Development of a Sustainable Exploitation Scheme for Europe's Rare Earth Ore Deposits

European REE market survey – Task 1.1.2

Development of a sustainable exploitation scheme for Europe's rare earth ore deposits - EURARE

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This report builds on numerous secondary data sources, including Eurostat, and uses data provided in the REE-reports by Adamas Intelligence (2016) and Roskill (2016) for reference. The purchase of these reports was financed from within resources allotted to WP1. Importantly, each report follows a different methodology in forecasting and assumptions which is reflected in the chapters of this report that draw on the data from these two reports: Chapter 4 draws on data from Roskill (2016) and Chapter 5 and 7 use Adamas Intelligence (2016) for comparison and reference. This background explains divergences in indications on the total REE market volume, both on the demand and supply side, which are also reflective of the uncertainties pertaining to the information accessible on the REE market.

The report was drafted in collaboration between GEUS and D'Appolonia; final editing by GEUS.

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Glossary

Abbreviation	Term
ACREI	China Rare Earth Industry Association
BM capacitor	Base Metal
BRIC	Brazil, Russia, India, China
CAPEX	Capital expenditure
CCFL	Cold Cathode Fluorescent Lamp
CFCs	Chlorofluorocarbons
CFL	Compact fluorescent lamp
CMP	Chemical Mechanical Planarisation
CRT	Cathode Ray Tube
DDWT technology	Direct drive wind turbine
DRC	Democratic Republic Congo
EC	European Commission
ECC	Emission Control Catalysts
EIP RM	European Innovation Partnership on Raw Materials
ENIAC	European Nanoelectronics Initiative Advisory Council
EoL	End-of-Life
EPoSS	European Technology Platform on Smart Systems Integration
ERECON	European Rare Earths Competency Network
ERTRAC	European Road Transport Research Advisory Council
ETP SMR	European Technology Platform on Sustainable Mineral Resources
EU	European Union
EUPVTP	European Technology Platform on Photovoltaic
EV	Electric Vehicle
FCC	Fluid Catalytic Cracking
FPD	Flat Panel Displays
GEUS	Geological Survey of Denmark and Greenland
GDP	Gross Domestic Product
GHD	Glass Hard Disc
GIG	Gadolinium-Iron Garnet
GMV	Gross Metal Value
GW	Giga Watt
HDD	Hard Disk Drive
HEV	Hybrid Electric Vehicle
HFCs	Hydrofluorocarbons
HID	High-intensity discharge lamp
HREE	Heavy Rare Earth Elements

HREO	Heavy Rare Earth Oxides
HSLA steels	High-Strength Low-Alloy steels
ICE	Internal Combustion Engines
ICT	Information and Communications Technology
IRR	Internal Rate of Return
IUPAC	International Union of Pure and Applied Chemistry
IX	Ion Exchange Methods
KET	Key Enabling Technologies
Kt	Kilo ton (1000 ton)
LCD	Liquid Crystal Displays
LCO	Lithium cobalt oxide
LED	Light Emitting Diode
LFL	Linear fluorescent lamps
LFP	Lithium iron phosphate
LPG	Liquefied petroleum gas
LREE	Light Rare Earth Elements
LREO	Light Rare Earth Oxides
MEP China	Chinese Ministry of Environmental Protection
MIIT China	Ministry of Industry and IT
MiMa	Center for Minerals and Raw Materials
MINT Countries	Mexico, Indonesia, Nigeria, Turkey
MIST Countries	Mexico, Indonesia, South Korea, Turkey
MLCC	Multi-Layer Ceramic Capacitor
MLR China	Ministry of Land and Resources (China)
MOFCOM China	Ministry of Commerce
MREE	Medium Rare Earth Elements
MREO	Medium Rare Earth Oxides
MRT	Molecular Recognition Technology
Mt	Million ton
NCA	Nikel cobalt aluminum
Next11 Countries	Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, Philippines, Turkey, South Korea and Vietnam
NFC	Near-Field Communication
NiMH	Nickel-Metal Hydride
NPV	Net present value
NREAP	National Revewable Enrgy Action Plan
OECD	Organisation for Economic Co-operation and Development
OLED	Organic Light Emitting Diode

OPEX	Operation expenditure
PDP	Plasma Display Panels
PEV	Plug-in electric vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PLZT	Lanthanum-modified lead zirconate - titanate
PM capacitor	Precious Metal capacitor
PM	Permanent magnet
PMSG-DD	Permanent Magnet Synchronous Direct Drive
Ppm	Parts per million
PSZ	Partially Stabilised Zirconia
PVC	Polyvinyl Chloride
R&D	Research and Development
RE	Rare Earths
REE	Rare Earth Element
REM	Rare Earth Metal
REO	Rare Earth Oxide
REPF	Rare Earth Phosphate Fertiliser
ROW	Rest of the World
SOFC	Solid Oxide Fuel Cell
SX	Solvent extraction method
SusChem	European Technology Platform for Sustainable Chemistry
Toe	Ton of oil equivalent
€TP	(European) Technology Platform
Tpa	Ton per year
TREE	Total Rare Earth Element
TREO	Total Rare Earth Oxide
TWh	Tera Watt hour
USD	United States Dollar
UV	Ultraviolet rays
VGO	Vacuum Oil Gases
YAG	Yttria-Aluminium Garnet
YIG	Yttrium-Iron Garnet
YSZ	Yttria-Stabilised Zirconia
WP1	Work-package 1
WTO	World Trade Organization

Definitions

Term	Context in this report
Alloy	A mixture of metals or a metal and another element. Alloys may be a solid solution of metal elements or a mixture of metallic phases.
Basket price	The value (USD) of one unit mass (1 kg) of separated REO, in which those REOs are in the same proportion as the deposit.
Capital expenditure	Funds used by a company to acquire or upgrade physical assets such as property, industrial buildings or equipment.
Didymium	A mixture of the elements Pr and Nd.
End-of-Life	A product at the end of its use-time.
Galfan	A galvanized product which is coated mostly with zinc, minor proportions of aluminium and traces of mischmetal.
Gross Domestic Product	The monetary value of all goods and services produced within a nation's geographic borders over a specified period of time.
Grade	*Grade* is a measurement of the metal content of *ore*. The *grade* is usually measured in %, grams per ton (ppm) or troy ounces per ton. The REO is normally measured in either ppm or %.
Heavy Rare Earth Elements	Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu and Y metals (as applied by EURARE in this report)
Heavy Rare Earth Oxides	Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu and Y oxides (as applied in this EURARE report)
Key Enabling Technologies	According to EC definition, they are technologies "knowledge intensive and associated with high R&D intensity, rapid innovation cycles, high capital expenditure and highly-skilled employment". They include: Advanced materials, Nanotechnology, Micro- and Nano-electronics, Industrial biotechnology, Photonics, Advanced manufacturing technologies.
Light Rare Earth Elements	The elements La, Ce, Pr, Nd, Sm (as applied in this EURARE report)
Light Rare Earth Oxides	La, Ce, Pr, Nd, Sm oxides (as applied in this EURARE report)
(Material) supply chain	Traces the flows of materials along different processing steps by establishing input-output structures for each of the processing steps and mapping geographical locations of these processing steps. Please note the value chain differentiation.
Mischmetal	Describes 'mixed metal', namely an alloy of rare earth elements.
Medium Rare Earth Elements	Sm, Eu, Gd, Tb, Dy metals (according to classification by Kirk-Othmer, 2005)
Medium Rare Earth Oxides	Sm, Eu, Gd, Tb, Dy oxides (according to classification by Kirk-Othmer, 2005)
Million ton	1 million ton (metric)
Next 11 Countries	Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, Philippines, Turkey, South Korea and Vietnam
Net present value	Difference between the present values of cash inflows and outflows
Operation expenditure	An expense a business incurs through its normal business operations, including e.g. rent, manpower, raw materials acquisition.

Parts per million	Measure of some ore grade: gram metal per ton of ore
Rare Earth Element	15 lanthanides plus Sc and Y metals
Rare Earth Metal	15 lanthanides plus Sc and Y metals
Rare Earth Oxide	15 lanthanides plus Sc and Y oxides
Rest Of the World	All countries of this world, excluding China. A term that can be traced back to the highly politicized debate on REE criticality.
Ton of oil equivalent	The amount of energy released by burning one tonne of crude oil. It corresponds approximately to 42 gigajoules.
Ton per year	Tonnage per year (production)
Total Rare Earth Element	Collective term for all REEs contained in a product, resource, reserve or basket
Total Rare Earth Oxide	Collective term for all REOs contained in a product, resource, reserve or basket
Value chain	Extends beyond the input-output structure and geographical mapping of processing steps of the (material) supply chain, to include analyses of governance structures (how firms interact and negotiate access to information and materials and with which outcomes), and of the regulatory dimension that affect how materials circulate.

Please note that references to rare earth elements (REE), when in the context of technology, are made to the precise chemical state in which they are used (e.g. as oxide or metal, using their chemical formula, e.g. for neodymium oxide, Nd_2O_3). In contrast, whenever the general topic of a chapter reaches beyond their technological use, the references might be more imprecise, and refer to e.g. 'REE-products', or individual elements as per their abbreviation in the periodic table, e.g. 'Nd'. However, these loose references are based on the understanding that the REE in these applications nonetheless are derived from prior processing to oxides, metals and used as ingredients in the manufacturing of components.

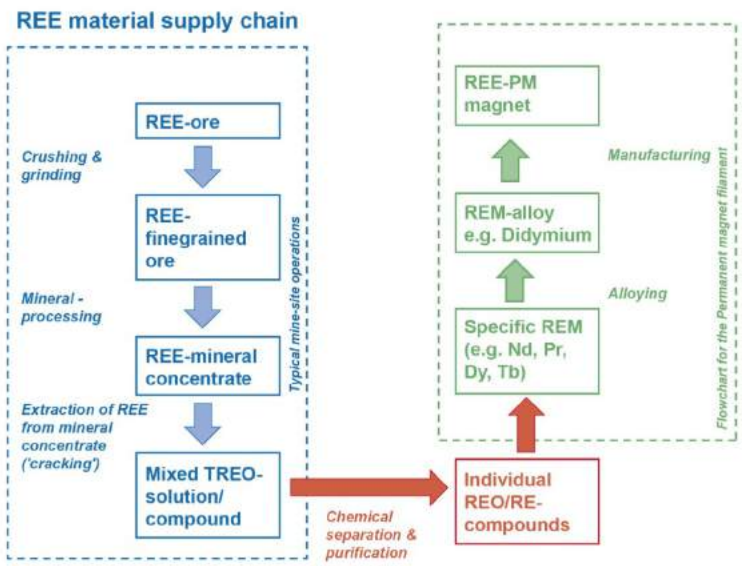


Figure a. Stylized illustration of REE-material supply chain.
Source: adapted from Machacek and Fold, 2014.
Note: The first line shows the generic processing steps which are part of any RE-processing sequence; the second line depicts a specific filament (processing segments particular to a specific intermediate sector), i.e. magnets.

Extended abstract

This market report, which is a result of the EURARE project, maps and contextualizes those industrial activities within the EU that are based on producing or consuming rare earth elements (REE). The objective of the report is to provide the context within which the products of EURARE-funded research are to be considered, and to develop a market forecast for the European REE-industry. More specifically, this report describes key issues around mining and processing of REE, and the intermediate REE-industrial sectors; elucidates the global and EU REE markets; and provides forecasts for REE-demand in various industrial sectors with a view to EU2020 renewable energy targets up to 2025 and 2030. These targets affect a number of technologies that use different suites of the individual REE.

The EURARE Work Package 1 (WP-1) partners have identified about 157 REE-occurrences and deposits located in 18 European countries, of which 34 are classified as deposits. Among these there are three EURARE-partner projects which are considered to have reached an advanced stage of exploration: Norra Kärr in Sweden, and Kringlerne and Kvanefjeld in Greenland. A fourth EURARE partner project is the less developed Fen Complex in Norway. Beneficiation studies were conducted by the EURARE project (WP-2) to investigate new routes for treating ore from these four projects and also some unconventional ore materials, for example red mud waste from bauxite processing. Promising beneficiation pilot-scale results have been achieved for the non-conventional ore from Kvanefjeld, Kringlerne and Norra Kärr deposits; less promising results have been achieved for the bench-scale test of the Fen-REE-ore. In WP-3 new methodologies have been developed for cracking eudialyte in which the the well-known problem of silica gel formation is avoided.

Additionally, the EURARE project WP-4 has developed potential alternative routes to the traditional separation routes of the mixed REE-compounds and more detail will follow in the road map deliverable (WP-6); this report presents common technologies used and findings available to-date. However, this report points to the fact that technological developments on their own cannot be portrayed as *the* solution to establishing an independent REE-supply chain in Europe, in the context of a globalized REE-market in which China holds a politically supported near-monopoly position.

It is in this light, that the attempts at opening alternative REE-mines outside China should be viewed. REE price dynamics are instrumental in the competition between the Chinese and non-Chinese REE-sectors. The main players in the European REE-sector are mapped in this study, which reveals that many of them are part of globally connected value chains in which they negotiate their REE-product input and prices with (vertically integrated) subsidiaries, including from within China. This access to REE-raw material in China through subsidiaries is not to be interpreted as a secure and stable source of supply, as raw material access in China might become increasingly restricted amid growing domestic demand. Importantly, REE-projects outside China will need not only a reliable process and viable feed source, facilities for REE-separation, as well as industrial off-takers with demand for the different suites of a European supply, but also a strategy for how to address fluctuations in REE-prices. Current REE-prices do not just reflect supply and demand, but are to a significant extent subsidized and controlled by the Chinese government through industrial policy. Moreover, prices and supply are affected by a significant illegal REE-supply.

While the advanced exploration stage of the three EURARE project partners is noteworthy, their development can be considered in the context of another six advanced-stage projects that have been identified. These include two projects in Australia (Dubbo, and Nolans), Canada (Kipawa, Strange

Lake and Nechalacho), and South Africa (Steenkampskraal). All of these projects, at the time of assessment, were considered developed due to a prepared feasibility study (see Machacek and Kalvig, 2016), and could all be regarded as potential new REE-players for 2025 and onwards. The potential total supply from these projects exceeds anticipated global REE demand, and thus there will not be room for all of them to reach the exploitation stage. The industrial demand for REE in the EU is small compared to that of China, and Japan, but could be about equal to the industrial demand for REE in the U.S. Establishment of a REE material supply chain from mine to market in Europe appears to need substantial and continuous political support, as a reliance on economic performance might be insufficient to maintain such a venture in the supply-demand situation described. The Japanese support of the Lynas separation plant in Malaysia, with feed material from Mount Weld in Australia, is illustrative.

Uncertainties remain as to the actual REE-volumes used by the industry in the EU. This is partially due to unclear reporting codes in the EUROSTAT statistical database, in which imports of individual REE remain grouped, and thus, obscured, despite a significant improvement in the recent revision. The lack of clarity inhibits clear-cut conclusions as to REE-volumes uses in the EU. Further, most REE-consuming firms remain reluctant to disclose their precise REE-volume use.

REE market demand scenarios for the EU have been developed, based on policy targets for energy – both electricity generation and energy efficiency improvements – and for transport, for the timeframe until 2025 and 2030. The scenarios are used to forecast demand in three REE-consuming sectors: (i) REE-permanent magnets in wind energy, (ii) REE-phosphor-based general lighting, and (iii) the transport sector with respect to REE-permanent magnets used in vehicles, REE-use in catalytic converters, and REE-use in fluid cracking catalysts to refine oil for automotive passenger cars. These forecast demand scenarios are compared with the potential supply from advanced stage REE-projects located outside China. The scenario forecasts suggest the following key points:

(i) increasing demand for REE-materials in the deployment of REE-permanent magnet driven wind turbine generators, especially in offshore technology, for the achievement of renewable energy targets in the EU. Specifically, the REE content to be installed is estimated at 74t Pr_2O_3, 1,740t Nd_2O_3, 18t Tb_4O_7, and 180t Dy_2O_3 annually until 2020.
(ii) reduced demand for REE-based phosphors, due to changes in general lighting technology (forecast demand of 723t Y_2O_3, 92t La_2O_3, 61t Eu_2O_3, 46t CeO_2, and 35t Tb_4O_7 in 2020).
(iii) the transport sector is forecast to have a growing demand for REE-permanent magnets contained in numerous small motors in the generic car (specifically for about 1,350 t Nd metal in 2020), alongside growing demand for REE-use in alloys of catalyst converters due to general rises in car demand. This is forecast to demand about 360t CeO_2 in 2020. As the share of diesel and gasoline driven passenger cars makes way for hybrid cars towards 2030, increasing demand for LREE in alloys of batteries are also forecast, namely about 1000t La metal, 840t Ce metal, 280t Nd metal, and about 80t Pr metal in 2020, and about 7,000t La metal, 4,300t Ce metal, close to 1,500t Nd metal and 430t Pr metal in 2030.

Given the risks attached to investment into building and maintaining a material supply chain from REE-mine to market outside of China, it also makes sense to examine flows of secondary REE-material from end-of-life applications. This would be particularly appropriate under the condition of targeted legislation that could enable, through specific targets and checks, and the installation and operation of well-governed collection systems, the closing of material loops through reuse and recycling.

1 Introduction

This report is the delivery DX of the FP7-Development of a sustainable exploitation scheme for Europe's Rare Earth ore deposits (EURARE) (Grant agreement no 309373) (30/01/13 – 31/12/2017). The report was elaborated during the second half of 2016.

The overall aim of the EURARE project is to contribute to the development of a sustainable European REE industry to safeguard an uninterrupted supply of REE raw materials and products. In particular, the REE products are critical to the industrial sectors, such as 'green-energy', automotive, electronics, machinery and chemicals. To achieve this aim, the EURARE project was designed to address all the main elements in the complex REE-material supply chain from the mineral resources and mining to the final products.

This market review is developed to elucidate the EU-based REE-industrial activities within the context of the global REE-market, and to set the scene and explain how technological process development within the EURARE project is to be understood in this broader context. Further, long-term policy based scenarios are developed to forecast the demand from the main European REE-consuming sectors and to put this into the perspective of the potential supply, generated by three European REE-exploration projects, which are as well partners in the EURARE.

The work has been organized under WP1 (Assessment of European REE resources and REE demand), and primarily undertaken by the partners Geological Survey of Denmark and Greenland (GEUS) (edit.) and D'Appolonia (DAPP). All EURARE partners have been consulted for comments and input as part of the final editing.

Chapter	Responsible project partner	Final editor
3	GEUS	GEUS
4	4.1 GEUS	
	4.2-4.10 D'APP & GEUS	
5	GEUS	
6	6.1 GEUS	
	6.2 D'APP & GEUS	
7	7.1& 7.2 D'APP	
	7.3 GEUS	
8	GEUS	
9	GEUS	

2 Scope of the report

Within the framework of the EU Raw Materials Initiative, the EU identified a list of 20 raw materials (a first list with 14 raw materials was published in 2011, followed by a revision to 20 raw materials in 2014) (European Commission [EC], 2014b). The list contains raw materials of high industrial and market relevance, and points out these materials as "critical" because of economic importance and supply risk associated with them. Heavy and light rare earth elements are included among these "critical raw materials" due to the risk associated with their supply, which is quasi-monopolized by China as the country accounts for about 88% of the global REE production (Roskill, 2016).

Growing demand for REE coming from different technological and market sectors, such as electronics and green technologies, amplifies concerns over the quasi-monopolistic supply situation. Indeed, REE find application in several intermediate- and end-products which are important for the research and development and manufacturing base of the European industry and consumer market. This report aims to assess, in a qualitative and quantitative way, the demand and supply for REE in the EU – viewed in a five-ten years perspective, as a basis for decision-making processes that concern the potential development of a European REE industry, from mine to market.

Indeed, Europe hosts several REE resources, some of which are explored and reached advanced stage; four of the most prominent European REE-projects are partners in the EURARE project, and ore-material from these projects has been used by the EURARE partners for technical tests related to the REE-material supply chain. These projects are: Kvanefjeld and Kringlerne in Greenland, Norra Kärr in Sweden, and the Fen Complex in Norway. Moreover, along with these mineral deposits, REE concentrations identified in by-products from the metallurgical industry, such as from bauxite residue (red mud) of primary aluminium production have been included in the technical tests.

This report works towards an understanding of the significance of European mineral ore deposits, and REE-containing industrial by-products, with a view towards their potential to supply sufficient, reliable and sustainable volumes of REE to the European market. In this context, the report discusses the REE separation technology which was developed in the EURARE project, traces the supply chain segments and relevant firms of the REE-industry landscape in the EU.

Several sources and specific literature have been used to estimate current REE demand at the global and European level and to forecast market trends in line with general megatrends and specific EU policies that affect REE-use in energy and transport. A common classification of the REE-industry into nine intermediate sectors is followed to enable a detailed analysis of the impact of REE-use on technological development and research, as well as manufacturing activity in the EU. The market opportunities for Europe are laid out in this process.

Ultimately, this report aims to provide a useful tool to point out the potential and challenges associated with establishing a European-based REE material supply chain, and considers the actual feasibility of achieving European autonomy regarding REE material supply. The report aims in particular at increasing awareness of end-users, institutions at different levels (i.e. local, national and European level) and industrial subjects on the opportunities present in Europe related to REE.

3 On REE exploration and supply – and the potential for a European mine

REE-mining operators have to manage not only one to three commodities which is normal practice in most mines, but rather the fifteen elements, which together constitute the REE. These elements may be hosted in a wide range of REE- minerals; and each REE-deposit may contain a suite of different REE-minerals. From a mining and beneficiation point of view, this s makes REE-mining operations more complex compared to the classical commodities such as copper, nickel, zinc, lead, and silver. Moreover, each of the individual REE has its own end-user markets, and price variations, and the mine management will have to ensure, that their products can meet the dynamic market requirements and demands Thus, the REE-distribution in the ore is crucial for the economics of new mining projects; ore suited to a specific, high value, end-user market may be more viable than high-grade ore projects where lower-priced REE are dominant. As opposed to the conventional metal mines, it follows that the grade alone is not the key economic variable– REE-distribution may be even more important.

New REE-projects are also challenged by the complexity of the processes transforming the REE-mineral concentrate into various types of separated commercial REE-product. This step, known as REE-separation, is technically complicated and it is capital intensive to develop a new separation plant; most separation facilities are found in China, and using such facilities requires a Chinese partner. Finally, the REE-mining operation is challenged by fact, that the main consuming market for the REE-products are located in China; potential non-Chinese REE-operators will either have to compete with Chinese companies or establish collaboration with a Chinese partner.

This chapter will outline some of these challenges, and will as well outline the REE-resource status both worldwide and in Europe, and introduce the most advanced exploration projects outside China, which are potential new REE-sources for Europe.

3.1 Definition of REE

The chemists defines the Rare Earth Elements (REE) as a group of 17 elements, comprising the elements scandium (Sc), yttrium (Y) and the 15 lanthanides (elements no. 57-71) (Figure 3-2), as defined by the International Union of Pure and Applied Chemistry (IUPAC). The definition applied in this report does however not include scandium and promethium, for reasons explained below. The term REE dates back to the discovery of the first unknown REE-minerals in Sweden in 1794; it took more than 150 years to identify all 17 REE. At the beginning of this period, the word “earth” referred to a metal oxide and not to soil. “Rare” at that time simply meant something strange or extraordinary. Today the name rare earth is misleading as the REE are known to be quite abundant in the crust. Given that the 12 most abundant elements (O, Si, Al, Fe, Ca, Mg, Na, K, Ti, H, Mn, and P) in the continental crust account for about 99% of its mass, this means that many of the commonly mined metals are rare in this context.

Though no uniform list can be presented, the REE are relatively abundant in the upper part of Earth’s crust, although with significant variations. The upper crust is assumed to contain 63 ppm of Ce and 33 ppm of La, which are the most abundant of the REE, to somewhat less than 0.3 pp for Tm and Lu, the rarest of the REE (Weng *et al.* 2015. La and Ce are both more abundant than the average crustal concentrations of Cu (28 ppm) and Pb (17 ppm) (Rudnick and Gao, 2003), whilst the rarer HREE are still more abundant than Au, Ag and platinum group elements (Rudnick and Gao, 2003), see figure 3.1.

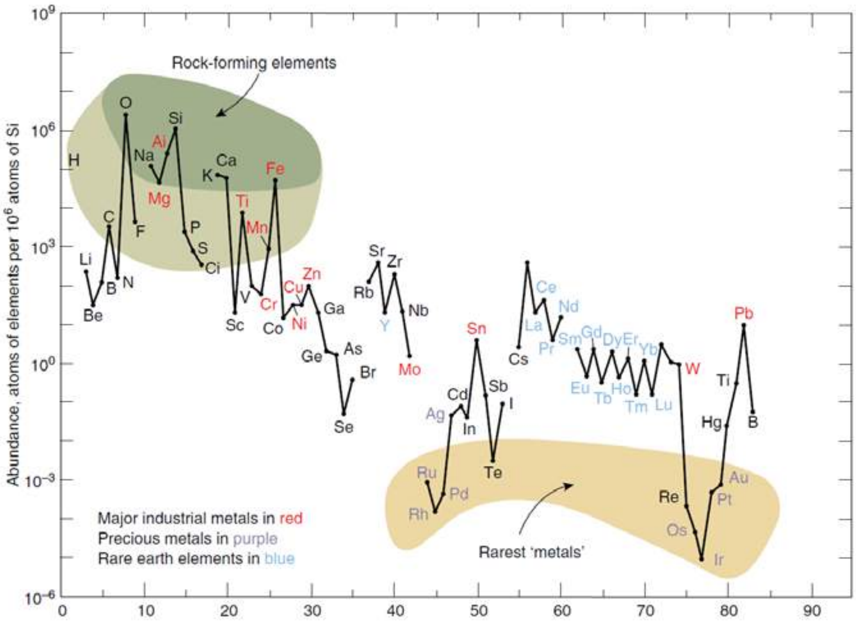


Figure 3.1. Abundance of chemical elements in the Earth's upper continental crust.

Note: The abundance is measured as a function of atomic number. REE are by orders of magnitude more abundant than precious metals such as platinum group elements (PGE's) gold and silver.

Source: Haxel *et al.* 2002.

Abundance of a particular element in the geosphere does not always equate to ease of exploitation. The feasibility of exploitation depends – among other things - on the geology, tonnage, grade, available processing technologies and -costs, and commodity prices.

