also because there are no substitutes for these metals.

So far, there are hardly REE recycling methods, called urban mining, because of the complexity and energy cost. Decreasing the dependency on REEs, by finding replacements or increasing the efficient use, is another area of current focus.

The prices of REEs have become volatile in recent years, sometimes changing by a factor of 10, which is a matter of industrial concern. In the Netherlands it affects manufacturers of transport equipment, metals and metal products, and machinery and equipment. The Netherlands has no restriction on the retail in materials but there are concerns that the limited availability of REEs has a negative economic impact. This also applies to the European Union as a whole, but there is as of yet no consensus about an approach to remedy material scarcity.

Introduction

Seventeen elements in the periodic table are known as rare earth elements (REEs). They are important for green and high-tech technologies and used in magnets in wind turbines and electric vehicles, automotive and industrial catalysts, photovoltaic thin films and energy efficient lighting, batteries for e-mobility, metal alloys, glass additives, electronics, ceramics and polishing materials.[2] Rare earth elements aren't as rare as the name suggests, as is illustrated in Figure 1,

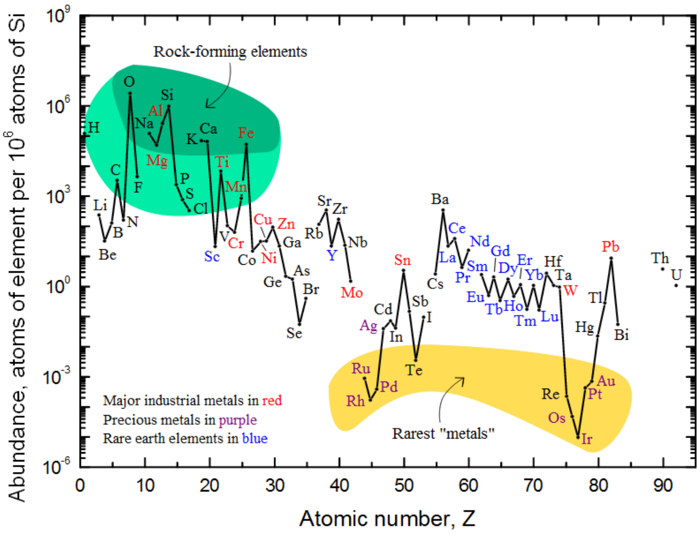


Figure 1. Relative abundance of rare earth elements

but the low concentration in which they are present in the earth's crust makes economic exploitation difficult. The elements have a risk of supply disruption in the short to medium term. Their criticality has been measured by the economic importance versus availability (supply risk). The five rare earth metals, dysprosium, terbium, europium, neodymium and yttrium may also have a high risk of supply disruption in the long term. They are used in magnets for wind turbines and electric vehicles or energy efficient lighting and other technologies of the EU's Strategic Energy Technology plan (SET-plan).[23] The elements cerium, indium, lanthanum, and tellurium are considered near-critical elements.

The economic impact of the growing scarcity of REEs has been the reason for the United States and the European Union to address their strategic positions on the criticality of these elements. This is illustrated in Figure 2 for the short- (3 years) and medium term (13 years) supply risk in relation to their importance toward clean energy, as reported by the U.S. Department of Energy.

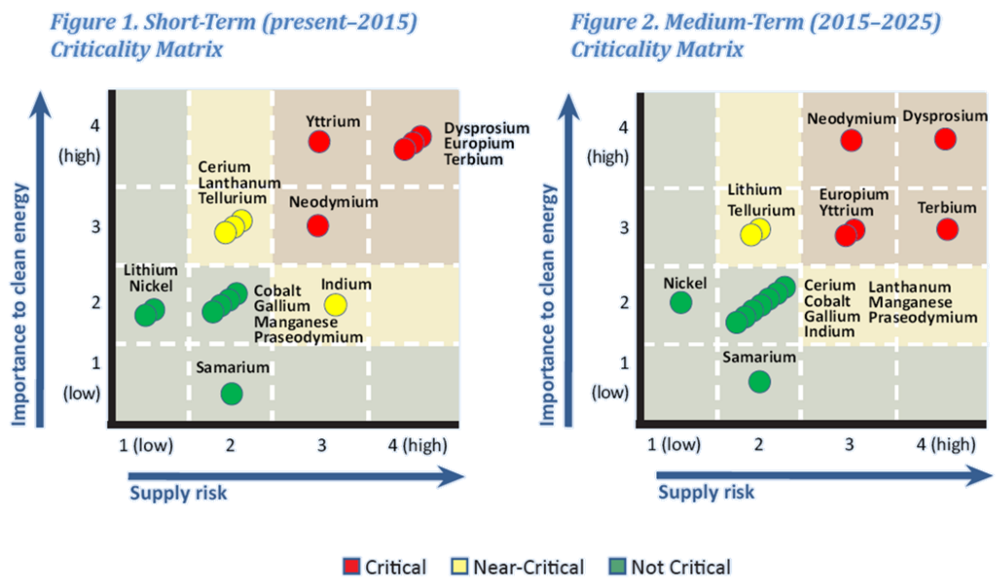


Figure 2. 2011 DOE short- and medium-term criticality matrix.(USGS)

Rare Earth Elements

The 17 rare earths (see figure 3) elements are divided into two groups, the heavy ones (HREEs) and the light ones (LREEs), without well-defined boundaries. All but scandium and yttrium are lanthanides. Their uses are given in the Application section. The underscored elements in the figure are the mist endangered ones (vide infra).

