The Greens | European Free Alliance
in the European Parliament

Öko-Institut e.V.
Institut für angewandte Ökologie
Institute for Applied Ecology

Study on Rare Earths and Their Recycling

Final Report for The Greens/EFA Group in the European Parliament

Darmstadt, January 2011

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We would like to thank the following colleagues for their input and constructive comments:

Dr. Georg Mehlhart (Öko-Institut e.V.)

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Note: Within the scope of this study, Öko-Institut has used and assessed numerous primary sources in a carefully neutral fashion, complying all the time with established principles of research. Nevertheless Öko-Institut cannot guarantee that the forecasted will actually occur, particularly in the case of the supply-and-demand-balance, since – as the study shows – there are numerous factors of influence which can change at short notice.

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°C	degree Celsius
a	anno = year
AFP	Analytical fingerprint
BAM	Barium magnesium aluminate
CAT	Cerium magnesium aluminate
Ce	Cerium
CFL	Compact fluorescent lamps
Co	Cobalt
Dy	Dysprosium
e.g.	exempli gratia = for example
e-bikes	electric bikes
EC	European Commission
EIB	European Investment Bank
EL	electro-luminescence
ELV	End of life vehicle
e-mobility	electric mobility
Er	Erbium
etc	et cetera
Eu	Europium
EU-27	Austria, Belgium, Bulgaria, Cyprus, Czech Republic, Germany, Denmark, Estonia, Spain, Finland, France, United Kingdom, Greece, Hungary, Ireland, Italy, Lithuania, Luxembourg, Latvia, Malta, Netherlands, Poland, Portugal, Romania, Sweden, Slovenia, Slovakia
EV	Electric Vehicle
FCC	Fluid cracking catalyst
Gd	Gadolinium
GMEL	Greenland Minerals and Energy Ltd.
H_{ci}	coercivity
HCl	Hydrochloric acid
HDD	Hard disk drive
HEV	Hybrid Electric Vehicle
HID	High intensity discharge (lamp)
Ho	Holmium

HREE	Heavy Rare Earth Element
HTS	High temperature superconductor
JOGMEC	Japan Oil, Gas and Metals National Corporation
JORC	Australasian Joint Ore Reserves Committee
K	Potassium
kW	Kilowatt
La	Lanthanum
LAP	Lanthanum phosphate
LCD	Liquid crystal display
LED	Light Emitting Diode
Li-ion battery	Lithium ion battery
LREE	Light Rare Earth Element
Lu	Lutetium
MFA	Material flow analysis
mg	Milligram
Mio	Million
MRI	Magnetic resonance imaging
n.d.	No data available
Nd	Neodymium
NdFeB	Neodymium ferrium boron
nGy/h	Nanogray per hour (Gamma dose rate)
NH_3	Ammonia
NH_4^+	Ammonium ion
Ni	Nickel
Ni-MH battery	Nickel metal-hydride battery
OLED	Organic light emitting diode
PHEV	Plug-in hybrid electric vehicle
Pm	Promethium
Pr	Praseodymium
R&D	Research and development
Ra	Radium
REE	Rare earth element
REO	Rare earth oxide (common trade unit)

RMB	Renminbi = official currency of the People´s Republic of China; principal unit is Yuan
Sc	Scandium
Sm	Samarium
SOFC	Solid oxide fuel cell
SSD	Solid state drive
SSEEC	Solid state energy efficient cooling
t	Metric tons
Tb	Terbium
Th	Thorium
Tm	Thulium
TREO	Total rare earth oxide
U	Uranium
UK	United Kingdom
UNEP	United Nations Environment Programme
VCM	Voice-coil-motor
WEEE	Waste Electrical and Electronic Equipment
Y	Yttrium
Yb	Ytterbium
YOE	Yttrium europium oxide

EXECUTIVE SUMMARY

The focus of this study for the Greens/EFA Group in the European Parliament lies on the development of a European strategy for a sustainable rare earth economy. It particularly addresses the recycling, the substitution and the efficient use of rare earths and develops a strategy towards a green rare earth economy.

The rare earth elements under analysis in this study by Öko-Institut include the 17 elements yttrium (Y), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu) and scandium (Sc) and the role they play in the case of green technologies.

The chapters 1 to 9 provide a comprehensive overview of methodological approaches to assess the criticality as well as global aspects such as rare earth mining, processing, trade, environmental impacts, applications, current and future demand and the expected demand-supply balance. Each chapter culminates in a conclusion, by means of which the reader can gain a quick overview of its contents. These data are not summarised in the executive summary. Instead, the executive summary focuses on the main target of the study, the development of a European strategy for a sustainable rare earth economy.

Background

During recent years technological innovations resulted in manifold applications using rare earths which lead to a steep increase in their demand. A relevant share of the increasing demand is caused by so-called “green technologies” which are designed to contribute to environmental protection in terms of reduction of the energy consumption, the further development of renewable energy carriers or air pollution control. There is serious concern that the demand of some individual rare earth elements such as neodymium, praseodymium, dysprosium, terbium, lanthanum, yttrium and europium might exceed the present supply within a few years. Even if China imposes no export restrictions it is to be expected that the increasing demand up to 2014 can only be met if further mines in addition to the two planned mines in Australia and USA are opened. The two mines in Australia and the USA have already obtained approval from the national authorities and started construction works so that large scale operation can commence around 2012.

The high demand and the expected supply shortages, additionally triggered by Chinese export restrictions, lead to a significant increase in rare earth prices. This steep increase is not only a burden for manufacturers and consumers. It offers the chance to address the problem of today’s rare earth supply in more depth and to build up a sustainable rare earth economy in all relevant sectors. The low prices in the past lead to a significant waste of resources. Until now, there has been almost no recycling of rare earths. The new prices might be a starting point to building up recycling systems for rare earth compounds. Similarly, science and industry are beginning to conduct research and development on options for a substitution of rare earth.

The high public interest in this issue further revealed the high environmental burden in the surrounding of the Chinese mines and processing plants. If the EU demands rare earth compounds for their green technology, it is up to the EU to contribute to a “greener” rare earth supply. The contradiction between the “green” application of rare earth and their high environmental pressures in production calls for action to be taken particularly by Europe, America and Japan where – besides China – the majority of the rare earths are consumed.

The action in the fields of recycling should be started now without further delay as it will take a minimum of five to ten years for the first large-size implementation to take place. The research for substitution options and efficiency should also be reinforced as soon as possible as it takes some years to move from successful research to industrial implementation.

Analysis of the substitution of rare earths and their efficient use

The examination of substitutions for scarce REE has shown that there is quite rarely a simple substitution of a REE compound by another compound. In most cases substitution requires a totally new product design. The identified options for substitution in the case of the major green applications are summarised below:

- Rare earths are currently used in around 14 % of newly installed **wind turbines** with a gear-less design and technical advantages in terms of reliability. A supply shortage of rare earths would lead to a shift to alternative turbine types. Further research on a higher reliability of traditional techniques with gears would support this substitution.
- Rare earths are used in permanent motors of **hybrid electric vehicles** and **electric vehicles**. Substitutions based on alternative electric motor designs are principally available. However, R&D is required for a higher performance of existing electric motor types and for the realisation of new motor concepts.
- Most new **energy-efficient lighting systems** contain rare earths (compact fluorescent lamp, LED, plasma display, LCD display). Substitutions are rare, particularly for compact fluorescent lamps. R&D is required for alternative phosphors with high efficiency and high light quality.
- Automotive **catalysts** contain cerium, and catalysts for petroleum cracking and other industrial processes contain lanthanum. Substitutions are rare, and R&D is urgently required for alternative catalysts.

Concerning a **higher efficiency** of the rare earth use, R&D is urgently needed in all fields of application and is also needed on the supply side to enable higher efficiencies in mining, beneficiation and processing. One example for high losses in the production chain is the traditional magnet production in China.

Nanotechnology is considered to be applied in some green applications in order to raise the efficiency by nano-sized rare earths. An attendant risk assessment is highly recommended.

Analysis of the current recycling activities of rare earths

Only a few industrial recycling activities are currently implemented for rare earths. Until now, there has been no large scale recycling of rare earths from magnets, batteries, lighting and catalysts. Principally, the recycling processes for the rare earths are quite complex and extensive if re-use is not possible and a physical and chemical treatment is necessary. Most of the recycling procedures are energy-intensive processes. The main post-consumer activities – the recycling of rare earths from electric motors and hard disks and other electronic components – will require intensive dismantling.

Several constraints for a wider recycling of rare earths were identified: the need for an efficient collection system, the need for sufficiently high prices for primary and secondary rare earths compounds, losses of post-consumer goods by exports in developing countries and the long lifetime of products such as electric motors in vehicles and wind turbines of 10 - 20 years before they could enter the recycling economy.

Advantages of recycling

The recycling of rare earths has several advantages in comparison to the use of primary resources:

- Europe is one of the globally large consumers of rare earths. Increasing amounts of waste from final products containing rare earths are arising in Europe. These **valuable resources** should be returned to the industrial metabolism by “urban mining”.
- The **dependency on foreign resources** will be reduced by supplying the European market with secondary rare earth materials.
- Apart from a few specialised industries and applications, the **know-how** in rare earth processing is quite low in Europe. The building up of know-how in recycling will widen the competency of enterprises and scientific institutions in Europe concerning rare earth processing.
- The processing of secondary rare earths will be **free from radioactive impurities**. The mining and further processing of primary rare earths is involved in most cases with nuclear radiation coming from radioactive elements of the natural deposits.
- The recycling requires some energy carriers and chemicals. On the other hand it saves significant amounts of energy, chemicals and emissions in the primary processing chain. It is to be expected that most recycling processes will have a **high net-benefit** concerning **air emissions**, **groundwater protection**, **acidification**, **eutrophication** and **climate protection**.

Strategy for the development of a European rare earth recycling scheme

Öko-Institut suggests that a recycling scheme as illustrated in Figure 1 should be developed.

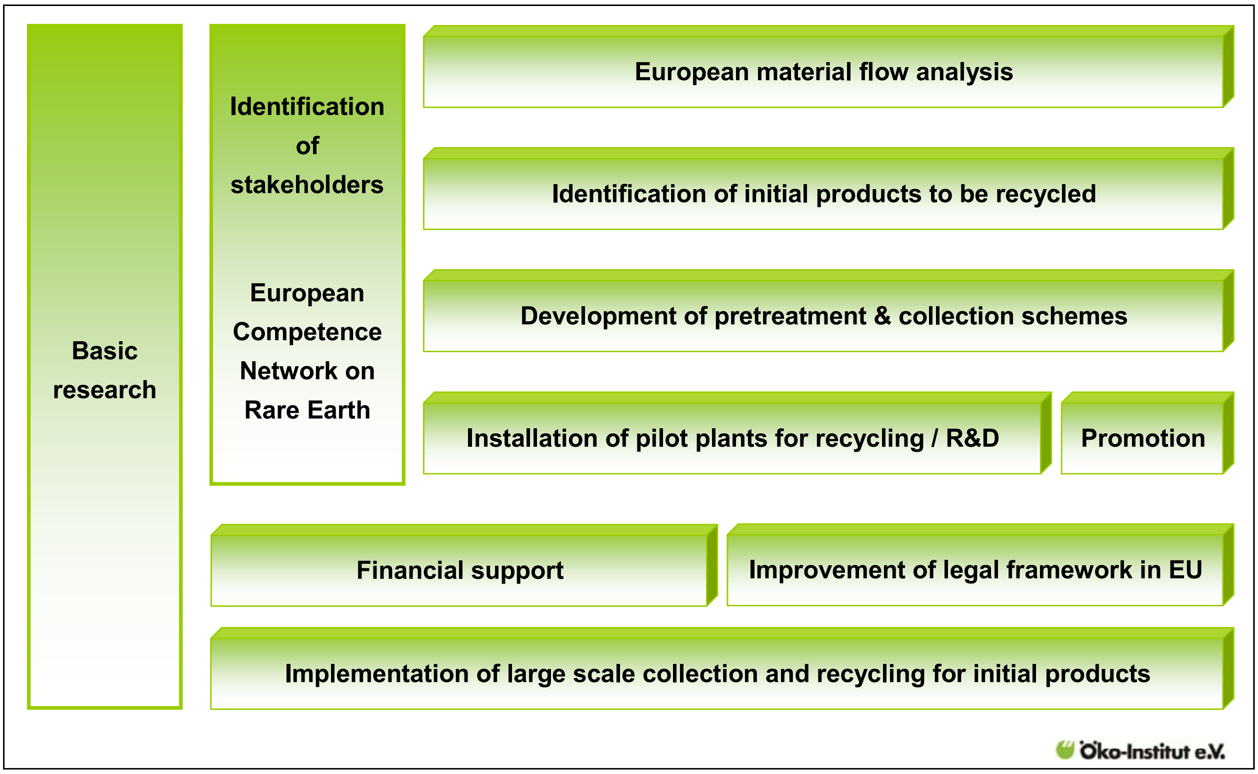

Figure 1 Steps towards a European rare earth recycling scheme

The main steps prior to large-scale implementation are described here in brief:

- A **European Competence Network on Rare Earths** with all relevant stakeholders such as recyclers, manufacturers, public authorities, politicians and researchers is seen as essential for a successful implementation.
- **Basic research** is necessary, as only a few companies in Europe are involved in rare earth refining and processing at the beginning of the added-value chain.
- A **European material flow analysis** (MFA) is necessary in order to identify in more detail the main material flows and waste streams and the main manufacturers and actors in the added-value chain. Currently, national research institutions have to rely on estimates from a few experts outside of Europe.
- The next step is the **identification of initial waste streams** on the pre-consumer and post-consumer level, e.g. waste from the magnet and lighting production, magnets from used electric motors, used lamps and screens, re-use of large magnets and recycling of spent catalysts.

- The treatment of many relevant wastes is already regulated by the Waste Electrical and Electronic Equipment Directive (hereafter WEEE), the EU End of Life Vehicles Directive (ELV) and the EU Battery Directive. Thus, the collection of rare earths containing wastes has to be integrated in existing **collection** schemes.
- The development of **pilot plants** is accompanied by large-scale R&D projects which aim to gain more insight into the complex chemical processes and the required sophisticated equipment.
- Recycling plants bear high **financial risks** due to the required high investment and the high uncertainty of the future price development of rare earths. Therefore, it should be analysed whether the European Investment Bank (EIB) could reduce financial risks for investments in rare earth recycling.
- A recycling scheme of rare earths not only requires adequate logistic and technical preconditions but also an appropriate **legal framework**. Hence, an important step will be the adaption of the legal EU framework in order to optimise post-consumer rare earth recycling. Potential relevant directives which should be verified in terms of modification for the support of a rare earth recycling scheme are the Ecodesign Directive, the WEEE Directive, the ELV Directive and the Battery Directive.

Recommendations for international activities

The development of a sustainable rare earth supply for Europe concerning environmental, social and security aspects requires a solid international co-operation. Important partners for the EU in facing this challenge are not only China but also Japan and the United States. Öko-Institut suggests three selected activities:

- Öko-Institut proposes an **EU-China co-operation** on sustainable mining which is designed as a large-size co-operation focusing on the sustainable mining of rare earths at one specific site with the target to optimise the efficiency, the environmental performance, the remediation of contaminated sites and the potential recovery of rare earths from old tailings. The EC would supply co-funding and expertise, and China would agree on an adequate rare earth supply.
- Green technologies call for “green metals”, and Europe should support a sustainable mining. Worldwide, there are manifold **initiatives for sustainable mining**. Among them are certification schemes addressing different problems such as environmental aspects, small-scale mining, safety issues and human rights. There is increasing interest in politics and industry on certified minerals, and today’s mining companies could be interested in certification schemes or similar co-operations with EU participation in order to highlight their environmental efforts.
- The high pressure on the opening of new mines outside of China by the steeply increasing demand raises the concern that new mines could be opened which do not

keep minimum environmental standards. One case could be the **Kvanefjeld deposit in Greenland** where the residues from the ore concentration (tailings) shall be stored in a natural lake with connection to the sea. The EU and the European Environmental Agency (EEA), which has a general co-operation with Greenland, should appeal clearly to the Greenlandic authorities to act carefully and responsibly.

FINAL REPORT

1 Introduction

In the last seven years international discussions about mineral resources with a special focus on metals have gained a new dimension.[1] Driven by the growth of the global economy and the enhanced pace of the emerging economies (China, India, Brazil, etc.), the global demand for many metals is increasing rapidly and the most forecasts predict further growth of metal consumption. Besides well-known mass metals like steel or aluminium, new challenges in the field of the so-called critical metals are under serious concerns. The EC defines the "criticality" of raw materials in its recent publication "Critical raw materials for the EU" (EC 2010): *"This means that raw material is labelled "critical" when the risks of supply shortage and their impacts on the economy are higher compared with most of the other raw materials."*

It could be stated that in many cases the discussions about critical metals are linked with new innovations and technologies – very often in the field of green technologies like electric vehicles, wind power, PV and many others. Therefore in many relevant publications synonyms like "green minor metals", "specialty metals", "technology metals" and "rare metals" are used for the term "critical metals". As part of the activities of the EC's "Raw Materials Initiative", the Ad-hoc Working Group on defining critical raw materials ranked 14 raw materials at EC level as the most critical metals (EC 2010). This group of 14 raw materials contains the whole group of rare earth elements (REE).

The rare earth elements under analysis in this study by Öko-Institut for the Greens/EFA Group in the European Parliament include the 17 elements: yttrium (Y), lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium[2] (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu) and scandium (Sc).

The large group of the REE is sub-divided into the heavy rare earth elements (HREE) and the light rare earth elements (LREE). Unfortunately there is no worldwide accepted definition for which REE belongs to the HREE or the LREE group. Therefore, crosschecks of data from different sources which refers to facts and figures and so on about HREE and LREE have to be carried out very carefully to avoid failures and misinterpretations (this holds especially for the contribution of yttrium). For this study Öko-Institut uses the definition of the USGS (USGS 2002), which defines yttrium (Y), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), lutetium (Lu) as HREE and lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), samarium (Sm), europium (Eu), and scandium (Sc) as LREE.

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[1] See, for instance, the special website developed by Öko-Institut: www.resourcefever.org.

[2] Promethium does not occur in nature as no stable isotope exists.

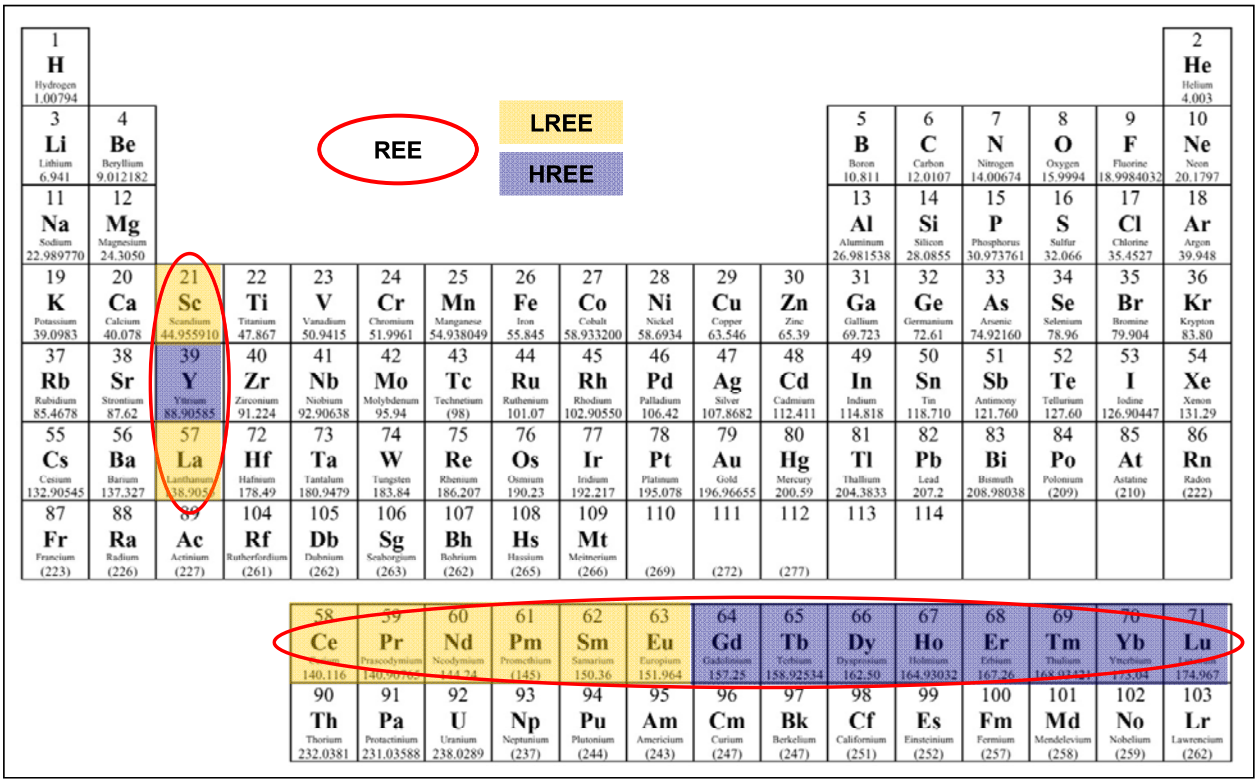

Figure 2 Rare earth elements and their position in the periodic table

Nevertheless, within the “Study on Rare Earth Metals and Recycling” Öko-Institut provides facts and figures, results and interpretations for the different REE as far as is possible. This approach recognises the fact that a handling of the criticality of the REE as a group of 17 elements or as sub-groups (HREE and LREE) is not sufficient for the numerous challenges and tasks regarding green technologies, demand growth, possible supply scarcities and environmental issues of mining and recycling.

2 Methodologies for determination of criticality

Against the background of rapid demand growths, increasing prices and possible supply restrictions of certain metals with high potential for future technologies having received increasing attention by media, scientists, enterprises and the politics, several classification systems to rank the numerous raw materials and metals have been developed in recent years. It should be mentioned that the purpose of these studies is not always the same und therefore a one-by-one comparison of the results could not be undertaken. In most cases a national or regional point of view is the driving force behind the classifications systems for criticality. For an overview the methodological approach of the report “Minerals, Critical Minerals and the U.S. Economy” (National Academies 2008) and the approach of the Ad-hoc Working Group on defining critical raw materials (EC 2010) are selected. Finally an approach of Öko-Institut for the UNEP will be briefly introduced.

In 2008 the National Academy of Sciences released a comprehensive report with the title “Minerals, Critical Minerals and the US Economy” (National Academies 2008). The motivation for this study is reflected by the following excerpt of the study’s preface: *“In the twenty-first century, the nature of the concerns over Earth resources has shifted once again. Energy and mineral commodity prices are relatively high for the first extended period since the 1970s, driven primarily by unexpectedly large demand growth in China, India, and other countries. At the same time, while the United States remains an important producer of energy and mineral resources, the extraction and production of these resources overall has shifted away from the United States toward other nations; U.S. import dependence for many commodities has increased and has raised concerns about reliability of the foreign supply.”* The driving force for the US study was clearly the assessment that the US economy faces increasing dependence on raw materials imports. So, the whole study and including the released criticality matrix has to be considered in the context of this motivation.

The US approach is based on two dimensions of criticality; **importance in use** and **availability**. The dimension of importance in use reflects the idea that some non-fuel raw materials are more important in use than others. The authors pointed out that the possibility of substitution is the key here. The second dimension, availability, includes several medium- to long-term considerations: geologic, technical, environmental, social, political and economic factors have to be taken into account. In addition, the consideration of the reliability or risk of supply in the short term is important. On this basis the authors have developed a two-dimension criticality matrix. The criticality matrix, as established in this report, allows evaluation of the criticality of a given mineral. A specific mineral or mineral product can be placed on this matrix after assessing the impact of a potential restriction on the mineral’s supply (importance in use: vertical axis) and the likelihood of a supply restriction (availability: horizontal axis). The degree of criticality increases as one moves from the lower-left to the upper-right corner of the matrix. The committee used a combination of quantitative measures and expert (qualitative) judgement in implementing the matrix methodology. The rare earths were determined by this methodology (as one of five out of 11 minerals or mineral groups) to fall in or near the critical zone of the criticality matrix.

The US approach was applied in a report on the critical materials strategy from the US Department of Energy in 2010 (DOE 2010). It focuses on nine individual rare earth elements and the metals gallium, tellurium, lithium, indium and cobalt and their importance to the clean energy economy.

In July 2010 the EC published the report “Critical raw materials for the EU” which was worked out by the Ad-hoc Working Group on defining critical raw materials (EC 2010). The EC report provides a pragmatic approach based on various existing methods. In line with other studies, the report puts forward a relative concept of criticality. This means that raw material is labelled “critical” when the risks of supply shortage and their impacts on the economy are higher compared with most of the other raw materials. It considers three main aggregated indicators or dimensions, i.e. the **economic importance** of the considered raw material, its **supply risk** (for instance restrictive measures from resource-rich countries) and an **environmental country risk** assessing the potential for environmental measures that may restrain access to deposits or the supply of raw materials. These three aggregated indicators are calculated for each raw material.

41 different raw materials were assessed by the Ad-hoc Working Group with this criticality approach based on the three main aggregated indicators/dimensions. In a first step the 41 raw materials are positioned in a two-dimensional matrix comparable with the US approach (see above). The vertical axis reflects the positioning of the materials in relation to the supply risks that have been identified. The production of a material in few countries marked by political and economic instability, coupled to a low recycling rate and low substitutability, will result in a very high supply risk. The results show for the rare earths the highest rank among all 41 assessed raw materials.

The horizontal axis reflects the positioning of the material in relation to its importance to the EU. For this dimension the rare earths are in the midfield. From this two-dimensional matrix a list of 14 different raw materials including the rare earths are assessed as critical, because they are of high economic importance and have a high supply risk. Finally the environmental country risk – the third indicator – was used to finish the determination of criticality. However, the overall result for the group of 14 was not altered by this indicator. It is important to note that the rare earths were ranked as the raw material with the highest environmental country risk among all assessed 41 raw materials.

In 2009 Öko-Institut completed a study for UNEP entitled “Critical metals for future sustainable technologies and their recycling potential” (Öko-Institut 2009). For the classification of selected “green minor metals” with a potential for sustainable technologies an own classification system with the three main pillars “demand growth”, “supply risks” and “recycling restrictions” was developed. To enable extensive classification and differentiation of the different metals, the following sub-criteria are taken into account by Öko-Institut:

- **Demand growth**
  - Rapid demand growth: > 50% increase of total demand until 2020
  - Moderate demand growth > 20% increase of total demand until 2020
- **Supply risks**
  - Regional concentration of mining (> 90% share of the global mining in the major three countries)
  - Physical scarcity (reserves compared to annual demand)
  - Temporary scarcity (time lag between production and demand)
  - Structural or technical scarcity (metal is just a minor product in a coupled production and inefficiencies occur often in the mining process, production and manufacturing)
- **Recycling restrictions**
  - High scale of dissipative applications
  - Physical/chemical limitations for recycling
  - Lack of suitable recycling technologies and/or recycling infrastructures
  - Lack of price incentives for recycling

In contrast to other ranking systems this classification system are not based on a national point of view, which means the results are universal and not specific to a single country or region. The availability of all REE could prove to be very critical following this approach for the period up to 2020 (for details see: Öko-Institut 2009). Within the REE group the availability of several elements could prove to be even more critical as the result of this report suggest.

As a group the REE have already been ranked highest in terms of criticality by the EC in July 2010 (EC 2010) and in previous assessments conducted by other organisations. This classification is justified without any doubt. For this study for the Greens/EFA Group in the European Parliament in late 2010 Öko-Institut has chosen an in-depth analysis approach for the individual REE, because the REE schematic rankings of the whole group of REE are not sufficient to produce detailed results as a basis for strategies. Based on the detailed results the proposed strategies for Europe regarding the REE are summarised in Chapter 12.

Conclusion on methodologies for determination of criticality

In recent years, several classification systems were developed to rank numerous raw materials and metals in terms of their criticality. Examples of such ranking systems are the report “Minerals, Critical Minerals and the U.S. Economy” by the National Academies 2008, the approach of the European Ad-hoc Working Group on defining critical raw materials (EC 2010), the approach of Öko-Institut for the UNEP and the recently published analysis of criticality of nine rare earth elements and five other metals by the US Department of Energy (DOE 2010). Due to their expected scarcity rare earths are taken into account in these reports.

There is a consensus in all approaches that some rare earth elements are critical or near-critical in terms of the supply risk and their importance for green technologies. Consequently, a more in-depth analysis which evaluates the criticality of the individual rare earth elements is necessary in order to produce detailed results as basis for political strategies.

3 Reserves

3.1 Global reserves

USGS (2010a) estimates the global reserves of the sum of all rare earth oxides to be at 99 000 000 t REO. This is quite high compared to the estimated world production of 124 000 t REO (USGS 2010a) in 2009. Hereby, the reserve is defined by the USGS as “the part of the reserve base which could be economically extracted or produced at the time of determination.” On the contrary, the reserve base not only comprises the resources that are currently economic (= reserves) but also marginally economic reserves, and some of those that are currently sub-economic. The reserve base was estimated to amount to 150 000 000 t REO by USGS (2008). In 2009, reserve base estimates of the USGS were discontinued.

It is to be expected that both the reserve base and the reserve will increase in the years ahead because the steep increases in REO prices lead to the exploration of new deposits. For example, the Chinese Ministry of Commerce announced in October 2010 that a new large rare earth deposit was found in Central China (MOFCOM 2010a). The rare earth reserves by country based on USGS (2010a) are shown in the following figure.

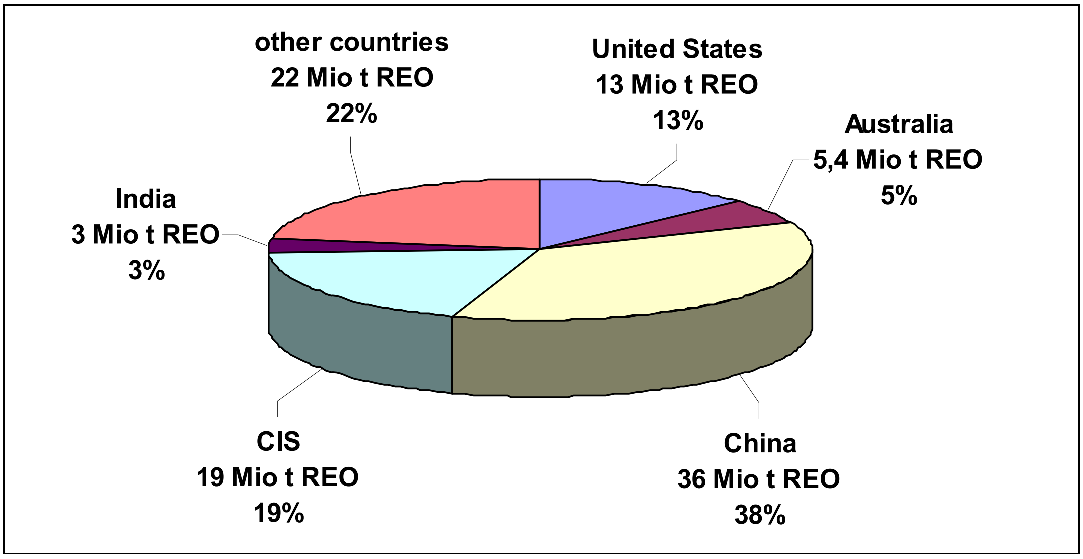

Figure 3 Global rare earth reserves by country estimated by USGS (2010a)

Though the Chinese produce more than 95% of the global production, their share of the reserves is much lower at 38 %. Large deposits are also found in the USA, Australia and states of the former Soviet Union.

However, the figures on the total reserves which refer to the sum of all rare earth elements do not reflect the need for a detailed look on the supply of individual elements. As discussed later in the study, shortages will be expected for some REE and their specific reserves are of importance.

The following chapters will provide some reserve estimations for the group of heavy rare earth elements as well as Chinese reserve estimations. Unfortunately, the USGS, Chinese, Australian and Canadian institutions have different definitions of reserves, reserve base and resources, which make it difficult or even impossible to compare the different national reserve and resource statistics. International attempts to harmonise the classification[3] are not developed in so far that they already provide harmonised reserve data on rare earths.

3.2 Reserves in China

Ministry of Environmental Protection (MEP 2009) presents data from the Chinese Society of Rare Earths (CSRE 2002) which indicate that China has 52 million tons of proved industrial reserves. The data are presented in Table 3-1.

Table 3-1 Distribution of REE reserves in tons REO (MEP 2009)

Provinces and regions	Industrial reserves	Measured reserves	Inferred reserves
Bayan Obo, Inner Mongolia	43.5 million	106 million	>135 million
Shandong	4 million	12.7 million	>13 million
Sichuan	1.5 million	2.4 million	>5 million
Seven Southern Provinces	1.5 million	8.4 million	>50 million
Others	1.5 million	2.2 million	>3.7 million
Total	52 million	131.7 million	>206 million

Additionally, geologists have discovered a large reserve of rare earths in central China's Hubei Province at the foot of Mountain Laoyin in Shiyan City (MOFCOM 2010a). The amount of the newly-found deposit was not known at the time this study was written. Therefore it is not included in the above statistics.

The Chinese statistics use their own classification for data on reserves which differs from the USGS classification. This might be the main reason of the difference to the USGS data, which estimate the (economical) Chinese reserve to amount to 36 Mio t REO, whereas the Chinese estimate their "industrial reserves" to amount to 52 Mio t REO. The table clearly

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[3] E.g. the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) and UN Framework Classification (UNFC) for Energy and Mineral Resources

shows that the major reserves are in Inner Mongolia at Bayan Obo, where the world largest rare earth mine is already in operation.

The next figure shows the regional distribution of the Chinese reserves.

Figure 4 Distribution of major rare earth resources in China

The next table shows the average grades of the ores and the types of minerals from the different provinces.