With a few exceptions, the REE are similar with respect to their ionic radii and oxidation states. This enables them to substitute for one another in crystalline structures, and is also the explanation for the occurrence of multiple REE within a single mineral (Castor and Hedrick, 2006). The most trivalent REE have similar ionic radii to Ca^{2+}, Th^{4+} and U^{4+}, and thus the REE can and do replace some of these elements in a number of minerals. The REE are therefore commonly found in rocks which contain Ca, Th, U and Sr.

Physically, the REE have a number of unique properties that make them useful for a wide range of applications. For example, REE such as Gd, Dy, Er, Nd and Sm have ideal characteristics for magnet manufacturing; and Y and Tb provide sharply defined energy states which can be efficiently used in lighting and laser applications. The REE are frequently grouped, according to their atomic weight and properties into the two groups: the light REE (LREE) and the heavy REE (HREE). The definition of these two groups is varying among scientific disciplines.

In accordance with EC (2013), the EURARE project (WP 1) applies a classification, in which the five elements from La to Sm (atomic numbers 57 through 62) belongs to the LREE (excluding the highly unstable and radioactive Pm), and the ten elements from Eu to Lu plus Y (atomic numbers 63 through 71 + 39) as HREE. Despite its low atomic weight, Y is placed in the HREE because its occurrence, ionic radius, and properties are similar to those of the other members belonging to HREE (Gupta and Krishnamurthy, 2004). Although Sc is considered to belong to the REE, and some REE minerals contain scandium in trace amounts (Gupta & Krishnamurthy, 2004), Sc is normally sourced as a byproduct from nickel and aluminum metal production and thus not considered as one of the REE-commodities, and will not be further discussed in this report. In contrast to the first definitions of LREE and HREE, the IUPAC classification refers to the elements from La to Eu as LREE and to the elements from Gd to Lu and Y as HREE. Frequently applied definitions of LREE and HREE are the LREE comprising the first seven members La to Eu and the HREE comprising the elements Gd to Lu, plus Y and Sc (Figure 3-2). The Chinese organisations define the LREE as La to Nd, as opposed to European definition, including as well Sm in this group. Further, the term medium REE (MREE) is used by some organisations, denoting Sm to Dy. Some of the classifications used is illustrated in Figure 3.2.

Element	Symbol	EURARE	IUPAC	China MLR I	China MLR II	China State Council White Paper
Lanthanum	La	LREE	Unpaired electrons in 4f shells	LREE	LREE	LREE
Cerium	Ce					
Praseodymium	Pr					
Neodymium	Nd					
Samarium	Sm			MREE	MREE	HREE
Europium	Eu	HREE				
Gadolinium	Gd		Paired electrons in 4f shells	HREE		
Terbium	Tb					
Dysprosium	Dy					
Holmium	Ho					
Erbium	Er				HREE	
Thulium	Tm					
Ytterbium	Yb					
Lutetium	Lu					
Yttrium	Y					
Scandium	Sc					

Figure 3.2. Classifications of REE elements in light REE (LREE) and heavy REE (HREE)
Source: IUPAC, 2005; China MLR I, II from China's Ministry of Land Resources (DZ/T 0204-2002); China State Council White Paper from Situation and Policies of China's Rare Earth Industry, Information Office of the State Council, PRC, June 2012 ("White Paper").

3.2 Current REE supply

In the second half of 2016, about 23 active REE-mining companies, located in China, Australia, Malaysia, Brazil, India, Russia, and Vietnam, comprise the upstream supply-chain for REE, exploiting an unknown number of operations. In addition to these operations, considerable illegal production is carried out mainly in China, though China is making some effort to legalize all operations. The sole US-producer, Moly Corp went bankrupt in 2016. An overview is given in Table 3.1, and the global supply side dynamics are described in more detail in chapter 5. The Australian group Lynas is operating the Mount Weld mining in Australia and a separation plant in Malaysia. This operation is the only non-Chinese large-scale REE-supplier.

3.2.1 Chinese REE-producers

The REE industry in China started to boom in 1986, encouraged by a national policy to support the Chinese REE-industry, and since 1990 China has been the world-leading REE producer. Since 2006 China has launched a series of stringent policies, including export licenses and quota systems, resource tax and export duty schemes. These were put in place to regulate REE mining and commercial activities so that China could keep its leading position as a quasi-monopoly producer and use this position to improve value-added downstream activities. In 2010, China cut its REE-export quota by 22.5%; this move was brought to the attention of the World Trade Organization (WTO) by a number of Western countries, and in 2014 the WTO ruled against China. This issue is further dealt with in Chapter 5.

China further consolidated its domestic REE industry in 2013 by forming 'The Big Six', comprising six state-owned, vertically integrated enterprises, controlling the REE supply chain. The "Big Six" includes: 1. Chinalco Rare Earth Corporation, 2. China Minmetals Rare Earth Corporation, 3. Xiamen Tungsten Corporation, 4. Baogang Group (province-owned; under the umbrella China North Rare Earth High Tech), 5. Guanschen-Guangdong Rising Nonferrous, 6. Ganzhou Rare Earth Group (city-owned). This way of organizing the Chinese REE-industry allows China to exploit the large LREE-resources from the Baotou Bayan Obo mine, located in Inner Mongolia, and from Sichuan province in the west and from Shandong province to the East. The HREEs are mainly exploited from ion-adsorption-type deposits, situated in the Southern provinces, such as Jiangxi, Guangxi, Hunan, Fujian, Guangdong, and Yunnan. Each of these provinces has been allocated a REE-production quota, enabling five of 'The Big Six' to be in control of about 74% of the REE production quota for the first half of 2016 (Liu, 2016).

China's production and consumption of REE is strongly regulated by the central Chinese Government, and production quotas and export quotas have been applied since 2006, as a measure to avoid declining prices. The official Chinese production quota for 2015 was set at total of 105,000 tpa (Zeuthen, pers. comm., Oct 2015), composed of 83% LREE and 17% HREE (Liu, 2016), from which the relative production figures for the Northern, Western and Southern provinces have been estimated (Figure 3.3).

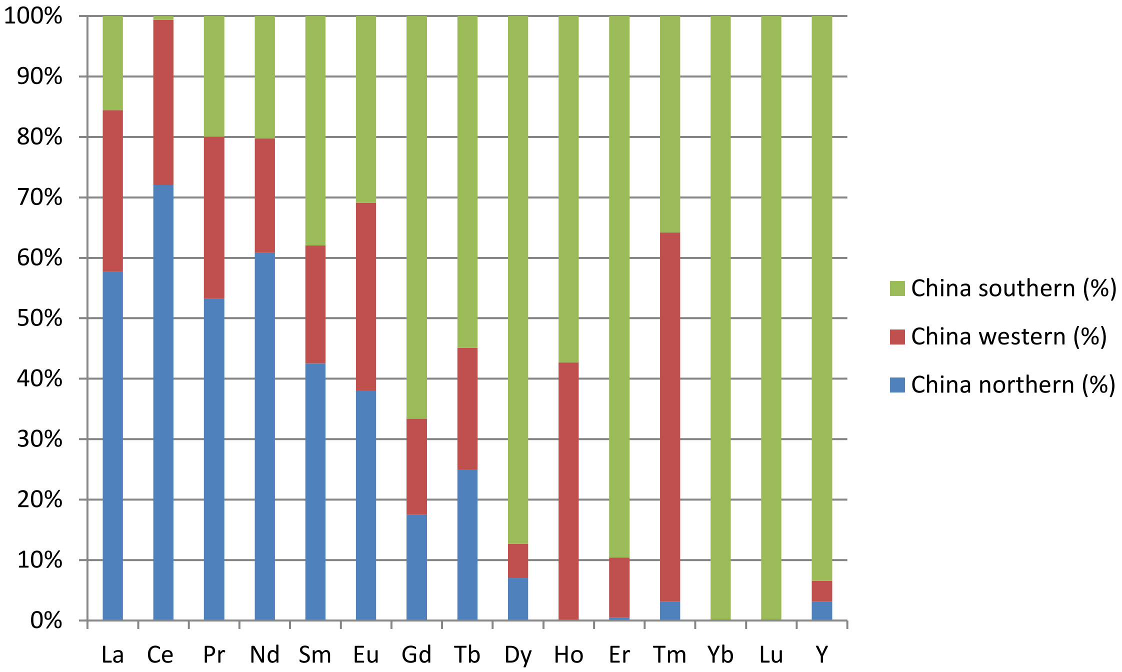


Figure 3.3. Estimated 2015 production in the three REE-regions.
Source: based on data from Liu (2016) and official production quota (Rao, 2016).

In 2015, the official global total REO production was 124,000 tons, of which China produced 85%, Australia 8%, and USA 4%, and the remaining small amounts were produced by India, Russia, Malaysia, and Thailand (USGS, 2016). Widely-varying production figures are published for 2014 (ref. USGS 2016, Brown *et al.* 2016; Adamas Intelligence, 2016), partly caused by confusion between REE and REO, as well as inconsistency with respect to the commodities included; e.g. in some cases REE-mineral concentrates are included, in other cases not.

Table 3.1. Variation in REE mine production statistics (2014)

Country	Mine production (2014) (ton) USGS (2016)	Mine production (2014) (ton) Brown *et al.* (2016)	Mine production (2014) (ton) Adamas Intelligence (2016)
US	5,400	4,200	
Australia	8,000	3965	7,191
Brazil	-		94
China (legal)	105,000	95,000	104,000
China (illegal)			24,500
India	NA		-
Malaysia	240	221	167
Myanmar			2,472
Russia	2,500	2,134	2,093
Thailand	2,100		-
Other	NA		5,908
Total	**123,240**	**105,519**	**146,425**

Sources: USGS, 2016; Brown *et al.*, 2016; Adamas Intelligence, 2016.

The main discrepancy in the annual production statistics may be due to the illegal operations which are in general not included, except for Admas Intelligence, 2016. The extensive contribution to the mine production is supported by Kingsnorth (2016), estimating the illegal figure to be about 30% of the national production quotas. A brief overview of current major global REO-operations is given in Table 3.1.

Development of new REE operations outside China is facing strong competition from the state-controlled and vertically integrated Chinese REE-industry (see also table 3.2.), which controls the REE-supply chain from mining to manufactured goods. Outside China, only two new producers of primary REE have begun production in the past five years – Lynas Corp at Mount Weld, Australia, and Molycorp at Mountain Pass, USA, of which the latter went bankrupt in 2015, and operations suspended in 2016.

Table 3.2. World REE-mining companies

Country	Company	Mine/ Region	Geol. type	Capacity (TREO tpa)	LREE/HREE enrichment	Product
Austr.	Lynas Corp	Mount Weld	Carb./laterite	22,000	LREE	Mixed and separated REO
Brazil	Nuclear Industries of Brazil	Buena Norté		1,500	LREE	Mixed and separated REO
China	Baotou Steel Rare Earth Co[1]	Bayan Obo	Carbonatite	59,500	LREO	Mixed and separated REO
China	Jiangzi Copper Rare Earth	Maoniuping	Carbonatite	2,5000	LREO	Mixed and separated REO
China	Minmetals Ganzhou Rare Earth Co.	Jiangxi	Ion-adsorp.	9,000	HREO	Mixed and separated REO
China	Xiamen Tungsten Co.	Fujian	Ion-adsorp.	2,000	HREO	Mixed and separated REO
China	Guangdong Rare Earth Industry Group	Guangdong	Ion-adsorp.	2,000	HREO	Mixed and separated REO
China	Chinalco Rare Earth Co.	Guangzi	Ion-adsorp.	2,500	HREO	Mixed and separated REO
China	China Minmetals Rare Earth Co.	Hunan	Ion-adsorp.	2,000	HREO	Mixed and separated REO
China	China Iron and Steel Research Institute Group	Weishan	Ion-adsorp.	2,600	HREO	Mixed and separated REO
China	China Minmetals Rare Earth Co.	Yunnan	Ion-adsorp.	200	HREO	Mixed and separated REO
India	Indian Rare Earth Ltd	Tamil Nadu	Placer	2,800	LREO	Mineral concentrate
India	Kerala Metals and Minerals	Kerala	Placer	240	LREO	Mineral concentrate
Malaysia	Pegang Mining Co.	Kinta Valley	Placer	100	LREO	Mineral concentrate
Russia	Lovozerskiy GOK	Lovozero	Alkaline	2,400	HREO	Mineral concentrate
USA	Molycorp *(operation abandoned 2016)*	Mountain Pass	Carbonatite	20,000	LREO	Mixed and separated REO
Vietnam	Lavreco/Sojitz/Toyota	Dong Pao	Placer	220	LREO	Minex and separated REO

Source: Adamas 2015; Jesper Zeuthen, pers. Comm. Oct. 2016.

[1] The company plans to amalgamate with Gansu Rare Earth Group to consolidate the nation's northern mining, separating, and processing operations under the umbrella of a new organization called China North Rare Earth High Tech Corporation.

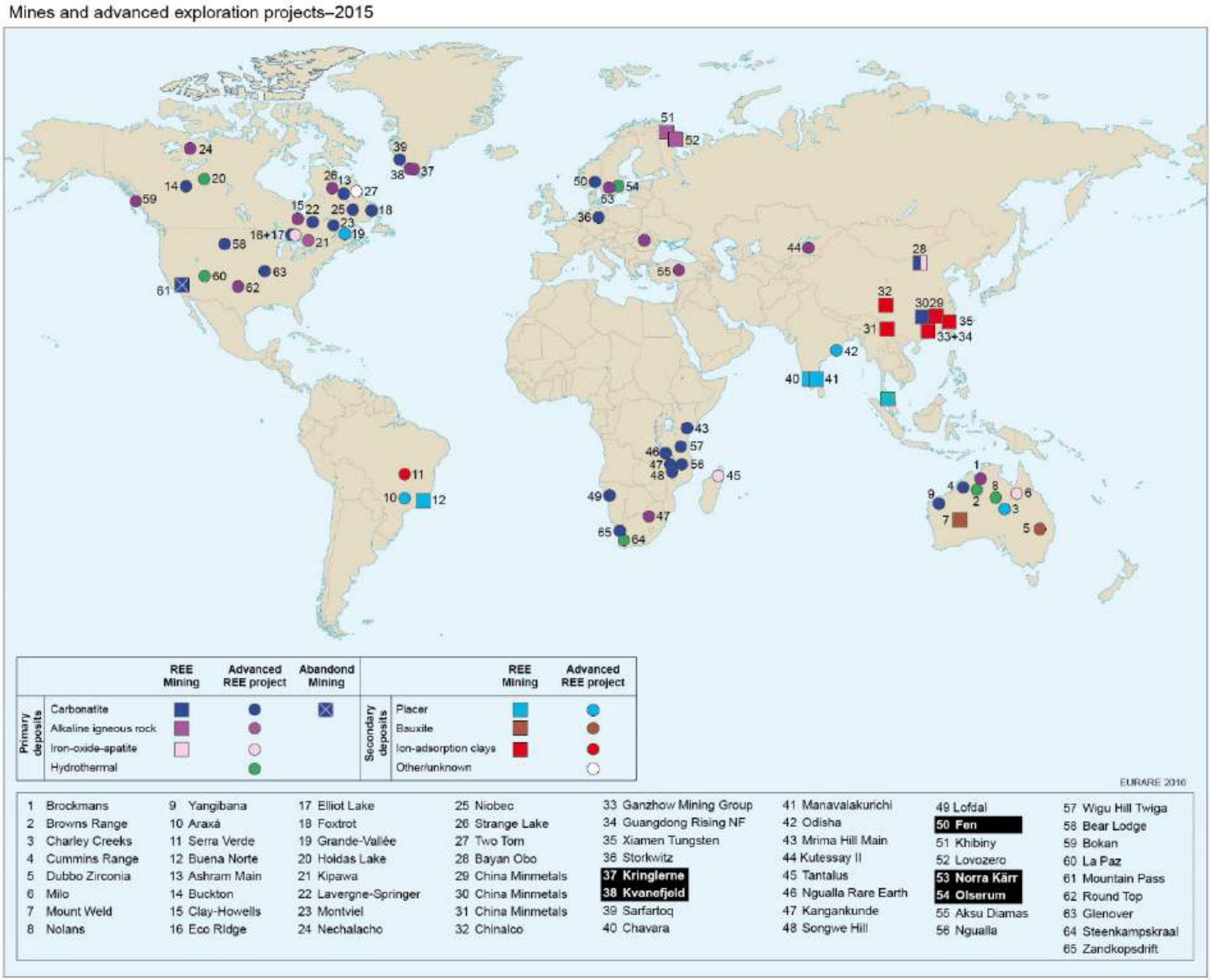


Figure 3.4. Major REE mining (Adamas, 2015) and advanced REE-exploration projects
Source: Technology Metals Research [TMR], 2015. Localities in black boxes: EURARE partner projects.

3.3 REE geology and mineralogy

Existing REE mines, and potential future mines, are situated where geological processes have concentrated the REE grade significantly above the crustal average – and where these resources have been discovered. Such REE-enrichment is the result of a diverse range of geological processes, which can be divided into primary (magmatic and hydrothermal) and secondary (weathering and sedimentary transport) types. The global distribution of these main groups of REE deposit types is shown in Fig. 3.4. As per September 2015, about 66 advanced stage REE-projects are being developed outside China (TMR, 2015), including the three deposits Norra Kärr, Kringlerne, and Kvanefjeld, under license to EURARE partners. In addition to these, there are many early stage REE-projects across the world that do not yet have formal resource estimates compliant with the international reporting codes.

A brief summary of the seven main geological types of REE deposit is given below, following the definitions agreed to by the EURARE WP1-partners:

Alkaline igneous rock deposits: In the magmatic environment, REE deposits are typically associated with alkaline igneous suites. In highly peralkaline magmas, REE-rich oxides, phosphates and/or silicates may be concentrated at certain horizons within the magma chamber because of the incompatible behaviour of REE. Alternatively, REE may be concentrated by late stage magmatic-hydrothermal activity. Significant deposits hosted by alkaline (potassium and sodium-rich) intrusions include Lovozero (Russia), Kvanefjeld and Kringlerne (Greenland), Strange Lake and Nechalacho/Thor Lake (Canada), and Norra Kärr (Sweden). In general, REE deposits associated with alkaline igneous rocks are rather low grade, but may be large tonnage and relatively enriched in the HREE. The REE are typically hosted in complex REE-silicate minerals (see Table 3.3 and Figure 3.5).

Carbonatite deposits: Carbonatites are unusual magmas with >50% modal carbonate minerals, most commonly found in continental-rift tectonic environments, often associated with alkaline igneous rocks. These low-degree mantle melts may contain high concentrations of REE and crystallise REE carbonates and REE fluorcarbonates (e.g. bastnäsite) as well as REE phosphates (monazite and xenotime). The carbonatite-associated deposits are dominated by LREE-enriched REE-minerals. Mountain Pass (USA), Mt. Weld (Australia), and Bayan Obo (China) constitute examples of carbonatites of which only the latter two are being exploited for REE.

Granite and pegmatite deposits: Granite and pegmatite-hosted REE deposits are associated with highly-evolved, residual melts formed by the fractional crystallisation of a fertile granite body. Deposits of this type were among the first sources of REE to be exploited in the early twentieth century, e.g. the Ytterby pegmatite in central Sweden. Whilst historically important, they are rarely promising exploration targets due to their small tonnage and complex mineralogy. However, they often have potential for by-products such as beryllium, fluorine and niobium.

Vein and skarn (hydrothermal) deposits: Vein and skarn REE deposits are characterised by mineralisation processes involving hot, aqueous solutions forming REE-bearing veins and replacement ore bodies (e.g. Bastnäs and Riddarshyttan, central Sweden). Carbonatite and/or alkaline magmatic bodies may be spatially associated and act as a metal and/or energy source. Examples of REE deposits where hydrothermal processes are recognized to have been important include Bayan Obo (China), Nolans Bore (Australia), and Steenkampskraal (South Africa).

Iron oxide-apatite deposits of the Kiruna type in the Svecofennian belt are also enriched in the REE due to apatite, including Kiruna and Malmberget in northern Sweden and the Grängesberg-Blötberget deposits in South Central Sweden (Goodenough *et al.* 2016). Some Iron-Oxide Copper Gold (IOCG) deposits such as Olympic Dam, Australia, carry the mineral apatite, which has the potential to produce REE as a by-product. The REE-bearing apatite is currently treated as waste during iron ore processing.

Placer deposits: Some of the REE-bearing minerals, such as monazite and xenotime, are relatively resistant to weathering and can be transported by sedimentary processes. As a result, they can become concentrated in heavy mineral sand deposits, referred to as placers. Such placer deposits can form in rivers, in arid environments (dunes), or in beach and shallow marine environments. Currently, mineral sand mining operations in India, Malaysia and Australia, which mine cassiterite (Sn), rutile (Ti), and/or zircon (Zr) , also stock-pile monazite and/or xenotime from which REE can be produced as by-products. This deposit type is also known from the geological record (palaeo-placer) where subsequent metamorphic processes may have upgraded the REE resource (e.g. Olserum, Sweden).

Bauxite deposits: Accumulation of residual clay minerals on karst limestone surface followed by chemical weathering under tropical conditions can lead to the formation of bauxite deposits. This process has the potential to generate near-surface bauxite deposits due to crystallisation of authigenic REE-bearing minerals, accumulation of residual phases and the adsorption of ions on clays and other mineral surfaces (Deady *et al.* 2014). The Mediterranean bauxite deposits have potential to produce REE as a by-product from aluminium production (Deady *et al.* 2016).

Ion-adsorption deposits: Ion-adsorption deposits are a specific type of laterite deposit. They are formed by in-situ chemical weathering of granitic rocks, resulting in adsorption of REE to clay mineral surfaces within the laterite profile. Such ion-adsorption clay deposits are typified by the occurrences in the Jiangxi, Guangdong, Hunan, and Fujian provinces of southern China and, despite being low-grade, are important sources for the more valuable HREE. These clay deposits are easily mined because the adsorbed REE can be released from the clays by simple acid leaching methods using leachates such as ammonium sulphate.

3.3.1 Importance of REE mineralogy

The REE can be incorporated into a range of different mineral types, such as carbonates, oxides, silicates, phosphates, each of them related to specific geological environments. More than 200 REE-bearing minerals have been identified (Kanazawa and Kamitani, 2006), though only a few are currently considered feasible for the extraction of REE: bastnäsite (carbonate mineral), monazite and xenotime (phosphate minerals), and loparite (oxide mineral). Research to establish methods for extraction of REE from many other minerals is currently under way. The most common REE minerals are shown in Table 3-2.

Each of the REE-minerals has a characteristic REE-ratio (Kanazawa and Kamitani, 2006). As can be seen in Figure 3.5, bastnäsite and monazite are dominated by LREE whereas xenotime is relatively enriched in HREE. With regard to mine production volumes, bastnäsite is the most important REE ore mineral and is extracted at the Chinese mining operations in Bayan Obo, Weishan and Maoniuping, and until 2015 was also mined at Mountain Pass (USA).

More recently, a number of REE exploration operations have targeted the alkaline igneous deposits that contain less conventional REE silicate ore minerals such as eudialyte, gadolinite, fergusonite and steenstrupine (see Figure 3.5). These minerals can be of interest because of their more balanced ratio of HREE to LREE which makes them a potentially highly valuable resource, but they were traditionally considered unsuitable for recovery due to their resistance to dissolution (Binnemans and Jones, 2015).

Table 3.3. Some of the most common REE minerals.

Mineral	Formula	Wt.% REO	Th,U	Other REE variant
Carbonates and fluorcarbonates				
Ancylite (Ce)	$SrCe(CO_3)_2(OH)H_2O$	43	-	La
Bastnäsite (Ce)	$CeCO_3F$	75	-	La,Nd, Y
Huanghoite (Ce)	$BaCe(CO_3)_2F$	40	-	
Parisite (Ce)	$CaCe(CO_3)_3F_2$	50	-	Nd
Synchysite (Ce)	$CaCe(CO_3)_2F$	51	-	Nd, Y
Phosphates				
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	-	-	-
Cheralite	$CaTh(PO_4)_2$	Variable	M	
Churchite (Y)	YPO_4 $2H_2O$	51	V	Nd
Florencite (Ce)	$(Ce)Al_3 (PO_4)_2 (OH)_6$	32	-	Sm
Monazite (Ce)	$CePO_4$	70	V	La, Nd, Sm
Xenotime (Y)	YPO_4	61	V	Yb
Oxides				
Aeschynite (Ce)	$(Ce,Ca, Fe, Th)(Ti,Nb)_2 (O,OH)_4$	32	V	Nd, Y
Cerianite (Ce)	CeO_2	100	V	-
Loparite (Ce)	$(Ce, La, Nd, Ca,Sr)(Ti, Nb)O_3$	30	-	
Yttropyrochlore (Y)	$(Y,Na,Ca,U)_{1-2}Nb_2 (O,OH)$	17	V	
Silicates				
Allanite (Ce)	$CaNdAl_2Fe_2+(Si_2O_7)O(OH)$	23	V	La,Nd, Y
Britholite (Ce)	$(Ce,Ca,Sr)_2(Ce,Ca)_3 (SiO_4 PO_4)_3 (O,OH,F)$	23	V	Y
Eudialyte	$Na_{15}Ca_6Fe_3Zr_3Si(Si_{25}O_{73})(O,OH,H_2O)(Cl,OH)_2$	9	-	
Fergusonite (Ce)	$CaNdAl_2Fe^{2+}(SiO_4)(Si_2O_7)O(OH)$	53	-	Nd, Y
Gadolinite (Ce)	$Ce_2Fe^{2+}Be_2O_2 (SiO_4)_2$	60	V	Y
Gerenite (Y)	$CaNdAl_2Fe^{2+}(SiO_4 (Si_2O_7)O(OH)$	44	-	Y
Kainosite (Y)	$Ca_2Y_2 (SiO_3)_4 (CO_3)H_2O$	38	-	
Keiviite (Y)	$Y_2Si_2O_2$	69	-	Yb
Steenstrupine (Ce)	$Na_{14}Ce_6(Mn^{2+})_2(Fe^{3+})_2Zr(PO_4)_7Si_{12}O_{36}(OH)_{23}H_2O$	31	V	
Fluorides				
Fluocerite (Ce)	CeF_3	83	-	La

Source: Based on Wall (2014).