Figure 3:
The REEs

HREEs	
Holmium	**Ho**
Erbium	**Er**
Thulium	**Tm**
Ytterbium	**Yb**
Lutetium	**Lu**
<u>Gadolinium</u>	**Gd**
<u>Yttrium</u>	**Y**
<u>Terbium</u>	**Tb**
<u>Dysprosium</u>	**Dy**
LREEs	
<u>Neodymium</u>	**Nd**
Europium	**Eu**
Lanthanum	**La**
Cerium	**Ce**
Praseodymium	**Pr**
Promethium	**Pm**
Samarium	**Sm**
Scandium	**Sc**

Critical Metals

The European Commission considers REEs to be critical, meaning that the risk of supply shortage combined with their impact on the economy is higher compared to most other raw materials. Three indicators have been used to define criticality, namely the *economic importance* of the raw material, *the supply risk* and *the environmental risk*. Several ranking systems agree that some REEs are critical or near-critical in terms of supply risk and their importance for green technologies. Synonyms for the name REEs are critical (rare) materials, specialty metals, green minor metals, and technology metals.

Besides the REEs, there are other metals considered to be critical. The European Commission identified 14 metals that have a development rate of more than 1 percent of the current world supply. These 14 elements are shown in table 1. Of these, neodymium, dysprosium, indium, tellurium and gallium are considered to be most at risk, because of the expected rapid growth in demand. These five elements are used extensively in wind and solar energy technologies. However, in spite of possible substitutes, it is not suggested that technologies with potential bottlenecks should be discouraged.[23]

Table 1. Level of risk of the critical metals (European Commission) [23]

Metal	Market factors		Political Factors		
	Likelihood of rapid demand growth	Limitations to expanding production capacity	Concentration of supply	Political risk	Overall risk
Dysprosium	High	High	High	High	
Neodymium	High	Medium	High	High	High
Tellurium	High	High	Low	Medium	
Gallium	High	Medium	Medium	Medium	
Indium	Medium	High	Medium	Medium	
Niobium	High	Low	High	Medium	
Vanadium	High	Low	Medium	High	Medium
Tin	Low	Medium	Medium	High	
Selenium	Medium	Medium	Medium	Low	
Silver	Low	Medium	Low	High	
Molybdenum	Medium	Low	Medium	Medium	Low
Hafnium	Low	Medium	Medium	Low	
Nickel	Medium	Low	Low	Medium	
Cadmium	Low	Low	Low	Medium	

To meet the European sustainability goals for 2020, the Strategic Technology Plan recommends enhancing research, development and demonstration in key low carbon technologies.[1, 27] An important component in this plan is the supply of critical metals to produce renewable resources and to improve energy efficiency. A reduction in the supply of critical metals could be an obstacle to achieve the targets.

The pressure on materials is increasing because of the growing world population and the rising world economy, which is for the third world countries much more (~6%) than for the United States and Europe. The overall increase of global welfare results in a changing consumptive behavior with a higher demand on materials. Suppliers may not to be able to keep up with the demand in spite of the increased production, causing higher prices and a larger market uncertainty.[1]

Reserves

How much of a material is physically present in the earth's crust (the resource) is less important than the amount that can be extracted (the reserve base). Most important is the part of the reserve base which can currently be economically extracted (the reserve). Materials are mechanically mineable as minerals when concentrated as clusters of multiple elements. Based on their global amount, supply is not a problem, but accessibility is. Mining operations are technically and economically only feasible when the minerals have a high ore concentration and when there is enough output to regain the high investment cost. A limitation is the depth in which the minerals are located, which is up to 50 km, while the deepest mine goes only as deep as 3.7 km. Much of the globe is covered by oceans, nature reserves and populated areas, which are also limitations for extracting minerals. Thus, whereas there is no scarcity of minerals in the earth's crust, the limitation in mining makes them scarce.[5]

Figure 4. World Reserves REE (source USGS 2012).

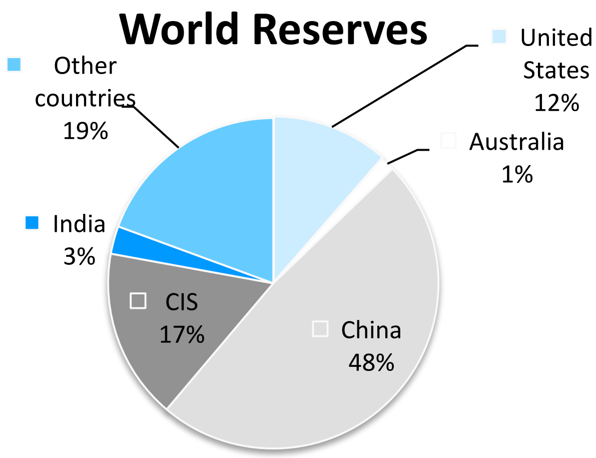


Table 2. World Reserves in million tons (USGS 2012)

United States	13
Australia	1.6
China	55
CIS	19
India	3.1
Other countries	22
Total	**114**

The estimated global reserves of all rare earth elements listed in Table 2 amounts to about 114 million metric tons. The estimated reserve base is 154 mtons (million tons). The reserve base defined as the marginally feasible reserves, will increase over the coming years because the rising REE prices will lead to searches for new deposits. The USGS estimate of the rare earth reserves by country is given in Table 2; countries like Canada, Greenland, South Africa, Malawi and Vietnam with significant reserves are listed under other countries.[6] Figure 4 gives an overview of the REEs reserves of which nearly 50% is located in China. Some REEs are more locally found than others.[4]

It is important to realize that the USGS and the Chinese, Australian and Canadian institutions have different definitions for reserve, reserve base and resource. This is a limitation in providing a comprehensive overview of the different national reserve and resource statistics. Whereas attempts are made to harmonize the data, this has not yet been accomplished. The uncertainty of reserves is illustrated by the Chinese REO reserves, which were estimated at 38 percent (36 million tons) of the world total in 2008 but at 50 percent (55 million tons) in 2012.

Reserves in China

China has indicated that its industrial REO reserves are 55 mtons.[7, 29] More than half of this is located in Inner Mongolia and Bayan Obo where the world's largest rare earth mine is found. The REE composition of bastnaesite, which is the most common mineral in Bayan Obo, is shown in Figure 5.