Table 3-2 REE resources in China: types of minerals and ore grades (Lin 2009)

Province	**Mineral**	**REE**	**Grades in % REO**
Inner Mongolia, Baotou, Bayan Obo	Bastnaesite and Monazite	Light REE in Iron-Nb-LREE deposit	6
Seven provinces, Southern China	Ion adsorption deposit	Middle and heavy REE	0.1-0.3
Sichuan	Bastnaesite	Light REE with high grade	6-8
Shandong	Bastnaesite	La, Ce, Pr, Nd with high grade	7-10

The Chinese describe the distribution of rare earth resources in China simply as "North Light, South Heavy". That means that light rare earth resources (La, Ce, Pr, Nd, Sm, Eu) are mainly found in the north of the country, while in the south middle or heavy rare earths (Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Sc, Y) are concentrated. The HREEs are extracted from ion adsorption deposits located in the seven provinces in the South of China (Jiangxi, Guangdong, Fujiang, Guangxi, Hunan, Yunnan and Zhejiang) (MEP 2009). The regional distribution of the HREE deposits is given in Table 3-3.

Table 3-3 The distribution of ion adsorption deposits in the South of China (MEP 2009)

Province	**Jiangxi**	**Guangdong**	**Fujian**	**Guangxi**	**Hunan**	**Yunnan and Zhejiang**	**Total**
Ratio in %	36	33	15	10	4	2	100

An overview of the ore composition of the different rare earth containing minerals is given in Table 3-4.

Table 3-4 Components of China's major rare earth minerals in REO% (Wang 2009)

Rare earth oxides	Bastnaesite	Monazite	Xenotime	Ion adsorption deposits	
				Longnan, Ganzhou, Jiangxi Province	Xunwu, Ganzhou, Jiangxi Province
LREE					
La_2O_3	27.00	23.35	1.20	2.10	**29.84**
CeO_2	**50.00**	**45.69**	8.00	1.00	7.18
Pr_6O_{11}	5.00	4.16	0.60	1.10	7.41
Nd_2O_3	15.00	15.72	3.50	5.10	**30.18**
Sm_2O_3	1.10	3.05	2.15	3.20	6.32
Eu_2O_3	0.20	0.10	<0.20	0.30	0.51
HREE					
Gd_2O_3	0.40	2.03	5.00	2.69	4.21
Tb_4O_7	—	0.10	1.20	1.13	0.46
Dy_2O_3	—	1.02	9.10	7.48	1.77
Ho_2O_3	—	0.10	2.60	1.60	0.27
Er_2O_3	1.00	0.51	5.60	4.26	0.88
Tm_2O_3	—	0.51	1.30	0.60	0.27
Yb_2O_3	—	0.51	6.00	3.34	0.62
Lu_2O_3	—	0.10	1.80	0.47	0.13
Y_2O_3	0.30	3.05	**59.30**	**62.90**	10.07

The next figure illustrates the major element distribution for China's largest deposit, Bayan Obo in Inner Mongolia, which mainly consists of bastnaesite. Its element distribution is representative for many light rare earth deposits.

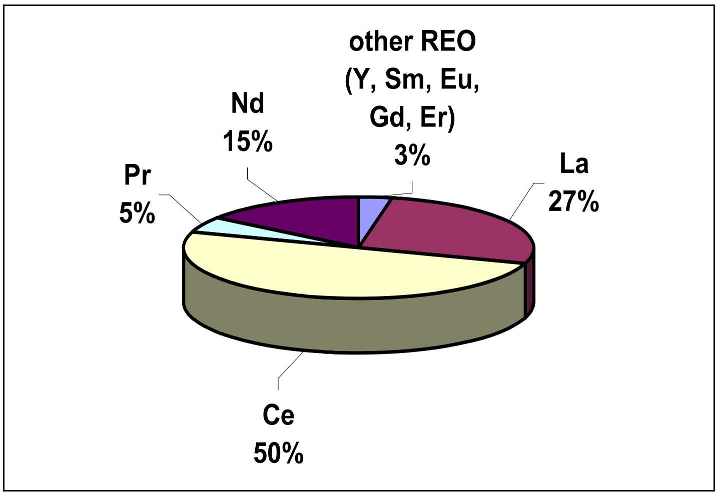

Figure 5 Rare earth composition of bastnaesite at Bayan Obo/Inner Mongolia (Wang 2009)

The ore composition is dominated by light rare earths, mainly cerium, lanthanum and smaller amounts of neodymium and praseodymium. Heavy rare earths such as gadolinium only occur in very small shares. Concerning the heavy rare earths, the seven provinces in the South of China which mainly possess heavy rare earths hold 1.5 million tons of industrial reserves. These reserves are quite small compared to the overall reserves in China and only have a share of about 3 % of the total reserves (see Table 3-1).

The next figure shows the major element distribution for two Chinese ion adsorption deposits in Jiangxi Province containing significant HREE:

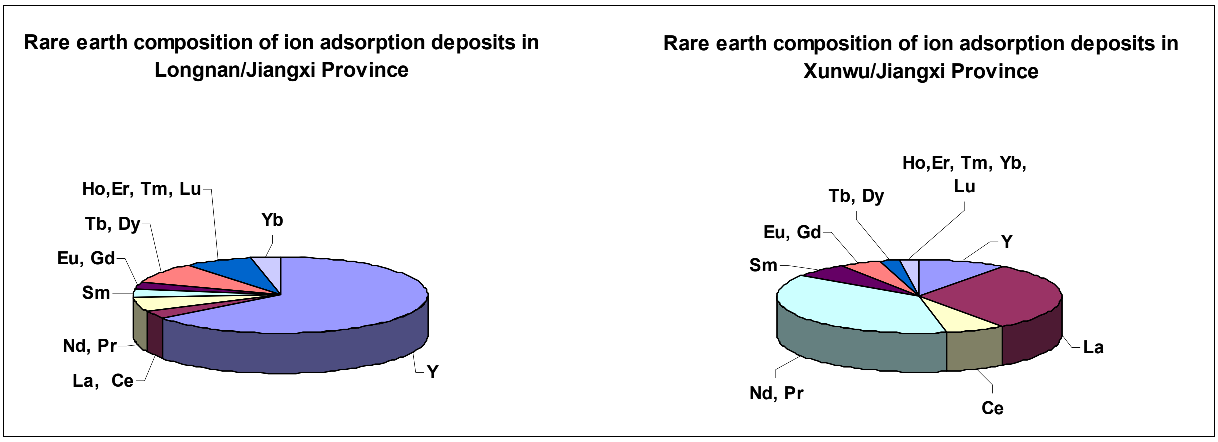

Figure 6 Rare earth composition of two ore deposits in the Jiangxi Province in southern China (Wang 2009)

The two figures for the ion adsorption deposits in the Chinese Jiangxi Province show the large variety of HREE compositions.

The only global production and reserve statistics for individual elements are available for yttrium. USGS (2010b) estimates that the Chinese reserves of yttrium amount to 220 000 t REO, which is equivalent to 41 % of the global reserves. The global mining of yttrium was around 8 900 t in 2008, with 8 800 t originating from China (USGS 2010b). Thus, the calculated ratio between economical reserves and actual production is around 25. For the total Chinese reserves of all REE, the picture is completely different: There is an annual production of around 120 000 t in 2007/2008 versus an economical reserve of 36 Mio t (based on USGS definition). This makes a factor 300. This comparison convincingly shows that the overall reserves are not the crucial issue. Instead, the pressing issue is the scarcity of some individual rare earths. As shown later, yttrium is one of the elements for which potential supply shortages are forecasted.

3.3 Reserves outside of China

Global reserves of all rare earth elements

Table 3-5 presents the reserve estimates of the USGS for the different countries. The main reserves outside of China occur in the United States, Australia, the states of the former Soviet Union and other states. Due to the lack of precise reserve estimations the sum of "other countries" is quite high at 22 Mio t. There are a number of countries where larger deposits are known. Among them are Canada, Greenland, South Africa and Malawi (BGS 2010). More details on the deposits of the United States are presented in USGS (2010f).

Table 3-5 Rare earth reserves by countries according to USGS (2010a)

China	**36**	**Mio t REO**
United States	**13**	Mio t REO
Australia	**5.4**	Mio t REO
CIS (former Soviet Union)	**19**	Mio t REO
India	**3.1**	Mio t REO
Brazil	**0.65**	Mio t REO
Malaysia	**0.38**	Mio t REO
Other countries: Canada, Greenland, South Africa, Malawi, Vietnam et al.	**22**	Mio t REO
Total outside of China	**64**	Mio t REO
World total	**99**	Mio t REO

Reserves in the European Union

There is only limited information on European rare earth deposits. The major findings are listed below:

- The British Geological Survey (BGS 2010) states that there has been no systematic, comprehensive evaluation of REE resources in Britain. Though small occurrences are known, they have no demonstrated economic potential.
- Oakdene Hollins (2010) cites news published on the website Metal Pages (2009) that there are possible exploration activities in Ireland.
- The German Federal Institute for Geosciences and Natural Resources (BGR 2009) records a potential rare earth output of a maximum of 1 400 t per year as by-product of iron mining in the north of Sweden.
- The BGR (2009) reports on a German deposit in Saxony with probable resources of about 40 000 t REO with an average grade of 0.5 %.
- Orris & Grauch (2002) cited in BGR (2009) mention reserves in Norway and Turkey.

Reserves of yttrium

Globally, there are no reserve estimations for individual REE except for yttrium. The estimations for yttrium are presented in Table 3-6.

Table 3-6 Yttrium reserves by countries according to USGS (2010b)

China	**220 000**	**t REO**
United States	**120 000**	t REO
Australia	**100 000**	t REO
India	**72 000**	t REO
Malaysia	**13 000**	t REO
Brazil	**2 200**	t REO
Sri Lanka	**240**	t REO
Other countries	**17 000**	t REO
Total outside of China	**320 000**	t REO
World total	**540 000**	t REO

Reserves of light and heavy rare earths

Principally, all deposits contain much more LREE than HREE. The chemical composition of the most important deposits is already described in literature, e.g. in USGS (2010a) with a detailed share of the individual elements or in aggregated manner in Oakdene Hollins (2010), and will not be repeated here in detail. However, representative examples for ore compositions were given in Chapter 3.2 for some Chinese ores.

Most of the deposits have a content of yttrium and other HREE of only a few percentages (see Table 3-4). The next figure gives an overview of the reserves of selected deposits outside of China which are compliant to the Australian JORC code or to the Canadian standard. The JORC code implies for the related deposits that appropriate assessments and studies have been carried out, including the consideration of mining, metallurgical, economic, marketing, legal, environmental, social and governmental factors. In order to be compliant with the JORC code, the assessments must demonstrate that an extraction could reasonably be justified. The data are published by the Australian mining company Alkane (2010b).

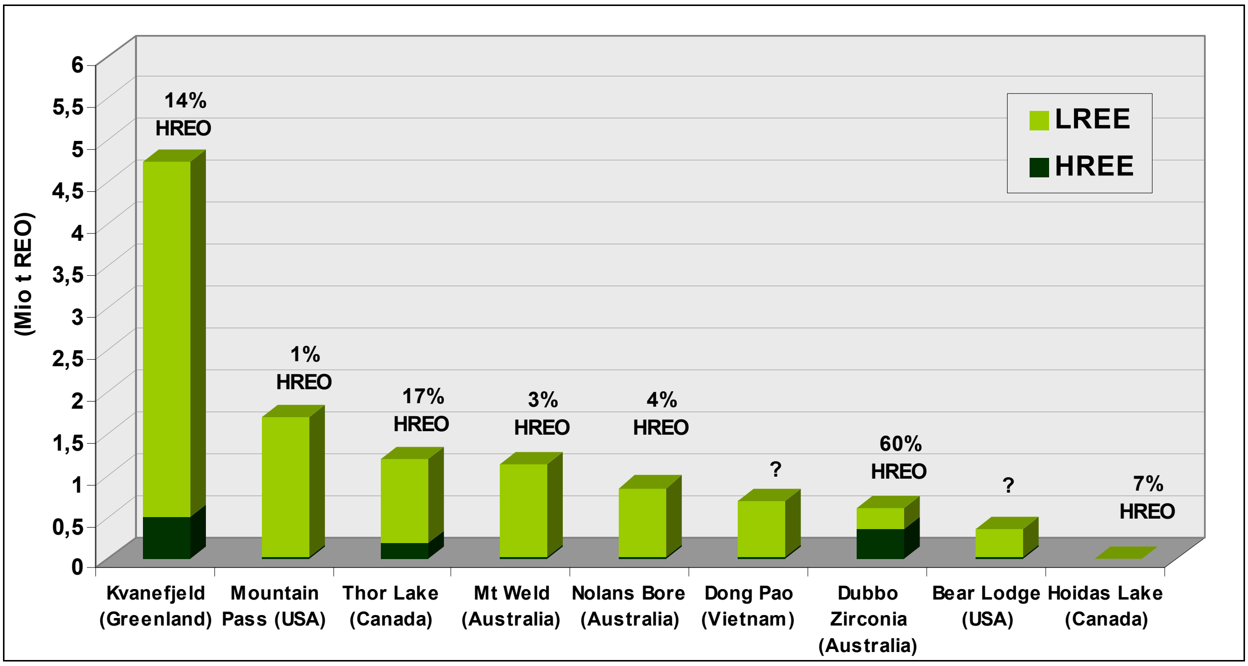

Figure 7 Reserve estimations of selected deposits which are compliant with the JORC code according to Alkane (2010b)

The major shares of the selected reserves of HREE are located at three sites according to Alkane (2010b): Kvanefjeld/Greenland, Thor Lake/Canada und Dubbo-Zirconia/Australia. The sum of these selected reserves is around 9.3 Mio t LREO and 800 000 t HREO (Alkane 2010b). Thus, the selected LREE reserves exceed the HREE reserves approximately by the factor twelve. The major element comprising around two thirds to the HREE-fraction is yttrium. The other HREE arise in much lower concentrations[4].

Further information on deposits where advanced exploration activities such as feasibility studies, laboratory tests or even construction works are already taking place is given in Chapter 4.3.

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[4] The Kvanefjield deposits contribute 7.7 % Y, 0.2 % Tb, 1.1 % Dy, 0.2 % Ho, 0.6 % Er, 0.1 % Tm and 0.5 % Yb according to GMEL (2010b). The Dubbo project and the Canadian Thor Lake project would produce an HREE with a share of Y amounting to around 2/3 (Alkane 2010a, Scott Wilson 2010).

Conclusion on reserves

The US Geological Survey (USGS) estimates the global reserves of the sum of all rare earth oxides to amount to 99 000 000 t REO. This is quite high compared to the estimated world production of 124 000 t REO in 2009. Hereby, the reserve is defined by the USGS as "the part of the reserve base which could be economically extracted or produced at the time of determination." Unfortunately, there are different definitions of "reserves", "reserve base" and "resources" globally which makes the comparison of different data sources difficult. Due to a lack of harmonised data this study refers to data from different classification schemes such as USGS estimations of global reserves, estimations on heavy rare earth elements (HREE) according to the Australian JORC code and data on Chinese reserves according to Chinese definitions.

The overall global reserves are spread with larger reserves in the United States, the states from the former Soviet Union, China, Australia, India, Canada, Greenland, South Africa, Malawi and other countries. However, the analysis showed that the total sum of reserves is not relevant for the forecast of shortages of individual REE. Hence, an individual analysis for selected rare earth elements is necessary.

Principally, all deposits contain more light rare earth elements (LREE) than heavy rare earth elements (HREE). Mostly only a few percentages of the rare earths are HREE. Among them are the potentially critical elements dysprosium (Dy), terbium (Tb) and yttrium (Y). According to the chosen definition for this study the LREE comprise eight REE, among them are the widely used lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd) and europium (Eu).

Presently, no data on overall reserves of HREE are available. An estimation from the Australian Mining company ALKANE for nine potential mines outside of China (one deposit in Greenland and Vietnam, two deposits in the USA and Canada, three deposits in Australia) calculates economically available reserves of HREE of about 800 000 t and reserves of LREE of about 9.3 Mt. Furthermore, quite large reserves of HREE and reserves of LREE are located in China. Concerning European rare earth deposits, there is only limited information on a few potential sites, and no extensive explorations are known.

4 Mining data

4.1 World production

The world production of rare earths in 2008 and 2009 according to USGS (2010a) is shown in Table 4-1[5].

Table 4-1 World production of rare earths 2008 and 2009 (USGS 2010a)

Country	t REO per year	Share
China	120 000	97.0%
Brazil	650	0.5%
India	2 700	2.1%
Malaysia	380	0.3%
Other countries	n.d.	
Total	**124 000**	**100 %**

The table illustrates clearly the dominance of the Chinese production. The development of the rare earth production is shown in Figure 8.

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[5] The table does not include the illegal production in Chinese mines. Kingsnorth (2010) estimates 10 – 20 000 t REO from illegal or uncontrolled mining.

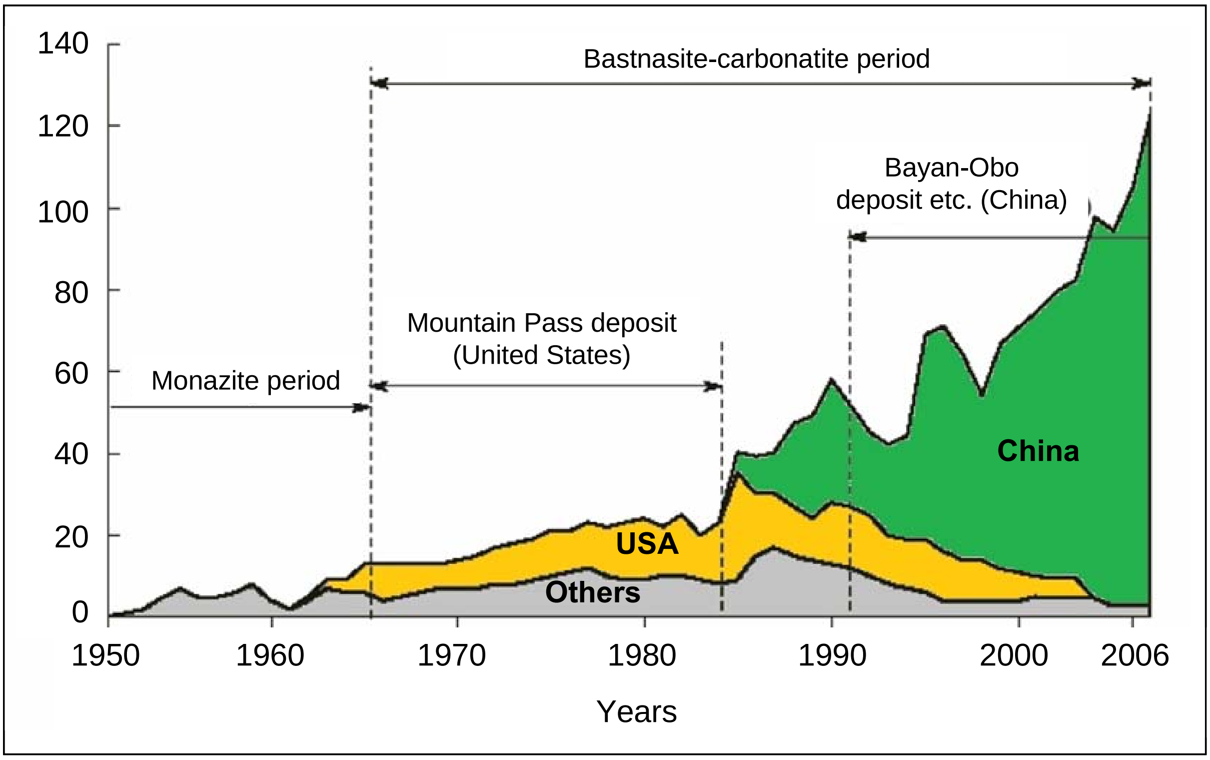

Figure 8 Global production of rare earth oxides [in thousand t] (Angerer et al 2009)

The figure points out the steady increase in the rare earth production and the continuous increase of the Chinese market share, particularly since 2002, when the American mine was closed due to environmental problems and low competitiveness because of low Chinese prices.

4.2 Mining in China

The following table shows the production of rare earth concentrates in China. The rare earth concentrates are the output from the concentration plants which are located next to the mine in order to produce a concentrate from the mined low-grade ore. The next step is the transport of the concentrates to the further processing and refining plants where different rare earth compounds are produced. The statistics on the output of these processing plants are given in Chapter 5.1.

Data sources are the Journal of rare earth information, the Chinese Society of Rare Earths and the National Development and Reform Commission (MEP 2009)[6].

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[6] When verifying the data, it was found that the total value is not equivalent to the single values in sum. The differences range between -100 and +400 tonnes. Nevertheless, it was decided that the original data would still be used since it was not clear whether the deviation occurred due to a typing error, is just a rough estimate or whether there are differences because other types of minerals like xenotime were cut off.

Table 4-2 Chinese production of rare earth concentrates from the different types of minerals from 2000 to 2007 in t REO

Year	Bastnaesite-Monazite-mixed type	Bastnaesite	Ion Adsorption deposits	Total
2000	40 600	12 500	19 500	73 000
2001	46 600	9 400	24 700	80 600
2002	55 400	13 000	20 000	88 400
2003	54 000	15 000	23 000	92 000
2004	46 600	21 701	30 000	98 310
2005	49 000	25 709	44 000	118 709
2006	50 377	37 000	45 129	132 506
2007	69 000	6 800	45 000	120 800

The total production in 2008 and 2009 remained constant at around 120 000 t REO (USGS 2010a). In addition to the Chinese legal production as presented in Table 4-2, Kingsnorth (2010) estimates 10 – 20 000 t REO from illegal or uncontrolled mining, and the China Securities Journal (2010) reports illegal exports of about 20 000 t REO in 2009.

The increase of the production figures of ion adsorption deposits from 19 500 t in 2000 to 45 000 t in 2007 is very remarkable. It reflects the increasing demand of the HREE. On the other hand this sharp growth enhances the pressure on the very limited reserves of ion adsorption deposits.

In May 2010, the notice on the consultative draft of "Entry Criterions for Rare Earth Industry" (MIIT 2010) was published by the Ministry of Industry and Information Technology of China. The aim is to improve the current situation of the rare earth industry in terms of lower environmental impacts, higher efficiencies and optimised management practices as well as closing regulation gaps. According to the 2009-2015 Plans for Developing the Rare Earth Industry from the Ministry of Industry and Information Technology (MIIT2009), China will not be issuing any new mining licenses of rare earths for the years from 2009 to 2015.

The mining technologies, their ecological impact and future policy issues are described in more detail in Chapter 7.3.

4.3 Mining activities outside of China

Currently, only a few amounts of rare earths come from other countries than China as presented in Table 4-1 (2 700 t from India, 650 t from Brazil and 380 t from Malaysia). Additionally, DOE (2010) indicates a Russian production of 2 470 t REO in 2009. Due to the high demand for rare earth and the decreasing Chinese export, there are many activities aimed at the opening of new mines outside of China.

The most advanced mining projects are re-opening of the Mountain Pass mine in California by Molycorp Minerals and the new rare earth mine at Mt Weld in Australia by Lynas with processing in Malaysia. Their operation is scheduled to begin in 2012 and 2011, respectively. When operating at full capacity they will each produce around 20 000 t REO light rare earths. Their technologies and environmental aspects are described in Chapter 7.4.

The next table gives an overview of further mining projects which are in an earlier stage. The table provides information on the potential annual production, the content of HREE and the stage of preparation. However, it is not certain whether these mining projects will be realised. There are many obstacles to overcome, such as technological challenges, environmental problems, funding of the capital intensive facilities and the approval procedures. If the environmental equipment is not appropriate, there are high environmental risks which are outlined in Chapter 7. The main technological challenges arise in the further processing of the rare earth ores and their separation. There is a marginal know-how in the countries outside of China, and the chemistry of rare earths is quite complex. Compared to the difficult processing, the mining and the first concentration step is quite similar to the mining of other metals and easier to handle.

Table 4-3 Selected current pre-mining activities outside of China (compiled by Öko-Institut)[7]

Country	Deposit	REO Output [t per year]	HREE Content (%TREO)	Stage of Implementation
Australia	Mt. Weld	10.000 - 21.000	3%	Mine in operation; Construction of concentration plant
	Nolans	20.000	4%	Metallurgical Tests
	Dubbo	2.500 - 3.200	60%	Construction of Pilot Plant
Canada	Nechalacho / Thor Lake	3.000 - 10.000	20%	Prefeasibility study
	Hoidas Lake	1.000 - 5.000	4%	Metallurgical test finished
	Benjamin River		30%	Drilling
	Douglas River		99%	Drilling
Greenland	Kvanefjeld	10.000 - 40.000	14%	Prefeasibility Study
India	Manavalakurichi, Chavara et al.	7.000		
Kazakhstan				
Kirghizia	Kutessay II		50%	Feasibility Study (Re-Opening)
Malawi	Kangankunde	5.000		
Mongolia	several			
South Africa	Steenkampskraal	≈ 5.000	8%	Feasibility Study
	Zandkopsdrift	20.000		Prefeasibility Study
USA	Mountain Pass	10.000 - 20.000	1%	Re-Opening
	Bear Lodge		2%	Scoping Study
	Bokan-Dotson Ridge		17%	Drilling
	Deep Sands	≈ 5.000	15%	Analysing drill results
	Elk Creek			exploratory stage
	Pea Ridge Iron Ore			Re-opening of iron mining
Vietnam	Dong Pao			

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[7] The data are compiled from manifold data sources (GWMG 2010a, GWMG 2010, RES 2010, Lynas 2010b, Oakdene Hollins 2010, Byron Capital Markets 2010, BGR 2010, GMEL 2010a, GMEL 2010b, USGS 2009b, Goldinvest 2010, Molycorp 2010, Ucore 2010, Thorium 2010, Wings 2010b, Bojanowski 2010 and home pages of the involved mining companies).

Additionally, BGS (2010) reports about some further projects which are in an early exploration state in Canada, USA, Namibia, Australia and Malawi. The German company Tantalus Rare Earths AG started the geological sampling at a potential deposit in Madagascar (Tantalus 2010). Japanese companies are involved in the development of rare earth mining in Kazakhstan, Vietnam and India (BGS 2010, BBC 2010, Reuters 2010, DOE 2010).

The time span needed in order to start the operation of a mining including the concentration of the ore depends on many site-specific factors. Based on the examples of the modernization at the Mountain Pass and the new implementations of Mt Weld, the following time ranges can be estimated which are required for the implementation of new mining projects. However the time schedules for specific mines may vary significantly because every mining has its specific challenges (environmental issues, type of mineral, type of mining, ore grade, financial equipment, social context, etc.):

▪ Feasibility studies, metallurgical tests, pilot plan:	around four years
▪ Installation of the mining equipment:	around one year
▪ Installation of the concentration plant to enrich the low-grade ore from the mine:	around two years
▪ Installation of rare earth processing plants from concentrated ore:	around four years

The approval procedure also requires several years and usually runs parallel to the project development and implementation. The operation of the Mountain Pass requires more than 20 permissions concerning environmental issues, building, work safety and others (Molycorp 2010b). Oakdene Hollins (2010) estimates a minimum time of 6 – 10 years before a mine starts operation. USGS (2010f) gives an overview of the time needed for the approval procedure and the construction work since the discovery of the deposit. The time spans vary significantly from 5 to 50 years.

Another aspect concerning the opening of new mines and rare earth processing plants is the high investment. Oakdene Hollins (2010) cites a document from an OECD workshop in 2009 with the estimate that typically capacity costs are more than 30 000 US$ per ton of capacity for separated REE. The figures are in the same range as data on investment compiled by Lifton (2010a) on mining and processing companies and their need of financial investment for the development of the rare earth production including processing: Molycorp (Mountain Pass, USA) more than US$ 500 million, Avalon Rare metals (Thor Lake, Canada): C$ 900 million for the Northwest Territories project, Lynas (Mt Weld, Australia): US$ 500 million, Arafura Resources (Nolans, Australia) more than US$ 500 million. The major investment costs in this context arise from the processing. USGS (2010f) also confirms the need of large sources and capitals and outlines that already the pre-mining activities (exploration, metallurgical process development, approval procedure) cause high expenses.

The specific production costs per unit of processed rare earth also show just a small contribution from the mining: Lynas (2010a) estimates the contribution of the overall cash costs for process rare earth oxides (finished REO) as follows: Mining 4 %; concentration of the ore 21 %, shipping from Australia to Malaysia (9 %) and refining and processing 66 %.

Conclusion on mining

The world production of rare earths was around 124 000 t REO per year in 2008 and 2009 according to data from the US Geological Survey (USGS). This is quite low compared with the annual primary production of other metals, e.g. 39 Mt aluminium or 22 Mt copper. More than 97 % of the production and a large share of the further processing are located in China. Small amounts are produced in Malaysia, Brazil, India and Russia. Additionally, around 20 000 t REO were illegally produced in China and are not included in the above given USGS data.

Due to the high demand for rare earths and the decreasing Chinese exports, there are many activities aimed at the opening of new mines outside of China. The most advanced mining projects are the re-opening of the Mountain Pass mine in California by Molycorp Minerals and the new rare earth mine at Mt Weld in Australia by Lynas with processing in Malaysia. Their operation is scheduled to begin in 2012 and 2011, respectively.

Additionally, there are numerous further mining projects which are in an earlier stage in Australia, Canada, USA, India, Kazakhstan, Kirghizia, Malawi, South Africa, Vietnam and Madagascar. However, it is not certain whether these mining projects will be realised. There are many obstacles to overcome, such as technological problems, environmental problems, funding of the capital intensive facilities and the approval procedures. The time span needed in order to start the operation of a mining including the concentration of the ore depends on many site-specific factors and is estimated to take a minimum of six to ten years.

5 Global rare earth processing

5.1 Rare earth processing in China

In terms of separation and smelting technologies, China owns internationally advanced rare earth technology. Since 1972, China has been conducting investigations on separation and smelting technologies of rare earth. It is the only country in the world that can provide rare earth products of all grades and specifications, stated Lin Donglu, Secretary General of the Chinese Society of Rare Earths in an interview by Xinhua News Agency's finance magazine (Beijng Review 2010). By now, there are about 24 domestic enterprises for rare earth mining and 100 rare earth enterprises (11 among them are joint ventures) for separating and smelting as well as refining production in China according to The Explanation of Compiling Emission Standards of Pollutants from Rare Earths Industry. Three major extraction areas are located in Inner Mongolia, Sichuan and seven provinces in the South of China, mainly in Jiangxi. Their technologies are described in Chapter 7.3.2.

China not only produces the rare earth containing intermediate products such as metals, alloys or carbonates but also manufactures most of the final products, e.g. phosphors, LEDs, catalysts, Ni-MH batteries, magnets. China's government encourages its enterprises to extend the manufacturing of these products with a higher value using high-technology at the end of the process chain in order to supply the growing Chinese market as well as for export.

5.1.1 Production statistics

Figure 9 gives an overview of the rare earth oxide production in China in 2006 and the contribution of specific elements. The detailed figures are presented in Table 5-2.

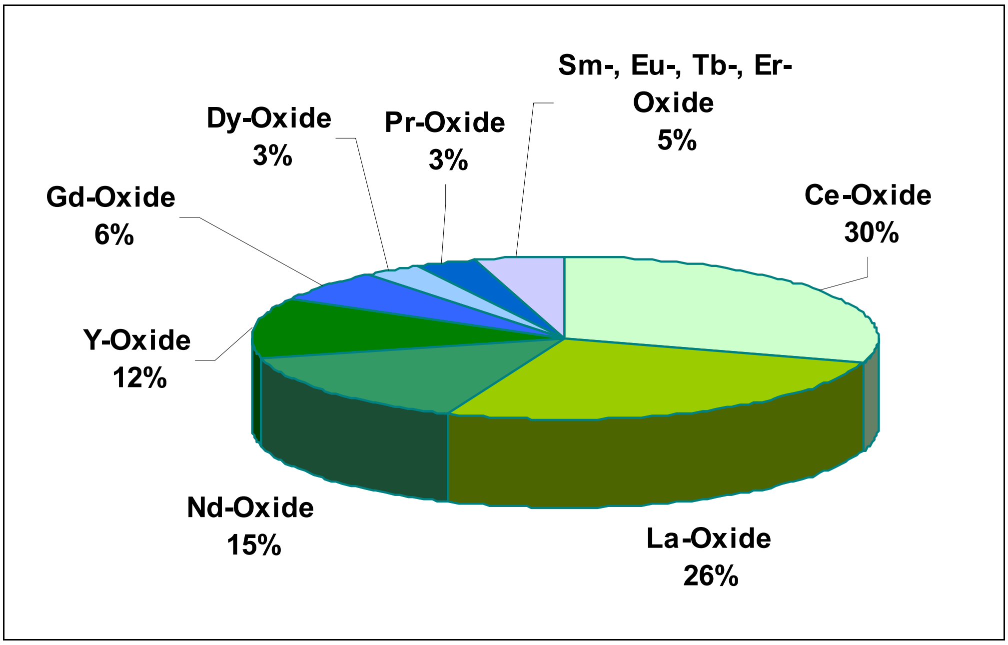

Figure 9 Share of individual rare earth oxides at the Chinese production in 2006 (MEP 2009)

The following tables show the production of rare earth chloride, carbonate and selected oxides, metals and polishing powder in China, respectively. Data sources are the Journal of rare earth information, the Chinese Society of Rare Earths, and the National Development and Reform Commission (cited in the Explanation of Compiling of Entry Criterions for Rare Earth Industry from 2009 (MEP 2009)).