Substantial variations in REE-distribution can occur within one type of REE-mineral, reflecting the local geological conditions under which the mineral is formed (Figure 3.5). This is particularly the case for the silicates, e.g. the eudialyte minerals from Kringlerne, Kipawa and Norra Kärr have different REE-compositions, but the figure also illustrates the different REE-compositions of bastnäsite in Bayan Obo, China and Mountain Pass, USA.

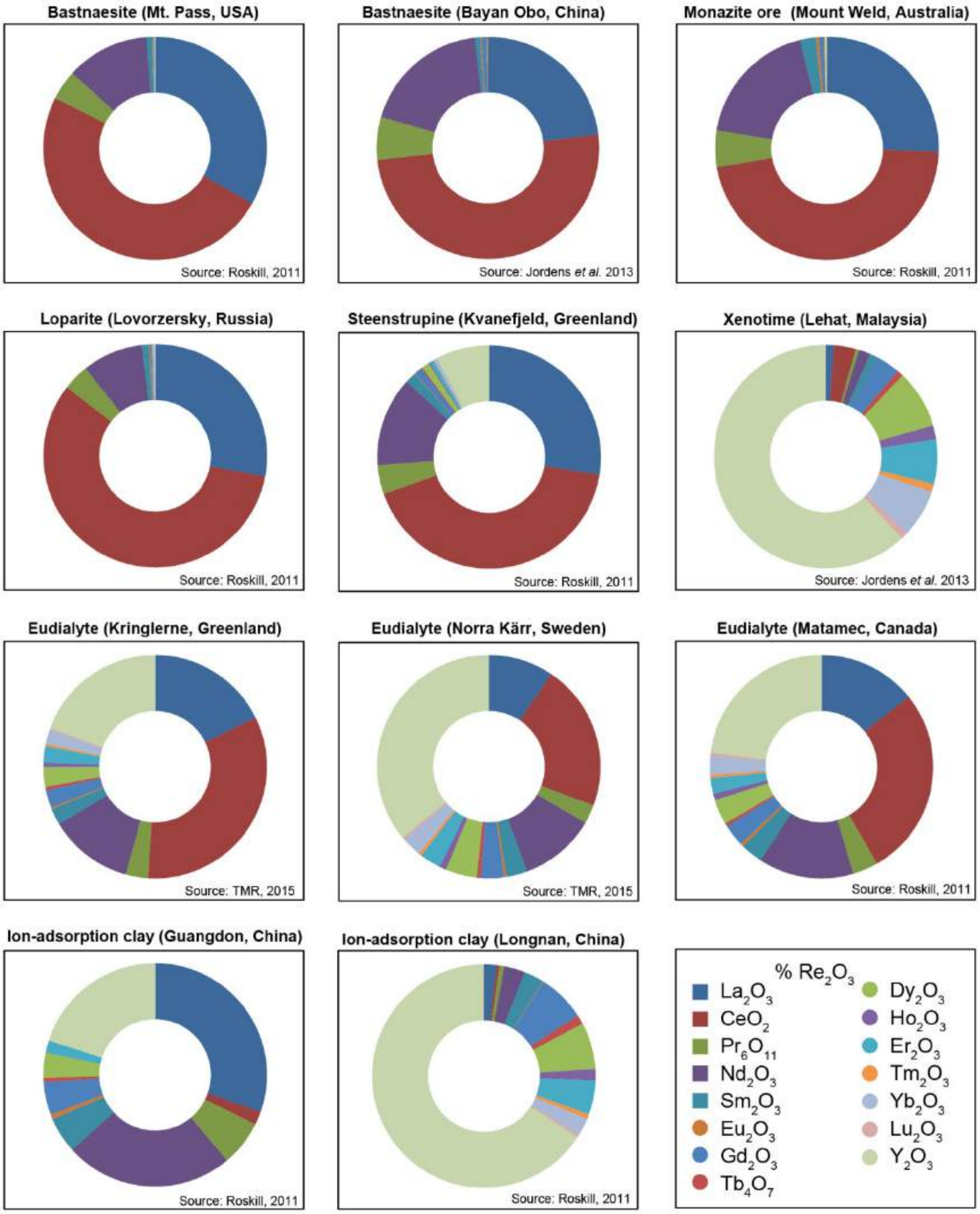


Figure 3.5. Proportions of individual REE concentrations in selected REE-minerals and ores.
Source: based on Roskill, 2011 and TMR, 2015.

The ore grade and relative enrichment of LREE to HREE impacts on the economic viability of each deposit. Many of the individual REE are used in specific industrial sectors. For example Pr, Nd, Sm and Dy are key ingredients in magnets, and the phosphors sector demands in particular Eu, Gd, Tb and Y. The mineralogy of a given REE deposit – and hence its REE-distribution - is therefore crucial to the economic viability of a project. REE-distribution can be even more important than the REE-grade; high grade alone does not necessarily make a REE-deposit economically viable. This is the so-called balance problem, referring to the mismatch between the demand and the supply of REEs, avoiding surplus production; this issue is dealt with further by Binnemans *et al.* (2013a) and Binnemans and Jones (2015).

REE-minerals are in many cases associated with uranium (U) and thorium (Th), either incorporated into the lattice of the REE-minerals or in associated minerals within the ore mineral assemblage. This is particularly the case for the alkaline igneous and carbonatite-associated REE mineralization, and also typically for placers. During the precipitation and selective dissolution, U and Th will exit the solvent extraction circuit and become radioactive waste. Some of the Th and U are removed during all the purification steps (precipitation, selective dissolution), but due to the strong extraction of Zr^{4+}, Th^{4+}, UO^{22+} and Fe^{3+} these metals will be extracted together with the HREE fraction (Email communication with respondent of Mintek, 2013). The radioactive elements can remain a part of the REE concentrate. Once they are liberated, they act as individual elements. For instance, the decay daughter of U-235, actinium isotope Ac-227 behaves like lanthanum and remains with the REE. U and Th are used as indicators for the presence of other radiogenic daughter products.

3.4 Benchmarking REE-exploration projects

3.4.1 Commonly used parameters

The steps involved in developing a REE project from the discovery of the occurrence, through exploration, to a mine, follow the same principal pathway as other types of metal exploration projects, though traditional geophysical methods cannot be applied if the occurrence is not genetically associated to sulphide systems. Once mineralization is recognized, the ore- and gangue minerals need to be identified and their textures studied, and mapping and drilling are carried out to define the resources at the project. Pilot studies for beneficiation and extraction will be carried out where appropriate; pre-feasibility and final feasibility studies will take place along with environmental assessments.

Exploration and development of a REE-deposit is very challenging, given the fact that each deposit is a multi-element deposit typically with a complicated mineralogy, which will require development of tailor-made beneficiation and cracking flow-sheets. REE-distribution is key to market acceptability and, consequently, to economics of a REE-deposit. In most metal exploration projects, the grade and the price of the main metal are the key parameters for evaluating an exploration project's feasibility to be further developed. For REE deposits evaluation is more complex, and a wide range of parameters can be used to evaluate the potential of any given REE project; some of these are directly related to the deposit mineralogy.

- *Ore grade (%)*, meaning the TREE content of one unit of the ore; this does not reflect the distribution of individual REE.
- *Ore tonnage*, meaning the volume of the ore (the economic part of the rock hosting REE-minerals)
- *Individual REE-grade (%)* based on the individual REE as a fraction of TREE, frequently expressed as HREE/LREE-%, reflecting the REE-distribution.
- *Ore value or gross metal value (GMV)*: TREO-value per unit mass of mineral resource (USD/ton), reflecting the in-situ value of the ore material, thus considering the ore grade, but not the tonnage and recovery of the ore. A high-grade ore dominated by LREE may reach a lower GMV than a low-grade ore dominated by HREE. Further, high GMV does not guarantee a market for the products.

- *Basket price* (USD/kg), reflecting the potential price if one kilogram of the TREO is extracted from the ore – not accounting for the ore grade or the total recovery rates. From this it follows that low grade ore may well result in high basket price and vice versa.

The above metrics are frequently used for comparing REE-projects. In Table 3.4 and Figure 3-6, for example, the TREO-value per unit mass is shown as compared to the TREO-basket price, for most of the projects listed in Table 3-3.

Normally, no value is attributed to the five HREE with limited, niche markets (Ho, Er, Tm, Yb, Lu). It should be noted that, as a result of poor market transparency, there is no standard set of prices for the REE-commodities, and thus metrics such as GMV and basket price are both dynamic parameters and may reflect company views.

In the calculations of GMV and basket price the following parameters are not accounted for: (i) deposit tonnage; (ii) costs associated with mining, extraction, and separation; (iii) mineralogy and processing level of difficulty; (iv) recovery loss (assumes 100% REO recovery from ore to final product, which is unfeasible); (v) specifications and salability of final products; and (vi) project economics (e.g. OPEX, CAPEX, IRR, NPV).

In some economic analyses a percentage discount is applied to the product sales price(s) reflecting the intent of final sale to be a mixed concentrate product (RE-oxides, RE-carbonate; RE-chloride), as opposed to separated REOs for which a price deck applies. Given that all REE projects will need to produce an intermediate product feed to the separation facility, project to project comparison could be based on prices for the mixed concentrate product. Alternatively, a tolling price would need to be added to the OPEX (mining through to mixed REO concentrate) to approach a possibility for comparison; though these cost figures most likely would be available only when an off-take contract has been signed with a separation facility operator. However, in order to compare REE projects, it is vital that they are all assessed to the stage of a common product. A project that intends to sell a mixed REE-carbonate will appear very different economically to one that has an REE separation facility on site.

3.4.2 Global REE reserves and resources

The terms reserves and resources used by geologists and mining engineers are in essence strict terms, though sometimes not applied correctly. The report follows the definitions of USGS (2012), in which a resource is a concentration of minerals in such form and amount the economic extraction is currently potentially feasibly, as opposed to a reserve, which could be economically extracted or produced at the time of determination. Further, resources may have been demonstrated to various degree, but a reserve is proven. Various institutions have defined set of rules which should be fulfilled in order to classify a resource as measured, indicated or inferred respectably. The relevant set of rules applied is always published along with the reserve/resource tonnage and grade figures, such as: JORC Code (Joint Ore Reserves Committee; mainly used by Australian groups); National Instrument 43-101, CIM guidelines, mainly applied by Canadian groups, SAMREC code, the South African Mineral Committee, CRIRSCO (Committee for Mineral Reserves International Reporting Standards, aiming at defining one international standard. These different ways of reporting are frequently causing confusing numbers, and may well as cause some of the statistic issues highlighted below.

Several global TREO reserve figures are reported. Weng *.et al.* (2015) published a global TREO resources figure of 619.5 Mt, split between 267 deposits and grading 0.63% TREO and hosting c.

554 Mt TREO, based on JORC, NI43-101, SAMREC and CRIRSCO mineral resource data gathered in 2013-2014.

The resource figure reported by Weng *et al.* 2015 is substantially higher than figures published by Technology Metals Research (ca. 100 Mt TREO), USGS (2016) (130 Mt TREO), and Adamas Intelligence (2016) (108 Mt TREO). However, large discrepancies occur as well between these global estimates (Table 3.4). The USGS (2016) estimate of about 130 Mt TREO includes China (55 Mt TREO), and Brazil is about a factor ten higher than the other two estimates. The Adamas Intelligence (2016) reports about 41.3 Mt TREO for Greenland as opposed to 35.6 Mt TREO given by Technological Metals Research (2015).

Looking from a tonnage point of view alone it appears that the global REE-reserve is sufficient for about 500 of years of production. However, as shown in section 3.5, neither the tonnage nor the grade alone makes a mine, because the REE-distribution, as well as many other parameters, should be considered. World resources are contained primarily in bastnäsite and monazite (USGS, 2016), and bastnäsite is the main source of LREE.

Table 3.4. Estimates of the global TREO tonnage

Country	**TREO (Mt)** (TMR, 2015) (see Table 3-3)	**TREO (Mt)** (USGS, 2016)	**TREO (Mt)** Adamas Intelligence (2016)
Australia	3.21	3.2	4.45
Brazil	2.64	22	2.29
Canada	35.44		38.19
China		55	
Gabon			2.64
Germany	0.02		0.02
Greenland	35.57		41.3
India		3.1	
Kenya	4.25		6.14
Kyrgyzstan			0.05
Madagascar			0.57
Malaysia		0.03	
Malawi			0.58
Mozambique			0.02
Namibia			0.02
Norway	4		0.90
Sweden	0.24		0.24
Turkey	0.35		0.35
Tanzania	1.77		4.63
USA	4.29	1.8	3.93
South Africa	1.2		1.34
Other Countries	1.24	41	
Total	90.99	130	108

Source: based on USGS, 2016; Technological Metals Research [TMR], 2015; Adamas Intelligence, 2016.

3.4.3 REE-exploration projects outside China

An overview of the most advanced stage REE-projects is given in Table 3.5, and locations are shown in Fig 3.9.

Table 3.5. Overview of advanced stage global REE-projects by assessment parameters.

Project	Country	Reserve Mt	Grade TREO Wt.%	Volume TREO Mt	In-situ TREO USD/t (MR)	Basket price USD/kg (Nov. 2015)	Geol. type
Brockmans	AUS	36	0.21	0.08	65.09	31.00	Alk
Browns Range	AUS	9	0.63	0.06	198.92	31.57	S&V
Charley Creek	AUS	805	0.03	0.24	5.36	18.38	Pla
Cummins Range	AUS	5	1.74	0.09	221.24	12.71	Carb
Dubbo Zirconia	AUS	73	0.89	0.65	146.85	16.50	Baux/Alk
Milo	AUS	187	0.06	0.12	9.42	15.27	Baux/Carb
Nolans	AUS	56	2.59	1.45	393.24	15.16	S&V
Yangibana (JV)	AUS	7	1.52	0.10	234.59	15.40	Carb
Araxá	BRA	28	4.21	1.19	487.38	11.58	Carb
Serra Verde	BRA	909	0.16	1.45	26.95	16.84	Ion
Ashram Main	CAN	240	1.90	4.55	255.86	13.48	Carb
Buckt	CAN	3,434	0.03	0.88	4.95	19.38	Carb
Clay-Howells	CAN	9	0.73	0.06	118.82	16.30	Carb
Eco Ridge	CAN	59	0.16	0.09	22.44	14.32	Carb
Elliott Lake Teasdale	CAN	52	0.19	0.10	25.34	13.31	Iron-REE
Foxtrot	CAN	14	1.01	0.15	179.83	17.73	Carb
Grande-Vallée	CAN	1,210	0.05	0.61	7.97	15.91	Carb
Hoidas Lake	CAN	3	2.40	0.07	377.56	15.72	S&V
Kipawa	CAN	27	0.39	0.11	83.66	21.19	Alk
Lavergne-Springer	CAN	17	1.16	0.20	154.41	13.27	Carb
Montviel	CAN	267	1.45	3.88	185.38	12.74	Carb
Nechalacho Basal	CAN	126	1.43	1.80	305.14	21.33	Alk
Niobec	CAN	1,059	1.73	18.36	242.34	13.97	Carb
Strange Lake Granite	CAN	473	0.87	4.12	175.08	20.09	Alk
Two Tom	CAN	41	1.18	0.48	163.60	13.84	Carb
Storkwitz	GER	5	0.45	0.02	54.71	12.11	Alk
Kringlerne	GRL	4,300	0.65	28.06	119.92	18.38	Alk
Kvanefjeld	GRL	673	1.09	7.37	144.57	13.20	Alk
Sarfartoq	GRL	8	1.72	0.14	242.64	14.12	Carb
Mrima Hill Main	KEN	133	3.21	4.25	492.35	15.35	Carb
Kutessay II	KGZ	1	0.26	0.05	78.01	30.15	Alk
Tantalus	MDG	628	0.08	0.56	13.91	16.81	Ion
Ngualla Rare Earth	MOZ	1	2.03	002	301.62	14.86	Carb
Kangankunde	MWI	3	4.24	0.11	460.40	10.86	Carb
Songwe Hill	MWI	32	1.48	0.47	219.51	14.85	Carb

Table 3.5 cont.							
Lofdal	NAM	2	0.59	0.01	181.28	30.65	Carb
Fen	NOR	486	0.90	4.00	.	20.20	Carb
Norra Kärr	SWE	31	0.61	0.19	139.87	23.12	Alk
Olserum	SWE	8	0.62	0.05	134.75	21.86	S&V
Aksu Diamas	TUR	494	0.07	0.35	9.92	14.21	Pla
Ngualla	TZA	42	4.19	1.75	519.34	12.39	Carb
Wigu Hill Twiga	TZA	1	5.27	0.03	403.26	7.65	Carb
Bear Lodge	USA	58	2.68	1.55	396.15	14.78	Carb
Bokan	USA	6	0.60	0.04	140.72	23.37	Alk
La Paz	USA	128	0.04	0.06	8.58	19.49	S&V
Round Top	USA	906	0.06	0.57	13.82	21.87	Alk (?)
Glenover (JV)	ZAF	10	2.13	0.22	393.93	18.48	Carb
Steenkampskraal	ZAF	1	14.00	0.09	2166.11	15.47	S&V
Zandkopsdrift (JV)	ZAF	47	1.89	0.89	271.46	14.34	Carb

Source: Data from TMR, 2015.
Note 1: Projects located within the EU28 in bold. Geological types: Alk: alkaline associated; Carb: carbonatite associated; S&V: Skarn and vein deposit (hydrothermal)[l]; Pla: Placer deposit; Baux: bauxite associated; Ion: ion-adsorption clay type.
Note 2: Basket price for Fen provided by Fen Minerals, based on Jan. 2017 China Export prices. In-situ values not estimated.

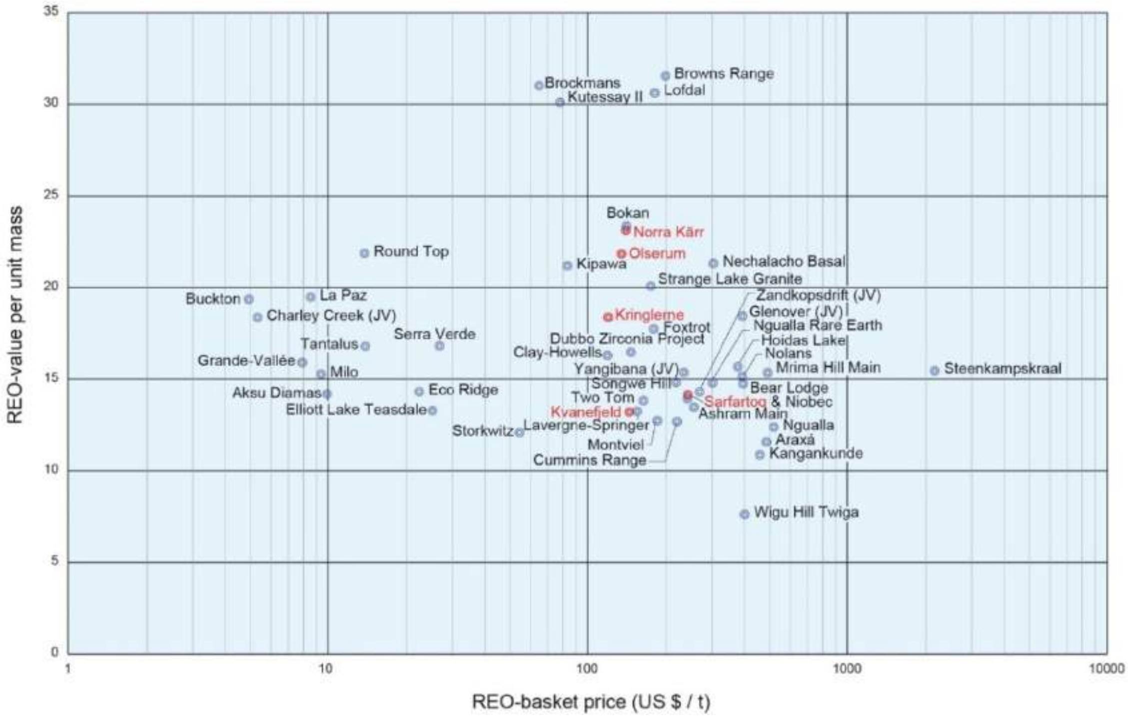


Figure 3.6. Value metrics for advanced stage REE- projects.
Source: based on TMR, 2015. (see values in Table 3.4 above).
Note: REO-basket price vs REE value per unit mass (based on Metal Pages FOB China - Nov 2015 prices).

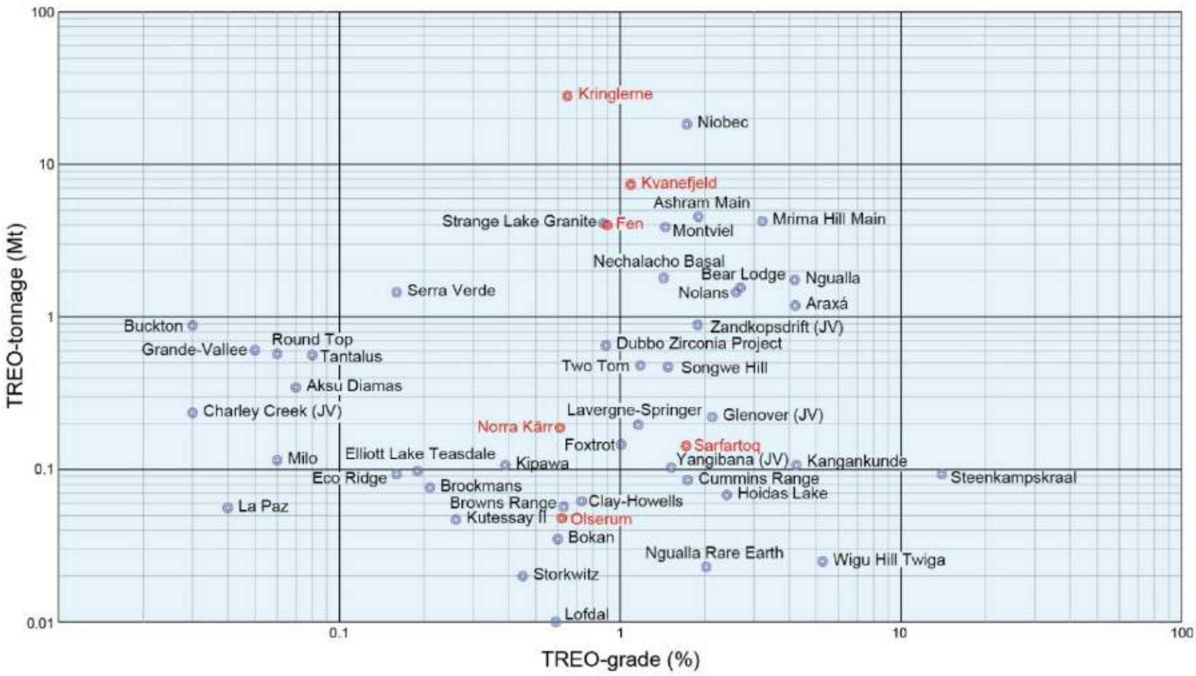


Figure 3.7. Value metrics for advanced stage REE- projects: TREO-grade vs TREO-tonnage (based on Metal Pages FOB China - Nov 2015 prices).
Source: Based on Technology Metals Research, Nov. 2015. (see values in Table 3.4 above)

3.4.4 REE-exploration projects in Europe

Europe has no operating REE-mine, but several REE projects are currently being explored or being technically and/or economically assessed, of which three have reached an advanced stage of exploration and development (pilot beneficiation and extraction studies; pre- and/or final feasibility studies). These include Kvanefjeld and Kringlerne, in South Greenland, the Norra Kärr, Sweden, all three are alkaline types. A number of carbonatite-hosted REE projects are currently explored, including Fen in Norway and Sarfartoq in Greenland, but have not reached the advanced stage yet.

However, more than sixty REE occurrences and deposits have been identified in course of the EURARE WP1 projects, and an overview of the REE-occurrences and deposits in Europe has been compiled by the EURARE project and published (Goodenough *et al.*, 2016) and very broadly summarized in Figure 3.8 and 3.9.

The REE-reserves for each of the projects Kvanefjeld, Kringlerne and Norra Kärr could potentially secure European REE supply for decades to come. However, it should be stressed that no mining company is obliged to sell their product to the domestic or near-by market. Thus in the event new REE-mining operations come on stream in Europe in the future, these products may not be destined for European end-users. The European REE deposits are benchmarked and the results are shown in Figure 3.6 and 3.7. Currently, the most advanced projects in Europe are:

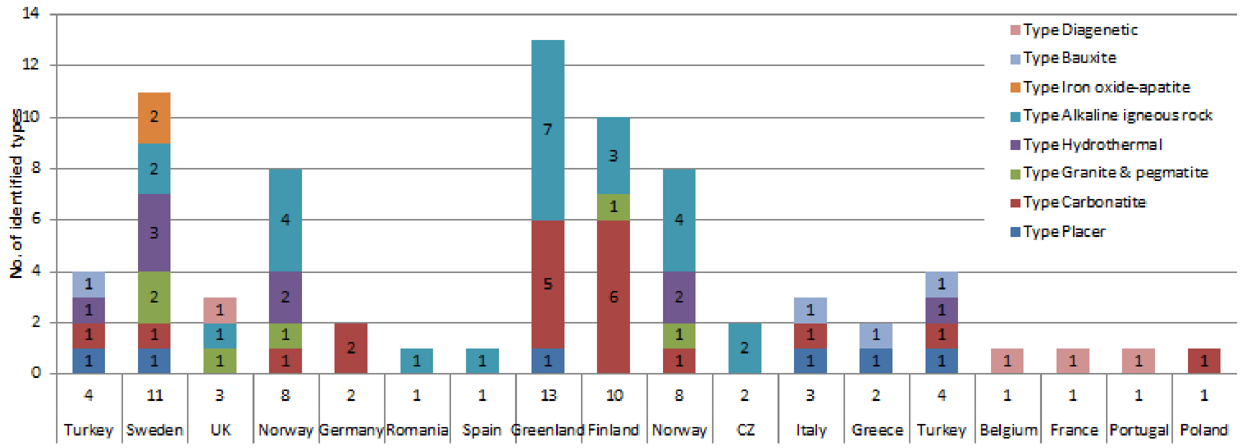


Figure 3.8. Number of identified deposit types in Europe
Source: based on Goodenough *et al.*, 2016.

Norra Kärr: Leading Edge (2017), the license holder of Norra Kärr, located in south-central Sweden, reported a probable NI43-101 compliant resource of 23.6Mt, grading 0.592% TREO; the PFS suggests an annual mining operation of about 1.150 Mio tpa, equivalent to about 6,800 tpa TREO, of which 3,611 tpa are HREO. The estimated lifetime is 20.5 years.