The light elements La, Ce, Pr, Nd, Sm and Eu are generally mined in the north of the country, while in the south the ores contain more of the middle and heavy metals Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc, Y. The materials mined in various Chinese provinces and their ore grades are shown in the Table 3.[30] Average ore grade from mines are around 1 – 10 %. [34]

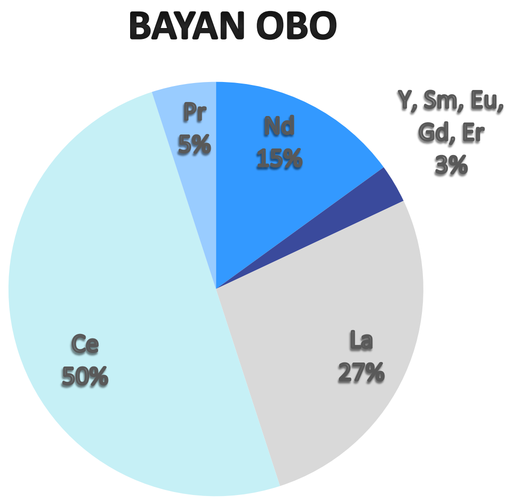


Figure 5. REE composition at Bayan Obo in 2006 (Wang).

Table 3. Ore grades in Chinese provinces (Lin 2009).[30]

Province	Grades in % REO	REE
Inner Mongolia, Baotou, Bayan Obo	6	Light REE
Seven provinces, Southern China	0.1 – 0.3	Middle and heavy REE
Sichuan	6 – 8	Light REE
Shandong	7 – 10	La, Ce, Pr, Nd

Reserves in Europe

Currently, there is little information about rare earth deposits in Europe. There has been a comprehensive evaluation of REE resources in Britain (The British Geological Survey 2010 BGS). After a series of tests, no economic potential was found, but exploration activities may be possible in Ireland.[9] Rare earth output of up to 1.4 ktons per year is feasible as by-product of iron mining in the north of Sweden. Nörra Kärr, South Sweden, has a mineral resource which consist of 327 ktons of REO with an average grade of 0.54%. A German deposit in Saxony probably contains 40 ktons of REO with an average grade of 0.5%.[10] There are also reserves in Norway and Turkey.[11] In contrast to the current production of China, around 130 ktons/year and a reserve of 55,000 ktons, the amount of REO which could be economically mined in Europe is very small.

Reserves of light and heavy rare earths elements

All REO deposits contain more LREEs than HREEs with yttrium being the most abundant element. No data on global amounts are available. The major share of HREEs outside of China is found in Australia (Dubbo Zirconia), Greenland (Kvanefjeld) and Canada (Thor Lake) and is estimated at around 0.8 mtons; for the LREE reserves this is 9.3 mtons. The three 'rarest' REEs are all HREEs, namely terbium, lutetium and thulium.

Production & Supply

Production

The amount of REO mined by each country is just a fraction of its estimated reserves (Table 4). The global production of REO was 134 ktons in 2010, which is only a fraction of common metals like aluminum (39 mtons). Nevertheless, the world demand for REO of 136 ktons for 2010 exceeded the supply. The estimated demand for 2015 is 185 ktons. Even though China is estimated to have at most 50% of the world's reserves in REO, it is dominant with 97% of the production of REE.

Table 4. Mine production, shares and reserves in ktons (HCSS and USGS 2012).

Country	**Mine production** (in ktons of REO)						**Share**	**Reserves**
	2005	**2006**	**2007**	**2008**	**2009**	**2010**	**2010**	**2010**
China	119	119	120	120	120	130	97,3%	55,000
India	2.7	2.7	2.7	2.7	2.7	0.55	0,4%	3,100
Brazil	NA	0.73	0.65	0.65	0.65	2.7	2%	48
Malaysia	0.75	0.2	0.38	0.38	0.38	0.35	0.3%	30
World total	123	123	124	124	124	134	100%	110,000

Most open mines were located in the USA until the mid-1980s, when China started to open its mines. In the ensuing years the production went entirely to China as the US mines closed for environmental and economic reasons (Figure 6).[12] The production in China increased from 73 ktons in 2000 to 120 kilo tons of REO in 2007 after which it stayed constant with a modest increase in 2010. Of this some 45 ktons is mined from the so-called "ion adsorption deposits'', which are rich in HREE. These deposits are limited, which enhances the pressure on these reserves.[7] Figure 7 shows the partition of rare earth oxides produced. China works on improving the rare earth industry to lower the environmental impact, increase efficiency, close regulation gaps (illegal mining), optimize management practices, and will not issue mining licenses for new mines until 2015 to improve current mining.[13, 14]

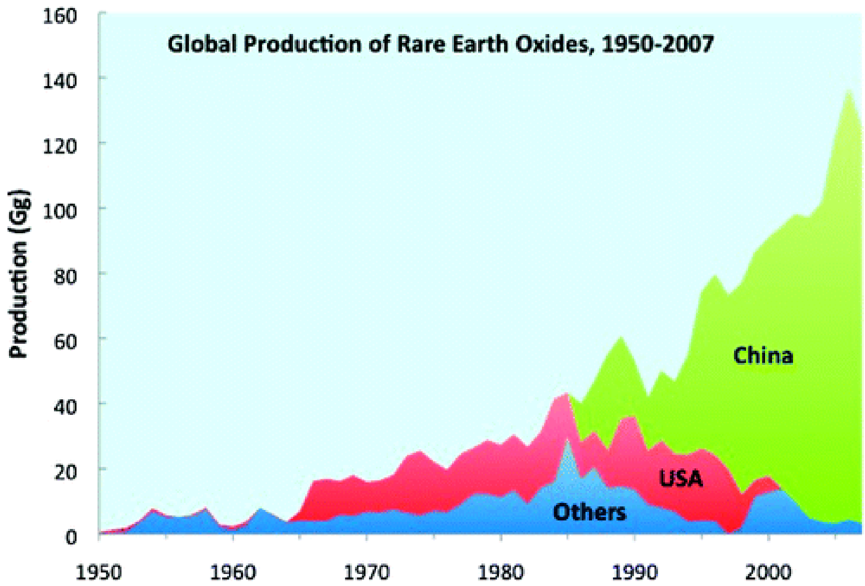


Figure 6. Global production on REO. 1950 – 2010 (USGS).