Table 5-1 Production of rare earth carbonate and chloride from 1987 to 2006 in t REO (MEP 2009)

Year	Rare earth carbonate	Rare earth chloride
1987	—	3 870
1988	221	4 054
1989	362	6 088
1990	237	4 490
1991	—	5 341
1992	256	7 280
1993	2 100	9 560
1994	2 849	11 656
1995	6 461	15 191
1996	6 260	15 711
1997	9 897	11 971
1998	13 338	12 071
1999	15 005	13 579
2000	16 673	15 089
2001	18 339	16 296
2002	20 007	18 107
2003	—	—
2004	3 800	9 800
2005	5 548	4 626
2006	4 846	4 846

Table 5-2 Production of major rare earth oxides from 1986 to 2006 in t REO (MEP 2009)[8]

Year	La_2O_3	CeO_2	Pr_6O_{11}	Nd_2O_3	Sm_2O_3	Eu_2O_3	Gd_2O_3	Tb_4O_7	Dy_2O_3	Er_2O_3	Y_2O_3	Sum
1986	66	160	-	44	12	3	30	-	-	-	100	415
1987	126	142	25	122	40	4	18	2	3	-	214	696
1988	227	169	32	204	50	6	21	2	5	-	339	1 055
1989	272	201	68	331	75	11	34	3	25	4	506	1 530
1990	274	277	106	505	105	14	37	5	51	2	468	1 844
1991	564	406	150	905	111	12	39	9	83	12	471	2 762
1992	474	464	111	834	99	12	50	11	67	24	498	2 644
1993	210	703	74	907	73	17	24	10	75	27	476	2 596
1994	655	1 352	157	1 355	136	32	48	12	124	44	854	4 769
1995	1 342	2 680	580	2 036	208	30	83	17	212	43	1 274	8 505
1996	1 548	3 503	400	3 090	252	40	102	29	255	28	2 033	11 280
1997	1 678	4 181	570	5 256	165	41	120	28	262	32	2 211	14 544
1998	2 888	4 950	762	6 200	248	125	90	64	292	98	2 675	18 392
1999	3 249	5 568	859	6 950	275	140	101	72	328	110	3 009	20 661
2000	3 954	6 190	990	8 500	322	162	117	83	365	123	3 344	24 150
2001	5 367	7 177	1 104	8 800	359	181	131	88	401	135	3 678	27 421
2002	5 832	7 425	1 143	9 000	372	187	135	96	438	147	4 013	28 788
2004	8 400	9 630	350	2 200	922	208	170	69	120	180	5 200	27 449
2005	18 750	15 580	2 470	2 096	739	342	683	388	128	967	5 591	47 734
2006	19 730	22 579	2 297	11 343	1 586	368	4 625	607	2 311	954	9 027	75 427

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[8] When verifying the data, it was found that the total value is not equivalent to the single values in sum. It has a maximal difference of 106 t. Nevertheless, it was decided that the original data would still be used since it was not clear whether the deviation occurred due to a typing error or just a rough estimate or whether there are differences because other types of rare earth oxides were cut off.

Table 5-3 Production of polishing powder and metal alloys from 1987 to 2006 in t REO (MEP 2009)

Year	Polishing powder	Rare earth metal alloys
1987	160	n.d.
1988	100	n.d.
1989	83	n.d.
1990	232	1 154
1991	334	1 149
1992	312	2 267
1993	418	4 059
1994	568	3 139
1995	665	4 112
1996	632	2 860
1997	600	3 307
1998	530	4 501
1999	1 800	5 063
2000	2 400	5 626
2001	3 200	6 389
2002	3 500	6 751
2004	4 900	13 200
2005	6 092	7 213
2006	n.d.	9 166

Table 5-4 Production of major single rare earth metals from 1987 to 2006 in t REO (MEP 2009)

Year	La	Ce	Pr	Nd	Sm	Y	Dy	Total
1987	22	—	—	29	6	—	—	57
1988	36	13	—	37	9	5	—	100
1989	2	9	—	108	5	2	—	127
1990	51	13	—	171	2	3	—	240
1991	6	2	—	145	1	2	6	161
1992	106	28	—	401	4	24	18	580
1993	11	12	—	469	6	4	4	506
1994	14	—	—	195	10	5	13	237
1995	59	—	—	393	21	1	19	494
1996	170	—	—	368	6	—	24	568
1997	185	—	—	1 200	7	—	37	1 429
1998	220	—	137	1 600	20	—	127	2 104
1999	248	—	154	1 800	23	—	143	2 368
2000	275	—	171	2 000	25	—	159	2 630
2001	303	—	188	2 200	28	—	175	2 894
2002	330	—	206	3 000	30	—	191	3 757
2004	380	—	—	3 900	350	—	780	5 410
2005	1 184	—	—	6 980	184	—	62	8 410
2006	2 034	—	—	7 032	489	—	1 280	10 835

5.1.2 The Chinese policy concerning the rare earth processing industry

To protect rare earth resources and develop in a sustainable way, China started a comprehensive series of regulations and standards. New policy statutes were made and promulgated including a mid- and long-term Development Plan for the Rare-Earth Industry and Rare-Earth Industrial Development Policy. The major plans and regulations concerning the management and capacities are described below. The environmental aspects are presented separately in Chapter 7.3.7.

5.1.2.1 Entry criteria for rare earth industry

In May 2010, the Ministry of Industry and Information Technology of China issued the notice on the consultative draft of “Entry Criterions for Rare Earth Industry” (MIIT 2010). This regulation clearly stipulates the minimum limitation of production scales, operation and technological equipment, the minimum capital ratio of fixed assets, as well as thresholds and requirements in terms of environment protection to assist the rare earth industry in sustainable development. One effect of this regulation is a concentration of the rare earth industry which forces small companies to merge with other enterprises.

Concerning production scales at the separation and processing level, the production capacity of separation and refinement of mixed types of ores should not be less than 8 000 t REO per year. The production capacity of separating and refining of bastnaesite should not be less than 5 000 t REO annually.

As regards production scales at the metal refining level, the production capacity of enterprises should not be less than 1 500 t per year. Furthermore, the capital ratio of fixed assets investment should account for at least 40 % of total investment.

The environmental standards determined in the regulation are presented in Chapter 7.3.7.

5.1.2.2 The 2009-2015 plans for developing the rare earth industry

This development plan is a mandatory planning compiled by the Ministry of Industry and Information Technology of China. According to the 2009-2015 Plans for Developing the Rare Earth Industry, rare earth industry in China will divide into three large districts: South, North and West (MIIT 2009). As for light REE mining, the focus is located in Inner Mongolia (Northern district) and Sichuan (Southwest district), with some development in Shandong as far as needed. The heavy REE mining is concentrated in the southern districts such as Jiangxi, Guangdong, Fujian and Hunan (China Net 2010). The aim of the Plan is to simplify management of China's rare earth resources by "designating large districts". Because of the scattered distribution of rare earth resources, it is difficult to carry out an efficient oversight of the industry (Hurst 2010).

According to the mandatory planning, from 2009 to 2015, the whole production of refined rare earth metals should range between 13 000 and 15 000 tons annually. The production capacity of separating and smelting enterprises should be between 12 000 and 15 000 tons.

Moreover, China is undergoing consolidation – mergers and acquisitions by large companies and closing of small plants. For the years from 2009 to 2015, China will not be issuing any new mining licenses of rare earths. During this period, the existing rare earth enterprises should put emphasis on improving the level of technical equipment, environmental protection and management capability. Meanwhile, mergers and acquisitions (M&As) in rare earth industry are promoted. Furthermore, a plan has clearly been specified to close down a number of small and illegal as well as inefficient separating and smelting enterprises in order to gain more control. It was reported that the government planned to cut down the number of enterprises from 100 at the moment to 20 (China Net 2010).

As for the monitoring aspect, the Ministry of Industry and Information Technology will oversee the industry by creating an examination and inspection system for rare earth extraction to guarantee that national directive plans are being implemented and executed.

5.2 Rare earth processing outside of China

Figure 11 on page 36 presents the shares of the different EU member states at the total rare earth compound imports of the EU-27. It shows that the main importers (import from outside the EU) in 2008 were France (38 %), Austria (24 %), the Netherlands (16 %), United Kingdom (8 %) and Germany (8 %). This corresponds to the location of the main rare earth processing industries in Europe. Selected industrial activities are listed below:

Table 5-5 Selected industrial activities in rare earth processing in Europe

Country	Selected companies	Products
France	Rhodia (formerly Rhone-Poulenc)	automotive catalysts, phosphors
Austria	Treibacher Industrie AG	catalysts, glass polishing powder, glass fusion, pigments and ceramic glazes, pharmaceutical products
Netherlands	Walker Europe	magnet production
	Goudsmit Magnetic Systems	magnet production
United Kingdom	Magnet Applications	magnet production
	Arnold magnetic Technologies	magnet production
	Less Common Metals Limited (subsidiary of Great Western Mineral Group)	alloys with rare earths
Germany	Vacuumschmelze	magnet production
Estonia	Silmet Rare Metals	rare earth separation, rare earth metal production

The list of European companies above shows that there are only a few industrial activities on rare earth refining and processing. The European companies are mainly involved in manufacturing processes for semi-finished or finished products which contain REE like magnets, alloys, automotive catalysts, etc.

Most of the core rare earth refining and processing activities are located in China and some processing is carried out in Japan. One example for the dominance of the Chinese rare earth processing is the permanent magnet production. There are only a few capacities for the refining of the intermediate products (alloys) in Japan and no capacities in Europe and the United States. Concerning the final magnet production, there are a small number of permanent magnet producers in Europe, whereas the United States is not currently producing neodymium permanent magnets. There is only one samarium cobalt magnet producer in the United States (GAO 2010).

The next figure shows the process steps and the national shares of the global processing of permanent neodymium magnets (data compiled from Molycorp (2010c) and GAO (2010)):

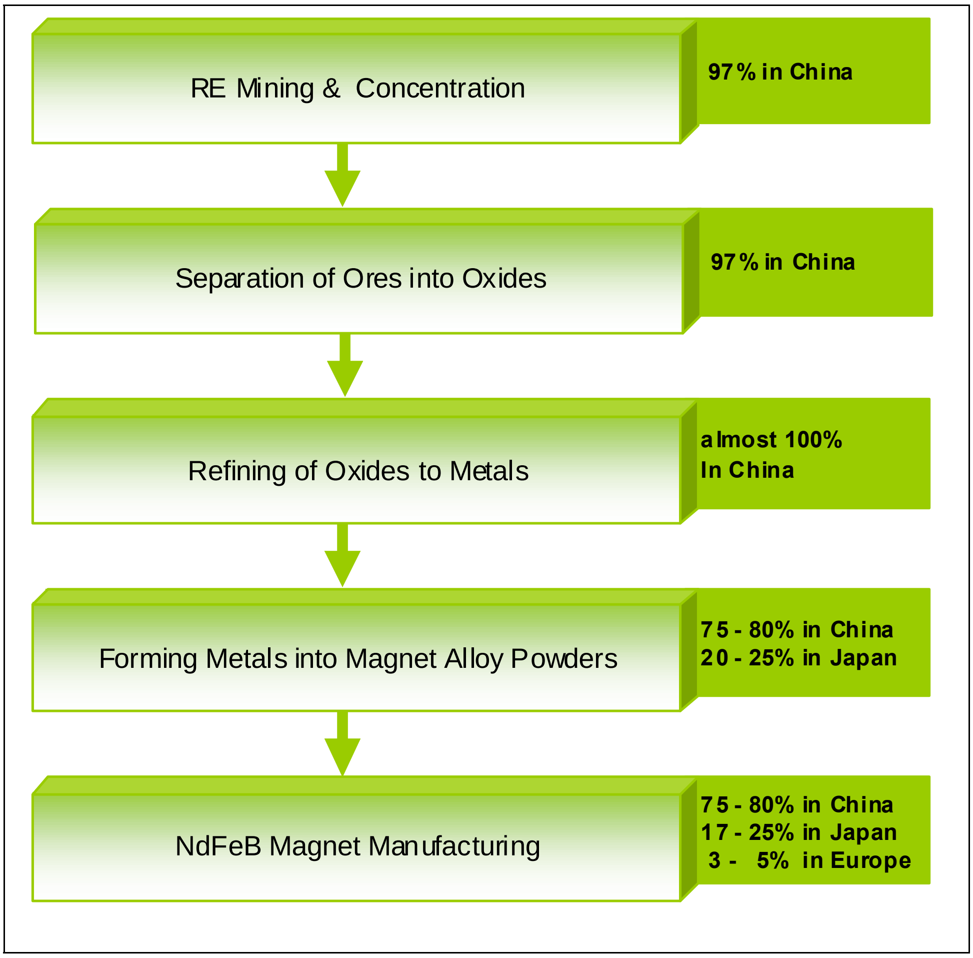

Figure 10 Process steps and national shares of neodymium magnet production (GAO 2010, Molycorp 2010c)

Even if some shares of the Chinese production were overestimated as there are some smaller processing facilities outside of China, the figures show very clearly the key fact that there is little processing technology for the first steps of rare earth processing and refining outside of China. The American company Molycorp Minerals is planning to resolve this problem by re-opening their rare earth mine and concentration plant at the Mountain Pass in California and complementing it with the whole rare earth processing chain including a neodymium permanent magnet production.

Conclusion on global rare earth processing

In terms of separation and smelting technologies, China owns internationally advanced rare earth technology. It is the only country in the world that can provide rare earth products of all grades and specifications. China not only produces rare earth containing intermediate products but also manufactures most of the final products. China's government encourages its enterprises to extend the manufacturing of finished products with a higher value using high-technology at the end of the process chain.

According to the “Entry Criterions for Rare Earth Industry” and the “2009-2015 Plans for Developing the Rare Earth Industry”, the rare earth industry in China will be divided into three large districts in order to undergo consolidation with mergers and closing of small plants. For the years from 2009 to 2015, China will not be issuing any new mining licenses of rare earths. During this period, the existing rare earth enterprises should put emphasis on improving the level of technical equipment, environmental protection and management capability. Furthermore, a plan has clearly been specified to close down a number of small and illegal as well as inefficient separating and smelting enterprises. An examination and inspection system shall also be created.

Besides China, Japan is able to carry out some rare earth processing. In Europe, there are only a few industrial activities on rare earth refining and processing. The European companies are mainly involved in manufacturing processes for semi-finished or finished products which contain REE like magnets, lighting systems, alloys, automotive catalysts, etc.

6 Rare earth trade

6.1 Global rare earths imports

The major importers of rare earths compounds in 2008 were Europe, USA and Japan (BGS 2010). The amounts of imported rare earths according to the national statistical offices are given in the next table. It should be noted that the different regions use a different statistical framework.

Table 6-1 Imports of rare earth compounds of Europe, United States and Japan in 2008

	Imports	Share of imports from China	Data source	Compounds included in the statistic
EU 27	23 013 t	90 %[9]	Eurostat 2010	Metals, intermixtures or interalloys of rare-earths, Sc and Y Compounds of rare-earth metals, mixtures of these metals, Y or Sc
USA	20 663 t	91 %	USGS 2010c	Rare-earth and Y compounds, Rare-earth metals, Mixtures of rare-earth chlorides, Ferrocerium and other pyrophoric alloys
Japan	34 330 t	91 %	Trade Statistics Japan 2010	Cerium-, Lanthanum- and Yttrium Oxide, other cerium compounds, others

In total, according to these figures, 78 006 t of REO containing compounds were imported in 2008 by EU 27, Japan and USA. Of these, around 71 000 t were imported from China.

The next figure shows the share of the European member states in terms of the total imports of rare earths compounds from outside the EU-27. Imports from other EU member states are not included.

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[9] The statistics from Eurostat provides no data on the origin of the imports to Austria. The share of Chinese imports in terms of total imports of all EU-27 members besides Austria is 90%.

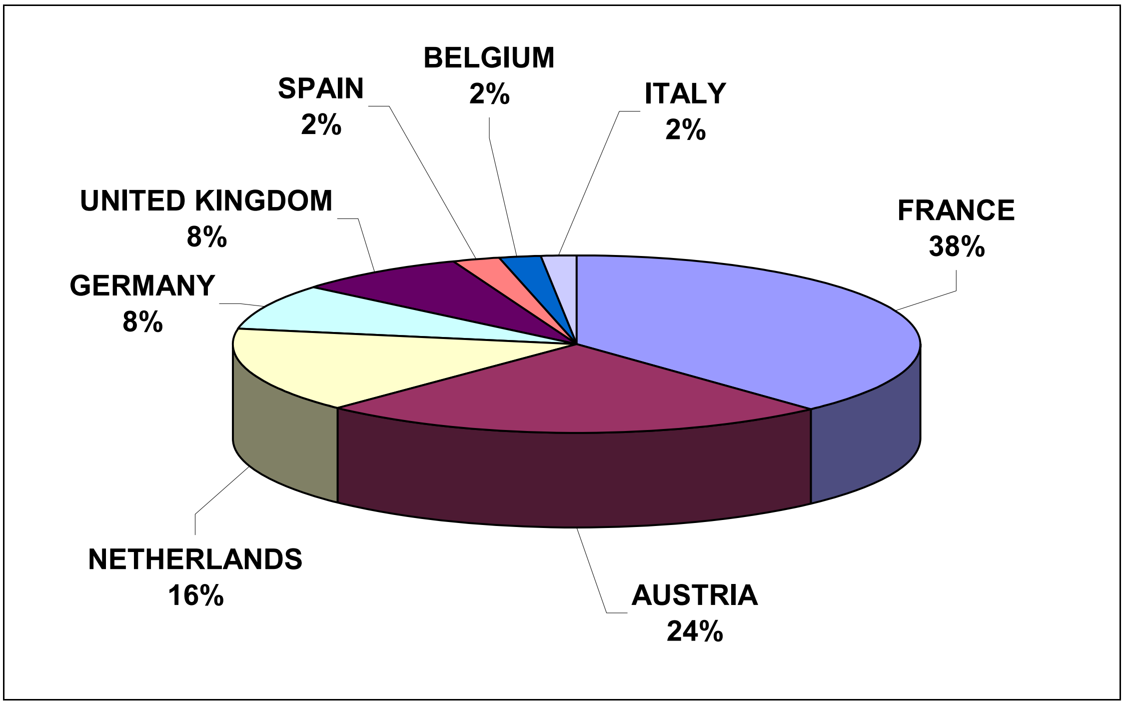


Figure 11 Share of different EU countries in the total rare earth compounds imported by the EU-27 (Eurostat 2010)

Figure 11 shows that the main importers of the EU-27 in 2008 were France (38 %), Austria (24 %), the Netherlands (16 %), the United Kingdom (8 %) and Germany (8 %).

6.2 Global rare earth exports

6.2.1 Chinese rare earth exports

In order to try to protect rare earth resources and promote the sustainable, rapid and healthy development of the rare-earth industry in China, the State Development Planning Commission of China has issued the Interim Provisions on the Administration of Foreign-funded Rare Earth Industry, which has been effective since 1st August 2002. It is clearly stipulated that foreign enterprises are prohibited to invest in mining and extraction of rare earth minerals in China. As for the separating and smelting areas, only joint-venture enterprises are allowed for foreigners. Foreign capitals are, however, encouraged in the fields of intensive processing and investigation regarding applications of advanced materials out of rare earths in China.

Figure 12 pictures the development of the Chinese export volume from 1979 to 2008 according to Chen (2010). Generally speaking, the exportation of rare earth increased gradually along the years. In 2006, the volume reached a peak with 57 400 tons and then declined from 2007 onwards.

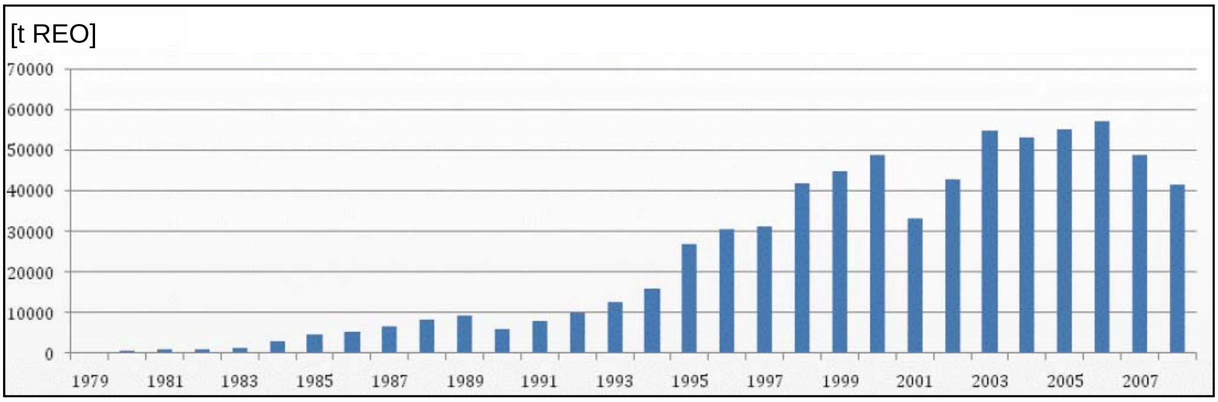


Figure 12 Gross exportation volume of rare earths from 1979 to 2008 in China (Chen 2010)

The export of rare earths decreased by 29 % in 2010 compared to 2008, as shown in Table 6-2.

Table 6-2 Chinese rare earths exports of state and foreign-invested enterprises from 2008 - 2010 (MOFCOM 2010b)

	2008	**2009**	**2010 (Approved exports)**
Chinese-invested enterprises (t REO)	34 156	31 310	30 258
Foreign-invested enterprises (t REO)	8 210	16 845	
Total (t REO)	42 366	48 155	30 258
Reduction in % compared to 2008	**0%**	**14%**	**-29%**

A detailed breakdown of the exportation volume between the first and second half-year is shown in Table 6-3. These data originally refer to announcements of the Ministry of Commerce of the People's Republic of China Department of Foreign Trade. The table shows the export quota realised by domestic Chinese-invested enterprises for 2008, 2009 and the first half of 2010. For the second half of 2010, the given amount of 7 976 tons also includes the foreign-invested enterprises.

Table 6-3 Export quota only for domestic Chinese-invested enterprises for 2008, 2009 and the first half of 2010 (MOFCOM 2010b)

Time coverage	**2008**	**2009**	**2010**
The first half of the year (t REO)	22 780	15 043	16 304
The second half of the year (t REO)	11 376	16 267	7 976*
Total (t REO)	34 156	31 310	24 280
Reduction compared to 2008		**-8%**	**-29%**

* For the second half of 2010, the given amount of 7 976 tons also includes the foreign-invested enterprises.

From 2009 to 2015, the rare earth export quota issued by China's Ministry of Commerce could be restricted to 35 000 tons according to the 2009-2015 Plans for Developing the Rare Earth Industry. The aims of control of rare earth exports are to regulate the current non-transparent situation of rare earth industry, to protect resources and the environment and to guarantee the supply of the rising domestic demand. Meanwhile, China is promoting renewable energy and green technology. The domestic demand for rare earth could therefore increase rapidly, as rare earth is related closely to the green industries such as wind turbines or electric vehicles.

All data given in the tables and figures above do not include the illegal exports from China. According to news on 9 October 2010 from China Securities Journal (2010), it was estimated that in 2009 about 20 000 t REO of rare earths were smuggled to foreign countries illegally, besides legal exports. Compared to the illegal quantity in 2008, 2009 presents an increase of 10 %. Thus, the sum of legal and illegal exports would be around 60 500 t in 2008 and around 68 000 t in 2009. A comparison of the Chinese exports with the import data of the major importers are quite informative: The import statistics from Japan, USA and EU as presented in Table 6-1 indicate rare earths imports from China of around 71 000 t in 2008. These high imports support the estimate for illegal exports in the magnitude of 20 000 or even more t REO yearly.

6.2.2 Non-Chinese rare earth exports

The main non-Chinese exporters of semi-products of rare earths are Japan, USA and Europe. These countries import primary material mostly from China and export processed semi-products. The following table shows the exports in 2008. For Europe, exports within the EU-27 are not included.

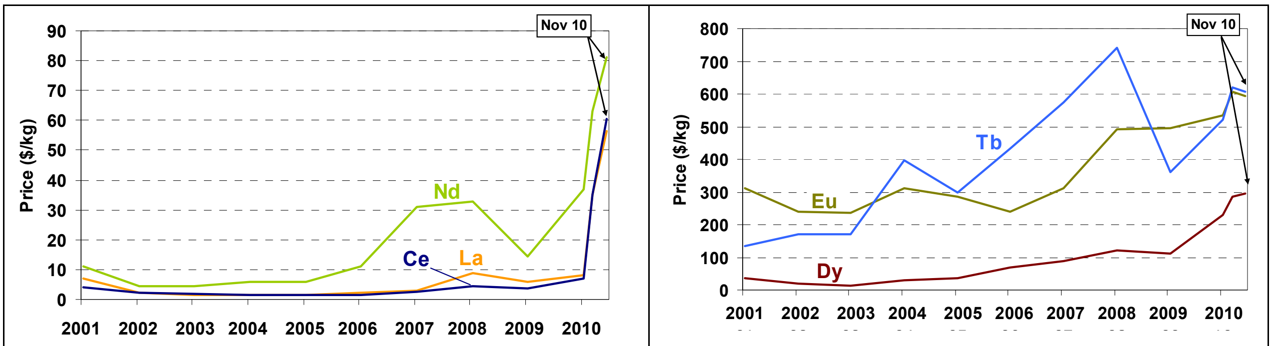
Table 6-4 Exports of semi-products of rare earths of Japan, USA and Europe in 2008

	Exports of rare earth compounds in 2008	**Data source**	**Compounds included in the statistic**
EU 27	4 704 t	Eurostat 2010	Metals, intermixtures or interalloys of rare-earths, Sc and Y Compounds of rare-earth metals, mixtures of these metals, Y or Sc
USA	8 253 t	USGS 2010c	Rare-earth and Y compounds, rare-earth metals, mixtures of rare-earth chlorides, ferrocerium and other pyrophoric alloys
Japan	8 997 t	Trade Statistics Japan 2010	Cerium-, lanthanum- and yttrium oxide, other cerium compounds, others

The main destination countries for Japanese exports are South Korea (33 %), China (17 %), Taiwan (15 %), Thailand (14 %) and USA (9 %).

6.3 Development of prices

Figure 13 shows the development of some selected rare earths oxides from 2001 to 2010.



a) Lanthanum, cerium and neodymium oxide

b) Europium, dysprosium and terbium oxide

Figure 13 Prices for lanthanum, cerium, neodymium, europium, dysprosium and terbium oxides from 2001-2010

The figure shows the moderate price development up to the end of the decade and the steep increase due to the increased global demand and the reduction of Chinese exports. The steep price increase not only affects the REE for which supply shortages are forecasted but also less scarce REE such as cerium. The detailed prices of selected rare earths metals and rare earth oxides are shown in Table 6-5 and Table 6-6.

Table 6-5 Prices of selected rare earths oxides on 22 Nov 2010*

Rare Earth Oxide	Price ($/kg)
Cerium	59 – 62
Dysprosium	284 – 305
Erbium	84 – 94
Europium	585 – 605
Gadolinium	43 – 46
Lanthanum	55 – 58
Neodymium	79 – 83
Praseodymium	71 – 80
Samarium	33 – 35
Terbium	595 – 615
Yttrium	53 – 70

*Data compiled from www.metal-pages.com and www.asianmetal.com; free-on-board; min purity 99% (Y min 99.999%)

Table 6-6 Prices of selected rare earths metals on 22 Nov 2010*

Rare Earth Metal	Price ($/kg)
Cerium	43 – 55
Dysprosium	372 – 415
Europium	710 – 800
Gadolinium	53 – 56
Lanthanum	42 – 46
Neodymium	97 – 100
Praseodymium	84 – 106
Samarium	44,50 – 53
Terbium	750 – 792
Yttrium	61 – 63

*Data compiled from www.metal-pages.com and www.asianmetal.com; free-on-board; min purity 99% (Y min 99.999%)

Conclusion on rare earth trade

China is the world leading exporter of rare earths. The exports in 2009 amounted to about 48 000 t REO legal exports plus additional illegal exports of around 20 000 t REO. The major importers of rare earths compounds were Europe, USA and Japan, importing a total of 78 000 t of rare earths containing compounds in 2008. Of these, more than 90 % were imported from China.

China reduced the official exports in 2010 by 29 % compared to 2008 (around 30 000 t REO in 2010) and announced further export restrictions for 2011. This policy and the increasing demand for rare earths lead to a steep increase in the prices of most rare earth elements.

7 Environmental aspects of rare earth mining and processing

7.1 Overview of the main process steps in mining and processing

The diversity of the deposits results in a wide variation in mining and processing technologies. Often, rare earths are exploited as a by-product of other metals. Examples are the largest rare earth mining at Bayan-Obo, where the main output is iron. Furthermore smaller REE extractions are by-products from titanium or uranium mining operations (BGS 2010). The most often practiced processing technique of the crude ore after mining is the concentration (also called beneficiation) by milling and flotation. This technique is used at Bayan-Obo, at the Sichuan mine, at Mountain Pass and in the short term also at Mt Weld. The next figure shows the main process steps in REE mining and beneficiation.

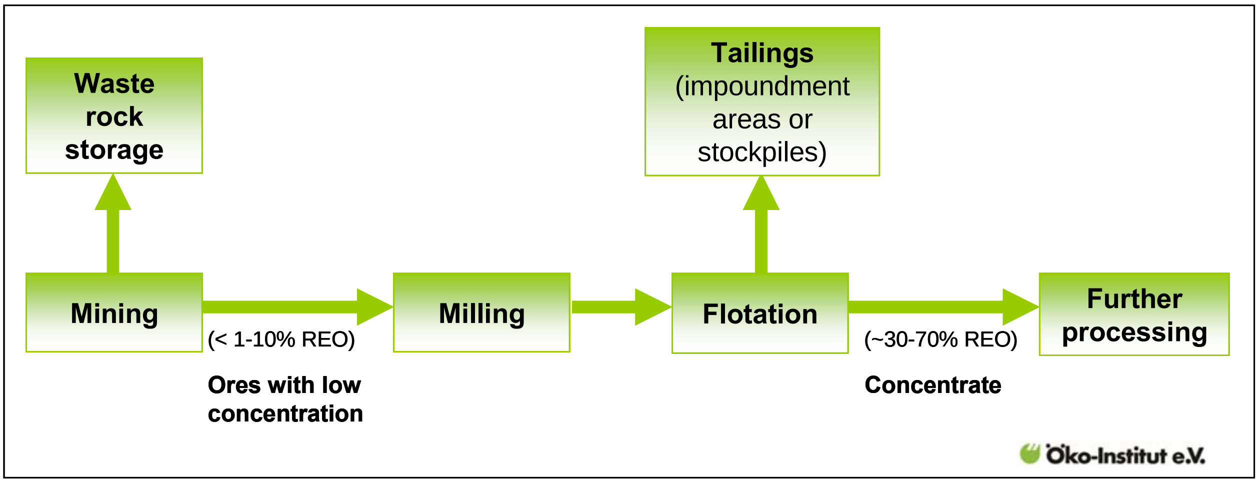


Figure 14 Main process steps in REE mining and processing

The first step, the **<u>mining,</u>** most frequently takes the form of open pit mining. However, there are also deposits which would require underground mining, e.g. the Canadian deposit at the Thor Lake.

In open pit mining, before reaching the ore rich in the metals to be extracted, the **overburden material** (soil and vegetation above the bedrock) as well as the **<u>waste rock</u>** (not ore-bearing or having a too low concentration of the ore) need to be removed and are stockpiled.

The second step after mining of the crude ore is **<u>milling</u>**. The ore is crushed and subsequently ground to fine powder in the mill with the aim of creating a high surface which is needed for the further separation.

The third step is the separation of the valuable metals from the rest of the ore by physical separation methods. The most commonly used method is **<u>flotation,</u>** which requires a lot of water and chemicals (flotation agents) as well as a high amount of energy (see, for example, Canino et al. 2005). The input into the flotation is the milled crude ore with usually low concentrations (grades) of REO (often between 1 and 10 %). The product of the flotation is an enriched concentrate with a higher REE-percentage (in the range of 30 – 70 %). The huge waste streams, called **tailings,** are a mixture of water, process chemicals and finely ground minerals. Usually, the tailings are led to **impoundment areas**, which can be either artificial reservoirs or even natural water bodies (e.g. lakes). They are surrounded by dams.

Finally, the concentrate undergoes **further processing**. It is transported to a refinery which can be off-site. There the REE are further extracted and separated into the different elements as required. This separation of individual REE is particularly difficult due to their chemical similarity.

An alternative mining technology is the in-situ leaching technology which is used in the Chinese HREE mining from ion adsorption deposits. It is introduced in Chapter 7.3.5.

7.2 Environmental risks

The next figure gives an overview of potential dangers for the environment if the mining and processing is carried out without or with insufficient environmental technologies. The red flashes in the figure symbolise the main risk spots. The size of the flashes is an indicator for the severity of the risk.