Kvanefjeld: Greenland Minerals and Energy Ltd (GME), the license holder of the Kvanefjeld REE-deposit, located in southern Greenland, reported measured JORC-code 2012 compliant resource of 143 Mt, grading 1.2% TREO, 303 ppm U_3O_8, and 0.24% Zn, equivalent to about 1.72 Mt TREO. RM Research (2016) reports planned total production of 31,078 tpa , including 9,901 tpa mixed CREO; 6,077 tpa La_2O_3, , 5,254 mixed La-Ce oxide; and 9,846 tpa $Ce(OH)_2$., based on a mine throughput of c. 3 Mtpa. Estimated lifetime is 33 plus years. GME envisages additionally 475 tpa of U_3O_8 and 6,079 Zn in concentrate. GME has signed a MoU with the Chinese REE-group Shenghe aimed at technical and commercial collaborations. GME has applied for exploitation lease in 2015, and the application is currently (Nov. 2016) being processed.

Kringlerne: Tanbreez Mining Greenland A/S, the license holder of the Kringlerne projects, located ca. 10 km South of Kvanefjeld, South Greenland , reports *'the current inferred resources is more than 4.7 billion tonnes of eudialyte bearing ore, which contains variable contents of extractable rare earth"* Tanbreez (2017). Tanbreez (2017) reports grades as follows: LREE: 0.5% and HREE: 0.15% in addition hereto 1.8% ZrO_2; 0.2% Nb_2O_5; and 0.02 Ta_2O_5. The detailed geological data are not disclosed, but initial drilling results suggest that Kringlerne has the potential to be the largest REE-resource in the world. The estimated mine throughput of about 1 Mtpa is envisaged to generate about 6,500 tpa TREO. The mining license for the Kringlerne project is currently under application.

Informal resource estimation for the Fen carbonatite in Norway, is reported (EURARE, WP1) to amount to about 486 Mt, including the søvite rock type only, grading about 0.9% TREO, and is therefore considered as one of the largest REE-deposits in the world. Other European projects that have been explored to the stage of informal resource estimation include Sarfartoq and Motzfeldt in Greenland, Olserum in Sweden, Aksu Diamas in Turkey, and Storkwitz in Germany. However, at the time of writing Fen is the only one of these deposits that continues to be the subject of active exploration.

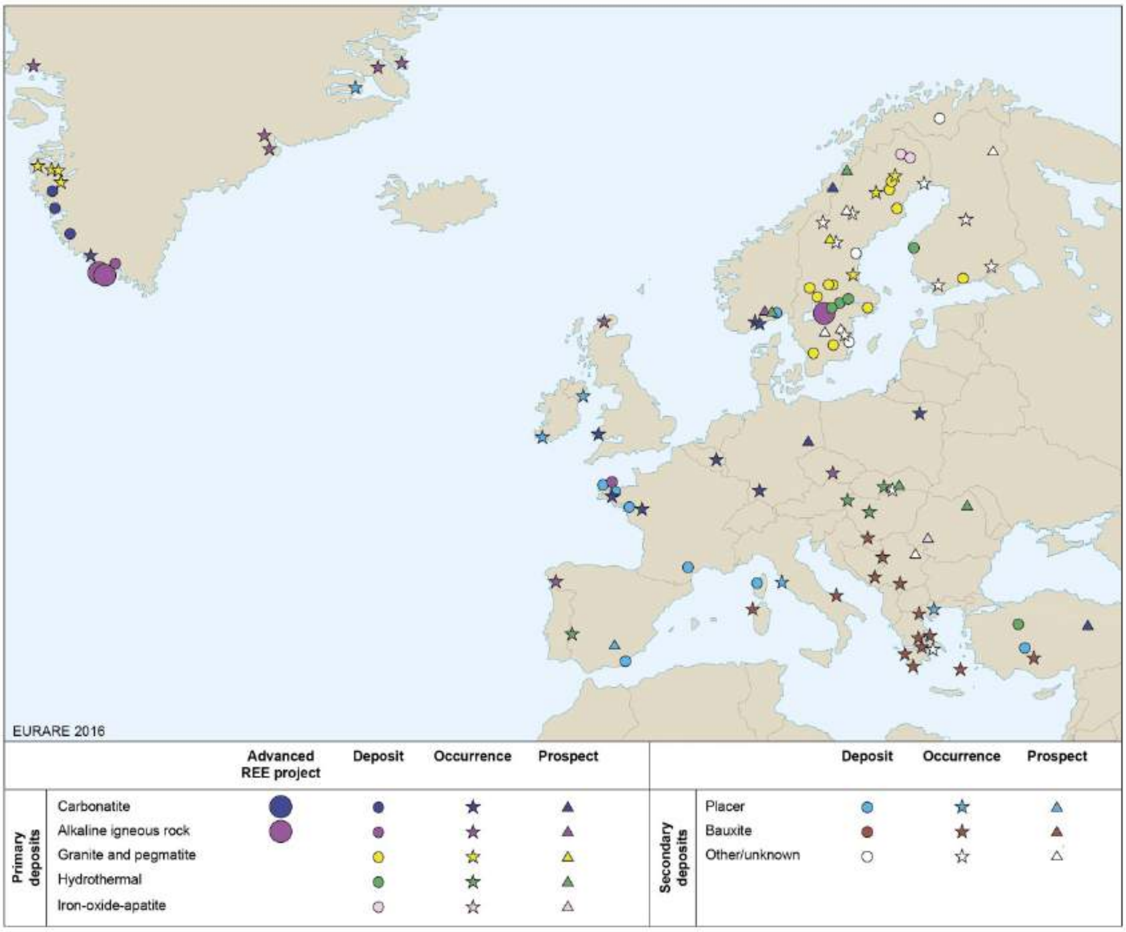


Figure 3.9. Location of REE occurrences, deposits and advanced stage projects in Europe. Details in Appendix II. Source: EURARE.

3.5 Initial steps in the REE-supply chain

3.5.1 Mining, beneficiation, and cracking (the typical mine site operations)

As a result of the wide range of mineralogy of REE ores, as outlined above, a number of different technologies can be used for the exploitation of these ores. Some are mined as the main product from hard-rock deposits (e.g. Lovozero, Russia); some are mined as by-products from large-scale iron mining operations as in Bayan Obo, China; some are extracted as by-products from heavy-mineral sand dredging operations, such as Manavlakurichi and Chavara in India; and some are leached out from ion-adsorption clay deposits, e.g. Xunwu/Longnan in South-East China.

Whatever method is used for mining, all REE-ores must be beneficiated to produce a REE concentrate. Each deposit will need a specific flow-sheet for the physical and chemical techniques and technology tailored to the particular operation, aimed for producing either REE-mineral concentrate or mixed REE-concentrate. Most REE operations currently follow one of three general routes:

1. *Hard-rock mining* (underground/open-pit): Drilling – blasting – hauling – crushing – milling – mineral separation – cracking the REE-bearing mineral
2. *Dredging operation*: Excavation – mineral separation – cracking the REE-bearing mineral
3. *Leaching operation*: Leaching ion-adsorption clay – collecting the pregnant solution.

Other procedures are also in development, for example for the extraction of REE as a by-product of aluminium production.

Typical techniques for beneficiation of hard-rock ores start with crushing and milling, where the ore is ground down to fine particles in order to free the REE-mineral(s) from the gangue minerals in the ore. For heavy mineral sands, crushing and milling may not be required. This stage is followed by specific treatments typically based on physical and chemical properties of the mineral, e.g. separation by gravity, flotation, magnetics, color or electrostatic separation technologies. The beneficiation product is a REE-mineral concentrate, which will subsequently be dissolved (cracked) in order to extract the REE. REE-mineral concentrates of some of the common REE-minerals, e.g. bastnäsite ((La, Ce) FCO_3), xenotime (YPO_4) and monazite ((Ce, La, Y, Th) PO4), for which routine cracking procedures exist are considered commercial products. This is currently not the case for less conventional REE minerals (e.g. eudialyte, synchisite, gadolinite, fergusonite, loparite and steenstrupine) for which no standard cracking procedures are available. However, in particular eudialyt, has been subject to new hydrometallurgical treatment tests as part of the EURARE project, (Davris *et al.* 2016) and may well make it possible to turn eudialyte-concentrates into commercial products in the future.

Most mining operations aim at adding as much value as possible to the product prior to shipment as well as reducing the amount of volume to be shipped. Therefore cracking is frequently done on the plant-site, producing a mixed REO-carbonate as the commercial product. Subsequently, the individual REE will need to be separated from this mixed product (see below).

For both route 1 and 2, the discharge composed by the gangue minerals forms the tailings. Mining REE as main products will frequently produce a tailings volume equivalent to 95% plus of the mill-feed; considering some of the advanced REE-projects this could amount to 1-3 Mtpa. Tailings may possess environmental risks and are therefore stored in large tailings-dams or used as back-fill in underground mines. Research conducted within the EURARE project assesses these environmental risks, with respect to radiogenic contents.

Ion-adsorption clays are typically leached with sodium chloride or HNO_3 and the leaching can be executed either in-situ, or as heap- or tank leaching. The ease of mining and processing compensates for the comparatively low grade of these 'ores'; it is not uncommon for 2-3,000 tons of clay to be mined and treated to recover one ton of REO. However, both methods have significant environmental consequences and the resultant environmental degradation in those areas where the ores are mined and processed has forced the Chinese government to implement strict environmental management standards (Roskill, 2011).

3.5.2 Chemical separation

With respect to physical and chemical properties, the REE have strong similarities; this makes the chemical separation of the individual REE a complicated process. Three types of separation technologies are applied by the industry (also illustrated in Figure 3.11.): (i) the fractional step method; (ii) the ion exchange method (IX), and (iii) the solvent extraction method (SX). The IX and

SX methods constitute the processing technologies applied on an industrial scale, close to 100% of which occurs in China (Izatt *et al.*, 2016).

To date, conventional chemical separation requires high CAPEX and OPEX, as well as cross-cutting knowledge of mineralogy, geology, chemistry and metallurgy. Up until February 2016, the discussions to minimize CAPEX centered on establishing a tolling station. It was argued that such a centralized facility would provide chemical separation services by processing a mixed REE solution (salts/oxides/chlorides/nitrates) from numerous suppliers of different REE-containing ore into individual REEs while complying with the quality requirements of potential buyers. However, two new separation technologies have been introduced in February 2016, both claiming to reduce CAPEX and OPEX significantly: (i) RapidSX^{TM} and (ii) Molecular Recognition Technology (MRT). The technology applied is briefly described below:

Fractional step method: Builds on the different solubility of the REE compounds in the solvent. This fractional step method has led to the production of most compounds of REE, which was a long process due to its complicated nature, specifically, the hundred fold repetition of the extraction for each element, which reduces the feasibility of this method at large-scale.

Ion exchange (IX) method: originally developed to remove the REE from U and Th, and later it was used to separate the REE. A single operation enabled the separation of multiple REE into high purity metals. The disadvantage was the lengthiness and need for discontinuity of the process, which led to the replacement of this method by solvent extraction. Nonetheless, ion exchange is still used for the production of high purity products.

Solvent extraction (SX) method: centers on a leach solution of REE which is forcibly stirred with an immiscible organic solvent which extracts the preferred elements and separation occurs after the disengagement of both non-miscible liquids. A conventional SX-plant has a multitude of mixer-settlers (also referred to as batteries) which require high capital investment.

RapidSX^{TM}: Innovation Metals Corp (IMC) released, in February 2016, a more efficient SX-technology, called RapidSX^{TM}. This had been developed with the aim of revolutionizing chemical processing, reducing both CAPEX and OPEX, and reaching product purities greater than 99%. The process has been tested on feedstock from Mineração Serra Verde ("MSV") deposit in Goias State, Brazil, and a patent application is pending.

Molecular Recognition Technology (MRT): Ucore Rare Metals (Ucore) and IBC Advanced stage Technologies Inc., released in February 2016 a white paper on a highly metal-selective green chemistry procedure, not based on the use of organic solvents; it has been applied for the separation of individual REE at >99% purity levels from pregnant leach solutions from the Bokan-Dotson Ridge deposit, Alaska (Press Release, 2015, March 2; Press Release, 2015, April 28) (Izatt *et al.*, 2016) argue that significant savings in CAPEX and OPEX can be achieved by use of MRT.

Generally, separation of the LREE, La-Ce-Pr-Nd, is relatively easy as opposed to HREE which pose more separation challenges as more specialized process knowledge is required to successfully separate them (Leveque, 2014). As illustrated in Figure 3.10, conventional separation technology requires several, *sequential* process steps to obtain an individual REE product, e.g. a REO such as neodymium oxide (Nd_2O_3) or lanthanum oxide (La_2O_3) that still contain proportions of other REE, e.g. 0.1% Ce and 0.01% Y. For instance, with solvent extraction methods, between 30 and 100 stages are needed for each separation cut between adjacent REE, to reach purity for individual REE of 99% up to 99,999% (5Ns) (Leveque, 2014).

Despite, or perhaps due to, non-existent patent-protection for the process, it remains challenging to successfully separate HREE. High demand is on tight and precise process control which involves both maintaining and adjusting operating conditions, and using solvents adequately under these conditions (Leveque, 2014). Solely one European player and one Japanese player were able to separate the HREE besides some of the Chinese companies in early 2014 (Interviews, 2013).

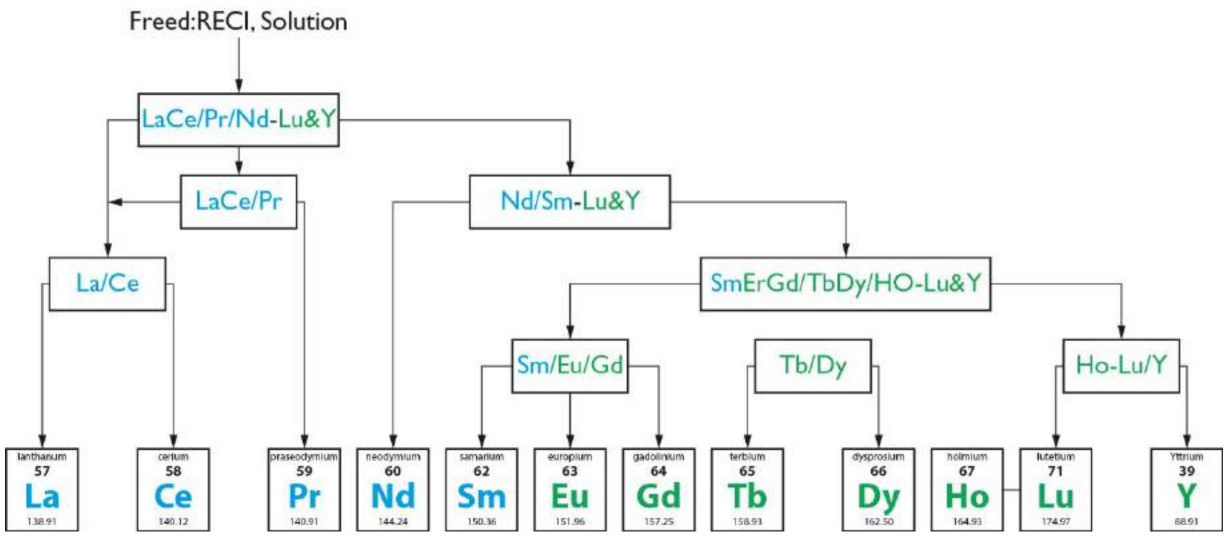


Figure 3.10. Example of a schematic REE solvent extraction (SX) separation process.
Source: adapted from Zhang and Zhao, 2016, p. 96.

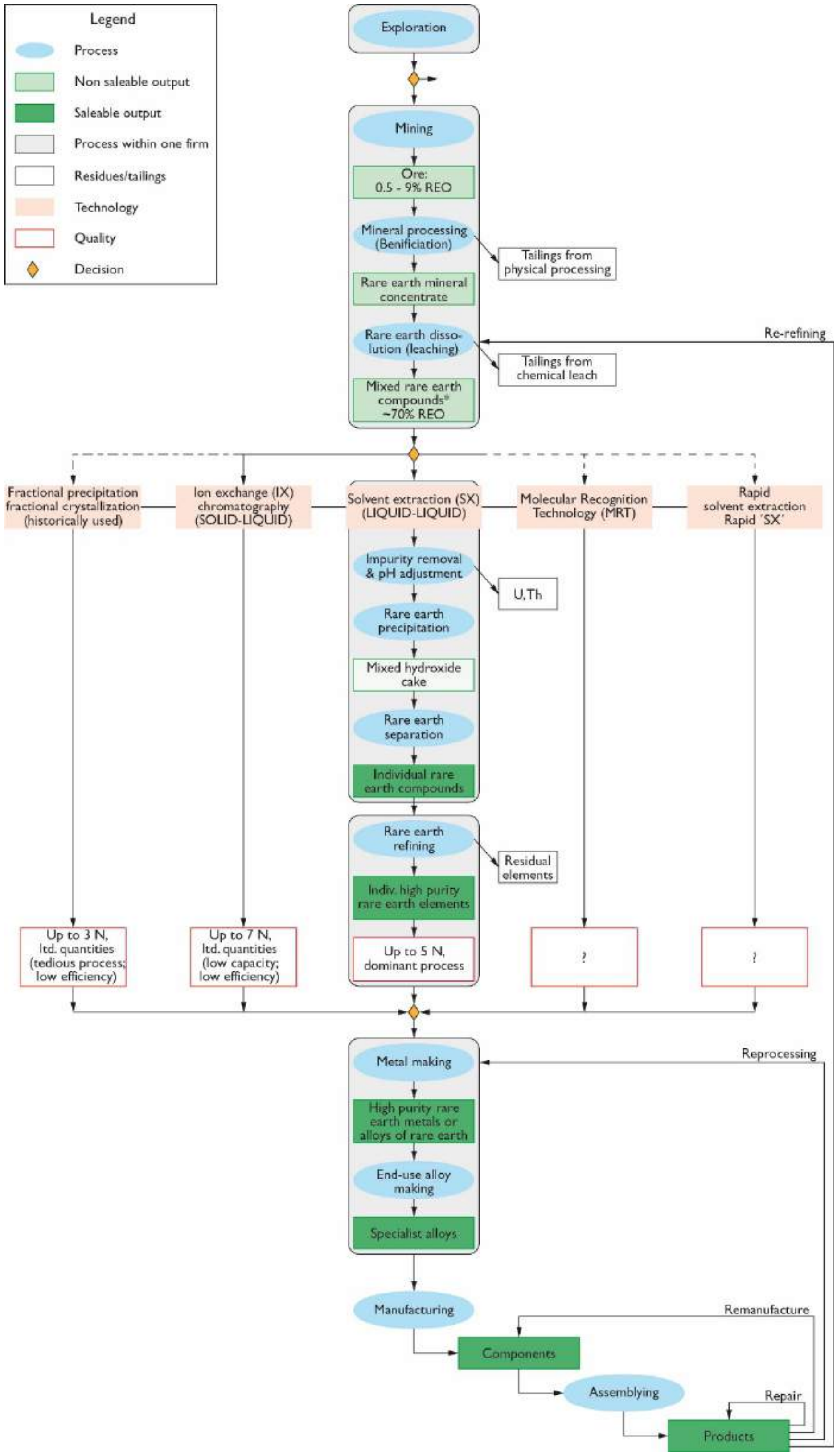


Figure 3.11. Generic material supply chain for REEs.
Source: MiMa-GEUS, 2016 based on Gupta and Krishnamurty, 2005.
Note: Purity indications for MRT and Rapid SX are not available but key to assessing the feasibility of these technologies. We have therefore left these boxes blank to indicate this lack of information.

The proposed Kvanefjeld project draws on SX to remove La and Ce from the RE-Chloride to produce La_2O_3, Ce_2O_3, mixed La-Ce-oxide, all at 99% purity, and a mixed critical REO (Pr to Y) (GMEL, 2015).

A new separation technology has been developed by the EURARE project, which has the potential to be an alternative to the MRT technology. The EURARE-technology involves appropriate ligands being grafted onto magnetic silica nanoparticles, which are introduced to the REE solutions. The produced adsorbents demonstrated rather quick adsorption kinetics, achieving at least 80% of maximal capacity within some few minutes. Considerable selectivity is observed, favoring retention of HREE (Dy in comparison with Nd and La) with distribution coefficients achieving values over 80:1. The magnetic nature of the nanoparticle allows for simple and robust solid/liquid separation with use of magnets. The principles of the EURARE technology are shown in Figure 3.12. Application of this technology in processing REE from both ore leachate and from dissolved components in recycling processes should offer efficient uptake and controlled release under precisely defined pH conditions.

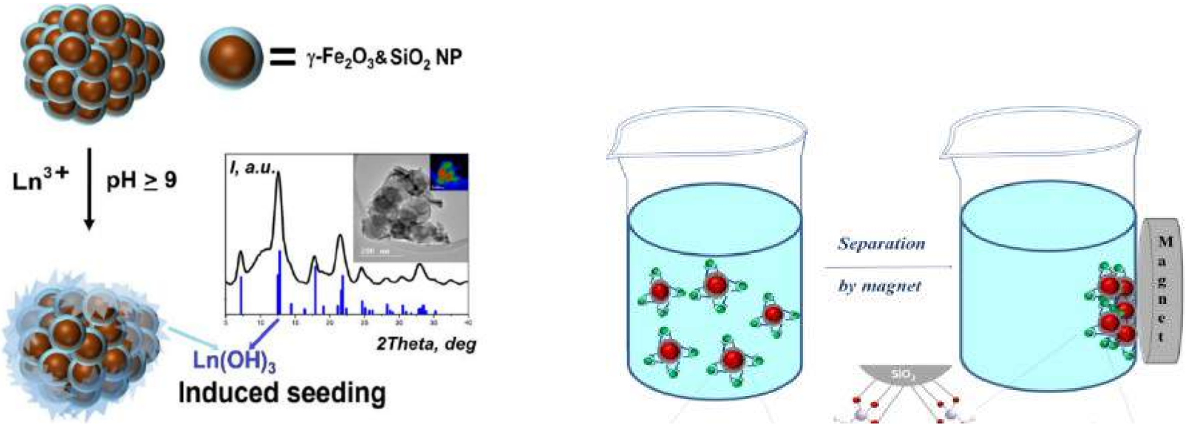


Figure 3.12. Principles in the magnetic nanoparticle separation technology.
Note: The figure to the left shows an approach for more specific extraction (separation of the other metals than REE), and the one to the right shows molecular recognition with a complexonate type ligand (while MRT is using crown-ether ligands). Complexonate ligands are derived from amino acids and are environmentally friendly in contrast to potentially hazardous crown-ethers.

Another extraction and separation technology developed by the EURARE project aims to both decrease the CAPEX and OPEX, and separate the HREE from aqueous chloride feed solutions using a neutral extractant (Larsson and Binnemans, 2015). Until now, neutral extractants could not efficiently extract REE from chloride solutions. The EURARE-technology involves an ionic liquid that effectively transports the REE from the chloride aqueous phase into the water-immiscible ionic liquid. This ionic liquid extraction technology will reduce CAPEX for the separation plant (less equipment and fewer extraction stages), and OPEX due to the exclusion of acidic extractants, easier waste water treatment. Moreover, the replacement of organic solvents by non-fluorinated water-saturated ionic liquids is an improvement on current technology, regarding health, safety and environmental standards.

A REE-separation plant 'REEtec' was established in Norway with a new and 'game changing' process for the manufacture of high purity REE (REEtec AS, 2016), though no further details have been released. REEtec is a sister company of Fen Minerals, one of the EURARE partners, and has been producing and selling small volumes of REE since 2015. A large unit with a capacity of several hundreds of tons for separation is planned to be installed in 2017, and it is anticipated for this unit to be operational from 2018 (personal communication with B. Bergfald, Dec. 2016).

4 Intermediate REE-industries/industrial sectors

The chemical- and physical characters of the REE's provide solutions for many challenges of modern business and home life. Figure 4.1 illustrates a general REE value chain from mineral raw materials up to final goods and services deployed on the market, including the production of REE salts and compounds and the manufacture of intermediate engineered products (magnets, catalysts, additives, etc.).

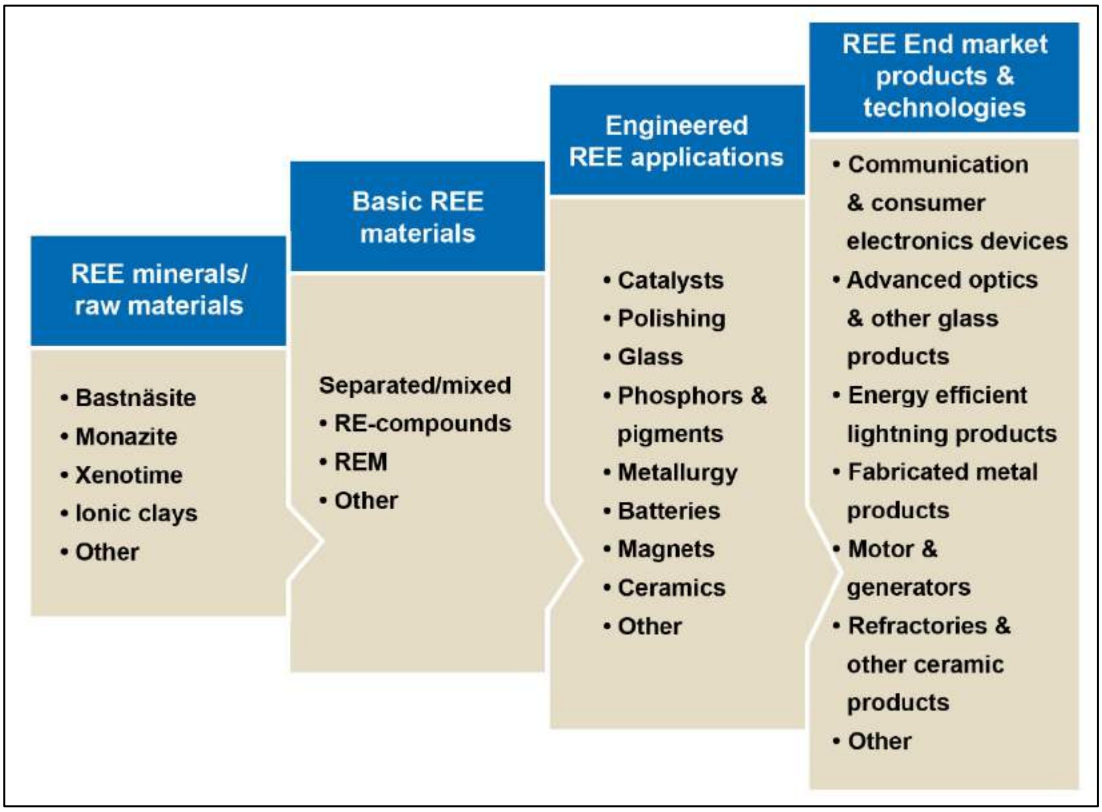


Figure 4.1. Simplified REE value chain.