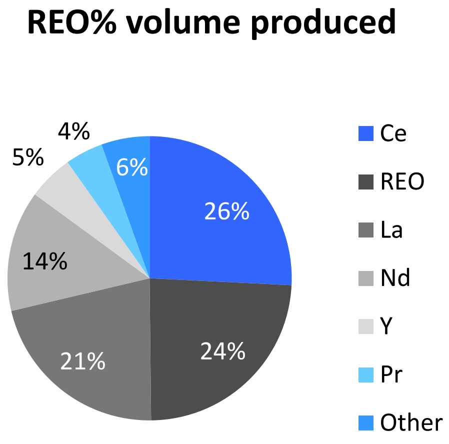


Figure 7. The ratio of the produced REE (Source: IMCAO).

Due to the high worldwide demand for REEs and the limit in Chinese exports, several mines outside of China will be (re)opened and there are advanced plans for additional ones. Mines to be re-opened in the near future (presumably 2-4 mines in 2014) are Mountain Pass in California, the Mt Weld in Australia and Hoidas Lake in Canada.[34] Each mine will produce about 20 ktons of REO annually. Planned projects are underway in Australia, Canada, USA, India, Kazakhstan, Kirghizia, Malawi, South Africa, Vietnam and Madagascar. This catching up is slow, in part because for some countries the know-how on separating REEs is limited, albeit that the mining process itself is similar to that for other metals.

The time span needed to set up a new rare earth production project or reopening a closed mine is around 11 years. The minimum time before actual production is between 6 and 10 years[9] of which about four are needed for studies, tests and pilots; one to install the mining equipment; two for installing the concentration plant to enrich the low-grade ore; and four years for installing the rare earth processing plant. The approval procedure also takes several years but usually runs parallel to the project development. The time span from the discovery of the mine until approval to produce varies from 5 to 50 years.[4] The high investment costs of new mines and production plants are also an important aspect. The investments for Mountain Pass, USA, Lynas (Mt Weld, Australia), Arafura Resources (Nolans, Australia) were each more than US$ 500 million (more than 390 million Euro).

Production quotas

China is not only the world's main exporter of REEs, it is also the only country that can provide rare earth products of all grades and specifications. The export of REO in 2009 was estimated at 48 ktons with an additional 20 kilo tons from the illegal circuit. This is a decrease of 11.8 percent compared to 2008.[34] China announced in 2011 that the export quota will reduce to 30 kilo tons with a total production of 94 ktons. In 2012-2015 more strict export quotas are imposed and the determination of the production of 3 mines of the total 8 mines in China, responsible for almost 40 percent of the Chinese REEs production. These restrictions led to an increase in the price of most rare elements. China does not only produce almost all the rare earths, it has also an increasingly dominating role in the manufacturing of most of the final products; the government stimulates companies to generate high tech value to the process chain.

Even though China is the biggest player in the production, Japan also has the ability for some rare earth processing. Even in Europe there are industrial activities on rare earth refining and processing, especially for semi-finished and finished products like magnets and lighting systems.

Import

In 2008, 78 ktons of REO were imported by the EU, USA and Japan of which 71 ktons came from China (Table 5). The 2010 global REO demand is shown in Figure 8 and per sector in Figure 9. The three main EU importers are France, Austria and the Netherlands.[20] Currently, the demand on elements is inelastic, because the substitutes are not readily available and will take a long time to match market demand. The demand of rare earth elements is expected to raise 8-11% per year.[34]

Table 5. Share of imports from China in 2008 in ktons

	Total imports	Imported from China	% total import
EU 27 [15]	23	21	90%
USA4	21	19	91%
Japan [31]	34	31	91%
Total	78	71	91%

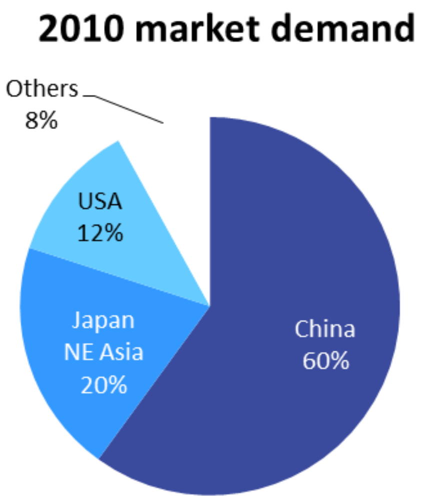


Figure 8. The global demand of REO (Source: IMCOA)

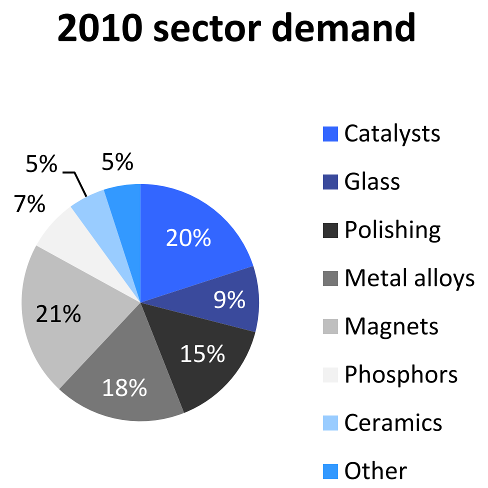


Figure 9. REO demand in terms of economic value (Source: IMCOA 2010)

Future supply

The future supply of REO will depend on:

- The development of the total Chinese production
- The development of the Chinese export quota
- Progress in installation works for Mountain Pass (USA) and Mt Weld (Australia) - short term
- Progress in installation works for other mines - long term

The supply forecasts for China for 2014 differ substantially. The estimate by Lynas of 114 ktons, with 4 ktons coming from recycling, is much less than the 160 to 170 ktons by Kingsnorth (table 6).[16, 17] For comparison, the production in 2008 was 125 to 140 ktons.