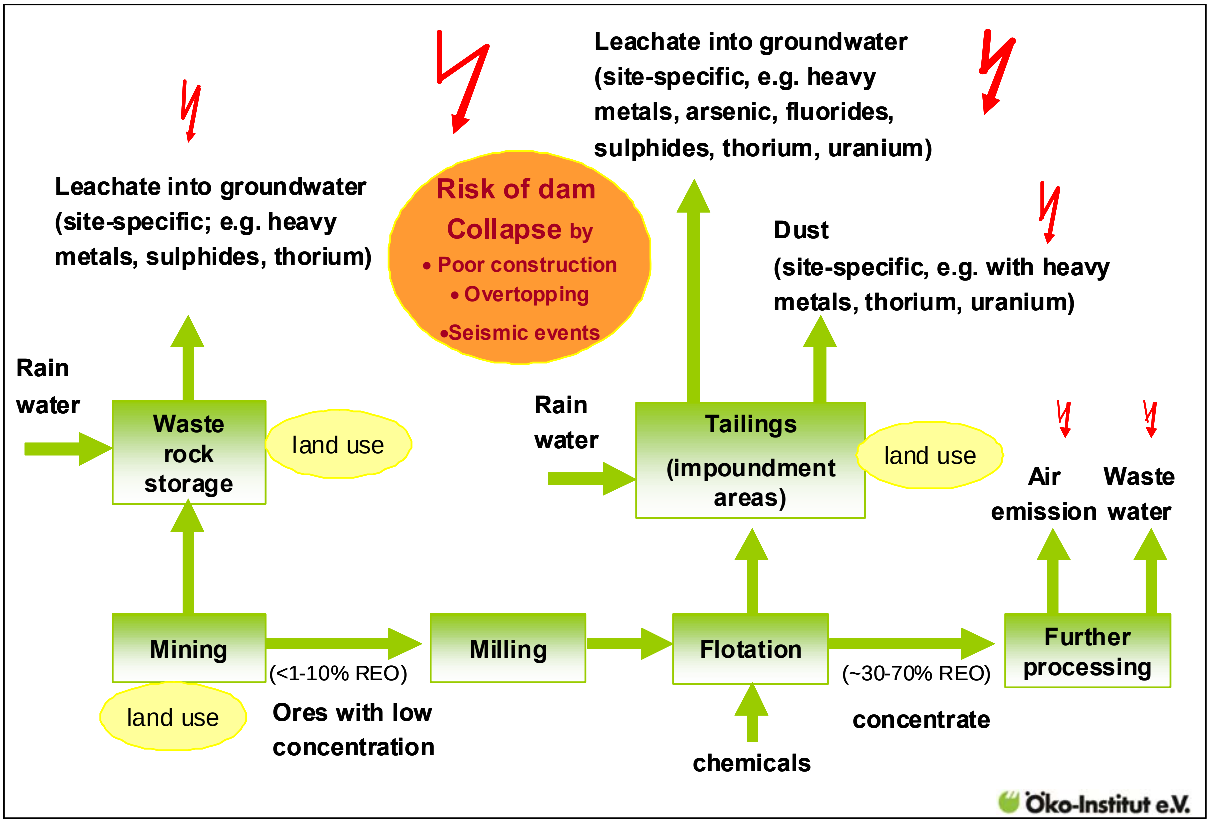


Figure 15 Risks of rare earth mining without or with insufficient environmental protection systems

The major short- and long-term risks are constituted by the **tailings**. The tailings consist of small-size particles with large surfaces, waste water and flotation chemicals. Usually, they remain forever in the impoundment areas where they are exposed to rain water and storm water runoff. During this continuous exposure to water, toxic substances can be washed out. If the ground of the impoundment areas is not leak-proof, there will be steady emissions to groundwater. Another serious risk is the storm water run-off when heavy rain falls occur and the impoundment areas are not able to store the huge amounts of storm water. Then, large amounts of untreated toxic water will pollute surrounding water bodies and soils. The composition of polluting water is site-specific as it depends on the composition of the host minerals and the used flotation agents. However, in most cases, the tailings include radioactive substances, fluorides, sulphides, acids and heavy metals. It is important to note that most of the rare earth deposits contain uranium, thorium and their further decay products. Only very few known deposits are free from radioactive substances. An ecological disaster will occur if the dam collapses and the highly toxic water and sludge flood the surroundings. There are several risks which might cause a dam collapse: the dam might fail due to overtopping from storm water, collapse due to poor construction or burst due to seismic events. These risks require a long-term monitoring as the dams must not only remain stable during the mining operation, but also keep intact over decades and centuries after the closure of the mine.

A similar risk is given by the **waste rock stockpiles**. They are also exposed to rain water, and toxic substances such as radioactive substances, fluorides, sulphides, acids and heavy metals will be washed out and spread into water bodies and soil, if no water management and water treatment is installed. In most cases, the potential release is lower than in the tailings, as the rock consists of coarse minerals whereas the tailings consist of finely milled particles.

Another environmental risk is the **open pit** itself, particularly after the closure of the mine. It will be exposed to rain water, which will wash out toxic and radioactive substances as described above for the waste rock stockpiles.

Besides the manifold risks due to toxic and radioactive water emissions, the mining and processing also causes serious **air emissions** if no adequate measures are taken. A main risk factor for the workers and the neighbourhood are wind-blown dust particles containing thorium or other radioactive substance. Further toxic substances in the dust might be heavy metals. The dusts arise from different sources: the mine and the mining operations, the milling, the transportation and storages as well as from the wind-blown dust particles from the waste rock stockpiles or the tailings. The two last-mentioned sources are a long-term risk if no adequate post-operative treatment will be implemented after the closure of the mine.

Further environmental harm is connected to the **land-use**. It covers the mine, the storage of the waste rocks, the tailings, the whole infrastructure and the surrounding areas, which are affected by pollution during the mining operation as well as after the mine closure. Another environmental burden is the **large water consumption**, particularly if the mining is carried out in dry areas.

The **further refining** of the rare earth concentrate is a very energy-intensive process and causes serious **air emissions** (e.g. SO_2, HCl, dust, radioactive substances) if no abatement technologies are installed. Depending on the used energy carriers, high CO_2-emissions will arise and contribute to **climate change**.

Furthermore, **radioactive waste** arises in most cases, as the majority of the rare earths deposits also contain thorium and/or uranium. The radionuclides are partly separated in the flotation and partly remain in the tailings. The other part enters the further processing with the concentrate and is subsequently separated. A safe disposal is required in all cases.

Table 7-1 summarises the major environmental risks:

Table 7-1 Major risks of REE mining and processing with insufficient environmental techniques

Risk	Affected compartments	Relevant toxic compounds
Overtopping of tailings dam	groundwater, surface water, soil	**Water emissions:** • in most cases radionuclides, mainly thorium and uranium; • heavy metals; • acids; • fluorides; **Air emissions:** • in most cases radionuclides, mainly thorium and uranium; • heavy metals; • HF, HCl, SO_2 etc.
Collapse of tailings dam by poor construction	groundwater, surface water, soil	
Collapse of tailing dam by seismic event	groundwater, surface water, soil	
Pipe leakage	groundwater, surface water, soil	
Ground of tailing pond not leak-proof	groundwater	
Waste rock stockpiles exposed to rainwater	groundwater, surface water, soil	
Dusts from waste rock and tailings	air, soil	
No site-rehabilitation after cease of mining operation	land-use, long-term contaminated land	
Processing without flue gas filters	air, soil	
Processing without waste water treatment	surface water	

Beside the impacts mining has on the environment, mining also entails social impacts which have to be carefully considered when planning and realising mining projects.

7.3 Environmental aspects of mining and processing in China

7.3.1 Overview

China currently operates several large mines and a large number of small – partly illegal – mines, the environmental problems of which are briefly described below in order to give a quick overview. Further environmental aspects are given in the following chapters.

- The **Bayan-Obo Mine** in Inner Mongolia is the largest rare earth mine in the world. The main product is iron ore, light rare earths are a side product. The surface mining extracts a bastnaesite-monazite-mix containing LREE and also thorium. There are severe environmental problems and health hazards in mining, concentration and further processing. Another large open-pit mine for LREE based on bastnaesite is the **Sichuan mine**. Here, the bastnaesite also contains thorium (MEP 2009).
- Heavy rare earths are mined from **ion adsorption deposits** in southern China. They belong to the few known deposits without radioactive accompanying elements. Nevertheless, there are serious environmental problems. The mining is carried out with in-situ leaching, a technique which requires no surface and no underground mining (Cheng & Che 2010). Holes are hereby drilled into the ore deposit. Then, the leaching solution is pumped into the deposit where it makes contact with the ore. The solution bearing the dissolved ore content is then pumped to the surface and processed. The Chinese government regards the in-situ leaching technology as more environmentally sound than other leaching technologies such as pond and heap leaching (MIIT 2010). However it should be noted that this leaching procedure is also problematic because it is not controllable hydro-geologically.
- There are **numerous small illegal mines** in China. There are estimations that around 20 000 t REO were illegally mined and smuggled outside of China. Probably, most of these mines have no environmental technologies at all, and there are reports of serious environmental damages and health hazards in their surroundings (Bork 2010, Zajec 2010).
- In the course of the **extracting, separating and refining processes**, a large number of chemical materials are applied, leading to a huge amount of waste gas, waste water and solid waste. Most facilities do not have sufficient treatment systems. Some small rare earth smelting separation facilities even do not have any system for environmental protection at all (Chen 2010).

The Chinese government is aware of these challenges and is willing to raise the environmental standards. Details on the mines, the processing and the Chinese environmental policy are presented in the next chapters.

7.3.2 Implemented technologies for mining and processing in China

Table 7-2 provides an overview of present mining and separation as well as refining methods in China's rare earth industry, differentiated according to the three types of minerals dominating in China.

Table 7-2 Overview of mining, extraction and separation methods adopted in China's rare earth industry (compiled based on MEP 2009)

Minerals	Mining & Beneficiation	Decomposition of rare earth concentrate	Separation and Refining of REO	Extraction of rare earth metal
1. Bastnaesite-monazite-mixed type (Bayan Obo mine, Inner Mongolia)	Surface mining: the ore is Iron-Niobium-REE deposit. The ore is crushed into gravel size and transported to the mill factory. Through low-intensity magnetic separation to high-intensity magnetic separation up to flotation process, rare earth concentrates (with 30-60% grade of REO) are produced as a co-product by main product iron.	Two following methods are used: a) acidic method REO are roasted at 400°C and 500°C in concentrated sulphuric acid to remove fluoride and CO_2. Then the solution is leached in water and filtered to remove the impurities. REEs are then leached in extraction agents like ammonium bicarbonate $(NH_4)HCO_3$ precipitation and hydrochloric acid. REE chlorides ($RECl_3$) are achieved. This method is used for 90% of products. b) alkaline method	For successive separation, liquid-liquid extraction is adopted mainly based on P507 ($C_{16}H_{35}O_3P$) and HCl. Then the solvent is precipitated by ammonium bicarbonate $(NH_4)HCO_3$ or oxalic acid $C_2H_2O_4$, The precipitate ($RE_2(C_2O_4)_3$ or $RE_2(CO_2)_3$) is heated and REO are formed by oxidation.	Light rare earth metals are extracted by molten salt electrolysis based on chloride or oxide. The middle and heavy rare metals such as Sm, Eu, Tb and Dy are obtained by metallothermic reduction in vacuum. The reaction is carried out at 1450-1750°C and needs an inert gas like Argon.
2. Bastnaesite (Sichuan)	Surface mining: the ore is alkali granite type rare-earth elements deposit. The ore is crushed into gravel size and transported to the mill factory. Two methods are adopted: -from gravity separation to magnetic separation -from gravity separation to flotation separation	The rare earth concentrates achieved a grade of 70% REO. The present treatment process of Sichuan bastnaesite in the industry is oxidating roasting-hydrochloric leaching process. The roast is carried out at 600°C to remove $CO_{2.}$. The RE concentrates are leached in hydrochloric acid, precipitated by sodium hydroxide solution and leached in hydrochloric acid again. REE chlorides ($RECl_3$) are achieved.		

Continuation of

Table 7-2 Overview of mining, extraction and separation methods adopted in China's rare earth industry

Minerals	Mining & Beneficiation	Decomposition of rare earth concentrate	Separation and Refining of REO	Extraction of rare earth metal
3. Ion adsorption deposits (seven provinces in the South of China)	Currently used mining method is ISL (In-Situ Leaching), which is a typical flow process coupled with chemical reaction and solute transport. Heap leaching and ponding leaching have been banned due to massive vegetation damage. The minerals are firstly leached in ammonium sulphate $(NH_4)_2SO_4$ through ion exchanging reaction. Then rare earth concentrates are obtained by precipitation with ammonium bicarbonate $(NH_4)HCO_3$ or oxalic acid $C_2H_2O_4$. Rare earth concentrates with a grade of 92% REO are achieved.		Concentrates are leached in hydrochloric acid (HCl) Extraction is carried out in P507 ($C_{16}H_{35}O_3P$)-system. This extraction reagent 2-ethylhexyl 2-ethylhexyl phosphate (P507) is widely used to extract and separate rare earth metals.	see above

7.3.3 Bayan Obo mine

The iron-niobium-LREE deposit at Bayan Obo is the largest discovered ore resource in the world. The primary product is iron. Rare earth is a secondary product of this deposit.

After more than 40 years of mining, the Main and East ore bodies have been exploited to 35%. In the operation period up to 2005, the recovery rate of mineral resources was less than 10%. Bo et al. (2009) indicated that present recovery rates of mineral resources are higher, at around 60% by state-owned and 40% by individually-owned enterprises. The thorium resource has not been utilised according to the Draft of Emission Standards of Pollutants from Rare Earths Industry (MEP 2009)[10].

The tailings are transported to large nearby territories and piled up. The tailings impoundment/reservoir of the whole mining operations (iron ore and rare earth concentration plants) is twelve kilometres in length and covers eleven square kilometres. According to Bradsher (2010) this area is about 100 times the size of the alumina factory waste pond that collapsed in Hungary on August, 4th 2010 releasing 600 000 to 700 000 cubic metres of toxic red sludge into its surroundings (WISE-Uranium 2010).

The Chinese Draft of Emission Standards of Pollutants from Rare Earths Industry (MEP 2009) indicated that the amount of tailings from the iron and rare earth mining in Bayan Obo has reached 150 million tons.

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[10] According to researches at Öko-Institut, there is no longer a demand for larger amounts of thorium. The former applications in lighting and welding electrodes are going to be phased out.

The radioactive element thorium (Th) is contained in tailings and residues. The measuring results presented by the Baotou Radiation & Environmental Management Institute in November 1998 showed that the average Th content is 0.0135% and the gamma-radiation dose rate of East, South, West and North ore bodies of Bayan Obo is 60.6-958.6 nGy/h, 54.5-546 nGy/h, 60.3-611.3 nGy/h and 49.7-599nGy/h, respectively, thus considerably exceeding the normal environmental conditions. It turned out that the environment was contaminated. The sample analysis of plants on ^{232}Th, ^{238}U, ^{226}Ra, ^{40}K showed that the specific radioactivity in plant tests is a factor of 32 and in soil tests a factor of 1.7 higher than that of references. This provides evidence that plants and soil at Baotou region have been contaminated (MEP 2009).

The Explanation of Compiling of Emission Standards of Pollutants (MEP 2009) also stated that Th-containing dust is emitted in a range of 61.8 t per year during the crushing process. Considering the human health aspect, the Healthcare Research Centre has proved in a twenty-year follow-up study on health effects following long-term exposure to thorium dusts that the mortality rate of lung cancer has significantly increased for the workers in Baotou (Chen et al. 2004).

Furthermore, Buckley (2010) reports on groundwater pollution from the tailing pond which affects the wells of the nearby villages, the livestock and the agriculture and causes serious damage to the health of the inhabitants.

Processing 100 thousand tons of rare earth concentrates per year during the extraction phase, approximately 200 tons of ThO_2 contained in sludge are left over. Using the sulphuric acid-roasting method during the production of one ton of rare earth concentrate, between 9600-12000 m^3 of waste gas containing fluoride, SO_2, SO_3 and dust may be emitted. Furthermore, 75 m^3 of acid-washing waste water and one ton of radioactive residues are generated per ton (MEP 2009)

7.3.4 Sichuan mine

The recovery rate of the mining and the concentration plant of the Sichuan mine has been less than 50% (Cheng & Che 2010).

Oxidising roasting-hydrochloric acid leaching method is currently mainly adopted in the treatment process of Sichuan bastnaesite in the rare earth industry. The problem associated with this method is that the purity of the cerium produced is low. Furthermore, fluorine and thorium are dispersed into waste residues and waste water.

7.3.5 Ion adsorption deposits

The scarce HREE from ion adsorption deposits in the south of China has at present an average recovery rate of 75% by applying the in-situ leaching method. Between 1970 and 1999 the recovery rate was only about 26% by using the ponding leaching method (Cheng & Che 2010).

7.3.6 Waste water from REE separation and refining

Since saponification with ammonia is still used for rare earth refining, a large number of waste water is produced. To separate one ton of rare earth concentrate with a REE content of 92% REO, 1 – 1.2 tons of ammonium bicarbonate are needed (MEP 2009) .

Overall, it is estimated that within the whole rare earth refining industry approximately 20 000 – 25 000 thousand t of waste water are generated per year, based on the production data of 103 900 t REO in 2005. The NH_3/NH_4^+-content of waste water ranges roughly between 300 and 5000 mg/litre. That factor exceeds the limit set by the government by more than ten to even 200 times (MEP 2009).

7.3.7 Chinese environmental policy

In the past, few environmental concerns were taken into account during mining and processing, and an efficient use of resources was not taken into consideration. Altogether, with the increasing importance of rare earths in applications, China has realised the current problems in the rare earth industry and the urgent need for an efficient use of resources and better management practices. China also identified a lack of regulation. In order to protect its rare earth resources and to develop them in a sustainable way, China started a comprehensive series of regulations and standards. New policy statutes were made and promulgated including a Mid- and Long-Term Development Plan for the Rare-Earth Industry and the Rare-Earth Industrial Development Policy. The environmental aspects are described in the subsequent chapters. Further issues such as the intended structure of companies including the closure of small mines and processing facilities are presented in Chapter 5.1.2.

7.3.7.1 Entry criteria for rare earth industry

In May 2010, the Ministry of Industry and Information Technology of China issued the notice on the consultative draft of “Entry Criterions for Rare Earth Industry” (MIIT 2010). This regulation clearly stipulates thresholds and requirements in terms of environment protection to assist the rare earth industry in sustainable development. It also foresees a restructuring of the rare earths industry. The major environmental aspects are:

- Mining of pure monazite minerals is banned due to the high-level radioactive elements and the resulting environmental damage.
- As for the operation and technological equipment, the facilities for the processing of bastnaesite and mixed minerals are obliged to install a complete treatment system for waste water, waste gas, and solid waste.
- Regarding ion adsorption deposits, ponding and heap leaching was banned due to massive environmental damage. Instead, the ISL- (In-Situ Leaching-) method shall be applied.

- Saponification with ammonia is banned from rare earth refining.
- Elementary metal refining should not adopt the process of electrolysing metals by their chlorides.
- With respect to the electrolysis system when using molten salt fluoride, facilities should be equipped with a treatment system capable of dealing with fluorine-containing waste water and waste gas.
- Fluor-containing solid waste should be disposed separately and must not be mixed with other industry residues.
- Requirements for an efficient electricity supply and specifications concerning the maximum energy demand per ton of rare earths produced are also indicated.
- Regarding the resource aspects, it is also required that the mining-loss rate for mixed rare earth minerals and bastnaesite should not be more than 10 %, while the ore dressing recovery rate of these ores should be not less than 72 %.
- The ore dressing recovery rate of ion adsorption deposits should not be less than 70 %.
- The recycling rate of ore dressing waste water of mixed rare earth minerals and bastnaesite should be not less than 85 %, while that of ion adsorption deposits should not drop below 90 %.
- The rehabilitation of plants and vegetation after mining of ion adsorption deposits should include at least 90 % of the affected area.
- The yield of refined rare earth metal should be more than 92 %.

7.3.7.2 The 2009-2015 plans for developing the rare earth industry

This development plan is a mandatory planning compiled by the Ministry of Industry and Information Technology of China (MIIT 2009). The major aim of the plan is to simplify management of China’s rare earth resources by “designating large districts.” The environmental aspects included in this plan are:

- For the years from 2009 to 2015, China will not be issuing any new mining licences of rare earths. During this period, the existing rare earth enterprises should put emphasis on improving the level of technical equipment, environmental protection and management capability.
- The plan has clearly specified the shutdown of a number of small and illegal enterprises as well as inefficient separating and smelting enterprises in order to gain more control.
- As for the monitoring aspect, the Ministry of Industry and Information Technology will oversee the industry by creating an examination and inspection system for rare earth extraction to guarantee that national directive plans are being implemented and executed.

7.3.7.3 Emission standards of pollutants from rare earths industry

The revision of Emission Standards of Pollutants from Rare Earths Industry was finalised by the Ministry of Environmental Protection of China in July 2010. It is estimated that this regulation will be effective soon. This standard sets specific thresholds (differentiated between existing enterprises and newly-established enterprises) for the amount of pollutants including waste water, waste gas and radioactive elements, especially thorium. In comparing these thresholds to those set in some industry countries, the Explanation of Compiling “Emission Standards of Pollutants from Rare Earths Industry 2009” found that certain thresholds in these emission standards were even more stringent than those in industrial nations.

7.3.8 Chinese research activities on clean production of rare earths

China actively endeavours to encourage and promote the national clean production towards a sustainable economic and social growth and development. This was reflected at the 6t^{h} International Conference on Rare Earth Development and Application in Beijing where Chinese experts presented many survey papers on clean-tech/green-tech applications (Lifton 2010b). Additionally, certain papers from the 2nd Academic Meeting on Rare Earths for Junior Scholars held by the Chinese Society of Rare Earths in 2008 analysed green or clean production of rare earth, besides investigating physical and chemical characteristics of rare earths in technical application. A website on patent information showed that 29 patents on the recovery of rare earths were taken out (Patent information 2010). The next paragraphs shortly summarise selected research projects:

- Che (2008) revealed in her study that the **tailings** from Bayan Obo lead to environmental damage and human toxicity. Furthermore, it means a waste of resources. Che (2008) discussed a **clean dressing process**, in which tailings are comprehensively utilised and which is “emission-free”.
- The University of Science & Technology Beijing obtained a patent in 2009 for achieving **full recycling and clean production in the rare earth leaching** process by applying the sulphate roasting method (University of Science & Technology Beijing 2009). The green production technology realises direct transformation from sulphate to carbonate by using the transformation technology of double decomposition reaction in chemical processes according to the principle of mutual transformation between solid substances with different solubility products. Non-rare-earth-compounds (such as ammonium sulphate and ammonium carbonate) and the like are fully recovered at low costs. Simultaneously, waste water can be fully recycled and reused.

- The **scandium** extraction grade from Bayan Obo deposit is relatively low. Cheng (2008) showed that the extraction rate of Sc^{3+} could reach 98 % by using liquid membrane emulsion technology.
- The present treatment of Sichuan bastnaesite in the rare earth industry is the oxidising roasting-hydrochloric acid leaching process. Luo et al. (2008) indicated that this method leads to pollution resulting from fluorine and thorium and generates cerium of low purity. Luo et al. (2008) demonstrated in their study that the oxidising roasting-sulphuric acid **leaching-extraction process** is a **promising alternative green process**, since it can not only produce high purity cerium, but also effectively realises the separation of fluorine and thorium. The results of their study indicated that stripping thorium from HEHEHP (2-ethylhexyl 2-ethylhexyl phosphate) is more efficient than stripping it from other phosphoric extraction agents. A thorium recovery of a maximum of 70 % could be obtained by a single stage stripping.
- In 2005, Grirem Advanced Materials Co., Ltd. developed an environmentally friendly hydrometallurgical separation processes. A **non-saponification solvent extraction** process based on hydrochloric acid and sulphuric acid was developed to separate **neodymium** and **samarium**. This method eliminates the generation of ammonia nitrogen waste water. The consumption of other extraction agents is decreased by 20 % due to a reduced number of processes which also imply greatly reduced costs (MEP 2009).
- The Beijing General Research Institute for Nonferrous Metals took out a patent in 2008 relating to a technological method for extracting and separating **quadrivalent cerium**, thorium and fluorine, as well as to a small extent trivalent cerium from rare-earth-sulphate solution. The synergistic extraction agents are based on P507 (2-ethylhexyl 2-ethylhexyl phosphate) or P204 (Di(2-ethylhexyl)phosphoric acid). Cerium, thorium, fluorine and iron are extracted into an organic phase. Then selective washing and back extraction are performed step by step. The advantages of this method are that the separation ratio of thorium is high, no emulsion is generated during the extraction process and all elements are extracted and separated in the same extraction system. With regard to the environment, since no ammonia saponification agent is adopted, there is no ammonia-nitrogen containing waste water, and fluorine and thorium are recovered (Beijing Nonfer-rous Metal 2008).
- Liu et al. (2008) studied green synthesis techniques of highly purified **dysprosium** iodide (DyI_3) for HID (High Intensity Discharge) lamps. The traditional synthesising method uses mercury iodide and dysprosium in a chemical reaction which pollutes the environment due to the poisonous mercury. A green synthesis was therefore investigated through a direct reaction between dysprosium and iodine in terms of reaction conditions. The results showed that anhydrous dysprosium iodide was synthesised with a purity of 99.95 % and a product yield of 88 %.

- In 2009, XIAN Technological University invented a method for an improved separation of heavy rare earth metals with an optimised membrane technology (XIAN Technological University 2009).

7.4 Environmental aspects of mining and processing outside of China

7.4.1 General outlook

The expected supply shortage of some REE has created manifold activities for the opening of new mines outside of China. Due to the tough timelines and the economic pressure, the incentive is quite high to implement new mining and processing facilities without considering the ecological impacts. Therefore, environmental aspects should be monitored attentively by the authorities and the public.

The following Chapters 7.4.2 and 7.4.3 provide an overview of two mining and processing projects which will probably start operation in 2011 and 2012: the Mountain Pass project in California (USA) and the Mt Weld project in the desert of Western Australia with further processing in Malaysia. These two projects passed national approval procedures, and it is to be assumed that major environmental aspects will be taken into account. However, the operation practice will not only depend on the installed technologies but also on the proper management and monitoring by the operating companies and the authorities.

The opening of new mines is discussed and exploration activities are carried out (drilling, laboratory tests and feasibility studies) on various other sites. One example is the Kvanefjeld deposit in Greenland which is presented in Chapter 7.4.4. Further countries where exploration activities are taking place are Canada, South Africa, Malawi, India and Vietnam, Kirghizia and Kazakhstan. There is some concern that some of these projects might be realised without sufficient environmental protection technologies.

In the past, xenotime from Malaysian placer deposits with very high contents of uranium (2 %) and thorium (0.7 %) was processed in Malaysia. Due to this high radioactivity level, the Malaysian processing industry failed and the plants were closed (Meor Yusoff and Latifah 2002, cited in BGS 2010). High levels of radioactivity also appear in monazite. Fortunately, the processing of beach sands containing monazite has been banned in Australia, China and Europe due to environmental concerns (Curtis 2009, cited in BGS 2010). However, nearly all deposits which are currently under exploration also have some more or less high contents of uranium and thorium and their decay products. The two outstanding exceptions are the ion-adsorption clay deposits in southern China as well as the Douglas River deposit in Saskatchewan, Canada (Kanasawa & Kamitani 2006, GWMG 2010a).

Against the background of the severe problems of accompanying radioactivity in mining, Kanazawa and Kamitani (2006) suggest that countries should examine geological structures similar to the ion-adsorption clay deposits in China in order to discover other radioactivity-free sources. Otherwise R&D for mineral separation, smelting and recovery should be promoted, including disposal of radioactive wastes.

The presence of thorium and/or uranium in the rare earth ores is not only of importance for mining and concentration but also for refining and further processing. In all process steps, radioactive wastes arise and have to be handled cautiously. An example for the arising of radioactive waste is the French company Rhodia Electronics and Catalysts which processes rare earths. This waste was classified and handled according the French law (ANDRA 2009).

Furthermore, the refining of the rare earth concentrate is a very energy-intensive process, causes air and water emissions and contributes to the global climate change.

7.4.2 Mountain Pass, California, USA

Due to environmental concerns as well as competition from lower-cost Chinese sources of rare earths beginning in the mid-1980s, production at the only mine of the United States at the Mountain Pass in California was stopped in 2002. Currently, the site is held by Molycorp Minerals, which is currently only generating revenue from products manufactured from its relatively small stockpile of rare earths. Molycorp Minerals plans the re-opening of the rare earths mining from 2012 to 2042 with an annual production of approximately 20 000 t. The average grade of the Mountain Pass ore is 8.2 % (using a cut-off grade of 5 %). The concentrate shall contain 68 % rare earths. The recovery rate shall be around 90 % according to Molycorp (2010a).

The planned re-opening required an extensive approval procedure which resulted in an approval in 2004. Smaller plant modifications and improvements are subject to a further permit procedure.

Due to the extensive public approval procedure, it is to be expected that the plant operation will run on an environmentally advanced standard, which will significantly reduce the environmental damage compared to old outdated techniques, if the management of the monitoring is carried out responsibly by the authorities and the operator.

The documents concerning the approval procedure are publicly available (Molycorp 2010c). According to Molycorp Minerals (Molycorp 2010a, 2010b) the major issues in terms of the environment are as follows:

- The ore at Mountain Pass contains 0.02 % thorium and 0.002 % uranium by weight, as uranium and thorium occur in the bastnaesite mineral. Therefore, radionuclides will be part of the tailings and the concentrate. For the permission of the new plant operation, Molycorp received a broad scope licence, which allows facility personnel to conduct the day-to-day management of radioactive materials under the oversight of a Radiation Safety Officer and a Radiation Safety Committee.
- Molycorp plans the installation of a salt recovery (recovery of hydrochloric acid, sodium hydroxide, sodium hypochlorite) and water recycling facilities in order to reduce the

water consumption. The aim is to reduce the fresh water consumption of the mid-1990s (when the mine had an output of 20 000 t REO per year) by approximately 90 %.

- The waste water generated from the mineral recovery operations as well as waste water from the treatment of pit water and ground water remediation systems would be evaporated in a series of on-site ponds.
- A groundwater remediation system will be operated.
- The open pit water will be pumped, treated and re-used. The facility is constructed with a series of storm water diversion ditches and settling ponds, along with a series of check dams and silt fencing to minimise erosion.
- The hazardous waste (mainly containing lead) shall be disposed of on exterior landfills for hazardous wastes.
- Flue gas treatment plants will be installed in order to reduce air emissions.
- The remediation of the area after mine closure was also part of the approval in 2004.

7.4.3 Mount Weld, Australia and processing in Malaysia

Lynas started mining (open pit) and the installation of a concentration plant at Mt Weld deposit in 2007. In 2008, about 800 000 t of ore with an average grade of 15 % REO were mined and stored. The concentration plant is supposed to start operation in 2011 and to produce a concentrate of around 40 %. Mining is planned for a period of eleven years whereas the concentration plant shall operate for 18 years. The production of REO-concentrate at Mt Weld shall start with 11 000 t REO per year and increase up to 20 000 t REO per year [Lynas 2010a]. The recovery rate will be around 63 %. The cut-off grade is set to 2.5 % [Lynas 2009]. Further processing will be carried out at the Lynas Advanced Materials Plant in Malaysia.

The Environmental Protection Authority of The Government of Western Australia provided the Ministerial Approval Statement to the Mining & Beneficiation Project at Mt Weld in 2006 (EPA 2006). In 2008, the Department of Environment and Conservation granted the works approval (DEC 2008). The documents include some information on the operating conditions. The main issues are listed below:

- The premises are located approximately 35 km from the next housing area and 20 km from a lake. The surrounding landscape is characterised by arid plains.
- Dust suppression techniques are required in order to ensure that dust emissions are of low significance.
- The tailings are stored in the tailing ponds. The tailing ponds will be equipped with an impervious layer on the base and on the walls. The authority state that they demand high standard of seepage management design. A groundwater monitoring system is required.

- Around 14 % of the water input to the tailing pond will be returned to the process plant.
- The tailing ponds will be deemed a contaminated site after plant closure.
- The pipelines will be controlled by electronic supervisory devices as well as by daily sight inspections.
- The tailings contain 500 ppm thorium oxide and 30 ppm uranium oxide. There are no details given on the management of the radioactivity. The approval refers to the management by the Radiological Council under the Radiation Safety Act 1999.
- The rehabilitation works of the overburden stockpiles have started (Lynas 2009).

Further processing of the concentrate with an output of up to 22 000 t REO per year will be carried out in Malaysia by the 100 % subsidiary of Lynas called Lynas Malaysia. The approval from the Malaysian authorities was obtained in 2008, and the construction works already started in 2008. The start of operation is scheduled for 2011. The environmental impact assessment for the Malaysian plant is not publically available via internet. Concerning the chosen location for the processing plant, Lynas argues that the processing of the Mt Weld material will be realised in Malaysia because of the good infrastructure, the skilled labour force with experience in the chemical industry and the nearby supply of the required chemicals.

7.4.4 Kvanefjeld, Greenland

Large resources of rare earths with a high content of HREE of about 14 % can be found in the Kvanefjeld region in southern Greenland, which is currently discussed for the joint mining of uranium and rare earths. Figure 7 on page 15 impressively shows the very large size of this deposit and its significant HREE contents in comparison to other deposits where pre-mining activities also take place. The interested mining company is Greenland Minerals and Energy Ltd. (GMEL) with its head office in Perth, Australia, which plans to start construction work in 2013 and to initiate production in 2015.

A very critical point for environmental hazards in this project is the tailing's management. According to current considerations GMEL favour tailings disposal in the nearby natural lake Taseq (GMEL 2009). Following an extensive study Risø (1990) concluded that the outlet from contaminated water from Taseq would cause pollution of the whole fluvial system (from the lake, via rivers, into the ocean) with radioactive substances, fluorine and heavy metals. It is very doubtful if waste water treatment installations at the outlet of the lake are capable to manage the large amounts of water particularly in times of heavy rain or snow melting.

The extensive work on the Kvanefjeld deposit (the results of which were published by Risø in 1990) was conducted by Danish authorities and scientists up to the early 1980s and also form the basis of the GMEL planning activities (GMEL 2010c). This work was carried out with the focus of mining uranium only and provides very detailed considerations and analysis results concerning environmental impacts. Beside the tailings impoundment it identified the open pit and the waste dump as the most important sources of pollution. In the long term (> 100 years) the tailings pond will be the most critical point. Risø (1990) compared two options: the direct inlet of the tailings into the sea and the tailings disposal in the nearby natural lake Taseq (see above). The latter was considered even worse in terms of environmental impacts than the direct inlet into the ocean.

Though waste disposal in oceans was frequently practised in the past, the procedure is not acceptable at all either. Equally, inlet of toxic tailings into natural water bodies has to be banned completely and does not meet any environmental standards. The situation in Greenland seems particularly critical when considering the fact that the expected climate change – it is linked to melting of glaciers and unfreezing of permafrost soils – might alter water bodies and the stability of soils considerably.

The next paragraph gives a short overview of the planned technologies for the GMEL-Kvanefjeld project and the progress of the (pre-)feasibility studies and approval issues:

Mining shall be carried out in a conventional open pit followed by uranium extraction with the Carbonate Pressure Leach- (CPL-) technology. The CPL-residue can then be processed and the REO concentrated by froth flotation, leached with acid and then refined to produce rare-earth-carbonate. The nominal forecast annual production amounts to approx. 44 000 t REO and nearly 4 000 t of uranium oxide; the overall plant recovery rates are 34 % and 84 %, respectively (GMEL 2009).