- From mineral raw materials up to end-products and technologies.

Source: adapted from Rare Earth Technology Alliance, 2014.

REE- salts, -compounds and -metal alloys are used in a diversity of products and applications belonging to several market sectors, including among other: catalysts, magnets, glass and ceramics, metallurgy and batteries, lighting, electric and other light vehicles, appliances and consumer electronics, communication devices, defence technologies, chemicals, oil refining, electric power, health care products and other final goods and services (Figure 4.1).

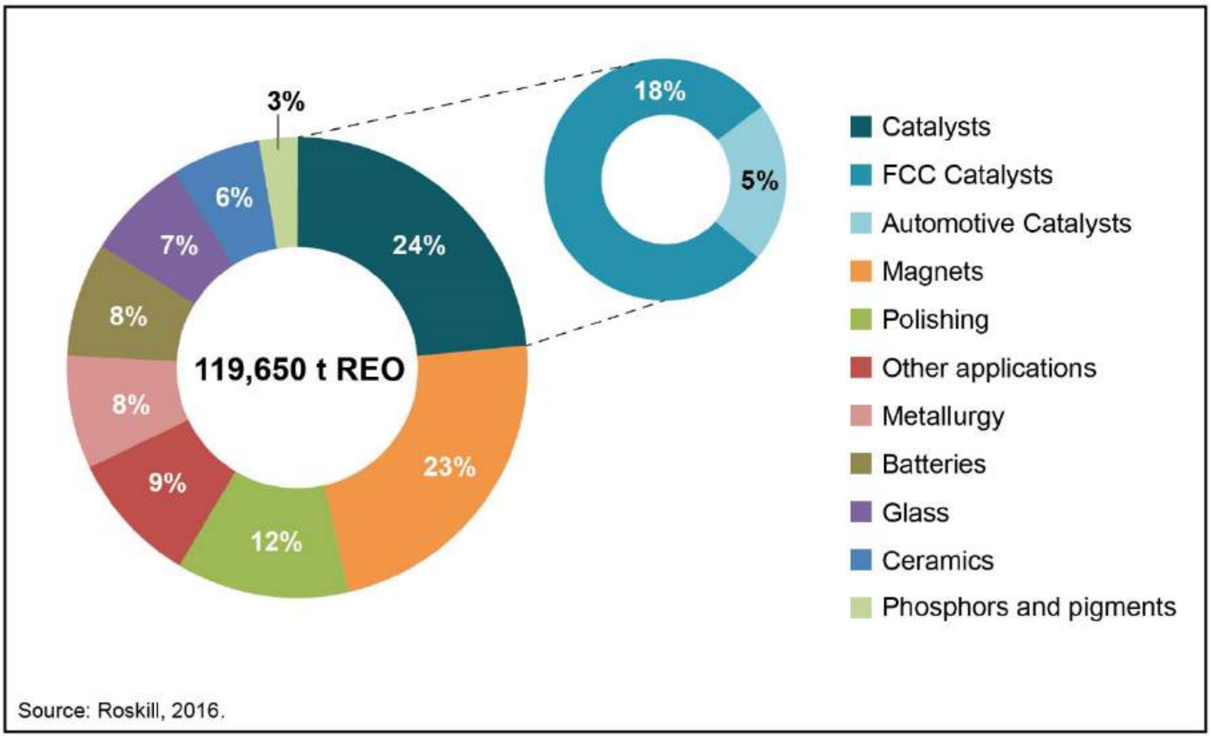


Figure 4.2. Estimated worldwide REO consumption in 2015[2].
Source: Roskill, 2016.

The global REOs consumption in 2015 was estimated to around 120,000 - 125,000 t REOs (Binnemans, 2015; Rollat et al., 2016)[3].

In the following subchapters an overview of the demand of REE for each of the nine intermediate sectors, commonly used for describing the REE-markets, is provided: (1) Catalysts; (2) Polishing; (3) Glass; (4) Phosphors and pigments; (5) Metallurgy; (6) Batteries; (7) Magnets; (8) Ceramics; and (9) Others. The relative importance of the sectors is shown in Figure 4.2.

4.1 The REE materials used by the industrial sectors

The REE-consuming sectors demand specific type and quality of the REE-products to fit to their needs; e.g. some sectors will need REO or REE-carbonate, whilst other sectors demand high purity of REM. Thus a wide range of REE-products are produced, tailored to each of the sectors and sub-sectors; the vast majority of these products are manufactured in China.

Purity is the main quality parameter applied for measuring the REE-products. The purity refers to the relative, thus proportional, maximization of some elements in the final REE-products as compared to the others. In other words, the product CeO_2, for example, could have a purity of 99.9% (see for

[2] RREE share in FCC catalysts include also REEs used in catalysts formulation in other chemical processes, such as hydrogenation and dehydrogenation, polymerisation, double bond isomerisation.
[3] Moreover Mkango Resources Ltd reports (http://www.mkango.ca/s/rareearths.asp) that “Adamas estimates that global TREO demand was approximately 125,000 tonnes in 2015 and will increase for individual REOs by 1 per cent to 13 per cent annually through to 2020. Adamas forecasts that in 2020, global TREO demand will conservatively amount to approximately 150,750 tonne”

instance Panadyne Abrasives, 2012-2016), or in industry jargon ‘three N’ or ‘3N’. This explains that the cerium oxide contains 99.9% cerium, yet traces of the other REE are still present which jointly account for 0.1%.

The configuration of the REE chemical separation plant is engineered to match specific purity levels defined by the industrial user, and the processes occurring during the chemical separation are therefore tightly controlled (see Figure a). Commonly, the client will test the REE-product in a qualification process that can take from a few weeks up to a year (Mintek, 2013; Lynas Annual Report, 2013). As a general rule, high-N products are orders of magnitude more expensive as opposed to low-N products. Consumers therefore try to find the adequate balance between price and quality.

The aim of maximizing purity of REOs is to reach the specifications set out by the intermediate industrial users of these separated REE, e.g. purity levels in the range of 99 to 99.9999%, depending on intermediate industry requirements (Leveque, 2014). For instance, firms which produce fluorescent lamp bulbs and use REE-phosphor-based powders to coat the bulbs demand purities of up to 99.9999%, as the purity of the specific REE (Eu, Tb, Y) affects whether the bulb will be able to meet the light spectra it should be showing.

The downstream segments of the filament of REE-based permanent magnets require several processing steps to obtain the material magnet producers require as input. The first segment in this REE-permanent magnet manufacturing process sequence is metal making. The individual REO are fed into the process which can involve amongst others molten salt electrolysis and electrolysis of REE-bearing ionic liquids, producing high purity REM, such as Nd metal, or alloys of REE, such as mischmetal (La-Ce; La-Ce-Pr; or La-Ce-Pr-Nd) used in the iron and steel industry and in the production of La-rich battery alloys (Kingsnorth, 2014), lighter flints or ferro-alloys (GWMG, 2012 and Roskill, 2011).

Didymium, a mixture of the elements praseodymium and neodymium, can be a further output of the metal making process which is supplied to magnet alloy producers. Residues such as SEG (Sm-Eu-Gd) and the heavier fractions are sold on for further separation (Roskill, 2011). High purity REE-metals and other metals are then used to produce specialist alloys, or so-called “super alloys” of aluminum or permanent magnet alloys such as NdFeB or SmCo (Roskill, 2011).

4.2 Catalysts

Catalysts are substances used to increase the rate of a chemical reaction by reducing the activation energy, i.e. the energy required by the system in order to convert the reactants into the products. Catalysts do not actively participate to the reaction; they are modified or consumed only in very minor quantities during the reaction itself.

The two main areas of applications for REE in the catalysis sector are associated to the formulation of catalysts for the Fluid Catalytic Cracking (FCC) in the petroleum processing, as well as in catalysts aiming at reducing emissions of pollutants within the exhaust gases originated from automobiles and other combustible engines: these applications account to respectively about 65-70% and 20-25% of the overall demand of REE in the catalysts sector (see Figure 4.2, Roskill, 2016).

Several of the REEs are used in catalysts formulation, both in processing and in automotive applications: they are mainly La, Ce and Nd and correspond to around 24% of total global REEs consumption (see Figure 4.2, Roskill, 2016).

4.2.1 Fluid Catalytic Cracking (FCC) catalysts

FCC process is used in the petroleum industry to obtain light fractions such as LPG and gasoline from high-molecular weight hydrocarbon fractions. Due to the higher octane rating of gasoline and higher yield in olefinic gases, this process has gradually substituted the thermal cracking. In particular, the employment of La, Ce and Nd rose in the 1960s, when zeolite-based cracking catalysts started to be used in oil refineries. These kinds of catalysts are typically constituted by a crystalline zeolite (representing 5-40% of the catalyst weight), i.e. the active component acting as a sieve to filter the crude oil, by a matrix typically of alumina (5-25 wt%), by a binder such as silica sol or gel (5-25 wt%) and by an inert matrix, i.e. the clay (Trigueiro et al., 2013; Henriques, 2012; Roskill, 2016). More details on the REE used for FCC shown in Table 4.1 to 4.4. Information about purity is based on American Elements and Metall Rare Earth Ltd.

Table 4.1. REE used for FCC

Main area of application	Main RE products	Main uses	REO (% of global REO consumption) - 2015 estimates
FCC	La, Ce, Nd Mainly REO and RE-compounds used; dominant purity specifications are 3-4Ns and 2-5Ns respectively.	Zeolite formulation: REE can be included in the catalysts formulation by exchanging part of the zeolite. The zeolite acts to retain catalyst effectiveness and enhance the hydrothermal, structural and chemical stability, thus obtaining a high yield in valuable petroleum products by cracking the heavier oil fractions. REE-containing zeolite catalysts: Around 2-4 wt% REOs (Zhao et al., 2017; Innocenzi et al., 2014), though the amount of REO used can vary according to the features of the petroleum treated. REO-mixture: Oxides of Ce (46%), La (20%), Nd (15%) or a La-rich mixture composed by up to 80% La-; 6-10% Ce-, and 15% Nd-oxides (BASF, 2017 - formerly Engelhard).	About 65-70% of the overall demand of REEs in catalysts (see Figure 4.2, Roskill, 2016).

Table 4.2. The FCC market trends/expectations/emerging markets

Opportunities	Increase of crude oil refining capacity and higher demand for lighter petroleum products (e.g. the relevant demand for gasoline in China, the increasing demand for propylene) New emission standards and regulations requiring for products with higher quality specifications.
Threats	Trend of replacing FCC process with hydrocracking of vacuum gas oil (VGO) to produce light products. Diffusion of "green technologies" (e.g. wind turbines, hybrid and electric cars) or other processes alternative to the fossil-based ones.

Table 4.3. The REE substitution in the FCC sector

	Description/comments/notes
Present situation	La is crucial for FCC catalysts because it provides thermal stability and selectivity, and substitutes forLa in FCC catalysts are known (Öko Institut, 2011). The only alternative can be considered the use of fluid cracking catalysts based on zeolites without REEs, but this leads to products with poor, yet still acceptable, performance (Binnemans *et al.* 2013a).
Trends	Experts state that there is an additional impetus for reduction or substitution due to the increasing prices of REEs like lanthanum (Öko Institut, 2011).

Table 4.4. REE recycling in the FCC sector

	Description/comments/notes	Recycling capacity/production (tpa) global/EU
Present situation	The large amount of REOs (up to 4 wt% according to the features of the petroleum treated) contained in the FCC catalysts represents a valuable potential for recycling. Currently some research activities are moving in the REEs recycling in FCC sector (Innocenzi et al., 2014; Zhao et al., 2016)	n.a.
Challenges	It is an open question whether a recovery of the REE (mostlyLa) from FCC catalysts could be interesting from an economic point of view in the next years. This is mainly depending on the price development of La (ÖkoÖko Institut, 2011).	n.a.

4.2.2 Automotive catalysts

Along with applications in petroleum processing, catalysts for automotive represent another large market for REO (i.e. 20-25% of the TREO demand for catalytic processes, see Figure 4.2, Roskill, 2016), aiming at reducing emissions of pollutants within the exhaust gases originated from automobiles and other combustible engines. Some details on REE usage in the automotive catalysis are shown in Tables 4.5 to 4.8. Information about purity is based on American Elements and Metall Rare Earth Ltd.

Table 4.5. REE used for automotive catalysts

Main area of application	Main RE products	Main uses	REO (% of global REO consumption) - 2015 estimates
Automotive catalysts	Ce, La, Nd Mainly REO and RE-compounds used; dominant purity specifications are 3-4Ns and 2-5Ns respectively.	CeO_2 or other Ce-compounds are used: (i) keeps up the catalysts efficiency by avoiding the formation alpha alumina phase; (ii) improves the oxidant features of the overall system and facilitates a water-gas shift on reaction.	About 20-25% of the total REEs demand (2015) for catalytic processes (see Figure 4.2, Roskill, 2016).

Table 4.6. The automotive catalysts market trends/expectations/emerging markets

Opportunities	The amount of REEs required for automotive catalysts' formulation depends on vehicle type (petrol, diesel or hybrid vehicle) and size. China is currently leading the worldwide vehicle markets (in 2015 it accounted for about 27% of the global production) (OICA, 2015). In addition, the demand for automotive catalysts is further affected by the fact that, unlike European customers, Chinese customers usually prefer large-size vehicles (e.g. SUVs), entailing major amounts of catalysts (Roskill, 2016). the automotive sector is influenced by changes in emissions standards: even though European regulations are more stringent, USA and BRIC countries are fostering a tighter emission control (e.g. India's and China's emission standards are now respectively equivalent to the ones of Euro III and Euro IV), thus offering opportunities for REEs (mainly Ce) to be used in catalysts.
Threats	Diffusion of "green solutions" for automotive sector (e.g. hybrid and electric cars) may reduce the demand for these products.

Table 4.7. REE substitution in the automotive catalysts sector

	Description/comments/notes
Present situation	In automotive catalysts REEs (mostly cerium) are responsible for enhanced thermal stability and emission reduction. Currently no substitution materials are known for the REEs used for automotive catalysts (Öko Institut, 2011).

Table 4.8. REE recycling in the automotive catalysts sector

	Description/comments/notes	**Recycling capacity/production (tpa) global/EU**
Present situation	Currently, recycling activities on catalysts from the automotive sector are based only on the recovery of platinum group metals (PGM) from catalytic converters. "Cerium oxide is not commercially recovered from catalytic converters; instead, it is sent to landfills along with the waste produced by processing the monoliths for their PGM content" (Biswas, 2013).	n.a.
Trends	The recycling of catalytic converters will continue to rely on the economic viability of recovering their PGM content (Biswas, 2013).	n.a.
Challenges	There are currently no commercially viable technologies to recover the cerium content of catalytic converters (Biswas, 2013).	n.a.

4.3 Polishing

REE-based polishing powders are essentially employed to finish the surface of glass products and electrical components, such as display panels, flat glass, optical glass and consumer electronics. Moreover, REEs (i.e. CeO_2) can also be used in jewellery as alternative to jeweller's rouge, i.e. a very fine powder of ferric oxide, to polish precious metals and stones (Roskill, 2016).

The global REE-demand in polishing was estimated to account for about 12% of the total global REEs consumption (see Figure 4.2, Roskill, 2016). Although CeO_2 is largely the most used REE compound, polishing powders can also contain traces of other REEs with minor polishing properties (i.e. La, Pr, Nd). The main advantages in using CeO_2-based polishes, making them the most used glass polishes, are related to the faster polishing operations, in which CeO_2 is mixed with water, and easier cleaning after use. In particular, most of the Ce is employed in traditional glass polishing applications (e.g. display panels, flat glass and optical glass, silicon microprocessors and disk drives), while the rest of the Ce is used in consumer electronics. Further details on the REE used in the polishing sector are shown in Tables 4.9 and 4.10. Information about purity is based on American Elements and Metall Rare Earth Ltd.

Table 4.9. REE used in the polishing sector

Main area of application	Main RE products	Main uses	REO (% of global REO consumption) - 2015 estimates
Display panels	Ce (mainly) Mainly REO and RE-compounds	CRT displays, liquid crystal displays (LCDs) and flat panel displays (for televisions, computer monitors, smartphones, tablets).	Around 12% of the total global REEs consumption (see Figure 4.2, Roskill, 2016).
Flat glass	Ce (mainly) Mainly REO and RE-compounds.	Decorative glass, mirrors, wired glass windows.	
Optical glass	Ce (mainly) Mainly REO and RE-compounds.	Lenses for personal cameras, sight corrective lenses, spectacles.	
Consumer electronics	Ce (mainly) Mainly REO and RE-compounds. High N-products required	Glass hard discs (GHDs), photomasks and silicon wafers for integrated circuits.	

The global economic downturn in 2009 and the later increased prices of Ce in 2011 significantly affected the overall market of REEs for polishing applications, which constantly had increased during the previous years, following the demand for polished glass and glass-like components in consumer electronics and optical products.

High prices in 2011 reinforced the role of China as the worldwide larger producer of Ce polishing powders, also considering its dominance in manufacturing of glass products and electrical components. Research activities are being carried out in China to improve the quality of polishing powders based on CeO_2, in particular by applying the CMP (i.e. Chemical Mechanical Planarisation) method to obtain higher grades powders for the polishing of electronic components (Roskill, 2016).

The price spike in 2011 boosted the industrial research both for improved technical solutions enabling the reduction of Ce use, as well as for alternative materials such as zirconia (especially for lower quality products). However, as price decreased again, these efforts to find substitutes were put on hold and the traditional use of CeO_2 were maintained.

Within the same approach, polishing industry developed solutions enabling the recovery and re-use of slurries from polishing operations: this led to the implementation of recycling steps within several polishing plants.

Table 4.10. Market trends/expectations/emerging markets in the polishing sector

Display panels	REEs consumption in display panels polishing is almost steady. The flat screens require less polishing than CRT displays: these reductions in the market are compensated by the large diffusion of flat screen televisions and computers, including large-size screens products, as well as the high demand for smartphones and tablets.
Flat glass	An almost steady demand.
Optical glass	Increasing demand is expected in the areas of optical glass products for personal, medical and scientific uses, such as sight corrective lenses or personal camera lenses. However, unpolished plastics are threating the polished glass market (e.g. in spectacles, the glass lenses are substituted with lighter weight polycarbonate lenses).
Consumer electronics	The consumer electronics sector, including glass hard discs and photomasks/silicon wafers for integrated circuits, has grown significantly and is expected to continue growing in the short-term. These applications require a high purity CeO_2. Within a longer-term scenario, however, solid state HDDs and cloud storage services could impact on the demand for component polishing in electronic applications.

4.4 Glass

REEs are used to provide specific properties to several kinds of glass for different purposes, from display panels to specialty optical glasses: they can act as colouring agents, as protective agents against different kinds of radiation (e.g. infrared, X-ray, UV), or can be used to remove impurities from glass, thus acting as decolouring agents.

The worldwide amount of REE employed as additives in glass manufacturing in 2015 was estimated to cover about 7% of the global consumption (see Figure 4.2, Roskill, 2016). Ce is the dominant REE used in this sector, though also La, Er and minor amounts of Gd, Nd, and Y are also employed in different technological applications within the glass sector. Moreover, small quantities of other REEs can be used: they include Pr, Sm, Eu, Ho and Tm.

Ce is utilised as a glass stabiliser to contrast effects of UV and high-energy rays (for example in display panels and in the bottling industry) or as decolouring agent to remove natural impurities from glass, such as iron oxides. In particular, a specific market for CeO_2 exists in Japan, where UV-resistant glass for vehicles is required by legislation to be used in vehicle front windscreens. Further market details are given in Table 4.11. Information on purity is based on American Elements and Metall Rare Earth Ltd.

Presently, display screens account for most of the demand for REE-glass additives, while the rest of the REE demand in glass sector is mainly covered by optical glass.

USA represents the principal market for glass coating based on REEs (e.g. used in scientific lenses, laser cavity mirrors, laser printer mirrors, slides for electron microscopy) mainly related to the defence sector. For glass coating, only high purity 4N-products of CeO_2, Ce-fluoride, La_2O_3 and Nd-fluoride, with addition of iron oxide, can be employed (Roskill, 2016).

Substitutes: Research activities focusing substitution and reduction of REE have been performed only for the past five years. In particular, Chinese industry is pursuing improvements in La-based optical glass, considering the foreseen future growth in demand for optical glass associated to the increasingly diffusion of smartphones, tablets and other electronic displays. The very specific role covered by REE-based additives used in glass manufacturing hinders the potential substitution of such compounds with other materials for most of the applications within this sector.

Table 4.11. REE used for the glass sector

Main area of application	Main RE products	Main uses	REO (% of global REO consumption) - 2015 estimates
Decolouring agents	Ce, Nd, Er Mainly REO and RE-compounds; purity in the range of 2-5Ns	Ce is used to remove natural impurities from glass; Nd_2O_3 or Er_2O_3 and didymium compounds in high level applications.	Around 7% of the total global REEs consumption (see Figure 4.2, Roskill, 2016).
Refractive index enhancing agents	La, Ce, Er, Gd, Nd, Yb, Y Mainly REO and RE-compounds; purity in the range of 2-5Ns	La_2O_3, and in some case Gd_2O_3 or Y_2O_3: used in optical glass for small lenses for consumer electronics and photovoltaics. La_2O_3 increases the refractive index of these kinds of glass. Er_2O_3 (but also La and Ce) is used as dopant in optical fibres for communication cabling. Nd-doped glass is used in optic fibre temperature sensors. Yb is used in high power optical fibres.	
Radiation/UV protection agents	Ce Mainly REO and RE-compounds; purity in the range of 2-5Ns	Ce hinders the oxidation of the metal ions present in the glass, avoiding or limiting darkening or browning of the glass over time due to UV, X-rays, nuclear or other high energy radiation.	
Colour filtering agents	Nd, Ce, Sm, Eu Mainly REO and RE-compounds; purity in the range of 2-5Ns	REEs used to filter specific colours from the light spectrum, in applications such as safety goggles and glass containers. Nd_2O_3 is used to filter yellow light (lamp workers, welders and glass blowers goggles). Sm_2O_3 is added to filter infrared light. Eu_2O_3 is added to filter UV radiation.	
Colour tinting agents	Nd, Pr, Er, Ce, Eu, Ho, Sm, Tm Mainly REO and RE-compounds; purity in the range of 2-5Ns	Nd, Pr, Er and Ce are used in glass colour tinting (providing respectively violet or pink, green, pink, or yellow colour).	

Recycling: The small amounts of REEs required in each glass product, as well as the large number of different products in which REE are used, make collection and recycling in glass industry an economic challenge.

4.5 Phosphors and pigments

Phosphors are defined as "optical transducers providing luminescence" (Rare Earth Technology Alliance, 2014). Within the phosphors, activators determine the emission spectra while hosts convert the energy gathered by the phosphors into radiant energy (light). REEs in the phosphors sub-sector are employed as doping elements, activators and in the host mixtures.

REE-pigments are used to stain ceramic tiles and to impart colour/improve the finish of ceramic glazes (Roskill, 2016).

The 2015-demand of REEs for phosphors and pigments was estimated to represent about 2% of the total global consumption of REEs: of this, around 80% of REOs are used in phosphors, while the remaining is employed for pigments (see Figure 4.2, Roskill, 2016).
Y_2O_3 is by far the most used REO in phosphors and pigments, followed by Pr_6O_{11}, CeO_2, La_2O_3 and Eu_2O_3. However, the type of REEs to be used in phosphors, their relative composition and content are dependent on the specific application and are typically considered proprietary information. Generally, the oxides of Y, Gd, and La are mainly employed as host materials in phosphor production. Several other REE find application in the phosphor sector primarily as activators, with a relevant role covered by Eu-activated red phosphors. Eu is widely used in TV and PC monitor screen panels and to a lesser extent in lighting and medical imaging, such as X-ray. Further details on the REE used in the phosphors sector given in Table 4.12 and 4.13; details on REE used in the pigments sector are shown in Table 4.14. Information about purity is based on American Elements and Metall Rare Earth Ltd.