The forecasts for the HREE production are more uniform. The estimates range from 30 to 45 ktons of REO, which means that the current production will not rise and could even decrease.[7, 16, 17] Only Mountain Pass and Mt. Weld will soon be in production and are expected to provide each around 20,000 tons of REO in 2014.

The projected demand for 2014 for the elements terbium, dysprosium, praseodymium and neodymium is higher than the estimated supply (Table 6). This may lead to shortages for permanent magnets for wind turbines and hybrid and electric vehicles. Consequently, options for substitution of permanent magnets have to be considered. The potential shortage of neodymium and lanthanum may limit the production of NiMH batteries, necessitating substitution by Li-ion batteries. Shortages of europium and terbium affect the production of energy efficient lamps and displays also because of the lack of substitution. Lanthanum is an indispensable element in catalysts for petroleum refining and processing for which there are no short term substitutions.

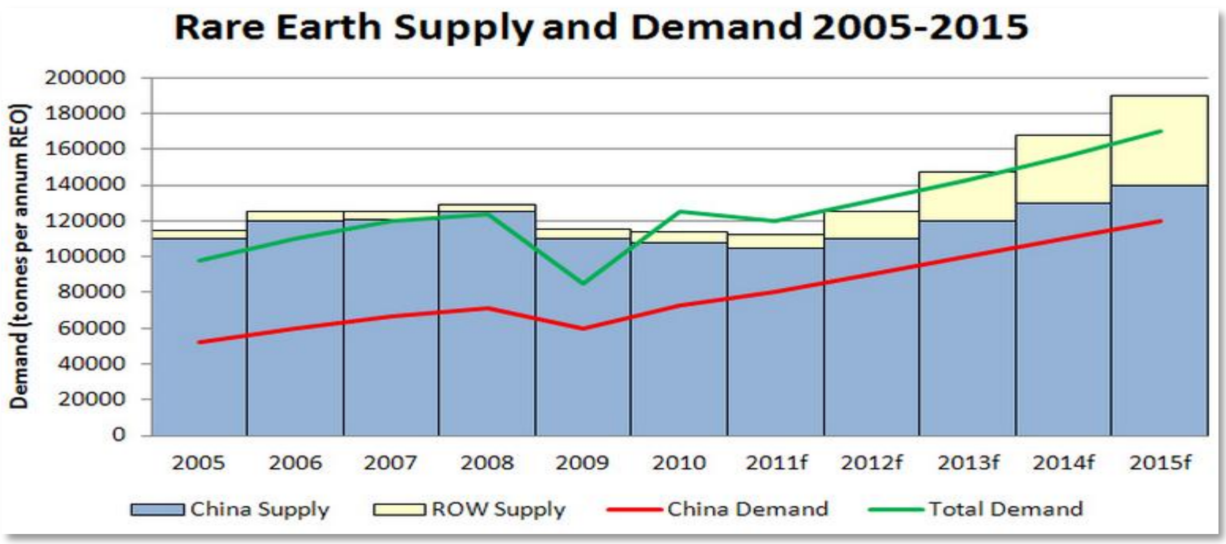


Figure 10. The supply and demand of REE 2005-2015, IMCOA 2011 (Kingsnorth)

Table 6. 2014 projected supply of REO and REEs (in kton/y).[16, 17, 20]

REO from China and elsewhere				**REE supply and demand** (in ktons/y)				
	Kingsnorth	**Lynas**			**Kingsnorth**		**Lynas**	
China				**Elements**	***Supply***	***Demand***	***Supply***	***Demand***
Mining	160–170	100		La	52–57	50– 55	43.4	57.1
Recycling		4		Ce	80–85	60– 65	66.5	59
Total	160–170	104		Tb	0.4–0.5	0.4–0.5	0.3	0.6
				Dy	1.8–2	1.9–2.3	1.7	2.8
Elsewhere				Y	9–13	10–14	9.5	10.7
Mountain Pass	20	20		Pr	10	7.9	9.1	16.1
Mt. Weld	21	22		Nd	33	34.9	31.2	45.4
Nolans Bore	-	-		Sm	4	1.4	3.5	1.2
Thor Lake	-	-		Eu	.9	0.9	0.5	0.6
Others		12		Gd	3	2.3	2.3	1.4
Recycling		1.8		Er	1	0.9	n.d.	n.d.
Total	41	55.8		Ho, Tm Yb, Lu	1.3	0.2	n.d.	n.d.
Total World	**190–210**	**169.8**		***Total***	**190–210**	**170–190**	**169.8**	**194.9**

* The estimated demand of the blue shaded elements exceeds that of the supply.

Market dynamics

The prices of many REEs have been highly volatile for some time and have fluctuated by a factor of up to 10. The demand for these metals has grown more rapidly than that for commodity materials largely due to the growth in clean energy technology and consumer products like cell phones, computers and panel televisions. The growing world population will keep REE prices under pressure even as new supplies come on-stream. These prices respond only slowly to the increasing demand due to, e.g., a lack of available capital and the long lead times to start new mines. Companies do adapt to the market dynamics by protecting themselves from price volatility and scarcity by taking defensive measures.