In December 2009 and February 2010 GMEL presented the Interim Reports of the Pre-feasibility Study (GMEL 2010c, GMEL 2009). As the Greenland government has recently relaxed restrictions on uranium deposits, the company now envisages the realisation of a definitive feasibility study (WNN 2010). According to the same article the Greenland government has stressed that although radioactive elements may now be surveyed, their extraction is still not permitted. However, a comprehensive review process into the exploration and exploitation of the radioactive materials was announced by the Ministry for Industry and Raw Materials. In this context, the cooperation agreement between the government of Greenland and the European Environment Agency on environmental issues signed in November 2010 (EEA 2010) might lead to an exchange of expertise and contribute to a sustainable course of action concerning the Kvanefjeld deposit and mining activities in Greenland in general.

7.5 Resource efficiency

The specific environmental burden of mined and processed rare earths could be reduced significantly by higher efficiencies in all stages of the production. The first losses occur in the mining process when the cut-off grade is chosen too high. This means that minerals with lower REO-contents are not further processed. The cut-off grade is site-specific as it depends on the kind of minerals and its properties in the concentration process.

The next losses arise in the concentration process. The mines show quite different recovery rates (ratio between REO output and REO input of the concentration plant). The Mountain pass concentration plant shall operate with a high recovery rate of about 90 % due to a very fine grinding of the minerals. Lynas states that the plant at Mt Weld will have a recovery rate of 63 %. The recovery of Chinese mines is reported to have been very low in the past. Currently, they range from 40 to 60 % for flotation and about 75 % for the in-situ leaching method (see Chapter 7.3.3 to 7.3.5). However, a site-specific analysis is necessary in order to assess in detail if higher recovery rates are possible and improve the overall performance of the plant.

Further losses arise in all stages of further refining and processing. They are also plant-specific.

The Chinese government is aware of the high potential of higher efficiencies as described in Chapter 7.3.7. Further aspects concerning the efficiency of rare earths used in different fields of applications is discussed in Chapter 10.

Conclusion on environmental aspects of rare earth mining and processing

The rare earth mining shows high environmental risks. The main risks are the tailings, which are a mixture of small-size particles, waste water and flotation chemicals and arise at the concentration of the mined ore. They are stored in impoundment areas. The tailing dam is exposed to manifold risks such as overtopping due to storm water, poor construction or seismic events. A failing dam leads to site-specific emissions such as thorium, uranium, heavy metals and fluorides. Generally, most rare earth deposits contain radioactive materials which impose the risk of radioactive dust and water emissions. Further potential damages are other air emissions, soil contamination, land use, etc.

There are serious environmental damages in the Chinese rare earth mines and their surroundings. The Chinese government intends to reduce the environmental harm by installing environmental technologies in the large mines and by reducing the numerous small illegal mines which probably have no environmental technologies at all. China also aims at higher efficiencies in mining and processing and is running some research projects on a sustainable rare earth economy.

The most advanced mines outside of China at the Mountain Pass in the United States and at Mt. Weld in Australia will provide environmental protection systems, which will significantly reduce the environmental damage compared to old outdated techniques, if the management and the monitoring are conducted responsibly by the authorities and the operators.

However, the global pressure for a steady rare earth supply might lead to further new mines outside of China with inacceptable environmental standards. One example of potential concern about environmental damage is the plan for joint mining of uranium and rare earths in Greenland. The interested mining company intends to store the tailings in a natural lake with connection to maritime waters.

8 Applications and demand of rare earths

8.1 Overview of applications and their demand in 2008

Figure 16 shows the main application fields and the range of global demand estimates for the years 2006 to 2008 by volume in t REO/a. The total demand was around 124 000 t REO in 2008 (Kingsnorth 2010).

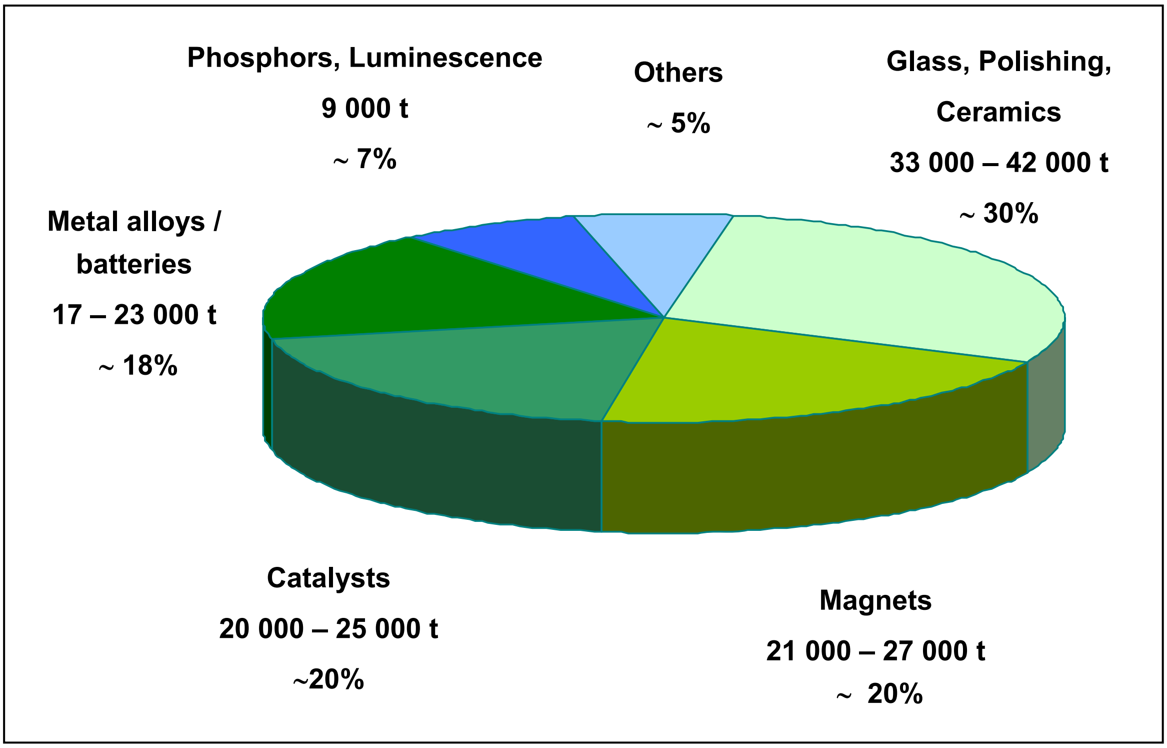

Figure 16 Global demand of rare earths by volume from 2006 to 2008, in t REO per year

The data in Figure 16 are compiled from various data sources such as the Australian consultant Kingsnorth from IMCOA, the mining company Great Western Minerals Group and the German Federal Institute for Geosciences and Natural Resources (Kingsnorth 2010, GWMG 2010b, BGR 2009). They refer, depending on the source, either to the year 2006, or to the year 2008. All these estimates do not include published documentation, which would enable more in-depth analysis and a plausibility check. Furthermore, all above-listed demand estimates and further estimations of the USGS for the US market refer to the demand estimates carried out by Kingsnorth from IMCOA. Up to now, larger research institutions and public bodies have not set up more detailed material flow analysis for rare earths, as has been elaborated for other metals. Such an analysis could provide more in-depth knowledge of the related application, but it requires a lot of manpower and the cooperation of experts from all sectors. This is especially true for rare earths, as they are used in many fields of high-tech applications and partly underlie confidentiality issues.

Figure 17 shows the same data as the previous figure and gives additional information on the used REE and specifies the kind of applications in more depth. The figure encompasses the different rare earths. The elements shown in a smaller font size play a minor role in comparison to the other elements shown in the figure.

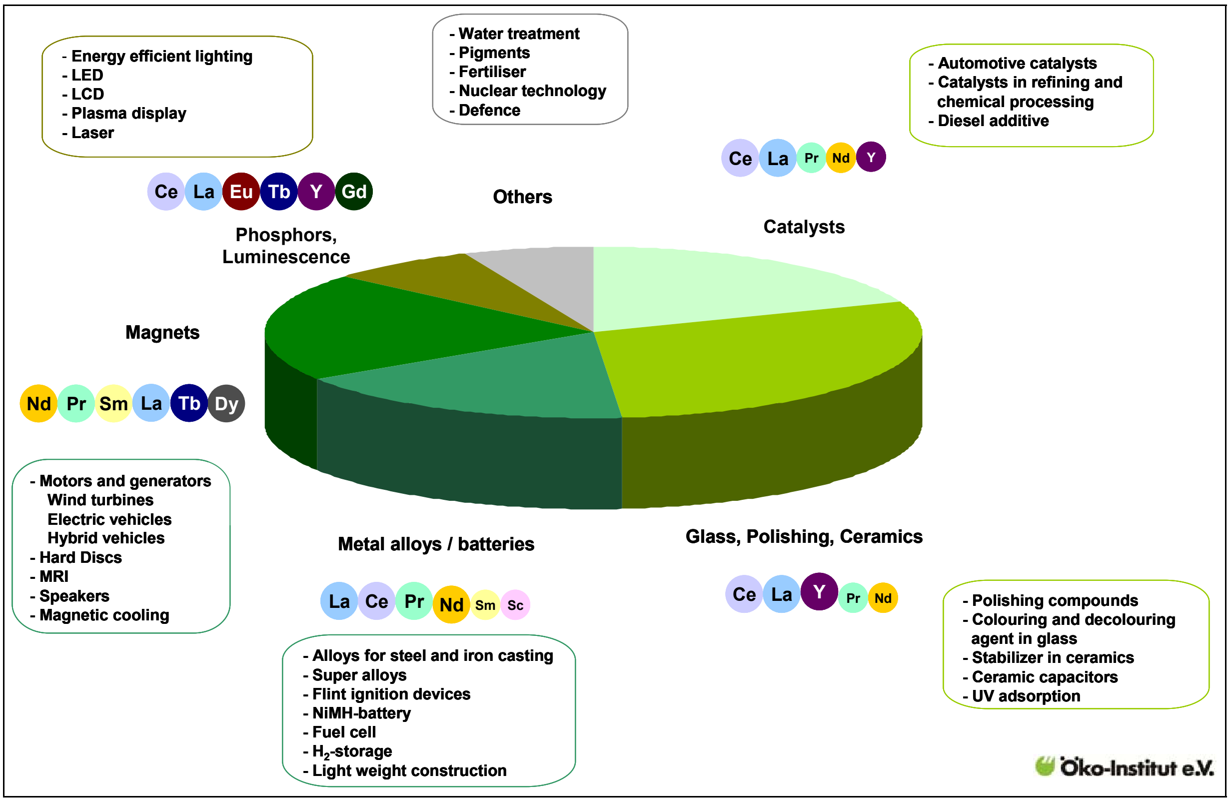

Figure 17 Global applications of rare earth elements (compiled by Öko-Institut)

The next figure shows the rare earth demand in terms of economic value according to Kingsnorth (2010). Due to significant differences in the used rare earth elements and the specific prices for the different applications, the demand distribution paints a somewhat different picture.

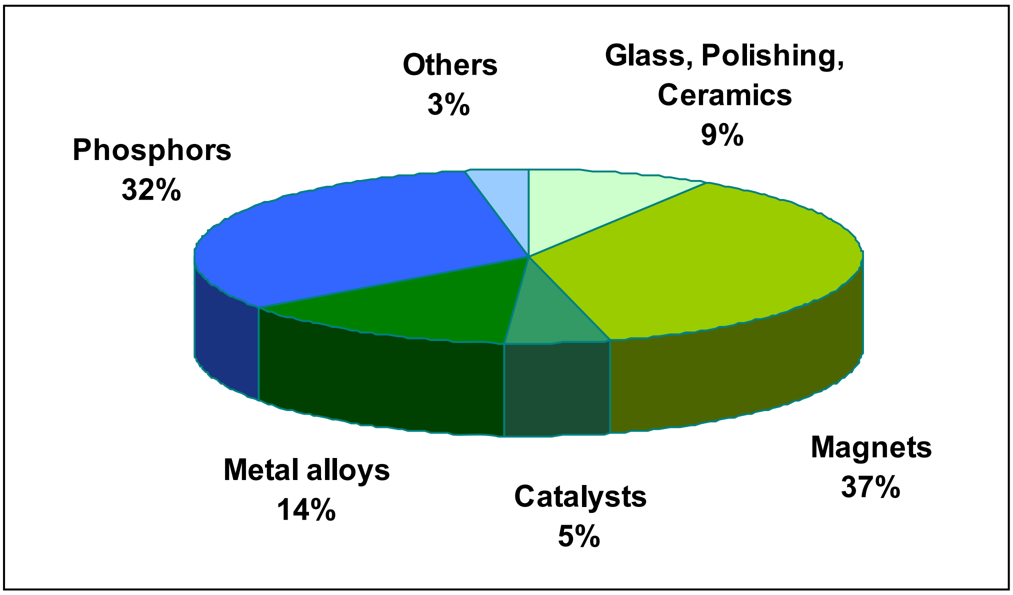

Figure 18 Global demand of rare earths in terms of economic value in 2008 according to Kingsnorth (2010)

Figure 18 shows that the most relevant fields of application economically are magnets and phosphors. For phosphors, expensive REE such as europium and terbium are used. For magnets, mainly neodymium and praseodymium (medium price) and dysprosium and terbium (high prices) are used. The applications glass, polishing, ceramics and catalysts are relevant in terms of their volume but less relevant in terms of their value. The main reason for this is that the cheaper REE cerium and lanthanum are used very frequently for these applications.

The demand for rare earths in China in 2008 is shown in Figure 19.

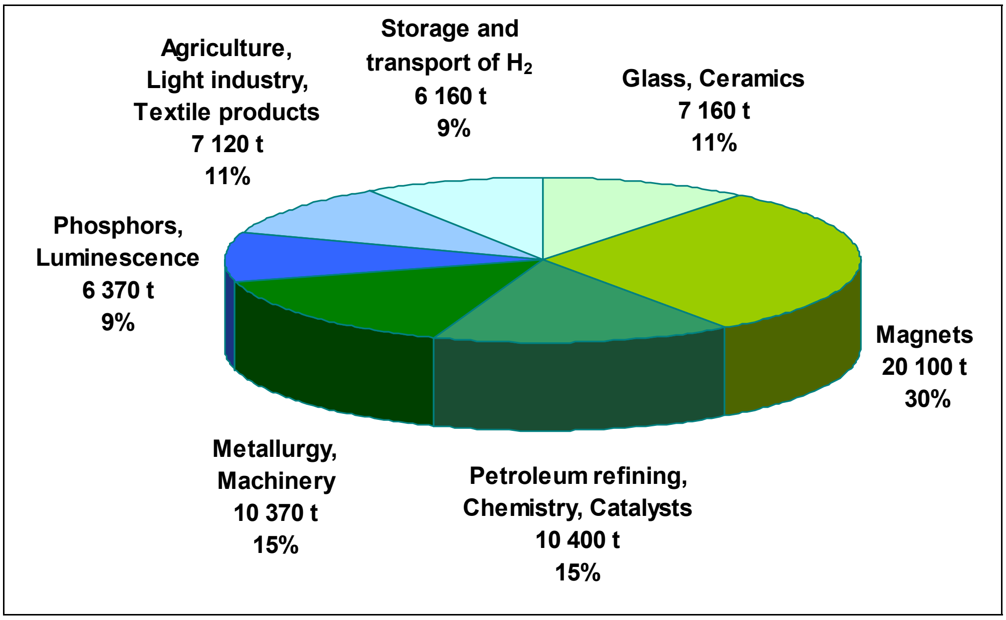

Figure 19 Demand of rare earths per volume in China in t REO in 2008 (Chen 2010)

Figure 19 indicates a higher share of permanent magnets for Chinese applications (30 %) in comparison to the estimated global demand (20 %, see Figure 16). A significant share of the Chinese permanent magnet is probably exported, as China is the only country worldwide which masters the whole magnet product chain as shown in Figure 10 on page 33.

Chen (2010) provides detailed information on the Chinese applications in 2007 and 2008. They are presented in Table 8-1. Furthermore, Chen points out that the consumption of rare earths in China has rapidly increased since 2004.

Table 8-1 Application of rare earths in China in 2007 and 2008 (Chen 2010)

Technology		**2007**		**2008**		**Δ2008/2007**
		t	**%**	**t**	**%**	**%**
Traditional materials	Metallurgy/Machinery	10 994	15.2%	10 370	15.3%	**-5.7%**
	Petroleum Refining/chemistry	7 548	10.4%	7 520	11.1%	**-0.4%**
	Glass/ ceramics	7 872	10.9%	7 160	10.6%	**-9.0%**
	Agricultural, light industry and textile products	7 686	10.6%	7 120	10.5%	**-7.4%**
	sub-total	34 100	47%	32 170	48%	**-5.7%**
Advanced materials	Luminescence	4 490	6.2%	2 870	4.2%	**-36.1%**
	Phosphors	2 800	3.9%	3 500	5.2%	**25.0%**
	Permanent magnets	22 250	30.7%	20 100	29.7%	**-9.7%**
	Storage and transport of Hydrogen, batteries	6 200	8.5%	6 160	9.1%	**-0.6%**
	Catalysts	2 710	3.7%	2 880	4.3%	**6.3%**
	sub-total	38 450	53%	35 510	52%	**-7.6%**
Total		72 550	100%	67 680	100%	**-6.7%**

The specific application fields are further described in the next chapters, and forecasts for their development are given.

8.2 Magnets

Rare earths are part of neodymium-iron-boron magnets (short forms: neodymium magnets, Nd-magnets) and samarium cobalt magnets. Both belong to the group of permanent magnets. The samarium cobalt magnets play only a minor role, as they were in many cases replaced by the more powerful neodymium magnets. Neodymium magnets are the strongest available magnets and exceed other permanent magnets such as samarium cobalt magnets by the factor 2.5 and other aluminium and iron based magnets by the factor 7 – 12. In ferrite magnets, small shares of lanthanum are included. These permanent magnets have low magnetic properties, but they are cheap, light, easy to magnetise and widely disseminated.

The strong neodymium magnets enabled the design of miniaturised application of electric devices such as small speakers (ear phones) and hard disks. Two further large fields of application are electric motors used in hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), electric vehicles (EVs)[11] and generators of wind turbines. Additionally,

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[11] Hybrid electric vehicles (HEVs) combine an internal combustion engine and one or more electric motors, whereas electric vehicles (EV) run exclusively with one or more electric motors. A plug-in hybrid electric

neodymium magnets are used for industrial equipment such as lifters or magnetic separators. A new application which might be implemented on a larger scale in the years from 2015 is the magnetic cooling.

The share of magnets of the total rare earth application is around 20 % in terms of the global volume. The share of value is higher at around 37 %. The basic chemical formula of Nd-magnetic material is $Nd_2Fe_{14}B$, which comprises a mix of neodymium and praseodymium (~ 30 %) and mostly the additives dysprosium (~ 3 %) and terbium in even lower contents. Neodymium and praseodymium belong to the rare earths which have a medium price, whereas dysprosium and terbium are very expensive elements (for details on prices, see Chapter 6.3).

Technical details on the applications motors, wind turbines and hard disks are given in Chapter 10.2 and Chapter 11.1, where recycling aspects, options for a substitution and options for a more efficient use of the REE are discussed. The next chapters analyse the main factors influencing the development of the future demand.

The future demand for permanent magnets is significantly determined by the three applications electric motors for hybrid and electric vehicles, wind turbines and hard disks. The following chapters analyse the expected development of the main application fields.

8.2.1 Electric and hybrid electric vehicles

The demand development of Nd-magnets in the field of e-mobility depends on three main drivers:

- the future production of hybrid electric (HEV), plug-in electric vehicles (PHEV) and electric vehicles (EV),
- the future production of electric bikes,
- the future motor technology and the share of motors using Nd-magnets in EV, HEV and PHEV and
- the specific neodymium magnets demand per electric motor.

Byron Capital Markets (2010) makes a forecast which includes the major producers of HEVs (Toyota, Chevy, Nissan, Ford and Honda) and e-bikes. E-bikes are already used in large quantities in China. An average annual growth rate of 50 % is estimated. Despite this high growth rate, Byron Capital Markets (2010) only calculates a moderate overall demand in

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vehicle (PHEVs) is a hybrid vehicle with rechargeable batteries, which can be plugged to an external electric power source for charging.

terms of HEVs even in 2015, because the assumed specific rare earth content of the electric motors is much lower in Byron's scenario than in scenarios of other experts. Byron assumes a demand of 193 g Nd per motor[12], whereas other experts expect up to 1.8 kg neodymium for the electric motor of the Toyota Prius. This means a difference in the baseline of a factor of 10!

Another uncertainty is the estimation of the number of hybrid electric vehicles. The number of hybrid electric vehicles to be sold is estimated by Byron Capital Markets to be 1.2 million HEVs and EVs in 2014; and to be 2.1 million by Iwatani (cited in Oakdene Hollins 2010). Optimistic scenarios by IEA (2009) and Fraunhofer ISI (2009) forecast 9 to 14 million sold HEV and EV for 2015.

Öko-Institut carried out an analysis of different scenarios for the development of e-mobility from different institutions (IEA 2009, Fraunhofer ISI 2009, McKinsey 2010, BCG 2009). The analysis revealed that the range of future scenarios is quite high. The projections for the year 2020 lie within the range of 9 to 33 million HEVs, EVs and PEVs sold in 2020. Electric vehicles are supposed to play a minor role up to 2015.

The annual sales of e-bikes are estimated by IEA (2009) to be more that 10 million. Byron Capital Markets (2010) estimates for 2010 and 2014 annual sales of 25 and 33 million e-bikes, mainly in China. Recent information delivered from Chinese experts to Öko-Institut confirms a current range of 20 – 25 million units for the annual production of e-bikes in China.

The main conclusion from these explanations is that the demand estimations for the rare earths in EV and HEV should be handled with caution, as there is a very high uncertainty in the economic development of the electric and hybrid electric vehicles market and the embedded technologies (type of motor, specific Nd-demand per motor, etc.). Two different scenarios outline the wide range of forecasts for the resulting Nd-demand: Byron forecasts an Nd-oxide demand of around 1 200 t in 2015. Oakdene Hollins (2010) calculate on the basis of the three projections developed by McKinsey (2009) and the assumption of 1 kg Nd per motor, the resulting Nd-oxide-requirement ranges from only 875 t in 2020 for a scenario with very slow growth of hybrid electric vehicles (only ~ 1 million HEV/EV in 2020) up to 23 000 t Nd-oxide demand in 2020 in a scenario with very high growth rates (~ 20 million HEV/EV in 2020). There is an additional uncertainty on the used motor technologies. The presented scenarios on the Nd-demand of future electric and hybrid electric vehicles assume that the motors are using permanent magnets. It is not considered that there are several

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[12] Byron Capital Markets assumes the use of sintered magnets of 650 g for a 55 kW motor, containing 193 g Nd and 24 g of Dy. According to Oakdene Hollins (2010), Lifton estimates 1 kg of Nd in the electric Prius motor, whereas Kingsnorth even estimates that 1.9 kg of Nd is required in the electric Prius motor. Angerer et al (2009) estimate the Nd-demand of 0.5 – 1 kg per hybrid electric vehicle.

options for motors without rare earths which are also favoured by manufacturers (see discussion in Chapter 10.2.1).

Nevertheless the e-mobility sector will be a driving force in terms of the demand growth of permanent magnets and rare earths like neodymium.

8.2.2 Wind turbines

Wind turbines are an important driver for the Nd-magnet demand. There are three different technologies for wind turbines and only one of them uses the Nd-magnets. All three systems are available on the market. The market share of current sales is estimated at 14 % for turbines with Nd-magnets (Fairley 2010). They work without gear, which makes them robust and a good candidate for off-shore applications. However, it is not clear how their market share will increase; different forecasts show a wider range (Oakdene Hollins 2010, Fairley 2010). Furthermore, a new technology based on high temperature superconductor (HTS) rotors is under research and development. In the superconductor material (Fischer 2010) there is no neodymium; instead yttrium is used. The possible substitution of wind turbines with Nd-magnets by the alternative generator systems is discussed further in Chapter 10.2.3.

Besides the market shares of the different technologies for the turbines, the global growth rate of wind turbines is a crucial driver. Figure 20 shows the current global capacity of wind power to be 175 GW in total.

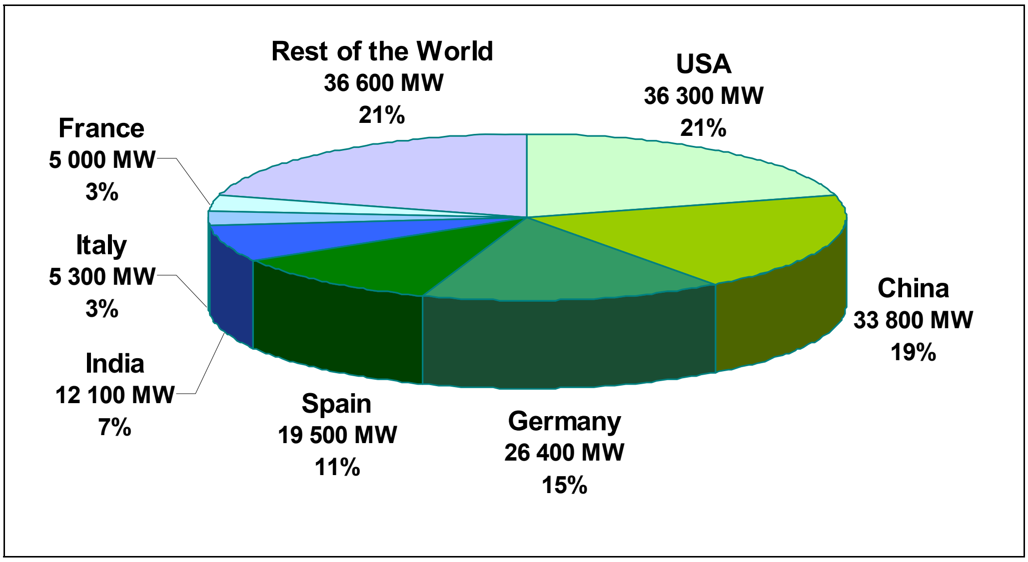

Figure 20 Global wind power capacities in June 2010 (WWEA 2010b)

Figure 21 presents the newly installed capacities in the first half of 2010. It shows convincingly that currently almost half of the new capacities are implemented in China.

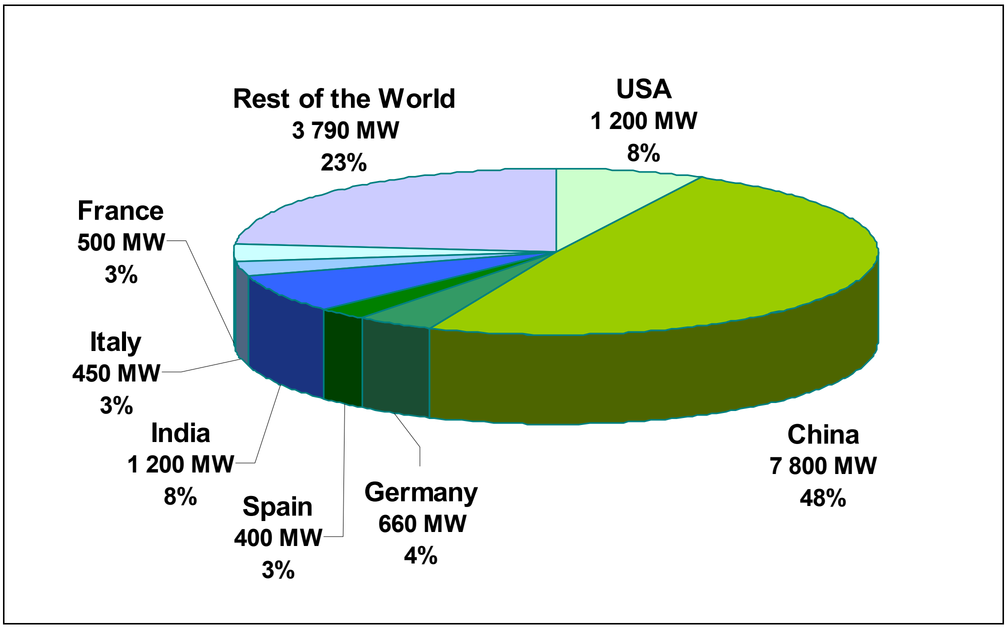

Figure 21 Newly installed wind power capacity in the first half of 2010 (WWEA 2010b)

The Chinese wind power is expected to continue to grow tremendously. The Chinese wind power capacity increased by almost 8 GW from the end of 2009 up to June 2010, corresponding to an increase of 30 % within half a year. According to Lifton (2010b) China plans to increase its wind power capacity dramatically up to 330 GW in 2020. This is the ten-fold capacity in relation to the current Chinese installations. In 2008 and 2009, the global newly installed capacities amounted to 27 GW and 38 GW, respectively (WWEA 2010a).

The calculated demand for the rare earths of different authors varies strongly due to different estimates of:

- the growth rates of installed wind power,
- the share of gearless turbines with neodymium magnets and
- neodymium, praseodymium, dysprosium und terbium required per kg of installed power.

These differences are described here in brief:

- High growth rates of newly installed global wind power capacities are part of different scenarios. For example, the forecast of Byron Capital Markets (2010) assumes high global growth rates of around 29 % yearly. Oakdene Hollins (2010) estimates an annual growth rate of newly installed wind power capacities of 22 % up to 2020. The corresponding forecasted total installed capacities in 2014 amount to 560 GW and 465

GW, respectively. Thus, a tremendous increase in comparison to the global capacity of 175 GW in June 2010 is forecasted.

- Byron Capital Markets estimates that 20 % of the turbines will be installed with permanent magnet-equipped generators, though it supposes that this figure is likely to be too high. Oakdene Hollins assumes a gearless contribution of 10 % up to 2014 and 20 % from 2015 onwards.
- There are different data on how much neodymium is necessary per installed MW electricity of the turbine. Lifton (2010b) estimates 667 kg neodymium-magnets per MW electricity, whereas the exploration company Avalon assumes 400 kg of neodymium magnet embedded per MW electricity (cited in Oakdene Hollins 2010).

The World Wind Energy Association counts the new installations in 2008 at 27 GW. Assuming a share of 14 % for gearless turbines with Nd-magnets and an average consumption of 400 kg Nd-magnet per MW electricity, the total Nd-demand in 2008 would have been about 450 t Nd and about 570 Nd-oxide, respectively.

Based on the forecast by Oakdene Hollins (2010), the Nd-demand for wind turbines is calculated as 1 200 t/a REO up to 2014 and 4 200 t/a REO from 2015 onwards. Summarizing the explanations above, it is to point out that it is currently not clear which direction the technology development will actually take. Therefore, for the wind turbines as well as for the electric vehicles, the forecasts should be taken into account with care, as there is a high uncertainty of the implementation of future techniques.

8.2.3 Hard disks and electronic components with Nd-magnets

According to the Japanese company Shin-Etsu (cited in Oakdene Hollins 2010) around a third of the Nd-magnets are used in hard disk devices. Öko-Institut estimates that around 1 700 t Nd (corresponds to 2 150 t Nd-oxide) were embedded in hard disks in PCs including laptops which were sold in 2008[13]. Here, some degree of substitution by the SSD technology which is described in Chapter 10.3 is expected. However, it is also expected that the substitution will occur gradually and will probably not affect all hard disk devices.

Furthermore, Shin-Etsu (cited in Oakdene Hollins 2010) estimates that about further 10 % of all neodymium magnets are embedded in optical and acoustic applications.

The future demand development of the permanent magnets in hard disks is probably almost linear to the sales of computers. The annual global growth of personal computers and particularly laptops is high. The market research institution Gartner forecasts a growth rate of 16 % for 2011 (Gartner 2010).

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[13] Calculation based on 291 million computer sales in 2008 and measurements by A. Manhart at Öko-Institut of magnets from hard disks (22 g per magnet, corresponding at 5.9 g Nd per hard disks for Nd-share of 27 %).

The future demand development of permanent magnets in optical and acoustic devices is probably similar to the sales of electronic goods. Average growth rates in the electronics sector are estimated at 5 % for the period from 2010 to 2013 by the industry research firm RNCOS (Daily News 2010).

These figures imply that the demand of the applications hard disks and other electronics should not be underestimated, even if the possible growth rates for wind turbines and electric and hybrid electric cars might be higher.

8.2.4 Magnetic cooling

A new technology which is currently under development is the magnetic cooling. It is based on the magneto-caloric effect phenomenon, in which a reversible change in the temperature of magnetic materials occurs in the magnetisation/demagnetisation process. The technology promises high energy savings of 50 – 60 % in comparison to the traditional compression refrigerating machines (EEC 2010, Katter 2010, Jiang 2008). Possible applications are refrigerators in household and commercial appliances, industrial cooling, heat pumps and air-conditioning systems.

The European Union is currently supporting the research project SSEEC (Solid State Energy Efficient Cooling) in which several prototypes for air-conditioning are constructed. The aim is to develop magnetic cooling devices which are suitable for industrial use by the end of 2011 (Katter 2010).

Rare earths are needed for these devices for both the magnetic source and the refrigerant. As a magnetic source, the neodymium magnets are the best option (Katter 2010). BGS (2010) reports in addition that gadolinium is a suitable refrigerant. Research has been carried out in China on magnetic refrigerants based on gadolinium-silicon-germanium materials (Jiang 2008).

Katter (2010) of the German company Vacuumschmelze, which is a relevant permanent magnet producer, expects that it might take some years until magnetic cooling will achieve economical relevance. He identifies the high costs for the magneto-caloric materials and the high amount of Nd-magnets required for magnetic refrigeration as a major barrier to a wide dissemination. With approx. 200 million cooling machines being sold worldwide each year, it is to be assumed that the magnetic cooling will require a significant amount of rare earths if the magnetic cooling technology is to be widely disseminated.