Table 4.12. REE used in the phosphors sector

Main area of application		**Main RE products**	**Main uses**	**REO (% of global REO consumption) - 2015 estimates**
Lamps and lights	**1.** Fluorescent lamps; **2.** LED lamps for domestic lighting and for LCD backlighting	1. Eu, La, Ce, Tb, Y; 2. Eu, Ce, Y, Gd, Lu, Pr, Tb Mainly REO and RE-compounds in the purity of 4-6Ns and 2-5 Ns respectively	**1.** Fluorescent phosphors; **2.** LED phosphors	Around 1.6% of the total global REEs consumption, corresponding to about 80% of REEs employed in phosphors and pigments sector (see Figure 4.2, Roskill, 2016).
Displays	1. CRT displays; **2.** PDPs; **3.** Other displays	1. Y, Ce, Eu, Gd, Tb; 2. Eu, La, Ce, Y, Tb, Gd; 3. Y, Ce, Tb, Eu Mainly REO and RE-compounds in the purity of 4-6Ns and 2-5Ns respectively	Display phosphors	
Medical sector	1. Medical radiography; **2.** Signage applications; **3.** Detection of counterfeit goods and for security	1. Eu, Y, Gd, La, Tb, Tm; 2. Eu, Dy; 3. Y, Yb, Er, Ho, Tm, La Mainly REO and RE-compounds in the purity of 4-6Ns and 2-5Ns respectively	1. X-ray phosphors; **2.** Long-persistent phosphors; **3.** Up-conversion phosphors (to convert infra-red into visible light)	

Table 4.13. Market trends/expectations/emerging markets in the phosphors sector

Lamp phosphors (Fluorescent and LED phosphors)	Boosted by regulatory (including EU legislation in 2009) and standardisation aspects, or by financial incentives concerning energy-efficient lighting, fluorescent lamps continue to replace incandescent lamps. LED lamps use respectively 80-90% and 40-60% less energy, compared to incandescent and fluorescent lamps (Green Living Ideas; Terra Pacific USA Inc., 2014). The LED technology require smaller amount of REE-phosphors and the lamps have a longer lifespan than the fluorescent lamps (approximately 50,000 hours and 10,000 hours respectively) (McKinsey, 2012). The requirement of HREE is significantly lower in LEDs than in fluorescent lamps for equivalent lumen output. McKinsey (McKinsey, 2012) estimated for the year 2016 an overall market size for LED, in terms of value, of about 41% (12% in 2011), while 51% (88% in 2011) is covered by other lighting technologies. LEDs diffusion is also related to their use as LCD backlights, in substitution to fluorescent CCFLs (cold cathode fluorescent lamps): LED penetration in this application (excluding OLEDs) was estimated to around 96% in 2016 (39% in 2011) (McKinsey, 2012). LCDs are currently the most important kind of flat panel displays: they typically use a liquid crystal layer (not containing REEs) to provide colour, with backlight lamps to illuminate it. Excluding OLEDs, in 2016 the penetration rate for phosphors as backlights associated to LEDs were estimated to exceed 99%: indeed, while CCFLs still have a minor role (around 3%) in backlights for LCD TVs, LED are almost monopolising backlights market for monitors, portable PCs and handhelds (McKinsey, 2012).
Display phosphors	REE-phosphors intervene in providing colours and illumination. The substitution of CRT displays with flat screens such as PDPs for large-size television screens, requiring less REE-phosphors, has significantly impacted on the consumption of REE in this sector: although small quantities of CRT displays are still produced in industrialising countries as a low-price alternative to flat panel displays (FPDs), REE-phosphors for CRT displays cover a minimal fraction of phosphors used in these applications. An emerging technology in this framework is the Organic LED (OLED) displays; OLED is mainly applied into smaller FPDs like tablets and smartphones, where they are estimated to account for about 20% of the related market (UBI Research, 2016), which is still ruled by backlight LCDs. OLEDs can potentially be employed in automotive tail lights and in large-size television screens, representing a potential valuable alternative to LED-based LCDs, particularly in the case of falling prices: they indeed offer a wider viewing angle, a thinner and more lightweight display, and a broader range of colours.
X-ray phosphors	The use of phosphors in medical X-ray imaging allows enhancing the quality of the pictures thanks to the capacity to transform X-rays to visible range and consequently reducing exposure time. However, the REEs market for X-ray application has decreased since the introduction of digital radiography, which is a faster technology entailing the use of less radiation and allowing improved images.

Substitution. The research of alternative materials to substitute REEs in phosphors applications have been mainly boosted by price spike in 2011. Despite some improvements in efficiency have been reached in lighting applications, thus enabling to partially reduce REE consumption, the identification of substitutes for REEs is very hard, essentially due to the high purity required for phosphors.

Recycling: Within a circular economy approach fostering the reduction of raw materials demand, recycling solutions have been investigated for phosphors recycling. In particular, Rhodia-Solvay developed a patented process (2012) to recover and recycle REEs from fluorescent lamps; this process mainly consists in physical and chemical steps and it allows recovering up to 95% of REEs contained in a fluorescent lamp (Walter, 2011). The plant reached its full capacity (i.e. 2,500 tpy of processed power) in 2013 (Binnemans et al., 2013c), even though further improvements are still required to reduce the overall costs.

Table 4.14. REE used in the pigments sector

Main area of application	Main RE products	Main uses	REO (% of global REO consumption) - 2015 estimates
Ceramic colour staining	Pr, Y, Nd, Er, Ce	Pr_6O_{11} covers most of the REEs demand for pigment application; for example it is mixed with different matrix to produce yellows (3-8% of Pr_6O_{11} in a zirconium silicate matrix) (Visentin et al., 2011), browns, oranges and greens (yellow stain mixed with a vanadium-based blue) colourants. Currently, no substitutes for Pr have been identified in ceramic colour staining. Other pigments used in ceramic glazes are orange, light purple and pink colour, created respectively starting from yttrium oxide, neodymium oxide and Er_2O_3. CeO_2 is used as opacifier, to provide white colour, or as additive to enhance glaze's shine. Pigment's market is mainly focused in China and Europe (Spain and Italy in particular).	Around 0.4% of the total global REEs consumption, corresponding to about 20% of REEs employed in phosphors and pigments sector (see Figure 4.2, Roskill, 2016).

4.6 Metallurgy

REEs are used in the manufacture of iron and steel to improve performances and properties of the final products. Among their different applications in metallurgical industry, REEs are employed in construction and automotive sector, including Hybrid Electric Vehicles (HEV) and Electric Vehicles (EV), in portable electronics, in fuel cell components, in high strength metals for aircraft manufacture and in magnesium alloys.

The REO demand for metallurgical applications in 2015 was estimated to account for about 8% of the total worldwide REOs consumption (see Figure 4.2, Roskill, 2016): in particular, Ce and La are by far the most used REEs in this field. In metallurgical applications REEs are usually applied as mischmetal or as REE-silicide. Mischmetal is an alloy made by a mixture of REE obtained by an electrolytic extraction; although different composition are available on the market based on Ce content, a typical mischmetal composition is: 48-56% Ce, 25-34% La, 11-17% Nd, 4-7% Pr, minor amounts of other REEs, 0.2-0.5% Fe and other impurities such as Si, Mg, S and P (MSE Supplies LLC, 2017; Metall Rare Earth Ltd, 2017). REE-silicide, which is usually less reactive than mischmetal, is instead constituted by REEs, silicon and iron in about equal proportions. Further details on the REE used in the metallurgical sector are shown in Table 4.15. Information about purity is based on American Elements and Metall Rare Earth Ltd.

In particular, the overall amount of REEs (mischmetal or REE-silicides) used to remove impurities in iron and steel casting have partially declined, due to the shift by foundries in Europe and North-America to magnesium ferrosilicon (FeSiMg) nodulisers containing much smaller amounts of REEs. Moreover, the employment of Ce to remove traces of sulphur from the molten materials, typically after deoxidation and desulphurisation stages, or to improve the mechanical properties (e.g. corrosion resistance) of the final product is decreasing. REE are where possible substituted by less expensive metals such as magnesium, calcium and other Group II metals are commonly used for such purposes.

Table 4.15. Consumption of REE for the metallurgical sector

Main area of application	Main RE products	Main uses	REO (% of global REO consumption) - 2015 estimates
Cast iron/steel	Mischmetal (mainly Ce, La, Nd, Pr), Ce Mainly REM and RE-compounds; purity in the range of 4-6Ns	The addition of REEs (as mischmetal or as Ce-rich silicide) in cast iron (e.g. 0.1% in case of mischmetal) (Jha, 2014) allows reducing or even removing impurities (e.g. oxygen, sulphur, lead, antimony) affecting morphology and properties of the cast material.	Around 8% of the total global REEs consumption (see Figure 4.2, Roskill, 2016).
HSLA steel	Mischmetal (mainly Ce, La, Nd, Pr) Mainly REM and RE-compounds; purity in the range of 4-6Ns	High-Strength-Low-Alloy (HSLA) is mainly used in the care industry (body, chassis and mechanical parts). HSLA steels currently account for about 40% of the total global steel demand (Largo Resources Ltd, 2017). Ce or mischmetal: used in small amounts, i.e. minor than 1 wt% (Jiangxi Xinji Metals Co. Ltd, 2017).	
Stainless steel	Y, Ce Mainly REM and RE-compounds; purity in the range of 4-6Ns	Highly alloyed stainless steels. Y: content up to 5% (Piekoszewski et al., 2011) added to improve performance at high temperature, oxidation resistance and ductility. Ce and Y: added to specialty stainless steels to be used as thin foil substrates in automotive catalysts. Ce: hardening agent in stainless or other steels.	
Specialty alloys	La, Gd, Y, Ce, Nd, Pr Mainly REM and RE-compounds; purity in the range of 4-6Ns	Minor amounts of REEs used in the metallurgy of micro-alloyed steels, super alloys. Main REE used: Gd, La: as alloying agents; Y: as stabilizers and mould formers; La, Ce, Y: improve oxidation resistance at high temperature in jet engine alloys) REE- manufacturing of pyrophoric materials.	
Mg-alloys	Y, Nd, Gd, Pr Mainly REM and RE-compounds; purity in the range of 4-6Ns	The addition of 3.5% REEs to Mg alloys allows thin-wall castings. (Rare Earth Technology Alliance, 2014). High temperature, low creep Mg alloys: 2-3% of Y; Nd and/or Gd can also be found in automotive applications, i.e. in engine blocks and other automobile components. Alloy ZE41 (about 1% REM), alloy WE54 (>5% Y, 3% REM), alloy ZRE1 (3% REM), alloy RZ5 (1.3% REM), designed for high strength at elevated temperature, castability and weldability (Rare Earth Technology Alliance, 2014). Pr: added to provide strength and corrosion resistance; Nd: added to provide heat resistance.	

Al-alloys	Y, Ce, La Mainly REM and RE-compounds; purity in the range of 4-6Ns	Al alloys, mostly used in niche applications. Y, La and Ce: <3 wt% (Lim et al., 2015; Elgallad, 2016; Chaubey et al., 2009) to modify mechanical properties, provide corrosion resistance and high-temperature performance. Ce- compounds: used in the electro-winning of aluminium.	

4.7 Batteries

Nickel-metal hydride (NiMH) batteries were introduced to the market in the 1990's, as an improvement of the existing nickel hydrogen technology, mainly based on nickel-cadmium (NiCd) batteries. Both are rechargeable batteries with almost similar electrochemical behaviour. But the NiMH batteries have better performances due to longer life-cycle, higher stability and lack of persistence issues. Moreover, the Cd-anode in the Ni-Cd-battery is replaced with a metal hydride in the NiMH battery, making the latter 'greener'. Due to such enhancements, NiMH batteries have been increasingly deployed in different growing markets (e.g. portable tools and consumer electronic applications), even if their largest use is in the emerging sector of HEVs.

In the last years, the employment of REEs, such as La-rich mischmetal, in the manufacture of NiMH to be included in the anode formulation of rechargeable batteries has increased. Within a typical NiMH battery, metal components represent more than 60% of the battery weight, of which Ni, Fe, Co and REEs account for about 18%, 15%, 4% and 17% respectively (Lin et al., 2015).

The amount of REEs consumed for metallurgy in 2015 was estimated to account for about 8% of the total worldwide REEs consumption (see Figure 4.2, Roskill, 2016): in particular, La is the most employed REE within NiMH batteries, followed by Ce, Pr and Nd. Additional details of the REE used in the batteries sector are shown in Table 4.16. Information about purity is based on American Elements and Metall Rare Earth Ltd.

Table 4.16. Consumption of REE in the batteries sector

Main area of application	Main RE products	Main uses	REO (% of global REO consumption) - 2015 estimates
NiMH batteries	La, Ce, Nd, Pr – all as high purity metals	The most used MH-battery is the AB_5 alloy system, where "A" and "B" represent respectively a REE or mischmetal and one or more transition metals (mainly Ni, Co or Mn). Several AB_5 alloys with different compositions are commercially available. While mischmetal (e.g. a La-rich mischmetal) content in the alloy can account for about 35 wt% (Lota et al., 2013), an example of REEs used in the formulation of a commercially available AB_5 alloy is: La (65%), Ce (25%), Nd (1-8%) and Pr (3-8%) (Zhang, 2011).	Around 8% of the total global REEs consumption (see Figure 4.2, Roskill, 2016).
Hydrogen storage application	La	La-Ni alloys present relevant hydrogen storage properties needed for a longer battery life. High costs have delayed consumer products for a bigger market and only niche markets occur.	

Lithium-ion (Li-ion) batteries are increasingly replacing NiMH batteries in computing, communication and consumer products (e.g. mobile phones and laptops), due to their easier manufacture in special shapes: indeed, electronics covers about 50% of the global market associated to lithium-ion batteries (Allied Market Research, 2016).
Although the manufacturing costs of Li-ion are still higher than the ones associated to NiMH batteries, Li-ion batteries are partially replacing NiMH batteries also in PHEVs and EVs, mainly because of their higher energy density and longer lifespan. Indeed, such types of electric vehicles can be charged by plugging them in a grid-provided electricity system and thus require batteries with higher energy density in order to guarantee a range as wide as possible between charging stations. the battery for HEVs are charged through the gasoline combustion engine, and for this purpose the high-power density NiMH batteries are more suited, and therefor still represent the most used batteries in HEVs, although in 2013 lithium-ion batteries accounted for about 20% of all batteries used in HEVs (CEC, 2015).

However, NiMH batteries maintain a relevant role in large-size, stationary applications in which power-to-weight is less important (e.g. back-up units), as well as in high-temperature applications where Li-ion batteries are unsafe. China currently leads the production of small-size NiMH batteries, while the large-size ones are mainly manufactured in Japan.

Recycling: Several processing technologies have been developed by Japanese (e.g. Toyota, Honda) and European companies (e.g. Umicore, Rhodia-Solvay) aiming at recycling of REEs, from NiMH batteries, as well as to reuse batteries in different applications. E.g. Toyota in 2013 promoted a system to reuse NiMH automotive batteries in stationary applications for residential use. However, the long lifespan (7-10 years) of NiMH batteries makes the lag time between sale and recovery of REE quite long, thus limiting the efficient implementation of recycling solutions at large scales (Roskill, 2016).

4.8 Permanent magnets

Permanent magnets are materials with a wide hysteresis loop that, if inserted in a strong magnetic field, are able to retain magnetic properties also once that the external magnetic field expires. The capacity of a permanent magnet to keep its characteristics under different “external environments” (e.g. changes in temperature, demagnetizing fields, etc.) enlarges the range of application fields in which it can be efficiently used.

Permanent magnets have a variety of uses, and are e.g. used in the following major groups: acoustic transducers, motors and generators, magneto mechanical devices, and magnetic field and imaging systems. In cars, magnets are being utilized in permanent magnet motors, controlling the power window, windshield wipers, and used for generators, as well as utilized in various types of sensors. Also magnets are used in amplifiers and loudspeakers, smartphones and other communication technology. The wind-turbine sector is a major consumer of permanent magnets. In addition, an emerging technology using REE-magnets, i.e. magnetic refrigeration, could potentially improve the energy efficiency of refrigerators for home and commercial use.

Although ferrites remain the most used rawmaterial for permanent magnets (in 2012 they accounted for about 80% of the global permanent magnets production) (Grand View Research, 2014), mainly because they are cheap and largely used in the fast growing automotive market, the NdFeB magnets cover an important share (around 80,000 tpa) (Binnemans, 2015) in the global production. Minor production shares then relates to AlNiCo and SmCo magnets (around 1,000 tpa) (Binnemans, 2015). However, in this production context the higher economic relevance is associated to NdFeB magnets: within a global market of permanent magnets of about USD 13.4 Bn in 2015 (Global Information Inc., 2016), the share in terms of value associated to NdFeB magnets was around 66% (Global Market Insights Inc., 2017).

In 2015, the amount of REEs consumed for magnets manufacturing (as primary metals, thus excluding recycled metals from scrap) was estimated to account for about 23% of the global REEs consumption (see Figure 4.2, Roskill, 2016). The most important REEs for permanent magnets are Nd and Pr, even though minor amounts of Dy, Gd and Sm are also used. Additional data on the REEs used in the permanent sectors are shown in Table 4.17, 4.18 and 4.19. Information about purity is based on American Elements and Metall Rare Earth Ltd.

Table 4.17. Consumption of REE in the permanent magnets sector

Main area of application	Main RE products	Main uses	REO (% of global REO consumption) - 2015 estimates
NdFeB magnets	Nd, Pr, Dy, Ce, Gd, Tb, Ho	NdFeB magnets present the highest theoretical maximum energy capacity of any other permanent magnets. NdFeB magnets used when high performance and efficiency, small size and low cost are required, such as in automotive, actuators, speakers, electronic equipment, domestic appliances and wind turbines. NdFeB magnets for wind turbines contain around 80-100 kg of NdFeB magnets per MW (gearbox wind turbines), and 700-1200 kg NdFeB magnets per MW (direct drive wind turbines) (Binnemans, 2015). NdFeB magnets: - Nd: 25-35 wt% (Binnemans, 2015). - Pr: Often used in the form of didymium (NbPr-alloy); sometimes used to substitute Nd, although it entails a lower magnetic strength. - Dy: Usually added to improve magnets performance at high temperatures. - Tb and Ho: Same as Dy. - Ce and Gd: Cheaper but less magnet strength; used as an alternative for Nd are then represented by Ce and Gd, with the latter only used in China because of the high availability. Composition of the best performing sintered magnet: Nd 31 wt%, Dy 4.5 wt%, Co 2 wt%, Fe 61.5 wt%, B 1 wt% (Binnemans, 2015).	Around 23% of the total global REEs consumption (see Figure 4.2, Roskill, 2016).
SmCo magnets	Sm	SmCo magnets can contain either up to 36 wt% (SmCo Series 1:5) or 25 wt% (SmCo Series 2:17) of samarium (Magnetic Component Engineering). The demand for SmCo magnets for high-performance applications (main advantages are resistance to demagnetization, to high temperatures and to corrosion/oxidation) is currently growing; they are used in many different applications ranging from small Hall-effect sensors to blocks used in motor applications.	

Recycling: Moreover, with the aim of reducing the raw materials consumption, the use of secondary Nd/Pr and Dy from scraps is being tested at different scales. In particular, swarf coming from shaping and cutting of the final magnet produce a potential source of secondary materials, although its exploitation at large scales is hindered by some issues, such as: the swarf often needs further treatment steps before being introduced in the formulation of new magnet alloys, mainly because of its content in dysprosium or in other alloying elements; improvements in cutting tools and relative yields are lowering the availability of swarf as source of secondary materials.

Some bottlenecks appear in the efforts to recover and recycle of REE from magnets:

- Efficient collection schemes are not available
- Target products contain small-size magnets, which are difficult to be recovered
- The wide variety in magnets composition complicates the set-up of generic recycling schemes;
- The low REE prices in 2012 slowed down the research into magnets recycling.

Magnets extraction technology from the end-products has been already developed, but further improvements required to efficiently separate and recover REEs from the magnets: in this latter field, several industries from Japan, as well as the French industry Rhodia-Solvay, have developed processes, but mainly targeting a technology to recover REE from magnets used in air-conditioning units (Roskill, 2016). An important boost to magnets recycling could come from the expansion of the market associated to large-size NdFeB magnets for wind turbines and HEVs: although the major size of such kinds of magnets makes their collection easier, their long life span (around 25 years) significantly impacts on the time in which a real recycling of the recovered magnets into lower-power applications can be carried out (Roskill, 2016).

Table 4.18. The REE substitution in the permanent magnet sector

	Description/comments/notes	**Target**
Present situation	Substitution: Ferrite or SmCo magnets could be used in substitution of NdFeB magnets for selected applications. Ferrite magnets, may by an alternative to NdFeB magnets in wind turbines.	Substitution of NdFeB with other magnets requiring minor amounts of REE
	Substitution: In some cases, Ce and Gd have been used to substitute Nd; though reduction of the magnetic properties is the result.	Substitution of Nd/Dy with other REE
Trends	Substitution: Ongoing R&D focusing on the potential replacement of Nd or Dy with other REE. For example, up to 25% of Nd can be substituted by Pr without significantly affecting magnetic properties of materials (Binnemans, 2014b).	Substitution of NdFeB with other magnets requiring minor amounts of REE
		Substitution of Nd/Dy with other REE
	Substitution: Attempts to eliminate the use of permanent magnets in some applications: e.g. induction motor systems for HEVs and EVs, which are however less performing than permanent magnets motors, or switched reluctance motors for cars.	Substitution of permanent magnets in specific sectors
Challenges	Substitution: No alternatives to e.g. NdFeB magnets are commercially available yet, particularly for applications where magnet size and energy efficiency are relevant.	Substitution of NdFeB with other magnets requiring minor amounts of REE
		Substitution of permanent magnets in specific sectors
	Substitution: SmCo magnets still do not represent a viable alternative to NdFeB magnets, mainly because of their higher prices and the limited availability of samarium.	Substitution of NdFeB with other magnets requiring minor amounts of REE

Table 4.19. Recovery/recycling of REE in the permanent magnet sector

	Description/comments/notes	Target
Present situation	Recovery and recycling of REE from magnets is quite far to be implemented at large scale. In addition, while magnets extraction from the end-products has been already developed, further improvements and research are required to efficiently separate and recover REEs from the magnets: in this latter field, several industries from Japan, as well as the French industry Rhodia-Solvay, have developed and proved processes, mostly focused on air-conditioning units, to recover REE from magnets.	REE recovery/recycling from final products
	With the aim to reduce the raw materials consumption, the use of secondary Nd/Pr and Dy coming from scraps is being proved at different scales. In particular, swarf coming from shaping and cutting of the final magnet product represents a potential source of secondary materials.	REE recovery/recycling from process wastes
Trends	An important boost to magnets recycling could come from the expansion of the market associated to large-size NdFeB magnets for wind turbines and HEVs: although the major size of such kinds of magnets makes their collection easier, their long life span (around 25 years) significantly impacts on the time in which a real recycling of the recovered magnets into lower-power applications can be carried out (Roskill, 2016).	REE recovery/recycling from final products
Challenges	Efficient collection schemes are still missing and need to be established or improved. Most of the target products contain small-size magnets (e.g. in consumer products or automotive applications) which are difficult to be recovered, even if the development of wind turbines and HEVs/EVs are fostering the diffusion of larger-size magnets. The wide variety in magnets composition complicates the set-up of generic recycling schemes. The drop in REE prices in 2012 slowed down the research into magnets recycling. Although the major size of magnets for wind turbines and HEVs makes their collection easier, their long life span (around 25 years) significantly impacts on the time in which a real recycling of the recovered magnets into lower-power applications can be carried out (Roskill 2016).	REE recovery/recycling from final products
	A large-scale recovery scheme of Nd/Pr and Dy from scraps is still hindered by some issues, such as: - the swarf often needs further treatment steps before being introduced in the formulation of new magnet alloys, mainly because of its content in Dy or in other alloying elements; - improvements in cutting tools and relative yields are lowering the availability of swarf as source of secondary materials.	REE recovery/recycling from process wastes

4.9 Ceramics

REE-elements are employed in the ceramic intermediate sectors as rawmaterial in the following three sub-sectors of the manufacturing of ceramic products: (i) refractories, (ii) electronic ceramics, and (iii) engineering ceramics. The estimated amount of REE consumed in 2015 covered about 6% of the global REEs consumption (see Figure 4.2, Roskill, 2016). Beside Y, which is the most important REE for this sector, Nd, Ce, La and Pr are mainly employed.In particular, high-grade Y_2O_3 with minimum purity of 99.999% (5N) is often required for ceramics applications (Rare Earth Technology Alliance, 2014). For example, Y_2O_3 is used (from 3 mol% to 8 mol%) (Inframat Advanced Materials, 2017) as stabiliser in yttria-stabilised zirconia (YSZ) or partially stabilised zirconia (PSZ) formulation; YSZ is employed, among others, in fuel cells components, in O_2 sensors, in fibre-optic connectors, as thermal barriers in jet engines, for automotive fuel control, in dental applications. Additional market details a given in Table 4.20. Information about purity is based on American Elements and Metall Rare Earth Ltd.

Table 4.20. Consumption of REE in the ceramic sector

Main area of application	Main RE products	Main uses	REO (% of global REO consumption) - 2015 estimates
Lining of furnaces and crucibles in metallurgical industry	Y, Ce Dominated by REO and RE-compounds; purity respectively in the range of 3-6Ns and 2-5Ns	REEs are used in the formulation of refractory materials used to line furnaces and crucibles in metallurgical industry: Y_2O_3, CeO_2; Ce-sulphide: improve resistance at high T and protect the refractory material (ZrO_2). Y_2O_3: utilised in refractory crucibles used for melting of reactive metals (Rare Earth Technology Alliance, 2014).	Around 6% of the total global REEs consumption (see Figure 4.2, Roskill, 2016).
Solid oxide fuel cells (SOFCs)	Y, Ce, Gd, Sm, La Dominated by REO and RE-compounds; purity respectively in the range of 3-6Ns and 2-5Ns	SOFCs are mainly used for mini-power grid applications as a back-up power or other locations not connected to the grid. : due to the increasing market for stationary fuel cells, SOFCs represent one of the most potentially strategic final application for REEs used in ceramic materials. The main REE used in fuel cells is Y. Y_2O_3 -stabilised zirconia (YSZ) is used in solid oxide fuel cells (SOFCs) to improve their stability and resistance at high temperature (500-1000 °C). Ce, Gd, Sm and La also used in SOFCs.	
Sensors	Y Dominated by REO and RE-compounds; purity respectively in the range of 3-6Ns and 2-5Ns	YSZ: used for in sensors aiming at monitoring the oxygen content in exhaust gases, in molten glass, and in molten steel. REE-containing sensors are also used in high temp and/or pressures environments. REE based sensors are used in air bag systems for cars under humid conditions.	
Sintering agents	Y, Ce Dominated by REO and RE-compounds; purity respectively in the range of 3-6Ns and 2-5Ns	Y_2O_3 used in sintering agents in structural products and coatings constituted by silicon nitride (Si_3N_4), sialons (Si-Al-O-N ceramics) or zirconia. Y_2O_3 has crystal characteristics suitable for sintering compounds which contributes to reduction of the sintering temperature and reduced process costs. Two SiAlON types are commercially relevant, but only one is REE-based: the beta SiAlON plus YAG (yttria-aluminium garnet). The beta SiAlON formulation: contains from about 3 wt% to 12 wt% of Y_2O_3 (Žilinska et al., 2011) and finds applications in components for cutting tools and industrial machineries. Si_3N_4 ceramics: contains 6 wt% of Y_2O_3 (Browne et al., 2012); mostly used in gas turbines, car engines, machine tools and in high performance bearings.	
Lead zirconate - titanate ceramics	La Dominated by REO and RE-compounds; purity respectively in the range of 3-6Ns and 2-5Ns	La_2O_3 is consumed as additive (96%) in lead zirconate - titanate ceramics (Roskill, 2015) PLZT material: (La-Pb zirconate - titanate) materials mainly used in optical shutters and modulators, colour filters and image storage devices.	