Figure 11. Price Index of REEs.[33]

Business

The Dutch industries with the highest dependency on critical materials are the manufacturers of transport equipment, of metals and fabricated metal products, and of machinery and equipment.[25] Several companies use rare metals in their products or deal with rare earths in another part of the business chain. They are sensitive to the reliability of rare metal supplies as scarcity is a cost to their business, but display a limited awareness among their stakeholders. By and large, all industries perceive mineral and metal scarcity as a pressing issue.[18]

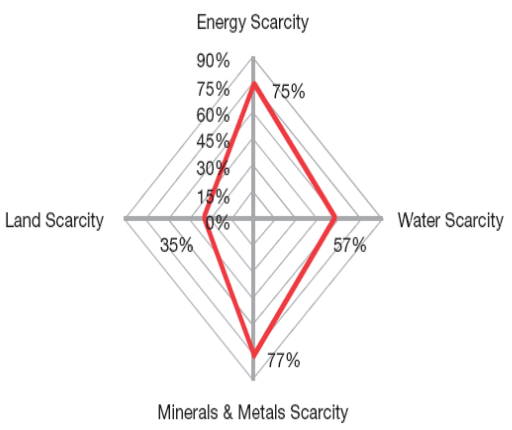


Figure 12. Relevance (in %) of the four scarcity topics as perceived by Lynas 2010

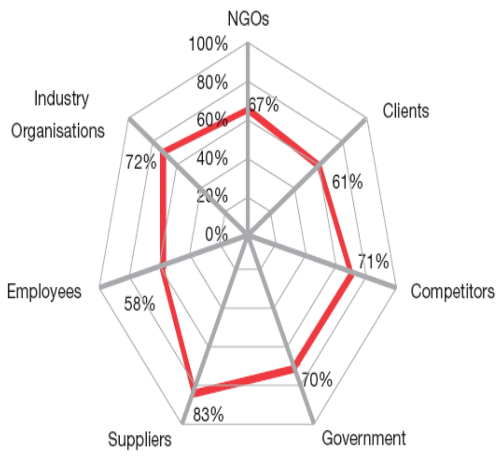


Figure 13. Stakeholder awareness of minerals and metals scarcity as a pressing issue, as perceived by respondents, Lynas 2010

Rare earth metals and the environment

Mining of REO entails environmental and sociological risks. For example, all monazite deposits contain thorium in significant amounts. Besides the typical contamination of soil, the main risk are the tailings, which are waste products consisting of a mixture of small-size particles, waste water and flotation chemicals that result on extraction of the mined ore. Tailing dams can overtop by storms, poor construction and seismic events, leading to emissions of, for example, thorium, uranium, fluorides and deposits containing radioactive materials, which increases the risk of radioactive dust and water as byproducts.

Figure 14. Bayan Obo REE mine in China

Chinese rare earth mines are known to cause environmental damage (Figure 14). By installing new technologies and taking other measures, the government tries to reduce the environmental impact of the mines. Another goal of the Chinese government is to reduce illegal mining, which causes the most serious damage to the environment, but also attempts are made to increase the efficiency and treating the products with more care.

A concern is also the sustainability of new mines emerging outside of China. The high demand for REEs and the pressure to start new mines can lead to inadequate environmental standards. For example, there are concerns about the Kvanefjeld deposit in Greenland.

Application

REEs are raw materials used for a multitude of products, as summarized in Figure 15.[20]

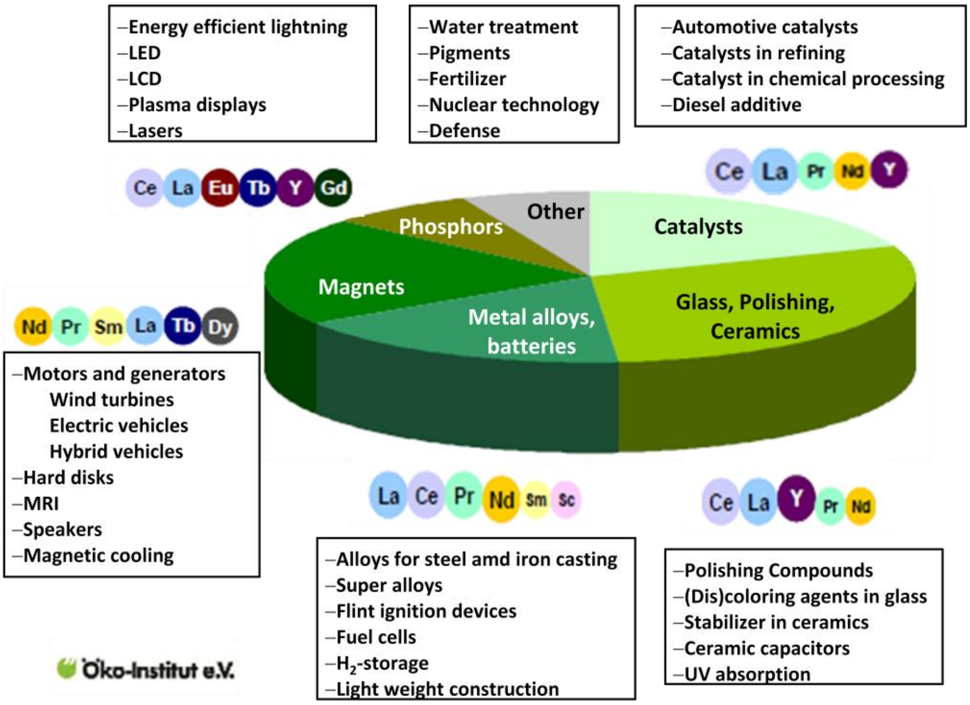


Figure 15. Applications of REEs. [20]

Established research institutions have not yet made an in-depth material flow analysis for REEs. The limited available data indicates that 30% is used for glass polishing and ceramics sectors, 20% for permanent magnets, 20% for catalysts, 20% for metal alloys and batteries and 7% for lightning. The highest grow rate is expected for magnets.[20]

Green technologies

Green technologies designed to reduce energy consumption and air pollution rely on the use of REEs. Within a few years, the demand for neodymium, praseodymium, dysprosium, terbium, lanthanum, yttrium and europium may exceed the present supply. Even without Chinese export restrictions this may occur in 2014 and can only be balanced with the timely opening of the Mountain Pass and Mt Weld mines. (Rare earth metals, like lanthanum, also play an important role in petroleum refining, but the sector's vulnerability to these metals is limited. For example, the recent large increases in lanthanum prices have added less than a penny to the price of gasoline.) Manufacturers of permanent magnets, which contain neodymium and dysprosium, are currently evaluating the tradeoff of their beneficial performance against technologies using metals that are less vulnerable to supply shortages. HREEs used in lighting phosphors may become in short supply if lighting efficiency standards are implemented globally. An increasing demand of fluorescent lamps will lead to a higher demand of europium, terbium and yttrium. Below a summary is given for the general use of REEs with specific ones given in the Appendix.