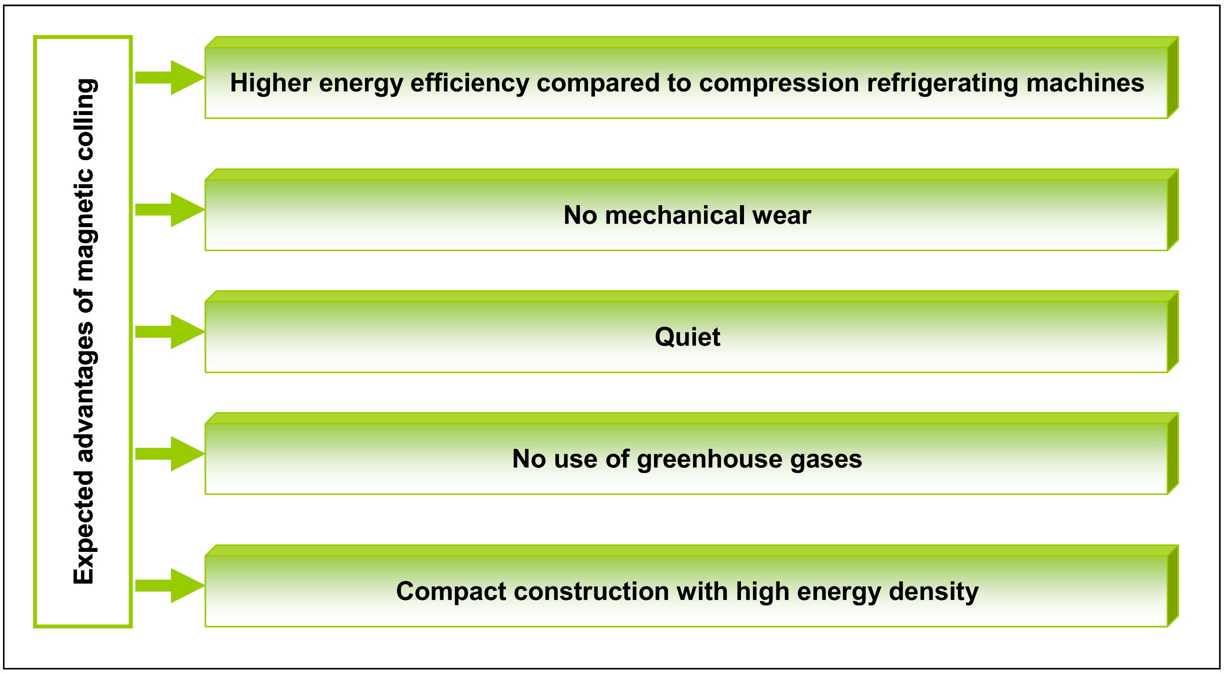

Figure 22 Expected advantages of magnetic cooling

8.2.5 Compilation of forecasts for the field of Nd-magnets

The analysis of a number of forecasts for the demand of rare earths in magnets shows a wide range as well as high uncertainty. The next table compiles the forecasts mentioned above in order to enable a general overview. Apart from the forecasts already mentioned, it includes an overall estimation by Fraunhofer Institut für System- und Innovationsforschung ISI & Institut für Zukunftsstudien und Technologiebewertung IZT (Angerer et al 2009) on the total Nd-oxide demand for permanent magnets in 2030. They estimate a demand of 21 000 - 35 200 t neodymium-oxide resulting from average global growth rates of between 7.5 % and 10 %. Thereby, their demand project is based on a significant lower estimate of the demand in 2006 (around 5 000 t Nd-oxide) than Kingsnorth (2010).

Table 8-2 Compilation of estimates for the demand of magnet applications (in t/a)

Estimates / scenarios		**Nd-Oxide Demand**			**REO Demand**
	Indicated year	**Hybrid and electric vehicles**	**wind turbines**	**hard disk in PC**	**Total of all magnet applications**
Fraunhofer ISI **Demand in 2006**	2006				5 000
Öko-Institut **Hard Disks in PCs**	2008			2 100	
Chen: Chinese demand	2008				20 100 (China)
Kingsnorth / IMCOA **Demand in 2008**	2008				26 250 (global)
Byron Capital Markets (2.2 million HEV and 33 Mio. e-bikes)	2014	1 029			
Oakdene Hollins: **Forecast for wind turbines**	2010-14		1 200		
Kingsnorth / IMCOA **Demand in 2014**	2014				38 000 – 42 000 (global)
Oakdene Hollins: **Forecast for wind turbines**	2015-20		4 200		
Oakdene Hollins forecast based on McKinsey scenarios **(very low growth rate of electric cars)** ~ 1 million HEV	2020	875			
Oakdene Hollins forecast based on McKinsey scenarios **(high growth rate of electric cars)** ~ 20 million HEV	2020	23 000			
Fraunhofer ISI **Demand in 2030**	2030				20 000 – 35 200

This summary shows a significant gap between the high demand estimates by the Australian expert Kingsnorth (2010) and the Chinese expert Chen (2010) on the one hand and the sectoral analyses on the other hand. The sectoral analyses indicate a comparably low share of the wind turbines, a comparably low contribution from hybrid and electric vehicles (apart from the 2020 scenario by McKinsey, which assumes that hybrid electric vehicles will dominate the fleet) and a comparably low contribution from hard disks in computers.

The high Chinese demand estimate for 2008 compared to the global demand estimate for the same year provided in Kingsnorth (2010) is plausible, as China is the main magnet producer and produced not only for the domestic market but also for the export.

The comparison of the total demand estimates and the sectoral analysis might indicate higher shares of many magnet applications in other fields such as industrial equipment (e.g. lifters or magnetic separators), electronics, medical advices and other motor applications. One further aspect which is probably not considered in the sectoral analyses is the high loss of material in the magnet production. This issue is discussed in Chapter 10.2, which analyses options for a more efficient use of rare earths.

The situation regarding data uncertainty clearly shows that there is an obvious need for more reliable information. Precise analyses and reliable demand forecasts require a comprehensive material flow analysis to be undertaken by a research group with independent experts from all relevant application fields who have additional know-how of the specific national features.

8.3 Phosphors and luminescence

Almost all future energy saving lighting and display technologies, such as compact fluorescent lamps (CFL), fluorescent tubes, LEDs, OLEDs, EL foils, plasma displays and LCDs require the use of rare earths as phosphors, providing a high energy efficiency and high colour quality. In the past, many chemical elements and compounds are being studied for their use in luminescence. Among the substances being analysed, rare earths in particular seem to be most promising in terms of their high colour quality and good energy efficiency. It seems very unlikely that this performance will be achieved without the use of rare earths from the current perspective.

Thereby, the REE europium, samarium, terbium, cerium, erbium, dysprosium, thulium, gadolinium, and lutetium play a role as activators. The matrix or host lattices partly contain REE like yttrium, lanthanum or cerium.

The share of phosphors and luminescence in total rare earth application is around 7 % worldwide and around 9 % in China, in terms of volume. However, the share in terms of economic value is much higher at around 32 % according to the estimate provided in Kingsnorth (2010). One reason for the high value of the phosphors is the high price of europium and terbium, which both cost more than 700 US $/kg (see details on prices in Chapter 6.3) in November 2010.

Lynas (2010a) estimates that around 84 % of the phosphors are globally used for lighting, around 12 % for LCD and around 4 % for plasma displays. Hereby, 74 % are estimated to be used for red light, 25 % for green light and 0.5 % for blue light.

Informative figures are given on the relevance of europium and terbium in lighting appliances for the total demand of these elements by NEDO (2009). NEDO (2009) estimates that Japan is the world's leading consumer of terbium and europium with around 70 to 80 % of demand generated by the need for fluorescent powder.

The growth of rare earth consumption in the sector of lighting is determined by following parameters:

- The global overall growth including all types of lighting is estimated at 7 % per year by Philips (2008) for the years 2004 to 2011.
- Incandescent bulbs are going to be phased out due to their high energy demand. For example, the European Union, Australia, Canada and the United States banned the sale of incandescent bulbs in the years ahead in accordance with national law (Jaspersen McKeown 2008, DOE 2010). They will be replaced by other lighting systems, mainly by compact fluorescent lamps (CFL) and halogen lamps. Besides these types, there are numerous other lighting systems. Most of the energy efficient lighting systems include phosphors based on rare earths.
- Currently LEDs which also contain rare earths still play a minor role in lighting with a market share of 2.4 % in 2008. The main current uses were decorative effect lighting and orientation light; they are also starting to replace other lighting systems, e.g. automobile headlights. However, their development is progressing rapidly, and wider uses at very high efficiencies are to expect, particularly if the current comparably high prices begin to decrease. Trendforce (2010) assumes a growth rate of 32 % from 2008 to 2013 with a market share of about 8 % in 2013.
- Cathode-ray tubes which were used formerly on a large scale in TV sets and monitors are currently replaced by plasma displays and LCDs. Both techniques use rare earths. In 2008, around 130 million television sets with plasma and LCD displays were sold (DisplaySearch 2010). DisplaySearch (2010) forecasts an increase to approx. 280 million in 2014. This corresponds to an annual growth rate of 14 %.

These different aspects highlight that a considerable growth rate for energy efficient lighting systems with rare earth elements is to be expected. Kingsnorth (2010) assumes an annual growth rate of 4 – 6 % between 2008 and 2014. It is possible that this projected growth rate is too low and that higher growth rates will occur.

More technical details are given in Chapter 10.5 and Chapter 11.3, in which recycling aspects and options for a substitution of the REE are discussed.

8.4 Metal alloys / batteries

This application field comprises various uses which are summarised below (BGS 2010):

- One of the oldest applications is the use of cerium and lanthanum in pyrophoric alloys which are used in flint ignition devices for lighters and torches.
- Mischmetal and cerium are used as minor alloys for casting of steel and iron. They improve the stability of the casted product.
- REE (Y, La, Ce) which are added to heat-resistant superalloys can dramatically improve their performance.
- REE are used for the solid state storage of hydrogen where a metallic matrix of different metals absorbs a large amount of hydrogen at room temperature. This procedure is better than storage as cryogenic liquid or compressed gas in terms of safety, volume and energy saving.
- REE are used in Ni-MH batteries which in turn are used in hybrid electric vehicles (e.g. Toyota Prius) and portable appliances.
- Scandium-aluminium alloys are a suitable material for light weight construction. Due to the limited availability, it is mainly used in military aviation and not disseminated in civil aviation. Angerer et al (2009) estimate the current scandium supply at 5 t per year and report a new Australian mining project with the production target of 200 t scandium oxide.
- A new technology still under development is the solid oxide fuel cell (SOFC) which is regarded as the most promising fuel cell technology. Yttrium is contained in the electrolyte, and electrodes with mischmetal containing rare earths might improve their performance and reduce their costs (BGS 2010). There is also research on fuel cells for electric vehicles which could operate without the expensive platinum or palladium catalysts. The research also explores the incorporation of mischmetal containing rare earths in this context (BGS 2010).

The share of the global applications of metal alloys and batteries in the total rare earth demand is around 18 % in terms of volume. The global share of economical value is lower at around 14 %. Figure 19 on China shows a higher share of volume for H_2-storage (9 %) and for metallurgy (15 %). In this data the use of rare earths in Ni-MH batteries is integrated in the data for H_2-storage.

8.4.1 Ni-MH batteries

Ni-MH batteries are used in hybrid electric vehicles and in portable appliances. Besides nickel and cobalt, they contain a mix of lanthanum, cerium, neodymium and praseodymium. This mix is also called “mischmetal”.

Pillot (2009) estimates that in 2009 the hybrid electric vehicles already had a larger share (57 %) in the total Ni-MH battery market in terms of value than the other applications (43 %). Since the HEV market is nascent, it could be expected that the demand for Ni-MH batteries will be dominated by the development of the HEV market in the years ahead. The resulting rare earth demand depends on several factors:

- The specific rare earth demand for a Ni-MH battery.
- The growth rate of hybrid electric vehicle market.
- The applied battery system is of high relevance as the alternative battery system – Li-ion batteries – use currently no or just small amounts of rare earths.

The analysis conducted by Öko-Institut on the basic assumptions of published forecasts (Oakdene Hollins 2010, Kingsnorth 2010, GWMG 2010b, BGR 2009, BGS 2010, Lynas 2009) shows that the demand for rare earths arising for Ni-MH batteries in hybrid electric vehicles is widely overestimated in literature and information distributed on the internet. These overestimates are based on assumptions regarding the rare earth content of the Toyota Prius battery. Former estimates provided by Lifton (cited in Oakdene Hollins 2010) and Kingsnorth (2008) range from 10 to 15 kg of lanthanum for one Prius battery. Latest data from Öko-Institut (Buchert 2010) base on a life cycle assessment for Ni-MH batteries for hybrid electric vehicles based on data from Toyota. These data indicate that the battery of Prius II has a REO content of 2.9 kg per battery[14]. This implies an overestimate by the factor 4 in most published forecasts.

The growth rate for the sales of HEVs has already been discussed in Chapter 8.2.1, which analysed the rare earth demand of motors of HEV. The figures there illustrated the wide range of different scenarios based on technical, economical and political developments in the field of e-mobility in the years ahead.

The share of Ni-MH batteries in terms of the total hybrid electric vehicle batteries is currently very high because the market is dominated by the Toyota Prius, which is equipped with a Ni-MH battery. In 2008, the Prius had a market share of HEVs amounting to approx. 83 %. However, in the long term, Li-ion batteries will replace Ni-MH batteries due to several advantages described in Chapter 10.5, where the substitution of rare earth elements is analysed. Other manufactures will start producing HEVs with Li-ion batteries and Toyota

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[14] The Prius battery has a weight of 35 kg and a share of 7 % of the rare metals. This makes a weight of 2.45 kg rare earth per car battery (corresponding to 2.9 kg REO).

announced that it will launch a newly developed Prius hybrid minivan with a lithium battery in 2011 (Reuters 2010b). The large Chinese market for e-bikes mainly operates with lead batteries.

8.4.2 Other appliances

There are no forecasts for the future growth of other applications such as pyrophoric alloys, alloys for casting, metallic super alloys and the solid state storage of hydrogen. It is to be assumed that the growth rates will not be smaller than the growth rates of the steel industry. Its growth is estimated at 5.3 % for 2011 (Worldsteel 2010).

8.4.3 Overall forecast

Kingsnorth (2010) estimates a rare earth demand in the field of metal alloys and batteries of 43 – 47 000 t REO in 2014, compared to a demand of 22 500 t REO in 2008. The average growth rate is given as between 15 % and 20 %. Possibly, this forecast and other demand analyses (Oakdene Hollins 2010, GWMG 2010b, BGR 2009 and Lynas 2010) contain overestimations due to the specific rare earth demand of Ni-MH batteries being set too high.

8.5 Catalysts

The rare earths cerium and lanthanum are widely used for catalysts. Cerium compounds are used in automotive catalysts and as diesel additives in order to improve a clean combustion. Lanthanum and cerium are important in the petroleum refining as fluid cracking catalysts (FCC). Further applications are used in chemical processing. The demand for rare earth as catalysts contributes to the total rare earth demand, constituting 20 % in terms of volume according to estimates of Kingsnorth (2009). Relatively low prices of lanthanum and cerium lead to a low share of value accounting for just 5 % in 2008 (Kingsnorth 2009). Nevertheless, these applications are highly relevant in terms of emission reduction, energy efficiency and the reduction of embedded precious metals (platinum, palladium and rhodium) in the catalysts due to an increased catalyst performance.

For the future, a further increase in the demand could be expected as the global stock of fuel driven vehicles increase steadily at approximately 3 % per year. Thus, the demand for automotive catalysts will grow as well as the demand for petroleum.

BBC Research (2010) forecasts an annual growth rate of 6 % for environmental catalysts. Kingsnorth (2010) forecasts an annual growth rate of 3 -5 % for all catalysts containing rare earths. Thus, he expects an increase in demand from about 25 000 t REO in 2008 to 30 - 33 000 t REO in 2014.

8.6 Glass, polishing and ceramics

The group “glass, polishing and ceramics” comprises many different uses. Table 8-3 presents the most frequent applications (BGS 2010, Avalon 2010):

Table 8-3 Overview of main applications in the group “glass, polishing and ceramics”

Application	Major REE
Polishing	
Polishing of high-quality glass surfaces (mirrors, television and monitors, cathode ray tubes, panel display, glass platters in hard disks)	Ce
Glass additives	
Colouring of glass (Ce – yellow and brown, Nd – red, Er pink)	Ce, Nd, Er
Decolouring of glass	Ce
UV-resistant glass (glass bottles, sunglasses, cover of solar cells)	Ce
Optics (optical lenses, optical filters, coatings)	La, Gd, Pr
Ceramics	
Ceramic capacitors, semiconductors and other components for LCD and electronics	La, Ce, Pr, Nd
Stabiliser for ceramic material	Y, Ce
High-temperature superconductors	Y
Pigments in ceramics	Pr, Y, Nd
Refractory material	Y, Ce
Laser	Y
Dental ceramics	Ce

The applications described have a high share of the total rare earth demand of about 30 % in terms of volume according the estimate from Kingsnorth (2010). Due to the manifold use of quite cheap cerium, the share of economical value was much lower at 9 % (estimated from Kingsnorth 2010).

Kingsnorth (2010) also gives more detailed estimates on the sectors for 2008:

Glass polishing	15 000 t REO (44 %)
Glass additives	12 000 t REO (35 %)
Ceramics	7 000 t REO (21 %)

Compared to the global demand, the consumption in China is comparably low, totaling 7 160 t. It is likely that a high share of rare earths for these applications is used in Japan. The Japanese New Energy and Industrial Technology Development Organization (NEDO 2009) states that Japan is the world's leading consumer of cerium, and more than the half of demand is for abrasives. The main uses here are flat panel display for TV sets and hard disks in computers.

Angerer et al (2009) analyse an upcoming application: the use of yttrium-barium-copper-oxide (YBCO) as high temperature super conductor of the second generation. Associated advantages of this application are lower costs and a potentially higher performance. Angerer et al (2009) estimate that commercial use will begin around 2013/2014 and assumes that this application might transform the electricity industry significantly in the long term, coupled with an increase of the yttrium demand for this field. However, Angerer et al (2009) estimate the demand of super conductors for yttrium at only 75 t in 2030, which is very small compared to the global yttrium production of almost 9 000 t in 2009 according to USGS (2010b).

Cerium-doped covers of solar cells absorb UV radiation. Thus, they prevent the darkening due to UV radiation and increase the lifetime of the solar cells. Since these UV wavelengths are not used by solar cells, their efficiency is not lowered (JDSU 2009, Messer 2009).

The growth rates for glass polishing is supposed to be in the range of the growth rates for plasma and LCD displays and computers, which are around 14 and 16 %, respectively as discussed in Chapter 8.2 and Chapter 8.3 (DisplaySearch 2010, Gartner 2010). The growth rate of ceramic application might be in the range of the growth of electronics, which is estimated by the industry research firm RNCOS (Daily News 2010) at 5 % for 2010 - 2013.

Kingsnorth (2010) estimates an increase in the demand of the whole application group of less than 5 %. Hereby, he expects almost no growth for glass additives and moderate growth rates for polishing and ceramics (estimates vary from 2 - 4 % to 6 - 7 %). Possibly, this is an underestimation of the potential demand increase triggered by the booming markets of PCs and flat screens for computers and TV sets.

8.7 Others

The group “others” comprises many smaller uses which do not fit into the categories presented above. Table 8-4 presents selected applications (BGS 2010, Avalon 2010):

Table 8-4 Overview of main applications in the group „others “

Application	**Major REE**
Pigments and paint (for better light resistant, higher durability, corrosion resistance)	Ce, Y
Defence (optics, surveillance, sonar transducer, microwave communication, laser, aircraft material)	Various REE
Fertilizer (mainly in China, added to phosphate fertilizer)	Ce, La
Nuclear energy (neutron absorber, reactor control)	Gd, Eu
Waste water treatment (new application)	Ce

The demand has a low share of the total rare earth demand of about 5 % in terms of volume (see Figure 16 and about 3 % in terms of value (Kingsnorth 2010).

Most of the defence applications are part of the large categories which were presented in the chapters above, as the defence sector requires equipment such as lighting, batteries, motors, electronics, computers and displays. Some further specific devices are listed here and in more detail in BGS (2010) and GAO (2010).

In co-operation with the United States Army Molycorp developed a portable device for purifying water. It further developed a material for the filtration of arsenic and other contaminants from process water (BGS 2010, Molycorp 2010c). Both applications require rare earths. In China, Sun et al (2008) analysed the use of $La_2B(B=Mn,Fe)TiO_6$ as a photocatalyst in the treatment of waste water containing phenol from the coal chemical production.

REE containing fertilizer is mainly used in China. BGS (2010) reports on REE compounds which are added to calcium superphosphate to create a “rare earth phosphate fertilizer” containing between 0.04 and 0.16 % REE. Research has shown that this fertilizer results in improved crop yields and less diseases of plants (Xiangshen et al (2006), cited in BGS 2010, Xu & Wang 2007).

Kingsnorth (2010) estimates an annual increase in the demand of the whole application group of 3 - 7 %, thereby increasing from 7 500 t REO in 2008 up to 9 000 – 12 000 t REO in 2014.

Conclusion on applications and demand of rare earths

The following green technologies currently use rare earths:

- *magnets (motors for e-mobility, wind turbines)*
- *automotive catalysts*
- *energy efficient lighting*
- *batteries for e-mobility*
- *industrial catalysts*

Further fields of application are:

- *metal alloys*
- *glass additives*
- *electronics*
- *ceramics*
- *polishing*

In 2008, around 30 % of the global rare earth consumption was used in the glass, polishing and ceramics sectors. Around 20 % were used for permanent magnets, a further 20 % for automotive and industrial catalysts, another 20 % for metal alloys and batteries and around 7 % for lighting. However, larger research institutions and public bodies have not established in-depth material flow analysis for rare earth, and the available data are estimates from few experts.

The demand for all applications is expected to grow in the short and medium term considerably. Of these applications, the highest growth rates are projected for permanent magnets (particularly for wind turbines, hybrid electric vehicles and hard disks). The global demand of around 120 000 t REO in 2008 is expected to increase up to 170 000 – 200 000 t in 2014.

9 Demand-supply balance

The supply risk of individual rare earths is indicated by the development of the future demand-supply balance. Most of the available forecasts refer to the year 2014 which is also used as a target year within this study.

In the following, the future demand and supply of the most relevant 11 REE are examined. For the group of holmium, thulium, ytterbium and lutetium, only aggregated data are available. Due to their limited supply (~ probably < 1 000 t/a), they are not yet significant. No data are given on promethium which is radioactive and therefore has only limited applications. Brief information is provided on scandium, which is produced in extremely low amounts (approx. 5 t annually), in Chapter 8.4 on page 77. A supply shortage is not to be expected for scandium according to the German Federal Institute for Geosciences and Natural Resources (BGR 2010a).

9.1 Future supply

The future supply depends on some key factors:

- development of the total Chinese REO production,
- development of the Chinese export quota,
- progress in installation works for Mountain Pass (USA) and Mt Weld (Australia),
- progress of other mining projects (approval, feasibility studies, construction work).

The development of the total Chinese production and the progress of mining projects outside of China are discussed in the following paragraphs. The relevance of Chinese export quotas and the progress of the advanced mining projects Mountain Pass and Mt Weld concerning the demand-supply balance are further discussed in Chapter 9.3.

Future supply by China

The total Chinese production in 2008 and 2009 amounted to approx. 120 000 t REO according to USGS (2010). Chinese data sources cited in the Explanation of Compiling of Entry Criterions for Rare Earth Industry 2010 specify a production of 120 800 t REO in 2007. In contrast, Kingsnorth (2010) estimates a legal production of 125 – 140 000 t REO in the years 2006 and 2008. In addition to these quantities of legal production, there are around 20 000 t REO which were produced illegally and seem not to be included in these data. The comparison of these figures shows that there are no accurate data on the current situation, particularly due to a relevant quantity of illegal production.

In the light of the Chinese 2009-2015 plan mentioned in Chapter 5.1.2, it is to be assumed that China’s rare earth industry will undergo a phase of consolidation and will not significantly increase their REO production. This is in accordance with Lynas (2010a) which forecasts a Chinese production of 114 000 t in 2014, with 110 000 t coming from primary mining and a further 4 000 t coming from recycling. In contrast, Kingsnorth (2010) estimates a higher Chinese production of 160 – 170 000 t REO in 2014 without recycling. This constitutes a significant difference of 50 000 – 60 000 t REO in the forecast of the Chinese REO production.

The forecasted production of rare earths from the Chinese ion adsorption deposits containing HREE makes for a more uniform picture. Chinese data sources (MEP 2009) specify a production of 45 000 t REO in 2007. Kingsnorth (2010) similarly estimates a Chinese production of 40 - 50 000 t REO in 2014, whereas Lynas (2010a) assumes a lower production of only 30 000 t REO. The main conclusion derived from these figures is that the Chinese HREE production will probably not rise and eventually even decrease.

Future supply outside of China

Table 4-3 on page 22 provides an overview of current mining activities. Despite the high number of intended mining projects, only two of them are sufficiently advanced to have obtained approval from the authorities and construction work has begun: Mountain Pass in California, USA and Mt Weld in Australia. The processing for the latter is located in Malaysia.

Their nominal capacity is an output of 20 000 t REO for each location, respectively. Operation shall commence in 2011 in Australia/Malaysia and in 2012 in California. It is uncertain whether the mineral companies will succeed in operating their plants at full load in a short term because the chemistry of rare earth processing and refining is very complex.

Lynas (2010a) further assumes that India and Russia might be able to increase their capacities up to 12 000 t in 2014, and estimates secondary rare earths from recycling of almost 2000 t in 2014.

Neither Kingsnorth (2010) nor Lynas (2010a) expect the opening of further mines with larger capacities until 2014, except for India and Russia. This is in accordance with Table 4-3 on page 22 which was compiled by Öko-Institut and shows that the listed mines (besides Mountain Pass and Mt Weld) have reached the stage of feasibility studies or drillings. From this point, it will take some years before mining and processing on an industrial scale can take place. More details on the time frames needed were presented in Chapter 4.3 on page 20.

Global supply forecast

Table 9-1 presents the forecasts from Kingsnorth (2010) and Lynas (2010a) and their estimated production for individual rare earths. The forecast of Kingsnorth (2010) is supplemented by other figures from Kingsnorth which are cited in Oakdene Hollins 2010. As mentioned above, both forecasts assume that Mountain Pass and Mt Weld commence operation before 2014, and that - besides the consideration of Russian and Indian mines in the Lynas forecast - no other mining and processing projects will be ready for production until

2014. The main difference is the estimate of the future mining in China. Additionally, both forecasts do not include the illegally mined quantities. This is reasonable as the Chinese government intends to control the rare earth industry more strictly and prevent illegal mining.

Table 9-1 Forecasted supply in 2014 stated by Kingsnorth (2010) and Lynas (2010a)

Company	**IMCOA/Kingsnorth**	**LYNAS**
Source	Kingsnorth 2010, figures in ( ) from IMCOA, cited in Oakdene Hollins 2010	Lynas 2010a
	t REO	**t REO**
China		
Bayan Obo Bastnasite	80 - 100 000	60 000
Sichuan Bastnasite	20 - 40 000	20 000
Ion Adsorption Clays	40 - 50 000	30 000
Monazite	8 - 12 000	
Recycling in China	-	4 000
Total China	**160 - 170 000**	**114 000**
Outside China		
Mountain Pass	20 000	20 000
Mt. Weld	21 000	22 000
Nolans Bore	0	0
Thor Lake	0	0
Others (India & Russia)	0	12 000
Recycling outside China	0	1 800
Total World	**190 - 210 000**	**169 800**
Forecast for individual elements in t REO:		
Lanthanum	52 - 57 000	43 400
Cerium	80 - 85 000	66 500
Terbium	400 - 500	330
Dysprosium	1 800 - 2 000	1 700
Yttrium	9 - 13 000	9 500
Praseodymium	(10 000)	9 100
Neodymium	(33 000)	31 200
Samarium	(4 000)	3 500
Europium	(850)	450
Gadolinium	(3 000)	2 300
Erbium	(1 000)	n.d.
Ho-Tm-Yb-Lu	(1 300)	n.d.
Total	**190 - 210 000**	**167 980**

The difference in these forecasts mainly concern the supply of lanthanum and cerium due to different assumptions of the increase in production in the Chinese mines in Batou (Bayan Obo mine) and Sichuan, which mainly contain light rare earths.

9.2 Future demand

Table 9-2 presents the demand forecasts of Kingsnorth (2010) and Lynas (2010a) for the year 2014.

Table 9-2 Forecasted demand in 2014 by Kingsnorth (2010) and Lynas (2010a)

Company	**IMCOA/Kingsnorth**	**LYNAS**
Source	Kingsnorth 2010, figures in ( ) from IMCOA, cited in Oakdene & Hollins 2010	Lynas 2010a
	t REO	**t REO**
Lanthanum	50 - 55 000	57 100
Cerium	60 - 65 000	59 000
Terbium	400 - 500	620
Dysprosium	1 900 - 2 300	2 800
Yttrium	10 - 14 000	10 700
Praseodymium	(7 900)	16 100
Neodymium	(34 900)	45 400
Samarium	(1 390)	1 200
Europium	(840)	560
Gadolinium	(2 300)	1 400
Erbium	(940)	n.d.
Ho-Tm-Yb-Lu	(200)	n.d.
Total	**170 - 190 000**	**194 880**

The magnitude of the forecasts is quite similar in both scenarios. The moderate differences stem from a range of generally high data uncertainties. Nevertheless, the trend is quite clear: The demand which was around 124 000 t REO in 2008 according to Kingsnorth (2010) is expected to increase rapidly within the next few years and continue to rise in the years after 2014 with similar growth rates, as many of applications are high-tech applications such as hybrid vehicles, wind turbines and energy efficient lighting which are only in the start phase.

9.3 Future demand-supply balance

The demand-supply balances resulting from the demand and supply forecasts presented above are shown in Table 9-3.

Table 9-3 Forecasted supply-demand balance for individual rare earths in 2014 by Kingsnorth (2010) and Lynas (2010a)

Company	**IMCOA/Kingsnorth**	**LYNAS**
Source	Kingsnorth 2010, figures in ( ) from IMCOA, cited in Oakdene Hollins 2010	Lynas 2010a
	t REO	**t REO**
Lanthanum	**-3 000 bis + 7 000**	**-13.700**
Cerium	**+15 000 bis + 25 000**	**7 500**
Terbium	**-100 bis + 100**	**-290**
Dysprosium	**-500 bis + 100**	**-1.100**
Yttrium	**-5 000 bis +3 000**	**-1.200**
Praseodymium	**(2 100)**	**-7 000**
Neodymium	**(-1 900)**	**-14 200**
Samarium	**(2 610)**	**2 300**
Europium	**(10)**	**-110**
Gadolinium	**(700)**	**900**
Erbium	**(60)**	**n.d.**
Ho-Tm-Yb-Lu	**(1 100)**	**n.d.**

Despite some data uncertainties, the overall picture presented in Table 9-3 is quite clear: There will be shortages in **terbium, dysprosium, praseodymium** and **neodymium** at a high degree of probability, even if China imposes no export restrictions. The sectoral analyses of the magnet applications identified high growth rates in many affected applications such as wind turbines, hybrid vehicles, hard disks and electronics which strongly support the expectancy of future supply shortages.

Further potential shortages might occur for **lanthanum**, **yttrium** and **europium** with a high degree of probability. Lynas and partly also Kingsnorth (2010) forecast shortages for all three elements, based on the assumption that Chinese REO production will not significantly increase in the coming years. The analysis conducted by Öko-Institut as provided in the preceding chapters supports this expectation. Only the scenario of Kingsnorth (2010), which assumes a significant increase in Chinese production, results in a positive demand-supply balance for La, Y and Eu. The main drivers for the demand of these REE are energy efficient lighting (La, Y and Eu), catalysts (La), ferrite magnets (La), Ni-MH batteries (La) and ceramics (Y).

The supply risk for the HREE terbium and dysprosium seems to be the highest, as the Mountain Pass and Mt Weld mines will not produce relevant amounts of these metals; and potential Chinese supply constraints regarding HREE cannot be compensated by relevant production capacities outside of China. Furthermore, China will probably not increase its HREE production in the next few years, though the global demand increases steeply.

A relevant supply risk of the LREE neodymium and praseodymium is the complex processing technology required for rare earths refining which might lead to delays in implementation in California and Malaysia.

The negative supply-demand balance after 2014 might be attenuated, if further mines besides Mountain Pass and Mt Weld start production of HREE and LREE, significant improvements in resource efficiency are implemented (particularly increasing the recovery rates in the rare earth mining and reduction of production losses in the magnet production) and relevant substitutions are realised. Furthermore, efficient recycling systems are required. These issues will be analysed in more depth in Chapter 10 and 11.

Another important issue is the high pressure on the fast opening of new mines from manufactures which require rare earths for their finished goods, coupled with the expectation of investors to make profits with rare earth production as long as possible supply shortages exist. This situation might lead to the rapid opening of new mines with inadequate environmental standards. Chapter 7 illustrated clearly the environmental burdens of mines and processing plants which are poorly designed or managed. National authorities, investors and mining operators are asked to act responsibly in designing and operating these plants in order to develop a sustainable rare earth industry. This is particularly true as appropriate environmental technologies are available and awaiting application.

The U.S. Department of Energy published in December 2010 an analysis of the criticality of selected rare metals (DOE 2010). The highest criticality in terms of supply risk and the importance to clean energy production are the five REE **dysprosium**, **neodymium**, **terbium**, **yttrium** and **europium**, which are also seen as critical by Öko-Institut as outlined in the paragraphs before. The element **praseodymium** is seen as less critical by DOE (2010) though it is widely interchangeable with neodymium and is mostly used in neodymium / praseodymium mixtures as it is found in mineral ores. The criticality of **lanthanum** is estimated to be near-critical by DOE (2010) and as critical by Öko-Institut. Hereby, DOE (2010) projects an additional supply of these elements not only from Mountain Pass and Mt. Weld but also from five further new mines (Nolans Bore/Australia, Nechalacho/Canada, Dong Pao/Vietnam, Hoidas Lake/Canada and Dubbo Zirconia/Australia) up to 2015. Considering the long time spans needed to develop new mining projects including the further rare earth processing, this forecast seems to be quite optimistic. However, apart from the evaluation of the speed progress of new mining projects, the assessment of Öko-Institut and DOE (2010) show a broad consensus.