		La_2O_3: influences electrolytic properties of ceramic materials and improves the optical transparency of PLZT compositions from 67% up to 98% (Roskill, 2015).	
Other applications	Nd, La, Pr, Ce Dominated by REO and RE-compounds; purity respectively in the range of 3-6Ns and 2-5Ns	Nd-, La-, Pr- and Ce-oxides are used in temperature-compensating capacitors, resistors and thermistors to customise and improves the energy density, dielectric and permeability features, and life-span. REEs are also employed into multi-layer ceramic capacitors (MLCCs). Nd: controls the capacitance of the product under temperature variations. La and Ce: responsible for the improvement of the dielectric properties. . Ba-titanate thermistors doped with REE oxides can be used as heat-actuated switches. REE-based advanced engineering ceramics are used as substitutes of metals in different applications (structural components, cutting tools and wear resistance parts).	

Given the wide range of different ceramics products and applications in which REEs are involved, including several niche markets, as well as the increasing boost towards the substitution of metals with engineering ceramics, an effective estimation of REE consumption trends for ceramics is quite difficult. However, in the ceramic capacitor-market, for example, base metal (BM) capacitors are gradually replacing precious metal (PM) counterparts, which will reduce the demand for Nd_2O_3 substantially.

4.10 Other applications

Minor amounts of REEs are applied in other market sectors and products, such as laser or microwave crystals and garnets, nuclear applications, carbon arc lights, textiles additives, medical applications, fertilisers, chemical compounds as reagents or paints drying agents, alloys for magnetic refrigeration, and other. Although most of these applications are associated to niche markets, the use of REEs in such technological fields increased during the years, reaching around 10% of the total global consumption in 2015 (see Figure 4.2, Roskill, 2016). In particular, Ce is largely the most used REE in other applications, followed by La and other minor amounts of Gd, Y, Pr, Nd and other REEs. Additional market details are shown in Table 4.21. Information about purity is based on American Elements and Metall Rare Earth Ltd.

Table 4.21. Consumption of REE in miscellaneous sectors

Main area of application	Main RE products	Main uses	REO (% of global REO consumption) - 2015 estimates
Microwave devices	Y, Gd, Nd, Ho, Tm, Er, Yb	Crystals and garnets for microwaves and laser: Y, Gd and Nd. followed by Ho, Tm, Er and Yb compounds as dopant agents. Yttrium-iron-garnet (YIG) used for microwaves and cell phones and laser. Gd-iron-garnet (GIG): Similar applications as above. Y- and Gd-based garnets: used as resonators in frequency meters, magnetic field measurement devices, tunable transistors, and Gunn oscillators.	Around 10% of the total global REEs consumption (see Figure 4.2, Roskill, 2016).
Lasers	Y, Nd	Nd oxide: employed as dopant in YAG lasers to improve absorption and emission performance. Frequently used in material processing and in medical applications. Y and Nd: Used as dopants to cause fluorescence (purity 5N or higher).	
Nuclear applications	Gd, Sm, Eu, Dy, Er, Y	Neutron absorbers in nuclear reactors: Frequently used REE are: Gd, Sm, Eu and Dy. Control rods: Sm, Eu, Er and Gd. Shielding purposes and neutron absorbing coatings: Gd and Eu, while Y can be utilised in piping. Detection of radiation leaks: Gd.	
Lighting applications	Ce, La, Eu, Pr, Yb	Industrial lighting and projectors: Several LREE-compounds (e.g. Ce, La, Eu, Pr and Yb) are mainly used in these fields, improves the lighting performance, in terms of e.g. quality and intensity. (Rare Earth Technology Alliance, 2014).	
Medical applications	Ce, Nd, La, Eu	Drug formulations: e.g. Ce-oxalate in motion sickness drugs, Nd-isonicotinate to treat thrombosis), and in medical applications (e.g. La nitrate used as an antiseptic, Ce-141 used in biological and medical research). Living tissue research: Highly sensitive luminescence is provided by Eu. (Rare Earth Technology Alliance, 2014).	
Fertilisers	La, Ce	Fertilizer for cottons and oil-plants in China: REE-oxides added to improve the overall plant growth. Superphosphate: REEs compounds are added to calcium superphosphate, thus obtaining a REE-phosphate fertiliser (REPF).	
Magnetic refrigeration	Gd, Nd, Tb, Er, La, Pr	Magnetic refrigeration technology: Gd-alloy used as a refrigerant surrounded by NdFeB magnets, which cause the heating and the cooling of the refrigerant itself by respectively increasing and decreasing the magnetic field generated by their movement. Alternative alloys are: e.g. Gd-Si-Ge alloy, Gd-Tb alloy, Gd-Er alloy, La alloys doped with Fe or Pr alloys doped with Ni.	
Other applications	Ce, La, Nd, (Pm), Gd, Pr, Ho, Yb	Synthetic gemstones: A niche market for Y. Paint dries: Ce, La and Nd can be included in the formulation.	

		Polymer colorant: Ce sulphide is used in polymer colorants in substitution of Cd compounds. Textiles: Mainly Ce and Pr, are used in textiles as dyes (e.g. Ce compounds), they are mainly used to give “protection” properties (water- or mildew-proof) to the fabric, as well as to face creasing effects or bleaching caused by sunlight; this application is restricted to China. Water treatment: Ce and La are also used in the formulation of products for water treatment of pools, spa, municipal and industrial wastewaters, aiming at removing e.g. phosphates.	

5 Global rare earth market

In 2015, the global REE market value was estimated to be in the range of USD 2-4 billion (Kingsnorth, 2016). The overall size of the REE market, in volume and value, is small with global REE production in an approximate range of 115,000 – 120,000 tpa (variations in estimates due to the share of illegal market size and uncertainties of production and smelting quota are described further on in this chapter). For comparison, in 2012, the size of the iron ore market was about 3,000 Mt, and of the tantalum-niobium market it was about 250,000 tons (Jenkin *et al.*, 2015). The REE market is a specialty market, characterized by business to business trade rather than exchanges on metal markets (such as the London Metal Exchange [LME]).

In addition, and as described in depth in chapter 3, the rare earth supply chain requires specific knowledge to span from the REE-mineralogy to chemical processing and intermediate and end-using sectors. This characteristic, jointly with the REE market size, is often used to explain the limited interest by large, established mining companies (such as BHP Billiton, Rio Tinto or Vale) to enter into mining projects with REE-bearing minerals as main product. The co- and by-product production of REE-minerals has a bearing on their supply i.e. when the production of the main product is adjusted; the production of REE-minerals is affected. For instance, REE are produced from hard-rock minerals at the Bayan Obo mine in China as a by-product of iron ore. With a change in political support for mining, and iron ore prices that affect the medium- to long-term plans for the production of iron ore; the production of REE minerals is also affected (unless stockpiles are processed).

Importantly, while this chapter provides estimates for demand and supply, it is noteworthy to highlight that these estimates provide an illustration of the overall development of the market rather than a minute detailed description of it. Obtaining an accurate reflection of the market size and dynamics is limited by:

- the difficulty of obtaining estimates of the illegal share of production, i.e. the extent of the activities of grey miners (as described in more detail in chapter 3),
- a limited understanding of the total production of REE-products in China (from mining to components) given that REE-production quota are official figures which are not necessarily representative of the total production,
- the volume of REE-stockpiles, and
- the difficulty in deciphering which product types are being circulated (i.e. mixed rare earth carbonates or REM), which is further complicated by statistical codes that aggregate product groups when accounting for imports and exports.

5.1 Global demand

Figure 5.1 illustrates the changes in the total rare earth demand from 1965 to 2015 per decade: In 1965, global demand amounted to about 5,000t TREO, while in 2015 it was estimated at approximately 145,000-150,000t TREO. Importantly, figure 5.1 shows the significant shift in regional demand patterns: In 1995, Japan accounted for about 43% of global demand, the USA for about 27%, Europe for 18% and the ROW for 12%.

In the two decades since 1995, the demand for REM (as opposed to RE-containing final consumer products) in China surged significantly to account for approximately 75% of global demand. Demand of REM in Japan reduced to 14%, followed by Europe and the ROW with about 4% and the USA with 3%. REM demand of China surpassed that of Japan, and it rose to account for three quarters of global demand over two decades only.

China developed a quasi-monopoly over time: Before the 1990s, less than 10 per cent of total REE production were separated REE which is in contrast to the more than 60 per cent separated REE production in 2011 (Kingsnorth, 2012). Simultaneously, when separated REE production was small in China in the early 1990s, exports of REE were also primarily mixed REE mineral concentrates (Kingsnorth, 2012). Until 2000, China exported mainly REE-containing components such as magnets, phosphors and polishing powders (Kingsnorth, 2012). Since the turn of the century, REE-exports by China increasingly included advanced REE-containing final consumer products such as batteries, mobile phones and LCDs (Kingsnorth, 2012). This development is on the rise since.

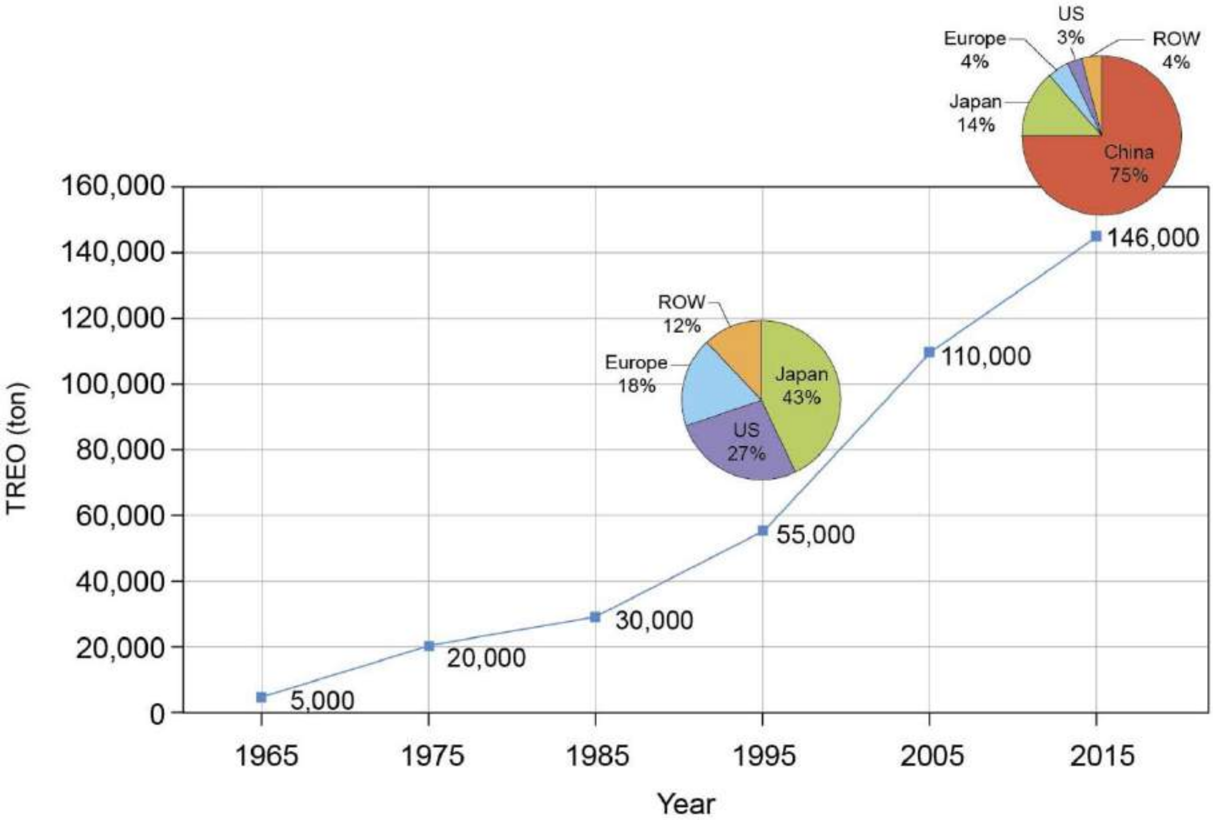


Figure 5.1. Total rare earth demand in decade changes (t REO), 1965-2015
Source: MiMa-GEUS, 2016 adapted from Kirk-Othmer, 2005; and Kingsnorth, 2016; market demand share pie in 1995: Kirk-Othmer, 2005, p. 11; market demand share pie in the 2015 column derived from Adamas Intelligence, 2014.

5.2 Global production and supply

This subtitle is to clearly communicate the difference of production and supply volumes, a distinction which is important to note in general, and particularly so in the global REE-market. As this subchapter proceeds, this distinction will be further explained and discussed, including with its implications for estimates of global supply volumes, and estimates on the supply-demand balance.

Figure 5.2. illustrates the dynamics in the REE-supply from 1983 to 2001, in two-year steps, to make changes in supply from a rather diversified supply landscape to a quasi-monopolistic supply transparent. In this diversity, the USA and China were the largest suppliers with similar production volumes until the early 1990s. Between 1993 and 1995 a significant change in the production volumes of these two producing countries is apparent: China has started to produce significantly higher volumes of REE-products and greatly surpasses the production of the USA, clearly illustrated in the divergence in 1995.

In a personal communication with Solvay (2013), it was pointed out that the competition about REE-separation technology clearly had China emerge as winner. This is reflected in the sharp drop of the production by the USA around 1995 and 1997, when the output of China rose significantly. Certainly, also presence and absence of environmental legislation at that time in the USA and China had an influence in production costs. After 1995, the production of REE-products ceased in Australia, Brazil, South Africa, Thailand and the DRC. By China's accession to the WTO in 2001, the country was a quasi-monopoly producer.

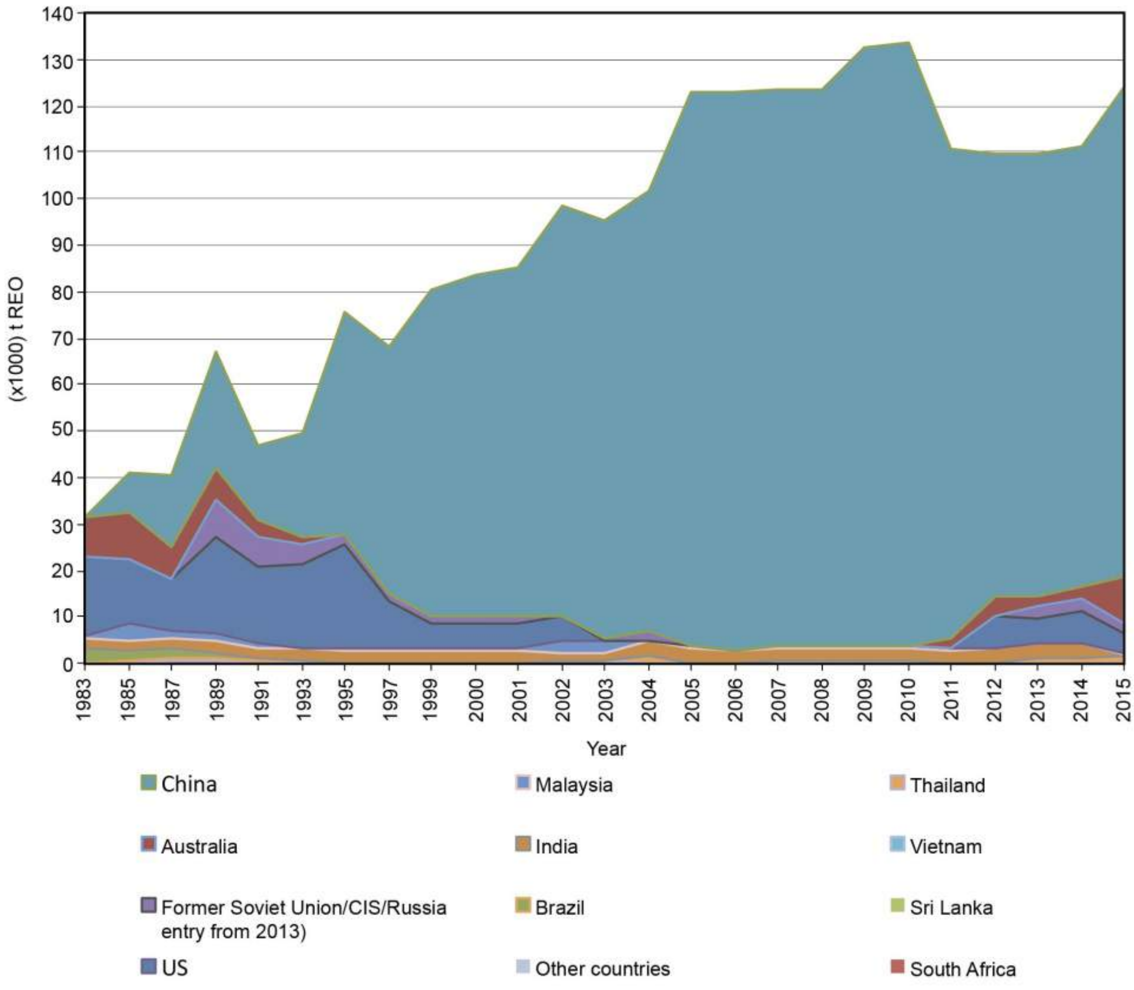


Figure 5.2. Dynamics in the REE mine production from 1983 to 2001.
Source: MiMa-GEUS, 2016, adapted from Castor and Hedrick, 2006, p. 771; USGS, 2016.
Note: The data flows have been stacked to enable a better comparison and visualization of the smaller supply contributions of some countries from the early/mid 1980s to the early 1990s, and from 2011 onwards.

Figure 5.2. also illustrates the near monopoly position of China from 2005 to 2010, next to small production volumes from Brazil, Malaysia, and India. Next to production from Russia, and India, the efforts to produce REE in the US and Australia are shown from 2012, clearly depicting the developments of 2015 when US production filed for bankruptcy, while production in Australia continued. Other, smaller producers remain among which Russia is dominant, next to a share from Thailand, Malaysia and Vietnam.

China produces and supplies the largest share of REE-products in and to the world market. It is therefore important to understand the REE-industry policy and regulation in China. This includes a discussion of government intervention, including export regulation that was in place until 2014, industry reorganization, resource conservation, and measures persued for environmental protection, all of which are briefly addressed in the next subsections.

5.2.1 Chinese domestic industrial policies

China counts numerous REE-producing mines, yet a total number is publicly unknown and estimates remain unclear. Therefore, and as this report addresses the EU-perspective of the REE-industry, we limit this discussion to listing the 'Big Six'.

i. Industrial consolidation

At the centre stage of the REE-industry development in China is the transformation of the mining, extraction and separation activities into the 'Big Six', as described in chapter 3, comprising (as per Zeuthen, 2016):

- Baogang Group (under China North Rare Earth High Tec)
- China Minmetals Rare Earth Co.
- Chalco
- Ganzhou Rare Earth Group (sometimes referred to via the associated China Southern Rare Earth Group, to which the Guangxi Rare Earth also seems affiliated)
- Guangxi Rare Earth
- Guangshen – Guangdong Rising Nonferrous (seemingly not Guangxi Rare Earth), and Xiamen Tungsten Corporation

The six major group capacities accounted for about 76% of total industry capacity according to Chen Zhanheng, Deputy Secretary General of the China Rare Earth Industry Association ([ACREI], 2016b). It is not easily established to which extent any of the 'Big Six' have integrated their operations to include manufacturing of REE-containing components, or even REE-based end-user products. However, a significant degree of integration is visible which serves to gain better governmental control of the industry.

ii. Resource tax

A resource tax is applied to the extraction of REE-bearing minerals in China. This tax varies according to the REE-bearing mineral that is mined. According to Zhang (2011), a rise in the resource tax from 0.4 Yuan for extraction of xenotime, and ionic clays, and from 3 Yuan for the extraction of monazite and bastnaesite was augmented to between 30 and 60 Yuan per ton of extracted mineral in 2011.

iii. Production/mining quota

The Chinese production quota was set at 105,000 t REO in 2016 (CN Stock, 2016). This production quota is the official figure provided by the Ministry of Industry and IT (MIIT), and this figure is to be interpreted in the context of production from unofficial sources (illegal production) which is estimated in the range of 25-30% of global REE supply in 2016 (Roskill 2016), or 30-40% of the total estimated supply of 175,000 t REO in 2015. Until 2012, the Ministry of Land and Resources (MLR) has also provided production quota (Hatch, 2012), which in effect translated into two sets of quota (one provided by the MIIT, and one provided by the MLR) which diverged slightly (see Tse, 2011, p. 8).

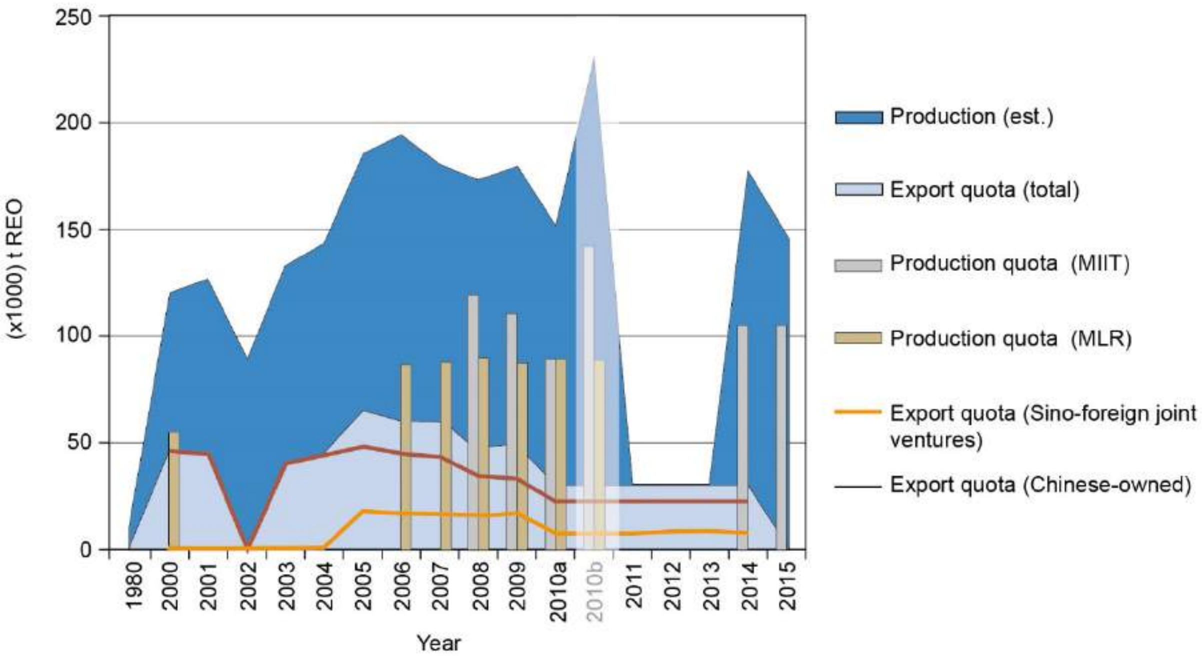


Figure 5.3 Overview of production and export quota developments, 1980 to 2015
Source: MiMa-GEUS, 2016 based on production quota modified from Tse, 2011 based on China Ministry of Commerce; 2010a - Tse, 2011, p. 4; 2010b Wang, 2011a in Wuebbecke, 2013.
Note: 2007-2011 quota differ slightly to Tse, they are based on MOFCOM, and so are the 2012 and 2013 total export quota from Adamas Intelligence, 2014, p. 132. For China's rare-earth production, consumption, and export quotas for 2000 through 2011 please consult Appendix B.

iv. Smelting and separation quota

These quota apply to the amounts of mined REE-minerals that can be processed to generate a useful product for further industrial use.

Table 5.1. Rare earth mineral and separation plan

Year	2009	2010	2011	2012	2013
Rare earth minerals plan *(assumed to be REO production)*	119,500	89,200	93,800	93,800	93,800
Smelting-separation products plan mandatory	110,700	86,000	90,400	90,300	90,300

Source: MLR, MIIT in Rao, 2016.

v. Pollution control standards

The Chinese Ministry of Environmental Protection (MEP) maintains a list of approved companies that meet the pollution control standards, upon which the distribution of mining quotas has been based since 2012 (Hatch, 2012; Adamas Intelligence, 2016; Liu, 2016).

5.2.2 Chinese export policies

Table 5.2 by Zhang *et al.* (2015) summarizes China's rare earth export policies in three different periods – a supportive, a restrictive and a prohibitive period. It lists the policies in place between 1985 and 2011, and summarizes their main content.

Table 5.2. China's REE export policies in different periods

Period	Year	Policy description
The supportive period	1985	Beginning of tax rebate policy implementation for rare earth products
	1992	Ministry of Foreign Trade and Econ. Cooperation issued the "Regulations on Rare Earth Exports"
	1998	Implementation of the license system of export quotas on rare earth products
	2002	China's State Planning Commission promulgated the "Provisional Regulations on Foreign Investment of the Rare Earth Industry"
	2003	Reduction of tax rebate rate of REM and REO from 17% and 15%, respectively, to 13%;
The restrictive period	2004	Reduction of tax rebate rate of REM from 13% to 0, and the rates of organic and inorganic chemical rare earth metals, Y, Sc, and mixtures thereof, dropped from 17% to 13%, to 5%.
	2005	Cancellation of tax rebates of REM, REO and RE- salt products; issuance of export quota for 51,000 t in this year
	2006	Imposition of export tariffs on REM, REO, etc. The tariff rate was 10%;
		Introduction of REM into "The Catalog of Prohibited Trade Commodities"
		32 types of REM, rare earth alloys and rare earth salt products were placed into "The Catalog of Prohibited Trade Commodities";
		42 types of REE products, such as REEl ores and REM, were placed into the administration of export license;
		47 enterprises obtained an export license in this year;
		An export quota of 46,000 t was issued in this year.
	2007	A tentative tariff rate for rare earth metals, Tb oxide, Dy oxide, etc. was set to 10%;
		The smelting process of rare earth ores, the separation and preparation technology of indiv. REE, etc., were placed into "the Catalog of Technologies Prohibited or Restricted from Import"
		41 enterprises obtained export licenses this year;
		The smelting of rare metals, such as tungsten, molybdenum, tin (Sn compound excluded) and antimony (incl antimony oxide and antimony sulfide); and the smelting and separation (ltd to JVs, cooperation) of REE were listed in restricted fields for foreign merchants. The *exploration and mining of tungsten, antimony and REE were forbidden for foreign merchants*;
		An export quota of 45,370 t was issued in this year.
The prohibitive period	2008	Increase of tariff rate of Y, Eu, Tb, Dy to 25%, and of others to 15%; Dy iron and NdFeB, previously excluded from taxation were imposed a tariff at 20%;

		24 enterprises obtained export licenses this year
		Export quota of 34,156 t of REE was issued in this year
	2009	China's MIIT examined and adopted the "Rare Earths Industrial Development Plan 2009-2015", stating that export quotas for China's rare earth would be limited to 35,000 t per year and the export of raw materials would be barred for the next 6 years;
		23 enterprises obtained export licenses in this year
		An export quota of 31,310 t of REE was issued in this year;
	2010	The State Council issued "The Opinion on Promoting Mergers and Acquisitions of Enterprises", which listed REE as key industries for M&A in an attempt to decrease rare earth exports
		22 enterprises obtained export licenses in this year
		An export quota of 24,280 t of REE was issued in this year
	2011	The tentative tariff rate of rare earth metal ores was 15%, and that of Nd metal rose from 15% to 25%;
		China began to impose a resource tax on rare earth ores ranging from 0.4 to 60 Yuan per ton;
		57 enterprises obtained export licenses in this year;
		An export quota of 30,184 t rare earth was issued in this year.
	2012	Introduction of separate export quota for LREE and HREE
		Introduction of Baotou Rare Earths Trading Platform launch October 2013
		Government-funded HREE stockpiles established in South China.
The controlling period	2013	Concerted effort to accelerate industry consolidation and vertical integration
	2014	Last year of export quota and duties, as the WTO DSB ruled these policies as inconsistent with WTO rules, and China lost the case.
	2015	China abandons export quota and duties and uses export licenses.
	2016	Chinese government issued the "Rare Earth Industry Development Plan (2016-2020)" on October 18, 2016 and plans further promotion of the rational development of rare earth resources, environmental protection, industry consolidation as the core of orderly production, and rare earth new materials development.