REEs in green technologies

- Magnets
- Automotive catalysts
- Energy efficient lightning
- Batteries for e-mobility
- Green industrial catalysts

REEs in other technologies

- Metal alloys
- Glass additives
- Electronics
- Ceramics
- Polishing

Urban mining

Recycling, substitution and the efficient use of REEs are the main components of urban mining. They were recently reviewed by the Öko-Institut and are summarized here in an abbreviated form.[28]

Recycling

Only few recycling methods for rare earth metals are currently implemented, but there is yet no recycling of REEs from batteries or magnets. The complexity of most recycling is due to dismantling required for post-consumer products, the often small quantities that are obtained and the physical and chemical energy-intensive treatment that the materials need before re-use is feasible.

bottlenecks for recycling REEs

- Need for an efficient collection system
- Need for high primary/secondary prices
- Loss of post-consumer goods through export
- Long product lifetimes (e.g. windturbines)

Advantages in recycling REEs

- Europe is the biggest REEs consumer and can convert the growing waste to resource
- Reduce the dependency on foreign REEs
- No radioactive byproducts
- Less negative impact on climate (groundwater, climate, acidification, and eutrophication)

The main steps needed for implementing large-scale collection and recycling are considered to be:

- A European competence network on REEs with relevant stakeholders and basic research.
- A European material flow analysis and identification of initial waste streams.
- Integration of the existing collection schemes for REEs, pilot plants, analysis of the financial risks, and setting up a legal framework.

Substitution

The past low price of REEs has led to much waste because of the lack of recycling. The recent high prices should be an incentive for change. Also substituting REEs for other elements is coming to the fore, but is still rare and counterintuitive due the better performance of REE products, and typically requires new product designs. Identified options for substitution in major green applications are:

- Gearless wind turbines use REEs. When other magnet types or gear-containing wind turbines become more reliable and efficient they could become viable alternatives.
- Motors of (hybrid) electric vehicles contain REEs. Substitution based on alternative motors exists, but more research is required to make them better performing.
- Energy-efficient lighting systems, like LCD displays and LED lamps, contain REEs. Research is required for phosphors substitutes with high efficiency and high light quality.
- Automotive catalysts contain cerium and petroleum cracking catalysts contain lanthanum. Research and development is needed for viable alternatives.

Policies

Recently, the Hague centre for strategies studies (HCSS) made policy recommendations, which are briefly summarized here.[32]

The Netherlands, being a small global player, should strengthen international political and economic relations as the uncertainty in material availability can have a negative effect on its economy.

Higher material import prices increases the cost of products and may affect the competitive position of Dutch small and medium enterprises. The government can take measures to smoothen this direct effect. Policies of other countries can have indirect effects and disrupt international retail dynamic, such as proactive governmental acquisitions, creating material supplies, retail restrictions, and land grabbing.

With the world acting as a multipolar system, the economic and political powers are shifting from the dominant West to the other parts of the world. The competition for materials has been increasing as a result of the growing number of players, causing less stability and more tension.[32] When large countries impose export quotas and focus on national productivity and bilateral contracts, this affects the free market and thus the Dutch competitive position, because the Netherlands has an open retail system without restrictions. Countries like China, Japan and South Korea are safeguarding materials for their national industries. The Netherlands should find ways to deal with this trend**.**

European level

The European Union has not yet developed a consensus approach, in part due to different emphases for different countries, but its cooperation is imperative also because Japan and the US are important partners for REE besides China.[35] The Öko-Institut recommends the EU to take the following steps:

- Supply China with technology for sustainable mining and recycling in exchange for supplies.
- Support green mining and green technologies with green metals.
- Appeal to Greenland to act environmentally responsibly in reopening the Kvanefjeld deposit.

Recommended specific European strategies are expand the output, increase recycling and reuse to reduce waste and to find substitutes for REE applications.[23]

Policies of the USA, UK and Japan

There is no common list of strategic minerals as it differs from country to country and changes over time. The USA has a strong national security approach with respect to strategic minerals. Japan has a comprehensive approach based on securing its high-tech, innovation-driven economy that is highly dependent on REEs. The United Kingdom is a strong promoter of free trade. Even though the policies of these countries differ, they share the concern of free trade restrictions.

Conclusion

There is no deficiency of rare earth elements in the Earth's crust (the resources), but the limited economic accessibility of REE makes them scarce, which has resulted in highly volatile prices in recent years. The estimated reserves of the rare earth ore is 114 million ton. The REEs are even becoming critical for the continued use in green and high-tech technologies. The metals with this short term risk are: dysprosium, terbium, europium, neodymium, yttrium, indium, tellurium and gallium. They are particularly used in wind and solar energy generation, especially permanent magnets and catalysts, batteries for e-mobility, energy efficient lighting, electronics, glass additives, and polishing materials. The Dutch industries with the highest dependency are manufacturers of transport equipment, metals and fabricated metal products, and machinery and equipment.

In 2010, China produced 130 kton of the REEs or 97% of the global amount. It also has a leading position in the entire production chain. The current best estimate of the Chinese ROE reserves is 55 mton. The worldwide growing demand (8-11% per year) on REEs is exceeding the supply, which is hampered by Chinese export quota and reduction of its illegal mining, and even the reopening of Mountain Pass in California and Mt Weld in Australia is not expected to provide adequate relief. Opening new mines has a lead time of about a decade and requires huge investments, which is often not economic given the current REO concentrate prices. Moreover, REO mining and REE separation could benefit from improved technologies.