Finally, potential supply shortages for “green” applications are summarised in brief:

- There will be shortages of rare earths for the production of **permanent magnets** in the short term, with a high degree of probability. The relevant elements are **terbium**, **dysprosium**, **praseodymium** and **neodymium** and the applications wind turbines, hybrid vehicles and electric vehicles are concerned. However, there are options for their substitution which are discussed in Chapter 10.2.
- The production of **Ni-MH batteries** for hybrid vehicles might become limited due to shortages in **neodymium** and **lanthanum**. This will probably lead to an accelerated substitution of Ni-MH batteries by Li-ion batteries.
- There will be shortages of rare earths for the production of **lighting devices** in the short term, with a high degree of probability. Significant shortages are to be expected for **europium** and **terbium**. Furthermore, the supply with yttrium and lanthanum might also become scarce. Relevant applications are energy efficient lighting such as compact fluorescent lamps, fluorescent tubes, LED, plasma and LCD displays. An additional supply risk for most of these applications is the lack of adequate substitutes for many phosphors in the short term (see Chapter 10.5).
- **Catalysts** in refining and processing might suffer from a **lanthanum** shortage. Here again, no substitutions are available in the short term.
- Future **new technologies** such as magnetic cooling, wind turbines with high-temperature superconductors (containing yttrium) and efficient and cost efficient fuel cells (containing yttrium and mischmetal) might suffer from supply constraints slowing down their future dissemination.

The compilation shows that most green applications listed above are closely related to climate protection and reduction of the depletion of non-renewable energy carriers. They contribute to a more efficient use of energy or to energy production by renewable energy sources. This applies to motors and batteries for hybrid vehicles and electric vehicles, energy efficient lighting, wind turbines, magnetic cooling and fuel cells. Additionally, catalysts contribute significantly to the enhancement of process efficiencies and the prevention of air pollution.

Conclusion on the demand-supply balance

Based on the foregoing demand and supply analysis, the future demand-supply balance for the year 2014 was analysed. It seems to be probable that the Chinese production will not increase significantly in the short term due to their planned course of consolidation. For the mining outside of China, it is probable that the mining projects Mountain Pass / United States and Mt. Weld / Australia will commence operation in the years ahead. The short-term implementation of further larger mines does not seem to be realistic.

Based on these assumptions, potential supply shortages for green applications can be identified:

- *There will be shortages of rare earths for the production of* ***permanent magnets*** *in the short term, with a high degree of probability. The relevant elements are* ***terbium****,* ***dysprosium****,* ***praseodymium*** *and* ***neodymium****, and the applications wind turbines, hybrid vehicles and electric vehicles are concerned. However, there are options for their substitution.*
- *The production of* ***Ni-MH batteries*** *for hybrid vehicles might become limited due to shortages in* ***neodymium*** *and* ***lanthanum****. This will probably lead to an accelerated substitution of Ni-MH batteries by Li-ion batteries.*
- *There will be shortages of rare earths for the production of* ***energy efficient lamps and displays*** *in the short term, with a high degree of probability. Significant shortages are to be expected for* ***europium*** *and* ***terbium****. Furthermore, the supply with* ***yttrium*** *and* ***lanthanum*** *might also become scarce. An additional supply risk for most of these applications is the lack of adequate substitutes for many phosphors in the short term.*
- ***Catalysts*** *in petroleum refining and processing might suffer from a* ***lanthanum*** *shortage. Again, no substitutions are available in the short term.*
- *Future* ***new technologies*** *such as magnetic cooling, wind turbines with high-temperature superconductors (containing yttrium) and efficient and cost-efficient fuel cells (containing yttrium and mischmetal) might suffer from supply constraints slowing down their future dissemination.*

10 Substitution and efficient use of rare earths

10.1 Overview

Facing possible scarcities of natural resources and the challenge to search alternatives for substitution, there are two options in principle: substitution of the REE by another material or another design approach of the products or their applications. The analysis of substitutions for scarce REE has shown that a simple substitution of a REE compound by another compound is a quite rare case. In most cases substitution requires a totally new product design. The following sub-chapters describe the options for substitution concerning the main fields of applications: motors/generators, magnets in electronic devices, batteries, lighting/luminescence and catalysts.

10.2 Magnets for motors and generators

10.2.1 Motor and generator types

In this sub-chapter a short description of the current relevant motor and generator types is given. An overview of these technologies is required to understand the substitution potentials of rare earths.

State of the art for electric motors for e-mobility:

Synchronous electric motor with a neodymium magnet:

- Currently the motor type with the highest efficiency!
- Use in most electric vehicles, e.g. from Toyota, Mercedes, Honda and BMW,
- Increasing use in high performance generator of wind turbines (market share about 14 % according to Fairley (2010)),
- Compact size,
- Expensive.

Asynchronous motor

- Mostly used motor in industrial appliances; produced in high quantities,
- Use in some electric vehicles, e.g. Fiat Seicento Electra, Ford E-Ka,
- Good efficiency at nominal load, low efficiency at some operations conditions,
- Low costs,
- No need for neodymium,

- Simple construction,
- Lower efficiency and bigger size than motors with neodymium magnets.

Alternatives:

Synchronous motor with electromagnets (external excitation)

- No need for rare earths,
- Higher copper demand than permanent magnet motors (factor 3),
- Broader realisation possible in the short term or the medium term,
- Conti is developing such a motor for a power range of 5 to 120 kW.

Permanent magnet motor with a SmCo magnet (synchronous motor)

- SmCo (Samarium-Cobalt) magnets are the first generation in the family of rare earth magnets, NdFeB magnets belong to the second generation,
- These motors were used for high-performance applications before the construction of motors with neodymium magnets,
- Due to their high costs their application is restricted. With increasing Nd-prices they might become competitive,
- SmCo magnets have a much higher magnetic energy product than ferrite, but lower than that of neodymium magnets,
- They can operate at higher temperatures than NdFeB-magnets (Hatch 2010).

Permanent magnet motor with ferrite magnet (synchronous motor)

- Lower magnetic properties (factor 4), therefore more volume und more weight (Benecki 2007),
- Lower efficiency – there are R&D activities for higher efficiencies, e.g. (Fang et al. 2009),
- Lower price,
- R&D project in Japan (Kudling 2010).

Reluctance motors

Technical advantages and disadvantages according to Matoy (2008):

- Simple and robust construction,
- Noise problems (loud)!
- Low price,

- Due to serious noise development no application in electric vehicles or wind turbines.

Hybrid motors (combination of permanent magnet and reluctance motor)

Technical advantages and disadvantages according to Matoy (2008):

- Combines the advantages of both motor types,
- Needs less neodymium than the permanent motor,
- High potential for the future!
- Still in the R&D phase.

10.2.2 Substitution of rare earths magnets in motors for electric vehicles

The analysis of the different motor types shows that there are alternatives to permanent magnet motors containing rare earths. There are asynchronous motors which are currently used in electric vehicles (e.g. Fiat Seicento Electra, Ford E-Ka). Generally, asynchronous motors are the most widely used motor type, and though they are less compact and less efficient in some operation conditions than the permanent motors, they also show advantages such as simple construction methods and low costs. They are an alternative, at least in mild hybrid vehicles. Therefore, the German government has included the research on asynchronous motors in its national development plan for e-mobility (Bundesregierung 2009).

Besides the industrially available asynchronous motors, there are three other motor types which show a potential to be an alternative to pure Nd-containing permanent motors:

- The synchronous motor with electromagnets (external excitation). Broader realisation seems to be possible for the short or medium term. Conti is currently developing a motor for a power range of 5 to 120 kW.
- A permanent magnet motor with ferrite magnet is currently under development in Japan. The higher volume of the weaker ferrite magnet shall be compensated by another geometrical arrangement.
- Hybrid motors which are a combination of permanent magnet and reluctance motor might show a promising potential for the use in electric vehicles. They need less neodymium than the pure permanent magnet motors and tend to have a better performance than the permanent magnet motors. The German government has included the research on reluctance motors in its national development plan for e-mobility (Bundesregierung 2009).

10.2.3 Substitution of rare earths in generators for wind turbines

Currently, the global market share of wind turbines working with gear drive and asynchronous or synchronous generators is 86 %. They work with electro magnets and thus without permanent magnets and rare earths (Fairley 2010). There have been wind turbines without gear drives (direct drive turbine) since 1991. They usually work with neodymium containing permanent magnets. One of the advantages of these turbines is the absence of a gear, which facilitate higher efficiencies and higher reliabilities. Furthermore, due to the compact permanent magnet motor, the gearless wind turbines are lighter than the types equipped with a gear drive. Therefore, they are an attractive option for offshore plants. But also onshore plants are running without gears. The main obstacle for increasing market shares of gearless wind turbines are the high costs for the permanent magnets.

The international market share of gearless wind turbines is estimated at 14 % (Fairley 2010). However, in Germany the market share is already much higher; the company ENERCON, which completely shifted to gearless drives, has a market share of around 50- 60 % (Kettwig 2009). The trend indicates that more and more companies are offering gearless turbines, and large companies such as Siemens and General Electric are developing new gearless turbines for the offshore applications.

There are manifold discussions about the future development of the market shares of gearless drives. There are two key parameters: The first one is the question of how successful the gears will be improved in order to achieve a higher reliability for conventional turbines with gear drive technology. The second issue is the future development of the price and the availability of the permanent magnets (rare earths!) which might inhibit future growth rates of direct drive turbines.

If there are shortages in neodymium, the following alternatives could be drawn upon:

- “Classic” wind turbine technology with gears for onshore and offshore plants. An overview of the largest protoypes (year 2006) shows that four companies have developed off-shore prototypes with gear and asynchronous generator for a capacity of 4 – 5 MW (Koenemann & Tschierschke 2006).
- Magnetic direct drive turbines with SmCo-magnets. However, SmCo-magnets are quite expensive, and the resources are also limited.

Furthermore, a new technology based on high temperatures superconductor (HTS) rotors is now under development. At the moment it is not yet clear whether this technology might be able to replace the gearless wind turbines with Nd-magnets. However, following announcements of the company AMSC (Terra Magnetica 2009, Fischer 2010), the design and implementation of turbines with HTS technologies for plants with capacity of 10 MW and more are planned. Currently, most off-shore turbines operate up to 5 MW. Nevertheless, the superconductors used for this technology also require a rare earth element – yttrium. The basic HTS wire substrate is nickel tungsten. Various buffer layers are applied before the superconductor — yttrium barium copper oxide — and a very thin cap layer of silver is also applied. (Fischer 2010). The resource implications (yttrium, tungsten, silver etc.) of this new technology have to be considered very carefully in the years ahead.

10.2.4 Substitution of dysprosium and terbium in permanent magnets

Most of the neodymium magnets consist of approximately 65 - 70% iron, 1 % bor, 30 % mix of neodymium/praseodymium, 3 % dysprosium and sometimes terbium (Oakdene Hollins 2010). High-performance applications (e.g. e-mobility) may even need a higher share of dysprosium.

The function of dysprosium is to enhance the coercivity (intensity of the applied magnetic field required to reduce the magnetisation of that material to zero) and thus the temperature tolerance, which is needed for applications with high temperatures such as motors or generators (Oakdene Hollins 2010). The use of dysprosium also tends to improve the corrosion resistance of the magnets (Avalon 2010).

The function of terbium is similar to that of dysprosium, but its use is limited to the very scarce supply and the high price. One particular quality of terbium is that it has less impact on the remanence (magnetisation left after an external magnetic field is removed, which should be low in order to achieve a high performance) than dysprosium according to Oakdene Hollins (2010).

Due to a forecasted supply shortage for dysprosium and terbium, industrial companies and researchers are looking for alternatives, but there is no decisive solution in sight. The following summarises different activities and options in this context:

- Benecki (2009) assumes that “magnet producers will likely be forced to offer NdFeB magnets with modified compositions, even if some performance is sacrificed. For example, a reduction of dysprosium or terbium content could result in an H_{ci} (coercivity) reduction of 10-30%. Cost considerations may eventually dictate such compositional changes for some applications.”
- Discussions with European magnet experts have shown that there is no commercially available substitute for dysprosium in neodymium magnets yet. An abandonment of terbium seems feasible for most applications which require no extremely high performance if the wider available dysprosium is applied to enhance the stability and the performance.

Furthermore, different research and development activities are being undertaken which focus on a better performance of the neodymium magnets with less dysprosium and terbium content than the current magnets. A research project of this kind is currently underway at St. Pölten University of Applied Sciences (Austria), in cooperation with the University of Sheffield (UK). The scientists are exploring the ideal composition and structure for high-performance permanent magnets intended for use in hybrid and electric car motors—specifically, how the proportion of dysprosium can be reduced without compromising the thermal stability of the magnets. By optimising magnets, the researchers suggest, hybrid and electric cars can be made economically competitive.

Another example is provided by Ames Laboratory, where researcher Bill McCallum is investigating how to lower the rare-earth content in the permanent magnets used in the traction motors of hybrid electric vehicles (Jenkins 2010).

Komuro et al. (2010) reports that effective processes have recently been developed to reduce the amount of terbium by sputtering or vaporising techniques for magnets which have a thickness of up to 10 mm. The terbium is diffused along grain boundaries in sintered neodymium magnets. The condensed terbium atoms near grain boundaries increase the coercivity without a large reduction of remanence. A new process for thicker magnets whereby the surface of the magnet powder is coated before sintering is described by Komuro et al (2010).

10.2.5 Substitution of neodymium magnets by SmCo magnets

The production of SmCo magnets is a difficult and expensive multi-step process. Therefore, these magnets are only used in a small number of applications, and the majority of permanent magnets are neodymium magnets. A substitution of neodymium magnets by SmCo magnets is only an economically attractive alternative, if the SmCo magnets become cheaper and/or the price of neodymium magnets rise.

Apart from the steep increase of Nd-prices in 2010, there are two developments which might lead to SmCo magnets having a higher market share:

- The Northeastern University (2008) presents a new one-step production process which might result in much cheaper SmCo magnets: “Unlike the traditional multi-step metallurgical techniques that provide limited control of the size and shape of the final magnetic particles, the Northeastern scientists’ one-step method produces air-stable “nanoblades” (elongated nanoparticles shaped like blades) that allow for a more efficient assembly that may ultimately result in smaller and lighter magnets without sacrificing performance.”
- SmCo magnets need – in contrast to neodymium magnets – no coating. Therefore, particularly small SmCo magnets might become economical if the neodymium prices continue to rise. The reason is that the economical advantage of not coating the

magnets is more relevant for small magnets as the costs of coating do not change much when changing the size of the magnet (Trout 2007).

However, a substitution of neodymium magnets by SmCo magnets will be strongly limited due to the resource limits of samarium. The samarium supply is estimated at 4 000 – 5 000 t in 2012 whereas the neodymium supply is estimated at 30 000 – 40 000 t in 2012 (Oakdene Hollins 2010). The rare earth breakdown of the minerals of mines in China, Australia, Canada, United States and Greenland shows that all minerals contain significantly more neodymium than samarium (Oakdene Hollins 2010). Thus, there is no potential for an enhanced samarium supply which might be able to substitute a significant share of neodymium. Additionally, the high costs and resource limits of cobalt contribute to the high price of SmCo magnets (Co prices range from 30 – 130 $/kg in recent years[15]; annual production in 2009 around 61.000 t) according to USGS (2010d).

Another drawback is the high environmental and social burden related to the cobalt mining in Democratic Republic of the Congo where armed conflicts on resources take place. Around 40 % of the global cobalt production is currently mined in the Democratic Republic of the Congo (USGS 2010g).

10.2.6 Substitution of rare earths demands by enhanced process efficiencies

According to Benecki (2007) there are actions that the magnet industry can take to address rising REE prices. First, the classic Chinese production process of producing blocks of NdFeB and then cutting them to the desired shape wastes tons of Nd and Pr each year. The Chinese need to shift to “press to shape” manufacturing, the process that has been common in Japan and the West for decades. The Chinese need to reduce the waste of precious rare earth materials inherent in their traditional “slicing and dicing” process.

According to Bax & Willems (2010) nanocomposite magnets could constitute a new generation of magnets; DOE (2010) sees nano-structured permanent magnets as one high-priority research area. In this context, Öko-Institut proposes the incorporation of a case-specific risk assessment in their development of all applications of nanotechnologies (Öko-Institut 2007).

10.3 Magnets in electronic devices, mainly disk drives

Approximately one third of the neodymium magnets were used in hard disk drives in 2007, and around 10 % of magnets were used in optical and acoustic devices (Oakdene Hollins 2010). In this application field they are used for small motors, writing/reading heads, speakers and ear phones and sensors.

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[15] Compare with Nd-price in October 2010 of around 80 $/kg.

Most hard disk drive systems currently use a voice-coil-motor (VCM) to actuate the read/write recording arm assembly. This motor usually contains a neodymium magnet. In principle, hard disk drives (HDD) with VCM can be substituted by a new generation of data storage devices, the solid state drive (SSD). The SSD is a data storage device that uses solid-state memory to store persistent data. It uses microchips and contains no moving parts. Compared to traditional HDDs, SSDs are typically less susceptible to physical shock, quieter, and have lower access time and latency. SSDs use the same interface as hard disk drives, thus easily replacing them in most applications. SSDs are still significantly more expensive than HDDs, but there are already some laptops working with SDD and more computer manufacturers are beginning to offer SSDs. There is still a need for further research, but it is to be expected that new developments will lead to lower prices and increasing performance, particularly in terms of capacity, life time and safety (Marwan 2010). Benecki (2009) assumes that “as solid state drive utilisation increases, their costs (and prices) will decline and they will gradually replace the traditional magnet-consuming VCM we have taken for granted for so many years. Shortages of rare earths would simply accelerate this transition.” However, it also seems possible that both technologies, HDD and SDD, will co-exist in the medium term. There are also hybrid drives commercially available which are a combination of a HDD and a SSD.

The partial substitution of dysprosium and terbium has already been discussed in chapter 10.2.4 (Substitution of dysprosium and terbium in permanent magnets). It is to be expected that the substitution of Dy and Tb is easier in these small-size applications than in permanent magnets for electric vehicles and generators, where operation temperatures are much higher.

The substitution of neodymium magnets by SmCo magnets is discussed in chapter 10.2.5 (Substitution of neodymium magnets by SmCo magnets). Due to constraints in price and availability, it will only be an option for a few sophisticated applications.

10.4 Batteries

Rare earths are used in Ni-MH batteries. Besides nickel and cobalt the MH-electrode contains a mix of different rare earth elements. The mixture varies between the manufacturers. Mostly, the main rare earths are lanthanum and cerium with additional input of neodymium and praseodymium (Luidold 2010).

Ni-MH-batteries are used in portable appliances (e.g. power tools) and hybrid vehicles (HEV) (e.g. Toyota Prius). Around 50% of the worldwide sales stem from use in HEV batteries.

The Ni-MH battery for hybrid vehicles is a mature technology and is used in the Toyota Prius with more than 2 million sales. However, there is little room for further improvements in energy power (limited energy and power density) and costs according to Bax & Willems (2010) which refer to a study conducted by the Rocky Mountain Institute. The future battery generations will be lithium-ion batteries. This trend is underlined by the fact that Toyota will start to equip the new Prius van with a lithium battery with a higher capacity in 2011. At the same time, the German government has set up a national development plan for e-mobility (Bundesregierung 2009). It also estimates that lithium-ion batteries have the highest potential for future energy storage systems. Additionally ZEBRA (high temperature) batteries, redox-flow and magnesium batteries and metal-air batteries might play an important role in the future. Thus, the broader use of Ni-MH batteries for hybrid vehicles is expected to phase out gradually. Pillot (2009) forecasts the market share of Li-ion batteries for HEV to rise to 35 % in 2020 (35 % in the base scenario and 60 % in the optimistic scenario). In 2009 the market share of Li-ion batteries for HEVs was approximately 2 %.

The trend for portable appliances is that Li-ion batteries gain increasing market shares. They have already largely substituted Ni-MH batteries in laptops and mobile phones and have relevant market shares in further applications such as cameras and power tools (ifeu / Öko-Institut 2010).

In summary, it is expected that the market share of Li-ion batteries will significantly increase in the years ahead. The use of Ni-MH batteries for HEV will phase out in the medium term. The same trend is to expect for most portable appliances. A shortage in rare earth supply might accelerate this development.

10.5 Lighting and luminescence

Phosphor materials emit light after absorption of energy. They are produced by dotting salt-like host lattices with metal ions in small concentrations. The colour of the light essentially depends on the properties of these metal ions, also called activators. As an example, in the following some metal ions and their corresponding colours are listed (Riedel et al. 2007):

Samarium (Sm^{3+}): red-violet

Europium (Eu^{3+}): red

Terbium (Tb^{3+}): green

Erbium (Er^{3+}): green

Thulium (Tm^{3+}): blue

Europium (Eu^{2+}): blue

Cerium (Ce^{3+}): green

Dysprosium (Dy^{3+}): yellow

White colour originates from the mixture of three colours. The temperature of the colour can be adjusted (warm or cold light), depending on the composition. As the spectra of the individual metals are limited, lamps with special requirements use up to eight phosphors, mainly lanthanides (Wickleder 2010).

Host lattices comprise compounds without rare earths such as $BaMgAl_{10}O_{17}$, $BaFCl$ or Zn_2SiO_4 as well as compounds containing rare earths such as Y_2O_3, La_2O_3 and $CeMgAl_{11}O_{19}$.

The following chapters describe the main areas of application: fluorescent lamps, plasma displays as well as electro-luminescence with a focus on LEDs (light-emitting diodes) and

LCDs (liquid crystal displays). Other fields of application with smaller quantitative relevance are laser and X-ray technology where REE are used, too (e.g. neodymium for lasers[16]).

10.5.1 Fluorescent lamps

Fluorescent lamps encompass the group of tube-like lamps (fluorescent tubes), compact fluorescent lamps (CFL), high intensity discharge (HID) lamps, and low-pressure sodium vapour lamps.

In the following the chemical composition of the most frequent luminescent materials (= phosphors) used in these lamps (Wojtalewicz-Kasprzak 2007) is provided:

Phosphors without rare earths:

Halophosphate: CaO, P_2O_5, MnO, Sb_2O_3, F, Cl (white, blue)

Phosphors with rare earths:

Yttrium europium oxide (YOE): **~ 95 % Y_2O_3 , ~ 5 % Eu_2O_3 (red)**

Barium magnesium aluminate (BAM): Al_2O_3, BaO, MgO, **~ 2 % Eu_2O_3 (blue)**

Cerium magnesium aluminate (CAT): Al_2O_3, **~ 11 % Ce_2O_3, ~ 8 % Tb_2O_3**, MgO **(green)**

Lanthanum phosphate (LAP): **~ 40 % La_2O_3, ~ 16 % Ce_2O_3, ~ 11 % Tb_2O_3**, P_2O_3 **(green)**

Inexpensive fluorescent lamps use halophosphate (light yield ~ 75 - 80 lm/W, low-quality colour reproduction), while high-quality fluorescent tubes use a three band phosphor containing REE (light yield ~ 100 lm/W, good colour reproduction); they contain 2 % halophosphate or three band phosphor, respectively, in terms of weight. In compact fluorescent lamps the three band phosphor constitutes about 0.3 % in terms of weight (Wojtalewicz-Kasprzak 2007). Guarde et al. (2010) reported on high rare earths contents in fluorescent powders from the recycling of used fluorescent lamps and tubes, particularly yttrium with up to 9 % and smaller amounts of europium (up to 0.6 %), lanthanum (up to 0.5 %), cerium (up to 0.4 %), gadolinium (up to 0.3 %) and terbium (up to 0.2 %).

The summary above shows that all three band phosphors use REE as activators. In many cases the host lattice is also dotted with REE like yttrium, cerium or lanthanum. According to USGS (2010b) yttrium cannot be substituted by other elements in the use as phosphor. Considering various phosphors Jüstel (2007) concludes that phosphors containing REE are superior to other phosphors. However, he mentions manganese (Mn^{2+}) as a possible alternative to terbium. Regarding phosphor technology shift, Lynas (2010a) mentions a potential decrease of Tb consumption amounting to 40 %. A Japanese research project which started in 2009 aims at finding a substitute for Tb and Eu by using a high-speed

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[16] Angerer et al 2009 estimate a very low demand of only 0.2 t Nd for use in laser crystals in 2030.

theoretical calculation method and combinatorial chemistry synthesis of materials (NEDO 2009). DOE (2010) states that there is no proven substitute for europium in fluorescent lamps and no proven substitute for europium as red phosphor in television screens.

Plasma displays make use of UV-rays and have a similar working principle as fluorescent lamps. Here, REE like europium, yttrium, terbium and gadolinium are used.

10.5.2 Electro-luminescence

Illuminants which are based on the phenomenon of electro-luminescence comprise LEDs (based on inorganic compounds), OLEDs (based on organic compounds) and EL-foils. LEDs or EL-foils are also used as backlight for LCDs.

In the medium term LEDs constitute a promising alternative to CFL. Their efficiency is already higher and a further drastic increase of their efficiency is expected. Wickleder (2010) states that various commercial LED-applications are already available. Nevertheless, to enable broader dissemination new phosphors capable of providing a better light quality need to be developed.

Currently, the REE gadolinium, cerium, terbium, europium, yttrium, lanthanum, samarium and lutetium are used in the host lattices and as activators.

Organic LEDs (OLEDs) are likely to be the next LED generation. Some commercial applications which also use REE like europium, terbium, samarium, lanthanum, gadolinium, lutetium, thulium and dysprosium are already on the market or are being developed (Huang 2010).

In future, LEDs might eliminate the need for lanthanum and terbium phosphors while continuing use of cerium and europium (DOE 2010). Future generations of OLEDs might even be free of all rare earths (DOE 2010).

10.6 Catalysts

Rare earths are used for industrial catalysts as well as for automotive catalysts. A very important example of rare earths used for industrial catalysts is FCC (fluid catalytic cracking) catalysts, which support refineries in the production of high quality products at high rates. Hykawy (2010) reports an estimate provided by G. Ragan from Albemarle, which assumes a global market of about 600 000 t for FCC catalysts with a rare earth content of approx. 2%, mostly lanthanum. This means an annual lanthanum demand of approx. 12 000 t for FCC catalysts. According to Hykawy (2010), P.Chang from BASF pointed out that lanthanum is crucial for FCC catalysts because it provides thermal stability and selectivity. Currently no substitutes for lanthanum in FCC catalysts are known, but experts state that there is an additional impetus for reduction or substitution due to the increasing prices of REE like lanthanum.

In automotive catalysts REEs (mostly cerium) are also responsible for enhanced thermal stability and emission reduction (Hykawy 2010). Currently no substitution materials are known for the REEs used for automotive catalysts.

Conclusion on substitution and efficient use of rare earths

The analysis of substitutions for scarce REE has shown that a simple substitution of a REE compound by another compound is a quite rare case. In most cases substitution requires totally new product design. The identified options for substitution for the major green applications are summarised below:

- *Rare earths are currently used in around 14 % of newly installed **wind turbines** with gear-less design and technical advantages in terms of reliability. A supply shortage of rare earths would lead to a shift to alternative turbine types. Further research into the higher reliability of traditional techniques with gears would support this substitution.*
- *Rare earths are used in permanent motors of **hybrid electric vehicles and electric vehicles**. Substitutions based on alternative motor designs are available. However, R&D is required to enable higher performance of existing electric motor types and to realise new electric motor concepts.*
- *Most new **energy efficient lighting systems** contain rare earths (compact fluorescent lamp, LED, plasma display, LCD display). Substitutions are rare, particularly in the case of compact fluorescent lamps. R&D is required for alternative phosphors with a high efficiency and high light quality.*
- *Automotive **catalysts** contain cerium, and catalysts for petroleum refining and other industrial processes contain lanthanum. Substitutions are rare, and R&D is urgently required for alternative catalysts.*

*Concerning a higher efficiency of the rare earth, **R&D** is urgently needed in all fields of application and is also needed to enable higher efficiencies in mining, beneficiation and processing. One example of high losses in the production chain is the traditional magnet production.*

*The use of **nanotechnology** in some green applications is being considered in order to increase the efficiency by nano-sized rare earth compounds. An attendant risk assessment is highly recommended.*

11 Recycling of rare earths – current situation

The recycling of rare earths could be stated as a very uncommon issue until today. A recent analysis of Öko-Institut conducted for UNEP on critical metals provided information on very small quantities of recycled rare earths with pre-consumer origins (permanent magnet scrap), but no indications of any post-consumer recycling of rare earth containing products could be found (Öko-Institut 2009). The reasons for this were quite dissipative applications, quite low prices of rare earths and a tendency of REE to move in the slags of smelter plants. Nevertheless the sharp increase of the rare earth prices in 2010 and the high media coverage of possible supply shortages and export restrictions by China have put the issue of recycling rare earths on the agenda worldwide. The following sub-chapters summarise the results of the intensive new analysis conducted by Öko-Institut in late 2010.

11.1 Recycling of rare earths from magnets

Research activities are being conducted on pre-consumer and post-consumer recycling in China and other countries. An important focus is the recycling of magnet scrap which arises in large amounts not only after consumption but already during the production.

- It is estimated that 20-30 % of the rare earth magnets are scrapped during manufacturing (Zhong et al. 2007). However, the recovery of the rare earths from production waste is not yet practiced (Shirayama Okabe 2009). Possible technologies are as follows (Oakdene Hollins 2010):
    - Re-melting the scrap and recover in an un-oxidised state. According to Oakdene Hollins (2010) the yields are expected to be low.
    - The recovery of the rare earth as oxide. However, the value of the oxidized rare earth is much lower than the value of the metallic rare earths, as the oxides have to undergo the energy-intensive reduction and refining process again.
    - Re-use of the magnetic materials for new magnets without a separation of the material mix.
    - Selective extraction of Nd and Dy directly from magnet scrap by using molten magnesium chloride as the selective extracting agent. Laboratory tests were carried out in Japan with temperatures of around 1.000 °C (Shirayama Okabe 2009).
- There are various studies in China on the recovery of rare earth metals from neodymium magnet scrap and waste. Wang et al. (2006) reported that Dy_2O_3 could be recovered to an extent of over 99 %. Furthermore, Tang et al. (2009) compared two methods employing Na_2SO_4 double-salt precipitation and oxalate secondary precipitation which achieve a recovery rate of Nd_2O_3 of more than 82 %. Zhang et al

(2010) researched a separation method based on the electrical reduction by using P507 extraction and comparing this with the traditional separation methods in terms of material consumption and costs. Test results showed that this newly electrical reduction technology may result in a recovery rate of 96.1 % of rare earth from neodymium magnet scraps und save 6 033 RMB (about 650 Euro) per ton of rare earth recycled.

- Shi (2008) invented a process for the recovery of neodymium from acid cleaning waste water which arises before NdFeB is electrically plated.
- Zakotnik et al (2009) recycled neodymium magnets from disk drives successfully by milling and re-sintering with the addition of 1 % new neodymium in a technical scale. Kawasaki et al (2003) developed a similar recycling process for sintered neodymium magnets by adding Nd-rich alloy powders to the ground magnet scrap powder before re-sintering.
- Current research is ongoing in Japan into the post-consumer recycling of rare earths from motors/generators (permanent magnets). Pyro-metallurgical and hydrometallurgical approaches are described which focus on the recovery of REE as metals. (Takeda 2009, Koyama 2009).
- Hitachi announced that it has developed a machine for the dismantling of neodymium magnets from hard disks and compressors (Clenfield Shiraki 2010). The machine has a capacity of 100 magnets per hour, about eight times faster than manual labour. The developed dismantling process shall commence operation in 2013.

11.2 Recycling of rare earths from batteries

- The Japanese JOGMEC's Metals Mining Technology Group has been creating technology to recover rare earths metals such as lanthanum and cerium from used Ni-MH batteries used for HEVs, and to refine the recovered metals for re-use in new batteries. The electrodes are first treated with a multi-element refinery process, then the separated reduction of the rare earths takes place (JOGMEC 2010). There are no references to the implementation of a plant of industrial size.
- The recovery of REE from Ni-MH batteries is examined by Luidold (2010). Despite other attempts to extract the REE out of slags from smelting operations by means of hydrometallurgical methods, this approach is aimed at the previous separation of the REE from the other materials.
- Researchers from Freiberg/Germany developed a hydrometallurgical process to recover rare earth metal from the slag of the pyro-metallurgical treatment of used Ni-MH batteries (Heegn 2009).
- The Chinese researchers Wu & Zhang (2010) studied the recovery of Ni, Co and rare earth (lanthanum, cerium, neodymium and praseodymium) from used Ni-MH batteries

by leaching with sulphuric acid. The tests showed recovery rates of 95 %. Gao (2009) also investigated the recovery of rare earth from spent Ni-MH batteries.

11.3 Recycling of rare earths from lighting and luminescence

There are some research activities and new patents in the field of post-consumer recycling. They are listed below:

- OSRAM holds a patent on the recycling of yttrium and europium from discharge lamps and fluorescent lamps (OSRAM 2009, Wojtalewicz-Kasprzak 2007).
- Guarde et al (2010) report on the recycling of fluorescent lamps and tubes and the output of a distilled powder fraction which contains up to 10 % rare earths. Currently this fraction is disposed (compare with more detailed figures in Chapter 10.5.1).
- Further research activities are being undertaken which focus on yttrium and europium recovery not only from lamps but also from TV tubes and computer monitors (Rabah 2008, Resende Morais 2010).
- A scientific overview of conceivable recovery methods for the recycling of rare earths fluorescent powder containing yttrium, europium, lanthanum and cerium is provided by the Chinese publication Mei et al (2007).