Recycling and urban mining of REEs is currently not yet available on a large scale. Bottlenecks are the collection methods, the highly fluxional prices of REEs, long lifetime of products, and non-optimal product designs for recycling. Advantages are the reduced dependency on foreign resources, the reduced environmental burden, and the reduced release of radioactive impurities. Steps needed to realize REE collection and recycling are: a European Competence Network, basic research, a material flow analysis, identify waste streams, integrate REE collection in existing collection schemes, pilot plants, financial risk analysis and an appropriate legal framework. The demand for REEs is inelastic, as substitutes aren't available or perform poorer, necessitating research and development

The Netherlands, being a small global player, should strengthen international political and economic cooperation because the uncertainty in material availability can have a negative effect on its economy. Direct effects can be the rising costs of Dutch products due to higher material import prices with indirect effect caused predominately by the material policy of other countries.

Appendix

Materials in Clean energy Technologies

		Photovoltaic Films	Wind Turbines	Vehicles		Lighting
	MATERIAL	*Coatings*	*Magnets*	*Magnets*	*Batteries*	*Phosphors*
Rare Earth Elements	Lanthanum				●	●
	Cerium				●	●
	Praseodymium		●	●	●	
	Neodymium		●	●	●	
	Europium					●
	Terbium					●
	Dysprosium		●	●		
	Yttrium					●
	Indium	●				
	Gallium	●				
	Tellurium	●				
	Cobalt				●	
	Lithium				●	
	Manganese				●	
	Nickel				●	

Figuur 16: Applications critical metals, USGS 2011

References

1. *Ministerie VROM en Buitenlandse zaken, November 2009, Schaarste en transitie, kennisvragen voor toekomstig beleid*
2. *U.S. Department of Energy, Critical Materials Strategy, December 2011*
3. *USGS 2008: U.S. Geological Survey, rare earth elements: critical resources for high technology*
4. *USGS 2010: U.S. Geological Survey, 2010*
5. *The Hague Centre for strategic studies & TNO, Rare earth elements and strategic policy*
6. *BGS 2010: British Geological Survey, rare earth elements, June 2010*
7. *MEP 2009: Ministery of Environmental Protection In: The Explanation of Compiling Emission Standards of Pollutants from rare Earths Industry 2009, October 2009*
8. *Wang 2009: Wang Guozhen, Current mining Situation and Potential Development of Rare Earth in China, China Nonferrous Engineering and research Institute, Journal of Sichaun Rare earth, No 3., 2009*
9. *Oakdene Hollins 2010: Oakdene Hoolins Research & Consulting: Lanthanide Resourches and Alternatives, A report for department for Transport and department for business, Innovation and Skills, March 2010*
10. *BGR 2009: Bundesanstalt für Geowissenschaften und Rohstoffe, Elsner, H., Liedtke, M.,Seltene Erden In: Commodity Top News Nr. 31, 2009*
11. *Orri & Grauch 2002: Orris, G.J. & Grauch, R.I.: Rare Earth Element Mines, Deposits and occurrences. – USGS Open File Rep., 02-189: 174pp: 2002, Tucson, AZ*
12. *Angerer et al 2009: Angerer, G., Rohstoffe für Zukunftstechnologien, Fraunhofer Insitut für System- und Innovationsforschung ISI, Karlsruhe in Cooperation with Institut für Zukunftsstudien und Technologiebewerkung IZT gGmbH, Berlin; 15 May 2010, Stuttgart*
13. *MIIT 2009: Ministery of Industry and Information Technology of China: The 2009-2015 Plans for Developing the Rare Earth Industry*
14. *MIIT 2010: Ministery of Industry and Information Technology of China: Notice on the consultative draft of 'Entry Criterions for Rare Earth Industry', May 2010*
15. *Eurostat 2010: Eurostat: External Trade, November 2010*
16. *Kingsnorth 2010: Kingsnorth, D., IMCOA: 'Rare Earths: facing New challenges in the New decade'presented by Clinton Cox SME Annual Meeting 2010, March 2010, Phoenix, Arizona*
17. *Lynas 2010a: Lynas Coorporation Ltd: Rare Earths. J.P. Morgan. Australia Corporate Access Days. September 2010, New York*
18. *PWC, Minerals and metals scarcity in manufacturing:the ticking timebomb,Sustainable Materials Management, December 2010*
19. *Sveriges Geologiska Undersökning 2010*
20. *Öko-Institut: Öko-Istitut, Study on Rare Earths and their recycling, January 2010, Darmstadt*
21. *European Commission, Annex V to the report of the Ad-hoc Working Group on defining critical raw materials, July 2010*
22. *U.S. Department of Energy, Critical Materials Strategy, December 2011*
23. *European Commission, Critical Metals in Strategic Energy Technologies, 2011, Luxembourg: Publications Office of the European Union*
24. *Sigma-Aldrich, Material Matters, Rare Earths Crucial Elements of Advanced Technologies, 2011*
25. *Centraal Bureau voor de Statistieken, Critical materials in the Dutch economy, Statistics Netherlands – Grafimedia, The Hague – Heerlen, 2010*
26. *Nationaal Initiatief materiaalschaarste (NIMS), February 2011*
27. *European Commission, Communication from the commission to the European Parliament, the council, the european economic and social committee and the committee of the regions, A resource-efficient Europe – Flagship initiative under the Europe 2020 Strategy, Brussels, January 2011*
28. *United Nations Environment Programme, Recycling Rates of Metals, 2011*
29. *Chinese Society of Rare Earth, Annual report, 2002*
30. *Lin Hecheng, The Development and Prospect of China's Rare Earth Production, Journal of Rare earth, 2009*
31. *Trade Statistics Japan*
32. *The Hague Centre for Strategic Studies, Op weg naar een grondstoffenstrategie, Juli 2011*
33. *The Economist, september 2, 2010*
34. *Oakdene Hollins Research and Consulting. Lanthanide Resources and Alternatives, March 2010*
35. *European Commission, Grondstoffen beschikbaar maken voor het toekomstige welzijn van Europa, 2012*