11.4 Recycling of rare earths from catalysts

The recycling of REE from spent catalysts (industrial as well as automotive catalysts) is not common due to relative low prices of REE in the past. A German source from 2001 reported that the 9 100 t (1998) of spent FCC catalysts from catalytic cracking processes in German oil refineries was completely used as cement additives (Hassan 2001), which means a recovery of the REE from the spent FCC catalysts was not an issue. It is an open question whether a recovery of the REE (mostly lanthanum) from FCC catalysts could be interesting from an economic point of view in the next years. This will mainly depend on the price development of lanthanum. From a technical point of view the large global mass flow of FCC catalysts – 600 000 t per year (Hykawy 2010) – with about 2 % REE content means an interesting REE potential for recycling from this specific application. It should be mentioned that Öko-Institut and Umicore (GFMS 2005), after in-depth investigations regarding the recycling flows of platinum group metals, came to the clear conclusion that the usual business-to-business relationships (e.g. between the catalysts suppliers and the oil refineries) are a very good pre-condition for very high recovery rates of the platinum group metals (almost 100 % collection rate of the spent catalysts). Nevertheless the development of a technically feasible and economically acceptable solution for the recycling of REE from FCC catalysts is a task for the future.

The recycling activities of the automotive catalysts focus worldwide on the recovery of the valuable platinum group metals (GFMS 2005). Therefore the recovery of the REE content (mainly cerium) from these catalysts has not yet become a focus. Currently the REE moves into the slags from smelter processes due to the high affinity of the REE to oxygen. It remains an open question whether a recovery of REE from spent automotive catalysts could feature in the future.

11.5 Recycling of rare earths from other applications

Further studies deal with highly specific recycling processes from cleaning water, ferrosilicon and waste from the aluminium production. They are briefly described below:

- Wang et al. (2005) conducted an investigation on recovering the rare earth metals from solid waste generated from aluminium production called red mud. The study firstly reviews the existing recovery methods of rare earth metals from red mud in China and abroad and secondly introduces the methods in Shanxi Aluminium Limited Company at the laboratory stage. There, red mud was roasted and rare earth metals were leached by HCl; finally scandium and other rare earth oxides were separated from liquid.
- Ferrosilicon which contains rare earths is used as a pre-alloy in the production of ductile graphite iron. Chen (2007) analysed the technological conditions of smelting rare-earth ferrosilicon by means of two thermal methods.
- The Japanese company Kosaka Smelting and Refining tries to develop ways to reclaim rare earths like neodymium and dysprosium from electronic scrap (Tabuchi 2010).

11.6 Challenges for an efficient rare earths recycling

The analysis shows that recycling plants and technologies are quite rare. The publications of the US Geological Survey from 2010 only mention rare earth recycling for small amounts of magnetic scrap (USGS 2010a) containing Nd, Pr and Dy and small amounts of yttrium from laser and garnet applications. Furthermore, there is no current industrial recycling process for the recovery of rare earths from Ni-MH batteries containing La, Ce, Nd and Pr (Oakdene Hollins 2010, Luidold 2010, Tabuchi 2010).

Oakdene Hollins (2010) provides an overview of the recycling activities of rare earth. Their conclusion is that a significant amount of research into the recycling of rare earth metals has been undertaken, most notably in Japan. The result of the research activities is that there are potentially a number of extraction processes but none of them has been developed commercially due to drawbacks on yields and cost. The evaluation provided by Oakdene Hollins (2010) is that the most attractive method is the treatment with liquid metals. They further state that most of the patents are from the early 1990s and that little progress was made in the following 15 years. Therefore they see a potential for further new developments.

Research conducted by Öko-Institut affirms the fact that few industrial recycling activities are being implemented. The latest publications show the following industrial recycling schemes:

- Sludge from shaping and grinding of magnet alloys is recovered (Shirayama Okabe 2009), probably in Japan.
- Recycling of yttrium is realised for small quantities, primarily from laser crystals and synthetic garnets (USGS 2010b).
- Magnets from MRI (magnetic resonance imaging for medical application) are being re-used (Shirayama Okabe 2009).

Principally, the recycling processes for the rare earths are quite complex and extensive if re-use is not possible and a physical and chemical treatment is necessary. Most of the recycling procedures are energy-intensive processes. The main post-consumer activities – the recycling of rare earth from motors and hard disks and other electronic components – will require intensive dismantling.

A large challenge for a closed-loop economy in the field of the rare earths is the recycling of the rare earths magnets, as it is the most important application with expected shortages in the rare earth supply. The following constraints have to be overcome:

- The transport of magnetic materials is restricted as their field can interfere with aircraft instruments. This requires demagnetisation before air transportation, other transport modes or regional recycling activities (Oakdene Hollins 2010).
- Most of the rare earth magnets are used in motors and HDD (hard disk drive). Here, the recycling requires a costly and extensive dismantling, as the magnet is quite small. Further, it has to be demagnetised before separation from the iron parts is possible. Additional work has to be conducted if the magnet is embedded in plastics.
- Electronic scrap is often recycled in classic pyro-metallurgical plants. Many metals can be recovered, but the rare earths are lost as they become a part of the slag which is currently not recovered.

General constraints for wider recycling of rare earths in most application fields are:

- The implementation of an efficient collection system has to be built up.
- Post-consumer goods such as end-of-life vehicles or electronic scrap are partly exported in developing countries. These exported goods will not be easily available for an efficient urban mining.
- Up to now, the prices for rare earths have been too low for the running of an economical recycling process, particularly when considering the complex dismantling and treatment processes and the quite high energy demand. Even increasing prices due to the current Chinese export restriction do not guarantee a long-term stability of

adequate prices for rare earths, which is a pre-condition for economic recycling processes.

- It will take a long time span for many of the devices containing rare earths to reach the end of their life time. In particular electric motors in vehicles and wind turbines should have life times of 10 – 20 years.

Conclusion on current situation of rare earth recycling

Only a few industrial recycling activities are currently implemented for rare earths. Up to now, there has been no large-scale recycling of rare earths from magnets, batteries, lighting and catalysts. In principle, the recycling processes for the rare earths are quite complex and extensive if re-use is not possible and a physical and chemical treatment is necessary. The main post-consumer activities – the recycling of rare earths from motors and hard disks and other electronic components – will require intensive dismantling.

Several constraints for a wider recycling of rare earths were identified: the need for an efficient collection system, the need for adequate high prices for primary and secondary rare earth compounds, losses of post-consumer goods by exports in developing countries and the long life time of products such vehicles and wind turbines of 10 – 20 years before they enter the recycling economy.

At the same time, the potential supply shortages and the steep increase in prices of rare earths are providing for the first time the opportunity to address the problem of today's rare earth supply in more depth and to seriously build up a recycling economy. The advantages of rare earth recycling include the utilisation of European resources, independence from foreign resources and environmental benefits. A corresponding strategy for developing such a European recycling scheme is provided in the next chapter.

12 Strategy for a sustainable rare earth economy

12.1 Background

In recent years tremendous changes have occurred in the global application of rare earths. Technological innovations and the research on rare earths resulted in manifold applications leading to a steep increase in the demand. A relevant share of the increasing demand is caused by so called “green technologies” which are designed to contribute to environmental protection by means of a reduction of the energy consumption, the further development of renewable energy carriers or air pollution control. There is serious concern that the demand of several different rare earth elements such as neodymium, praseodymium, dysprosium, terbium, lanthanum, yttrium and europium might exceed the current supply within a few years. Even if China imposes no export restrictions it is to be expected that the increasing demand can only be met if further mines are opened in addition to the two mines in Australia and USA which have already obtained approval from the national authorities and begun construction works so that large-scale operation can commence around 2012.

The high demand and the expected supply shortages, additionally triggered by Chinese export restrictions, lead to a significant increase in rare earth prices. This steep increase is not only a burden for manufacturers and consumers. It provides an opportunity to address the problem of today’s rare earth supply in more depth and to develop a sustainable rare earth economy in all relevant sectors. The low prices in the past have led to a significant waste of resources. To date there has been almost no recycling of rare earths. The new prices might be a starting point for setting up recycling systems for rare earths.

Similarly, science and industry are beginning research and development into options for the substitution of rare earths. The Chinese export restrictions revealed the high vulnerability of the EU and other developed countries. Alternative technologies with less or without application of rare earths attract more attention. Research projects started which aim to develop green technologies and other applications which require no or less rare earths.

The high public interest in this issue has further revealed the high environmental burden in the surroundings of the Chinese mines and processing plants. If the EU demands rare earth technology for their green technology, it is up to the EU to contribute to a “greener” rare earth supply. The contradiction between the “green” application of rare earth and their high environmental pressures in production calls for action to be taken particularly by Europe, America and Japan where – besides China – the majority of the rare earths are consumed.

Action in the field of recycling should begin now without further delay as it will take a minimum of five to ten years for the first large-size implementation to take place.

The recycling of rare earths has several advantages compared to the use of primary resources:

- Europe is one of the largest consumers of rare earths worldwide. Increasing amounts of waste from final products containing rare earths arise in Europe. These valuable resources should be returned to the industrial metabolism by “urban mining”.
- Dependence on foreign resources will be reduced by supplying the European market with secondary rare earth materials.
- Apart from a few specialised industries and applications, the know-how in rare earth processing is quite low in Europe because most of the European rare earth handling involves the subsequent processing of refined material. The upstream processes are mainly being carried out in China and to some degree in Japan. The building-up of know-how in recycling will widen the competency of enterprises and scientific institutions in Europe.
- The processing of secondary rare earths will be free from radioactive impurities. The mining and further processing of primary rare earths is associated with nuclear radiation coming from radioactive elements of the natural deposits in most cases. Therefore, primary rare earth processing generally produces radioactive waste.
- The recycling requires some energy carriers and chemicals. At the same time it saves significant amounts of energy, chemicals and emissions in the primary processing chain. The accurate net benefit for recycling is process-specific and can be identified by a life cycle assessment. It is to be expected that most recycling processes will have a high net-benefit concerning air emissions, groundwater protection, acidification, eutrophication and climate protection.

The next chapters will firstly address strategies for action within the European Union in order to promote a sustainable rare earth management. Related issues are the developing of recycling schemes and actions required for improvements concerning a more efficient use of rare earths and improvements of alternative applications which work without the use of rare earths. Secondly, aspects related to foreign affairs and the potential contribution of the European Union to an environmentally sound mining will be addressed.

12.2 Development of recycling schemes

Öko-Institut suggests taking action in the short term in order to establish a European recycling scheme for rare earths. The development and implementation might take some years. When a relevant amount of products containing rare earths which now enter the market reach the end of their life cycle and are available for recycling such an collection and recycling scheme should be implemented.

The next figure provides an overview of main steps toward a European recycling scheme as suggested by Öko-Institut.

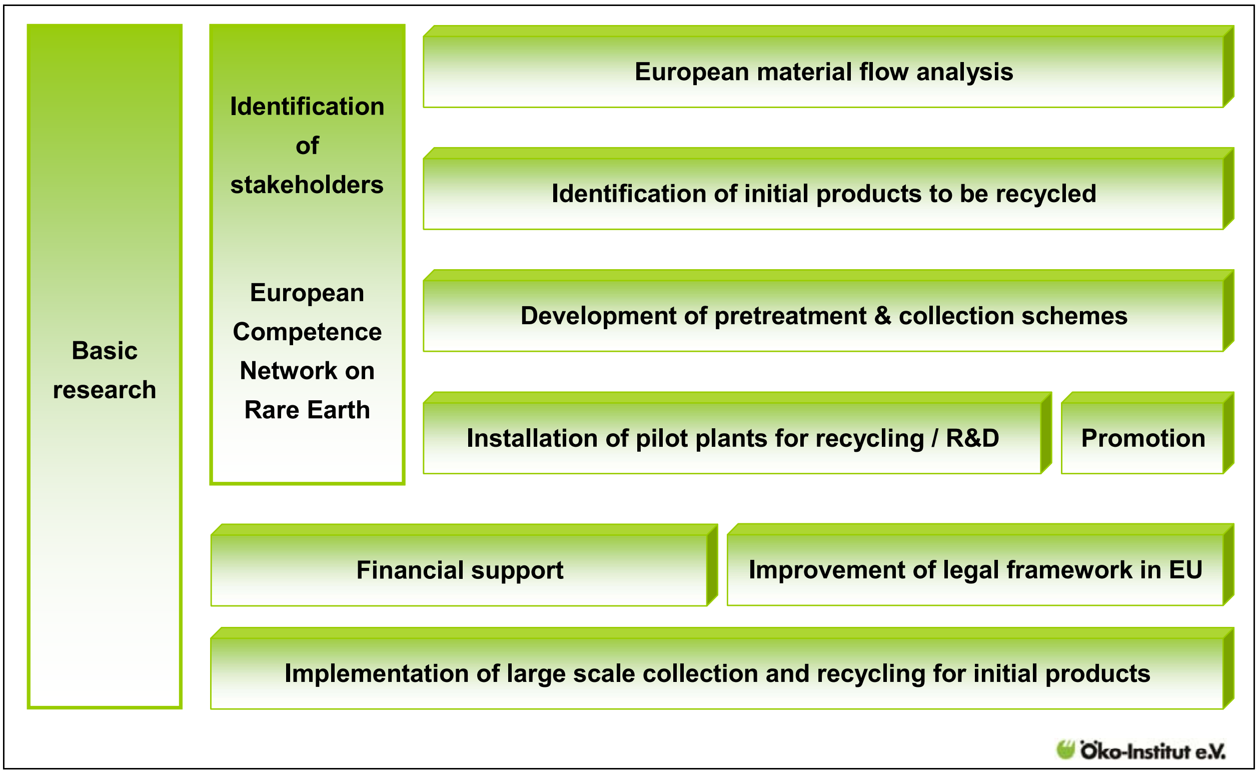

Figure 23 Steps towards a European rare earth recycling scheme

The different steps are described in more detail in the following.

12.2.1 European competence network on rare earth

A European network which comprises all relevant stakeholders on all levels is seen by Öko-Institut as indispensable for the development of a recycling scheme for rare earths. Relevant stakeholders are recycling companies, manufacturers of finished goods, producers of semi-finished goods, research institutions, public authorities and politicians. Similar national networks already exist. One example is the Dutch Materials Innovation Institute M2i which is a public-private partnership between industry, knowledge institutes and the government of the Netherlands (M2i 2009).

Öko-Institut therefore proposes that a European Round Table should be set up, which brings together all relevant stakeholders from science, circular economy and companies contributing to the value-added chain of products containing rare earths. The spectrum comprises a lot of different sectors such as rare earth refining, the production of industrial products (e.g. catalysts or polishing powder), the production of specialty products (e.g. optical high-tech devices) and the production of largely disseminated consumer products (e.g. compact fluorescent lamps).

12.2.2 Basic research on rare earth processing

Due to the fact that there is no rare earth mining in Europe and only a very few companies are involved in rare earth refining, there is a need for enhanced basic research in Europe on rare earth processing. This knowledge might be necessary in order to build up a large-scale urban mining on rare earths and to establish more independence from the process knowledge which is currently mainly available in China and Japan. The United States is currently planning to develop a knowledge base in order to be able to process the rare earths to be mined from the re-opened mine (Mountain Pass) from 2012 onwards. The current situation in magnet production is representative for other sectors. The large scale of China's know-how and capacity in all stages of production is clearly shown by Figure 10 on page 33.

The first step to building up more know-how on rare earths in Europe would be the detailed identification of gaps of knowledge and competences in Europe related to rare earth processing. As a further step Öko-Institut proposes the creation of chemical chairs which carry out basic research on rare earths and their sustainable management.

12.2.3 European material flow analysis

The key aim of a European material flow analysis is to close significant data gaps and to gain broader knowledge on the material flows in Europe related to rare earths. The analyses in the previous chapters have shown that little data is available on the manifold and mostly young applications using rare earths. The global demand and supply forecasts of national research institutions such as the American USGS, the British BGS and the German BGR have to rely on the knowledge and estimates of a few experts mainly outside of Europe. The data situation of the rare earth flows should be improved within Europe and globally in the near future. This is a critical point for a sustainable economy of rare earths as more in-depth knowledge is indispensable to facilitating a successful course of action in terms of recycling and a more efficient use of rare earths.

The first step to enabling a European material flow analysis is to identify the main manufacturers and actors in the added-value chain related to rare earths. This step is linked with the build-up of a European Competence Network. The next task should be to identify the main material flows and to estimate the amount of rare earths which will be embedded in specific waste streams and available for recycling. Close co-operation with the European rare earth processing industry is regarded by Öko-Institut as essential to obtaining robust results.

12.2.4 Identification of initial products

Building up the recycling scheme step by step and beginning with a couple of initial products suited to recycling is highly recommended. These products should encompass, for example, a large amount of rare earths, high economic relevance, a design allowing an easy dismantling or a high concentration of the rare earth in the waste stream. The material flow analysis will provide a more detailed picture of the rare earth material flows in products and waste streams.

Based on current knowledge, potential initial waste streams could arise on the pre-consumer level (waste arising during manufacturing) from the magnet production, the lighting industry, the upstream rare earth processing industry, the industry using polishing powder and the production of IT-devices and electronics.

In quantitative terms, the post-consumer waste will be much more relevant. The following products might prove to be appropriate initial products for a new recycling scheme when the end of their life cycle is reached: magnets from electric motors and generators (arising in wind power plants, hybrid and electric vehicles, hard disks and e-bikes), lamps (fluorescent lamps), displays (plasma display and LCD) and possibly automotive catalysts. Spent industrial catalysts are also a promising candidate.

12.2.5 Development of collection and pre-treatment schemes

Based on knowledge gathered from the material flow analysis and the selection of initial products, the next step will be to design a collection and pre-treatment scheme.

The treatment of many wastes which contain rare earths is already regulated by existing guidelines, e.g. the WEEE Directive, the ELV Directive or the Battery Directive. However, there are not yet specific regulations for rare earths. The specific requirements for collection schemes for waste containing rare earths have to be integrated in procedures already implemented. Another aspect is the consideration of required pre-treatments. For example, magnets have to be demagnetised before transportation, or batteries have to be discharged due to safety issues.

12.2.6 Development of pilot plants

The next step is to design pilot plants needed to learn more about the complex recycling processes. This step also comprises research activities on the specific recycling procedures. In most cases, it will be necessary to set up large-scale R&D projects as rare earth recycling often requires high-technology based on complex chemical processes and sophisticated equipments. Some ongoing or past R&D projects are described in Chapter 11. The overview shows the high complexity of most of the project tasks.

12.2.7 Financial issues

The investment in recycling plants bears a high risk for investors, as outlined below:

- Most of the recycling plants will require a high long-term investment due to the required complex technologies.
- There is a large number of mining projects with uncertainty about their realisation (see the overview provided in Table 4-3 on page 22). If a high number of projects were

realised, it could not be excluded that REE prices will decrease again in the medium to long term, thus depriving recycling of its economic basis.

- Generally, there is high uncertainty about the future price developments. Reliable data on the demand and the supply situation are scarce, the rare earth stocks of companies and nations are unknown and speculations on rare earths prices might cause turbulences on the trade markets.

Therefore, it should be analysed whether the European Investment Bank (EIB) could reduce financial risks for investments in recycling.

An example of financial instruments outside of Europe are programmes from the US Department of Energy which support the production of clean energy components and new vehicle technologies by providing loan guarantees, loans or tax credits (DOE 2010). The Japanese administrative institution JOGMEC promotes a stable supply of metal resources, providing funding for research and field survey, loan guarantees and financial assistance to mining projects, maintaining stockpiles and disseminating information on mineral availability issues (DOE 2010).

12.2.8 Legal framework

A recycling scheme of rare earths not only requires appropriate logistical and technical requirements but also an appropriate legal framework.

The first task of this step will be a screening in order to identify the sectors where the collection and treatment is already regulated and sectors where no regulation takes place, e.g. wind turbines.

The next step will be to adapt the legal EU framework in order to optimise post-consumer rare earth recycling. In this context, specific issues might be addressed, e.g. the obligation to conduct magnet recycling from dismantled wind power plants or the prevention of exports of valuable electronic scrap and catalysts to developing countries where no recycling of speciality metals takes place (compare Öko-Institut & Eurometaux 2010). Öko-Institut further proposes verification of whether the Ecodesign Directive (2009) and related regulations should be adapted in order to support the dismantling and recycling of rare earth components from energy-using products. Another issue which should be discussed for rare earth components in electronic devices and automotive applications are the overall recycling quotas which are required by the WEEE Directive, the ELV Directive and the Battery Directive. These compulsory quotas do not consider the ecological relevance of the recycled substances. Hence, the WEEE Directive and ELV Directive mainly support the recycling of the basic materials but not the recycling of scarce and precious metals which have a high ecological relevance but only contribute a low share in terms of volume. The rare earth recycling should be addressed by specific requirements, e.g. the obligation for dismantling of selected rare earth containing components.

Concerning the ELV Directive, Öko-Institut proposes the introduction of the obligation to dismantle the electric motors of hybrid electric and electric vehicles prior to the shredder. A more in-depth analysis (material flow analysis) should verify whether an obligatory dismantling of further smaller components would be justified.

12.2.9 Large scale implementation

The last step is the large scale implementation of the developed recycling schemes for the selected initial products. This step not only comprises the beginning of the rare-earth specific collection, pre-treatment, and recycling (refining plants in industrial scale) but also the monitoring of the performance, its optimisation and the outlook for widening the existing recycling scheme. To enable broader dissemination, the export of recycling technologies and the development of a wider product range might be considered.

Conclusion on the development of a recycling scheme

Öko-Institut proposes the development of a recycling scheme based on the following steps prior to a large scale implementation:

- *A* ***European Competence Network on Rare Earths*** *with all relevant stakeholders such as recyclers, manufacturers, public authorities, politicians and researchers is seen as essential to successful implementation.*
- ***Basic research*** *is necessary, as only a few companies in Europe are involved in rare earth refining and processing at the beginning of the added-value chain.*
- *A* ***European material flow analysis*** *(MFA) is necessary in order to identify the main material flows and waste streams and the main manufacturers and actors in the added-value chain. Currently, national research institutions have to rely on knowledge and estimates from a few experts outside of Europe.*
- *The next step is to* ***identify initial waste streams*** *on the pre-consumer and post-consumer level, e.g. waste from the magnet and lighting industry, neodymium magnets from electric motors, used lamps and displays, re-use of large magnets and recycling of spent catalysts.*
- *The collection and treatment of many relevant wastes is already regulated by the WEEE Directive, the ELV Directive and the Battery Directive. Thus, the* ***collection*** *of rare earths containing wastes has to be specified and integrated in existing collection schemes.*
- *Large-scale R&D projects can develop* ***pilot plants*** *in order to learn about the complex chemical processes and the required sophisticated equipment.*
- *Recycling plants bear* ***high financial risks*** *due to the required high investment and the high uncertainty of the future price developments of rare earths. Therefore, it should be analysed whether the European Investment Bank (EIB) could reduce financial risks for investments in recycling.*
- *A recycling scheme of rare earths not only requires appropriate logistic and technical requirements but also an appropriate* ***legal framework****. Hence, an important step will be to adapt the legal EU framework in order to optimise post-consumer rare earth recycling.*

12.3 Strategy for enabling a more efficient use of rare earth and substitution

The sectoral analysis as presented in the previous chapters has shown that the potential for an increase in the resource efficiency in the processing and the use of rare earth is quite different. It is likely that the knowledge and research on efficiency issues is not the same for all applications.

Most available information relates to magnet production and magnetic applications. The analysis showed that the traditional production technologies usually have high material losses whereas newer sinter technologies have much better material efficiencies. The high prices and the expected shortages of the minor elements dysprosium and terbium lead to some research activities aimed at achieving a similar performance with less specific input of these very scarce elements. This example shows that the research into efficiency issues in this context is in early stages. This is not surprising as the applications themselves are mostly very young. In the past, the major aim has been to develop workable applications. Now, the next phase, which focuses on improvements and high efficiency rates, is beginning.

The expected supply shortages even lead to serious considerations of how scarce rare earths can be substituted. According to the in-depth analysis presented in Chapter 10, alternatives seem to be feasible in some applications, whereas other sectors do not offer quick solutions. In most cases, rare earths cannot just be substituted by another element or another compound. Instead, the whole technical design of machines and applications has to be changed. For example, the alternative to an electric motor containing a neodymium magnet is an electric motor with a different mode of operation and a distinct design, which has specific advantages as well as disadvantages.

The screening of the different applications (see Chapter 10) showed that further R&D is necessary to develop feasible technologies for rare earth substitution in the field of green technology and to achieve higher material efficiencies.

The available information was the best for neodymium magnet applications such as wind turbines, electric vehicles, and hybrid vehicles and the Ni-MH batteries. The analysis showed that in principle alternatives are available. Nevertheless, intensive research is necessary to develop these alternative products in terms of high efficiencies, economic competitiveness and reliability. Examples are alternative electric motor types, operating either with traditional techniques which should be further improved or younger motor designs which need further research to reach the technical maturity for wider use. Another example is wind power. Here, gearless wind turbines using neodymium magnets still provide the smaller share of new installations. But a higher reliability is expected in large-size plants, particularly in off-shore plants. The main conclusion on these competing technologies is not to focus exclusively on the rare earth technologies but to work simultaneously on increasing the reliability of the traditional systems with gears and on improving the research of next generation technologies like high-temperature superconductors (HTS).

The analysis of the green technologies such as energy efficient lighting and catalysts showed in the first place that no fast solutions seem to be feasible without the use of rare earths. There are almost no options for alternative techniques which operate without rare earths and have an equal performance and economical competitiveness. Intensive research in these fields is highly recommended.

Another aspect to be considered in the improvement of efficiency is the future role of nanotechnology. The application of nano-sized rare earth compounds are being considered in green technologies such as magnets, batteries, fuel cells, H_2-storage and catalysts. The principal aims, the improvement of energy efficiency or material efficiency, is desirable. In order to avoid negative secondary effects, Öko-Institut proposes the carrying out of a corresponding risk assessment.

12.4 International aspects

Besides activities within the EU which aim to promote the recycling and the efficient processing of rare earths and to improve research on alternatives for substitution, the EU faces a tremendous task in terms of action on the international level. Even if the recycling of rare earths (for example) succeeds in the medium term in the EU (this would be a real success and progress), the global demand for primary rare earths will increase up to 2020 and beyond, driven by many applications in the field of green technologies.

The development of a sustainable rare earth supply for Europe concerning environmental, social and security aspects requires solid international co-operation. Important partners for the EU to face this challenge are predominantly China, and Japan and the United States.

In the next sub-chapters, selected potential international activities of the EU proposed by Öko-Institut are presented.

12.4.1 Co-operation with China on sustainable rare earth mining

Despite different new mining projects in other countries like USA, Australia etc., China will remain the world’s largest producer of primary rare earths for the next decade at least. China’s authorities are well aware that China is facing many challenges with regard to its rare earth mining and processing industry, which require a lot of investments, human resources and capacity building. Having examined the official Chinese government plans for the rare earth industry for the next years, this conclusion is well-founded and clear. Europe has a well-regarded knowledge and technology base and much experience in the field of environmental protection (e.g. decontamination of soils, landfills, mining areas, groundwater protection etc.) which should be offered to China to enable a fruitful and fair co-operation between the EU and PR China in the field of rare earths. The idea is to offer China a partnership: an exemplary re-cultivation of a large rare earth mining site in China on the one hand and an export of a certain amount rare earth compounds extracted and processed from this mining site to the EU on the other hand.

Such an EU-Chinese partnership on rare earth mining could include the following aspects:

- Signing of an official large framework agreement between the EC and the Chinese government,
- Installation of a common expert round table to define and select the first common project in practice: selection of an appropriate rare earth mining and processing site,
- Line-up and schedule for common activities, e.g. the enhancement of recovery rates for rare earths (mining and processing), reduction of environmental pressures from former mining activities (remediation of contaminated sites); assessment whether a second treatment of tailings (extraction of remained rare earths in the tailings) could be promising, reduction of environmental pressures of the current and future mining, concentration and processing activities, etc.,
- Definition of the practical steps in detail: negotiations about the contribution of European experts, institutions and companies,
- Agreement about the co-funding of investments by the EC,
- Agreement about the amount of rare earth exports to the EU,
- Outlook for further EU-Chinese projects within the partnership on rare earths.

The basic idea is to support China, which has supplied the world economy with rare earths for many years, to improve its rare earth industry in facing the challenges of the years ahead relating to the development of a sustainable rare earth economy.

12.4.2 Promotion of environmentally-friendly mining

The analysis of the environmental impacts from rare earths mining and processing as presented in Chapter 7 shows the high environmental burdens of mines which are not equipped with adequate environmental techniques. The high pressure on the opening of new mines by the steeply increasing demand raises the concern that new mines outside of China could be opened which do not keep minimum standards.

At the same time, the comparably young sector of rare earth mining and processing provides an opportunity to build up the new mining activities based on the experience of decades of mining of other metals. In these decades, environmental technologies have been developed after experiencing environmental hazards and health impacts. Today, these environmental technologies are available and should be strongly applied. An additional opportunity is provided by the fact that all future mines need completely new approvals; there is no reason for weakening environmental standards as is often practiced for existing installations.

As Europe uses a high share of rare earth in green technologies, it should consistently promote and support environmentally-friendly mining by means of its political instruments and its diplomacy. Chapter 4.3 provides some figures on the economical contribution of the mining to the added-value chain. It shows that the financial contribution from mining and beneficiation is smaller than the contribution from further processing. This implies that higher costs of an environmentally sound mining will not lead to significant price increases of rare earth compounds. This implies that higher costs of an environmentally sound mining will not lead to relevant price increases of rare earth compounds. When considering further that rare earths are usually found in very low concentration in final products, the consumer prices will probably not be seriously affected by higher costs resulting from environmentally sound mining.

During the last decade, manifold initiatives aiming at a sustainable mining have been developed. In the political arena and in industry there has also been increasing interest in the certification of sustainable raw materials (Manhart 2010). It should be discussed how rare earth mining can be integrated in existing schemes or whether an additional initiative specifically promoting “green and social rare earth mining” might be helpful. In order to give a picture of the wide range of approaches, selected initiatives on sustainable mining are summarised below (BGR 2007):

- The German Federal Institute for Geosciences and Natural Resources (BGR) developed in cooperation with authorities in Rwanda and Democratic Republic of Congo pilot projects on certified trading chains on tin, tantalum, tungsten, gold and coltan (BGR 2010b).
- The German Federal Institute for Geosciences and Natural Resources (BGR) developed an analytical fingerprint (AFP) which is able to determine the origin of a specific ore. The basic principle is that each deposit holds a specific “fingerprint” which can be detected in the laboratory not only for concentrates but also for refined products. BGR developed the AFP for tantalum (coltan) concentrates (BGR 2010b). There are further AFP activities for gold, platinum group metals, copper and cobalt (BGR 2007, BGR 2010b, Perelygin et al 2008).
- The Kimberley process – a co-operation of 71 nations – resulted in a certification system for diamonds and the implementation of a related EU directive. The major aim is to ban imports of diamonds whose revenues are used to finance civil wars.
- The International Council on Mining and Metals (ICMM) established in 2001 comprises 18 mining and metal companies as well as 30 mining associations and global commodity associations. Its aim is the sustainable development in the mining sector.
- The International Cyanide Management Code (ICMI) is an initiative for the certification of the gold mining industry with the aim of an environmentally sound handling of cyanide. It holds 28 members which covered around a third of the industrial gold production in 2006.

- The Green Lead project with co-operation from UNEP, national authorities and mining industries aims at the certification of lead-acid batteries which meet criteria concerning environment, health protection, work safety and social responsibility.
- The Initiative for Responsible Mining Assurance (IRMA) is a multi-sector effort, launched in Vancouver, Canada, in June 2006, to develop and establish a voluntary system to independently verify compliance with environmental, human rights and social standards for mining operations. Its target is mainly the mining for jewellery manufacturing.
- There are numerous initiatives focused on small-scale mining of diamond, gold and platinum.

Today's mining companies could be interested in a certification scheme or similar co-operations as a large number of mining projects are being planned. The worst case would be that technologically advanced mines would have to close again when other mining operators start to supply cheaper "dirty" rare earths. Therefore, the promotion of environmental sound mining is an international issue of tremendous urgency. One component of a certification scheme could be the analytical fingerprint which can be used to identify the origin of minerals if other control mechanisms prove to be insufficient.

12.4.3 Supporting sustainable development in Greenland

One selected example of environmental concern is the intended joint mining of rare earths and uranium from the Kvanefjeld deposit in Greenland which was described in Chapter 7.4.4. The prefeasibility study formerly launched by Danish authorities and the current project scheme which envisions the inlet of radioactive and toxic tailings in a natural lake with connection to sea water raises the concern of potential high environmental hazards concerning the lake, its surroundings and maritime waters, even if waste water treatment technologies are installed.

At the same time, the deposit contains high shares of the most scarce heavy rare earth elements (HREE); high profits are expected. Therefore, Öko-Institut highly recommends that Europe appeals clearly to the Greenland authorities to act carefully and responsibly. Furthermore, the co-operation agreement between the government of Greenland and the European Environmental Agency (EEA) signed in November 2010 should support a responsible course of action within this project.

Conclusion on recommended international activities

Concerning international activities, Öko-Institut proposes three selected activities:

- *Öko-Institut proposes an **EU-China co-operation** on sustainable rare earth mining and processing which could be designed as a large-size co-operation which focuses on the sustainable mining of rare earth at one specific site with the aim of optimising the efficiency, the environmental performance, remediation of contaminated sites and a potential recovery of rare earths from old tailings. The EC could supply co-funding and expertise, and China would agree on a defined amount of rare earth supply.*
- *Green technologies call for "green metals", and Europe should support sustainable mining. There are manifold **initiatives for sustainable mining** and certification schemes addressing social and environmental aspects. Today's mining companies are showing increasing interest in certification schemes or similar co-operations with EU participation in order to highlight their environmental efforts.*
- *The high pressure on the opening of new mines brought about by the steeply increasing demand raises the concern that new mines outside of China could be opened which do not keep minimum standards. One case in point could be the **Kvanefjeld deposit in Greenland** where the residues from the ore concentration (tailings) shall be stored in a natural lake with connection to the sea. The EU and the European Environmental Agency (EEA) should appeal clearly the Greenland authorities to act carefully and responsibly.*

13 Literature

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