Source: data for 1985 to 2011 adapted from Zhang *et al.*, 2015, p. 83, who analyzed and named the three periods; data for 2012 and 2013 from ERECON, 2014; data for 2014 and 2015 from WTO, 2015.

Export quota. The export quota were allocated by the Ministry of Commerce (MOFCOM) until end of 2014, when the decision on the case brought forward to the WTO by US, Japan and the EU was that China's allocation of export quota was unruly, and it was recommended to abandon the export quota system. The export quotas were allocated bi-annually, dividing LREE and HREE production between Chinese-owned and Sino-foreign joint ventures.

Export taxes. These taxes are levied on REE-product exports from China, and were introduced in late 2006 with 10% on rare earth exports, increased to 15% on selected REE-products in 2007, and were modified and raised as of 2008, according to the following:

Table 5.3. Export taxes

Products	Tax
Eu, Tb, Dy, Y as oxides, carbonates or chlorides	25%
All other rare earth oxides, carbonates and chlorides	15%
Nd metal	15%
All other rare earth metals	25%
Ferro rare earth alloys	20%

Source: OECD, 2010, p. 118.

Refund of VAT on rare earth exports from China. Jointly with the raising of export taxes, China cancelled the refund of VAT (16%) on exports of REE products which were not further refined, while maintaining the refund on higher value-added exports (e.g. magnets and phosphors). This resulted in the increase in 31% of costs for non-Chinese rare earth processors for rare earth products used in e.g. the production of Ce polishing powders and REE-based magnets (OECD, 2010).

WTO case and ruling of the Dispute Settlement Body's Appellate Body, 2012 to 2014
The US, the EU and Japan brought the case of China's export restrictions on a number of rare earths, tungsten, and molybdenum to the WTO. These export restrictions comprised export duties, export quotas, and certain limitations on the enterprises permitted to export the products (WTO, 2015). Table 5.4 summarizes key facts of the case:

Table 5.4. WTO case and ruling of the Dispute Settlement Body's Appellate Body

Parties		Agreement	Timeline of the dispute	
Complainants	US, EU, Japan	Accession Protocol, Working Party Report, Marrakesh Agreement, GATT Art. XI and XX	Establishment of Panel	23.07.2012
			Circulation of Panel Report	26.03.2014
Respondent	China		Circulation of AB Report	7.08.2014
			Adoption	29.08.2014

Source: WTO, 2015.

The following are excerpts from the summary on the case provided by the WTO (2015):

- *Accession Protocol (export duties)/Marrakesh Agreement/GATT Art. XX (general exceptions): The Panel found that China's export duties on rare earths, tungsten, and molybdenum were inconsistent with its Accession Protocol.*

- *GATT Art. XI (quantitative restrictions)/GATT Art. XX(g) (general exceptions – exhaustible natural resources): The Panel found that China's export quotas on rare earths, tungsten, and molybdenum were inconsistent with GATT Art. XI. The Panel also concluded that the export quotas were not justified under the exception in GATT Art. XX(g), which allows WTO Members to implement GATT-inconsistent measures "relating to the conservation of exhaustible natural resources". (…) The Appellate Body further concluded that the burden of conservation did not have to be evenly distributed, for example, between foreign consumers, on the one hand, and domestic producers or consumers, on the other hand.*

- *Working Party Report (trading rights): The Panel found that China maintained restrictions (minimum registered capital, prior export experience and export performance) on the trading rights of enterprises exporting rare earths and molybdenum contrary to Paragraphs 83 and 84 of China's Working Party Report. (…) In this respect, the Panel considered that China's trading rights obligations were distinct obligations and that breaches of these obligations had to be justified separately from the justifications that China had advanced for the imposition of export quotas in violation of Art. XI of the GATT 1994.*

Export license system. In January 2015, the MOFCOM announced that export quotas were no longer a part of the export policy, with export licenses to steer exports instead (The Guardian, 2015).

Export volumes in 2016
In September 2016, China's rare earth export volume was 3,674t. In the period January to September 2016, China's exports of rare earths totaled about 35,000t, and it is anticipated that the total export volume of REE products in 2016 was in excess of 40,000t (ACREI, 2016a, b).

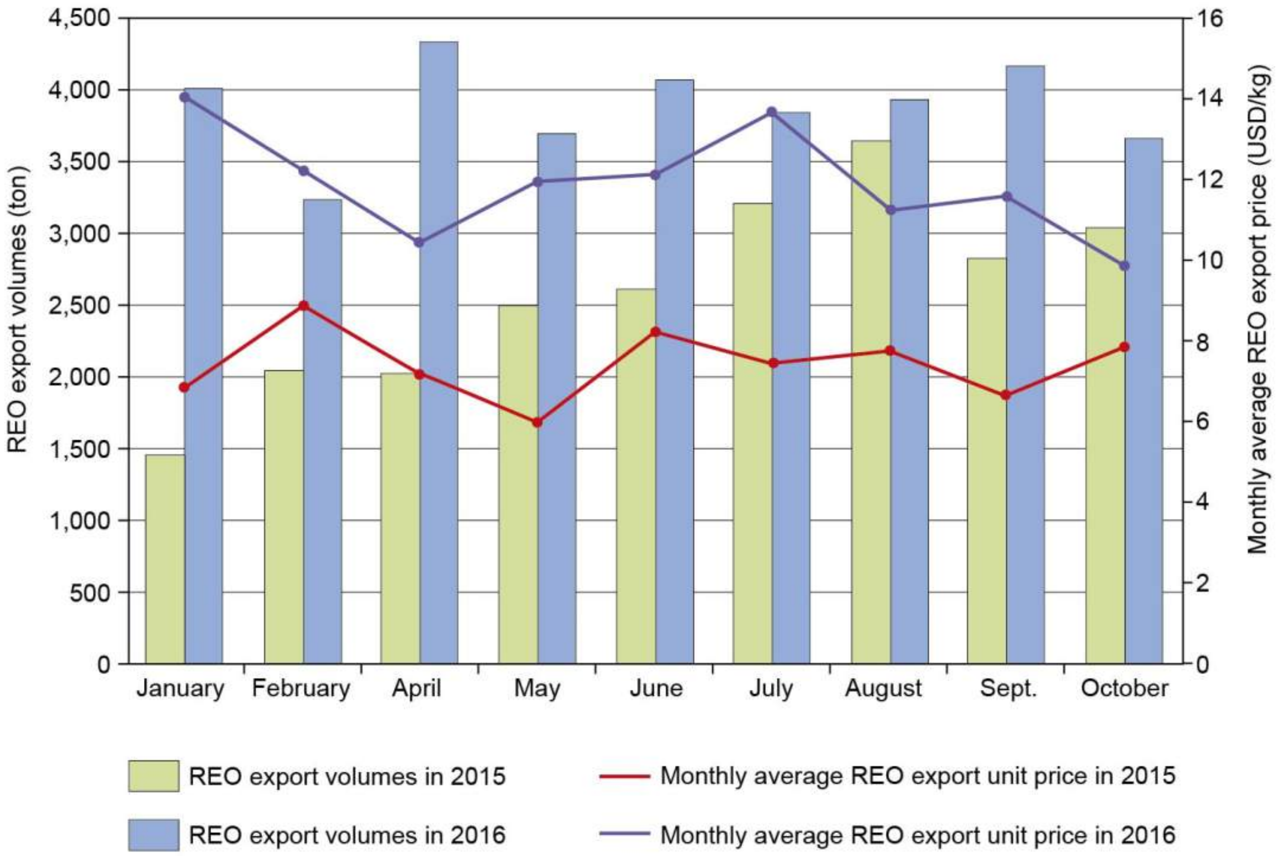


Figure 5.4. Monthly comparison: REO export volumes and average REO export prices , China
Source: ACREI, 2016a.
Note: The columns refer to REO export volumes in 2015 and 2016, while the graph illustrates the average REO export unit price in USD/kg.

The uncertainty about the extent of illegal production remains, jointly with estimates about stockpiling activities in China. Data are available from numerous primary and secondary sources (i.e. MIIT; MLR and MIIT in Rao, 2016; ACREI, 2016a) on the production quota (105,000t), the smelting and separation quota in China (90,300t), and the export volume of REE products in 2016, as stated above (more than 40,000t). Illegal production in China is estimated to be around 30% of the production quota, which would augment production in China to about 136,500t.

Figure 5.4. illustrates the total estimated production in China (left column), and attempts an approach towards an estimate of REO volumes that might legally and illegally be available outside China. The estimates include approximately 60,000t of legally exported Chinese REO together with Australian production (10,000t REO) to which the smaller production of Russia (2,500t REO), Thailand (2,000t REO) and Malaysia (200 t REO) are added. With an inclusion of the 30% estimate of illegal production made entirely available outside China, this figure would rise to 90,000t REO available outside China.

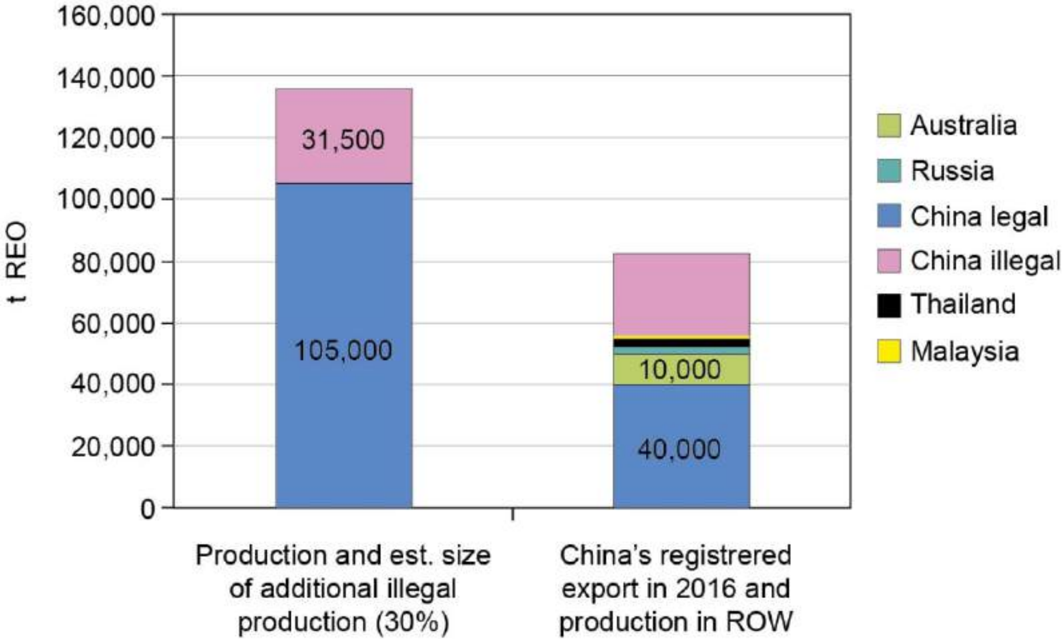


Figure 5.5. Estimated REO production, and REE-product availability outside China, 2016.
Source: Mine production estimated from USGS (2016), and 30% share of illegal production from Kingsnorth (2016), and Liu (2016).

These uncertainties on total REE production, stockpiling and illegal market share have a bearing on REE-product prices, yet the extent to which these price dynamics are steered by supply-demand dynamics and by government control, as well as illegal production, can only be estimated. Table 5.5 provides a snapshot of REE product free-on-board (FOB) prices in October 2016.

Table 5.5. FOB sales prices of REE product exports from China, October 2016

REO oxides of typically traded quality	Oct 2016, FOB China (USD/kg)
Ce oxide 99.5-99.9%	1,65
Dy oxide 99.5% min	184,43
Er oxide 99% min CIF Europe	27
Eu oxide 99.9% min	71,86
Gd oxide 99.999% min	22,78
La oxide 99.5-99.9% min	1,92
Nd oxide 99.5-99.9% min	39,24
Pr oxide 99.5-99.9% min	49,55
Nd-Pr oxide 99% min	38,51
Sm oxide 99.5% min	1,88
Tb oxide 99.99% min	425,12
Y oxide 99.999% min	3,67

Source: Mackowski, 2016.

Despite the named uncertainties, China is clearly the major player in the global REE industry. The country produces and consumes the majority of REE, REM and rare earth alloys (REAs).

5.2.3 Other small producers

Brazil

Estimates for the production of REE in Brazil suggest that volumes in the range of 500 to 700 t were produced between 2005 and 2008, following a significant drop to close to 200 t in 2009, and a decrease to about 100 to 150 t in the years 2011, 2012 and 2014 (with peaks of about 300 t in 2010 and about 350 t in 2013), and mine closure in 2015 as a result of ore depletion and complete using up of residues that contained concentrated REE (Adamas Intelligence, 2016).

Russia

For the past decade to 2015, Lovozerskiy GOK was the sole producer of REE-ore, and REE concentrates of between 6,000 and 9,000 t loparite annually in Russia, from the Kola Peninsula (Adamas Intelligence, 2016). Chemical cracking (separation) and concentration occurs at Solikamsk Magnesium Works' plant in the Ural Mountain region, where processing to separated REO and separated rare earth compounds also occurs (in an estimated similar volume as in Estonia (Adamas Intelligence, 2016) since 2013. The concentrate is shipped for further processing and refining to oxides and metals, to Estonia (where an annual production capacity of 3,000 t REO exists) or to Kazakhstan (with two plants, one of which a JV with Japan) (Adamas Intelligence, 2016).

India

It is estimated that the production of REE-containing minerals as a by-product of heavy mineral mining amounted to several thousand tons of monazite annually between 2005 and 2015; thereof, only a small fraction is processed further and the remainder stored for future use (Adamas Intelligence, 2016). In 2005 and 2006, production estimates are at about 960 t each year (ibid.), and official statistics of the Indian Bureau of Mines report small production volumes in 2007, 2008 and 2009, and none in 2010 and 2011 (ibid.). Estimates refer to a production of about 16 t of REO equivalent in 2012, and no production in 2013 and 2015 (Adamas Intelligence, 2016).

Malaysia

REE are also produced as a by-product of heavy mineral mining in Perak, contained in xenotime and monazite. Industrial concentration has had only one major producer, Pegang Mining Corporation, pursue operations since 2005. Official statistics by the Malay Ministry of Mines give a production estimate in the range of 25 to 895 t of monazite annually between 2005 and 2015, and up to 2015 t of xenotime annually over the same period (Adamas Intelligence, 2016). It is estimated that Malaysia's annual TREO production was in the range of about 20 to 700 t of REE concentrates between 2005 and 2015, producing about 200-240 t of REE per year since 2013 (Adamas Intelligence, 2016; USGS, 2016).

Myanmar

It is estimated that Myanmar Ye Huan Mining produced about 2,500 t of TREO, mostly LREE, in the disputed region of Kokang on the border with China between 2008 and 2015 (Adamas Intelligence, 2016).

5.2.4 Recent producers

Australia (and Malaysia)

In 2011, REE-production recommenced with Lynas Corp. at Mount Weld in Australia. The Mount Weld deposit is a highly weathered carbonatite complex, with REE being mined from the weathered zone. The first separated REOs were produced in 2013, including about 1,140 t of LREE and about 65 t of MREE (Samarium-Europium-Gadolinium [SEG]) and HREE. A subsequent ramp-up of production resulted in production of an estimated 7,000 t LREE and about 400 t mixed SEG and HREO. In 2015, estimates suggest a total LREE production of about 11,000 t and additional 1,000 t of mixed SEG and HREO (Adamas Intelligence, 2016). A debt amendment was proposed by Lynas (of USD 400 million) in 2016 for approval by its shareholders (Investorintel, 2016a). This amendment was crucial to continue n the Lynas production, including of the chemical separation at the LAMP plant of Lynas in Malaysia of REE-containing chemical concentrate from Mount Weld.

US

Between 2000 and 2002, Molycorp produced about 5,000 t of TREO annually from stockpiled ore at the Mountain Pass carbonatite mine. No production took place between 2003 and 2007, and production was resumed in 2008, running until 2015 with about 5,000 t of TREO annually. In 2015, Molycorp declared bankruptcy, which was approved in 2016, and the production of REE-products at Mountain Pass in California has closed down.

5.2.5 Other illegal production

Overall, Adamas Intelligence (2016) differentiates between illegal and undocumented mining, the latter might occur at legal mine sites but without documentation, entering material supply chains and stock piles. Further, a distinction is important between illegal production and processing, which has been described earlier. In the following, the illegal production outside China is briefly mapped:

Brazil

The Amazonian region has been noted as an area of illegal rare earth mining operations (Adamas Intelligence, 2016).

Thailand

In 2014, an illegal rare earth mine was uncovered and closed by Thai police officials after the discovery of illegal REE-bearing dickite exports (Adamas Intelligence, 2016).

Vietnam

The production of REE from the Dong Pao mine in Lai Chau province triggered illegal mining sites operated by hundreds of miners that smuggle rare earth exports to China. In 2012, more than 10 illegal mines were uncovered which produced REE next to other minerals and gold (Adamas Intelligence, 2016).

6 EU rare earth market

The EU rare earth market initiates at the processing segment of separating mixed REE into REO, and formulating these. Figure 6.1 is based on Eurostat (2016) data and illustrates changes in the source of RE-compound and RE-metal imports into the EU for four product codes from 2000 to 2015 (previous to their expansion to 12 product codes as of 2016, table 6.1). China remained the major source for REE-product imports since 2000 and until 2014, while the five year intervals of figure 6.1 reveal an interesting pattern:

In 2000, the EU-share of REE-metal and -alloy imports amounted to 27,290 t in 2000, and revealed that more than 90% originated in China, while that share had reduced to 67% of the 17,126 t imported in 2005, with Russia accounting for almost a quarter of the imports (23%) in the same year. In 2010, total RE imports were at 11,421 t, and the import share from China rose again to 85%, with 13% from the US, and 0,42% from Russia. After 2014, imports rose again to beyond 2010 levels, and to 11,989 t in 2015 (figure 6.1) when close to half of the total imports into the EU stemmed from the US (from Mountain Pass directed towards processing in Estonia), while the import share from China was at 32% and from Russia back at 21%.

Imports of REE-metals and -compounds into the EU have more than halved since 2000: The first significant decrease in RE-metal and RE-compound imports into the EU occurred at the time of the first export quota allocations by China in 2005. The second reduction of imports into the EU took place between 2005 and 2010. Since, total imports remained rather static around 11-12,000 t REE with a reduction in imports from China, and variances in the contributions of the second and third largest import partners, the US and Russia.

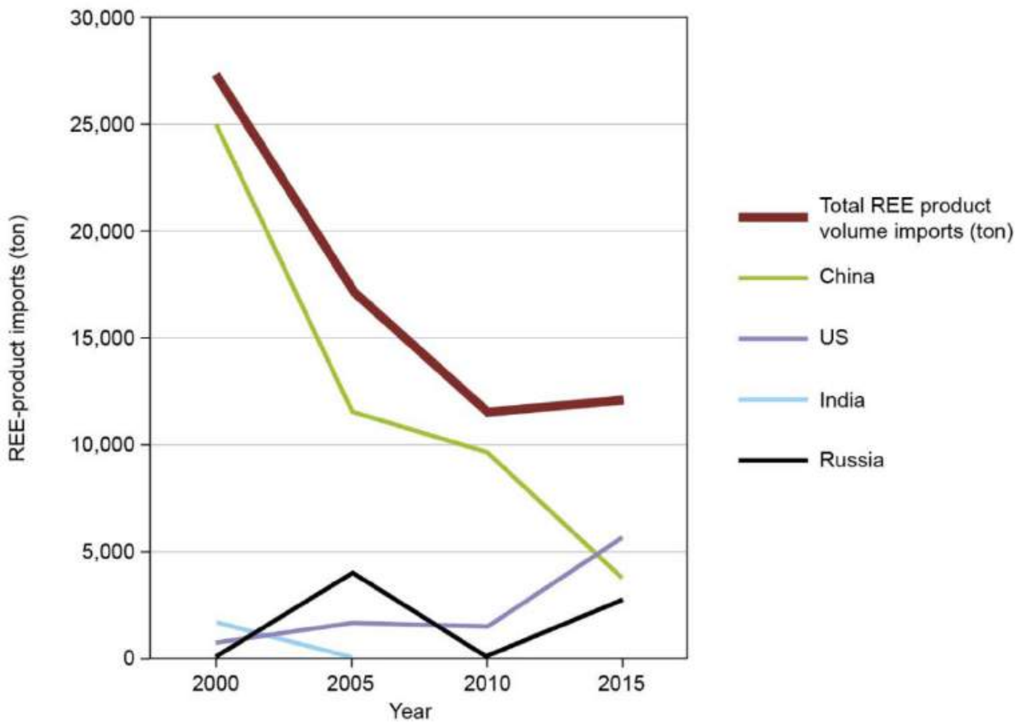
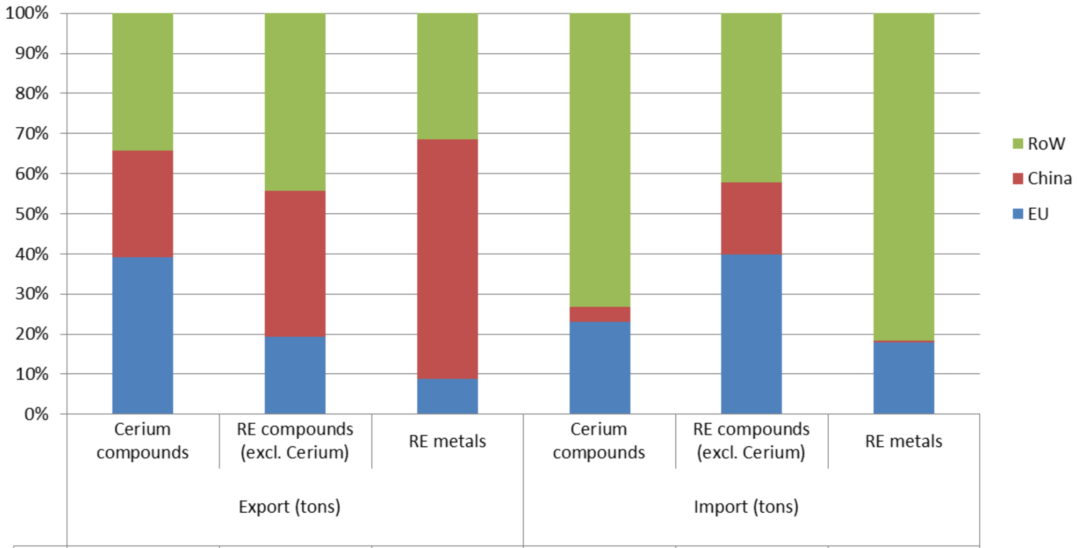


Figure 6.1. Total EU-import of REE-metals and -compounds, 2000 – 2015.
Source: MiMa-GEUS with data retrieved from Eurostat, 2016.
Note: REE-metal and –alloy imports are summarized from four HS product codes (28053010, 28053090, 28461000 and 28469000) for which data is available for the time period, and by importing country.

Figure 6.2 draws on Ce-compounds, other RE-compounds and REMs to report the share of EU industry exports (first three columns from the left) and imports (last three columns) in 2015 compared with China and the Rest of the World[4] (RoW) (elaboration from COMTRADE database, Jan. 2017). The figure does not include REE-containing ore or mineral concentrates. As a consequence, the figure also excludes the trade (import – export) between Australia and Malaysia concerning the ore extracted by Lynas in Australia, and exported to Malaysia for subsequent processing.



	Export: Cerium compounds	Export: RE compounds (excl. Cerium)	Export: RE metals	Import: Cerium compounds	Import: RE compounds (excl. Cerium)	Import: RE metals
RoW	10,232	26,475	3,146	20,223	23,406	7,807
China	7,915	21,666	5,972	1,029	10,003	59
EU	11,667	11,587	887	6,345	22,125	1,708

Figure 6.2. EU-share of import and export of RE-compounds and metals in 2015.
Source: D'Appolonia based on data from COMTRADE database Jan. 2017.

Figure 6.3 details EU-imports of REE products from partner countries over the same period. The detailed import per product code and partner enables a view of the potential import dependency for a particular REE-product. In general it can be seen that imports from China cover the range of the four CN-8 product codes of Eurostat (2016) (indicated with white background in table 6.1). Largest volume imports from China are cerium compounds, followed by compounds, which are not further specified. In 2015, however, imports of compounds from the US and Russia, arguably from Mountain Pass and Lovozero, respectively, exceeded imports of compounds from China. Both the imports of cerium compounds and compounds have reduced since 2000.

[4] Australia, Brazil, Canada, India, Japan, Kazakhstan, Malaysia, South Africa, South Korea, USA, Vietnam

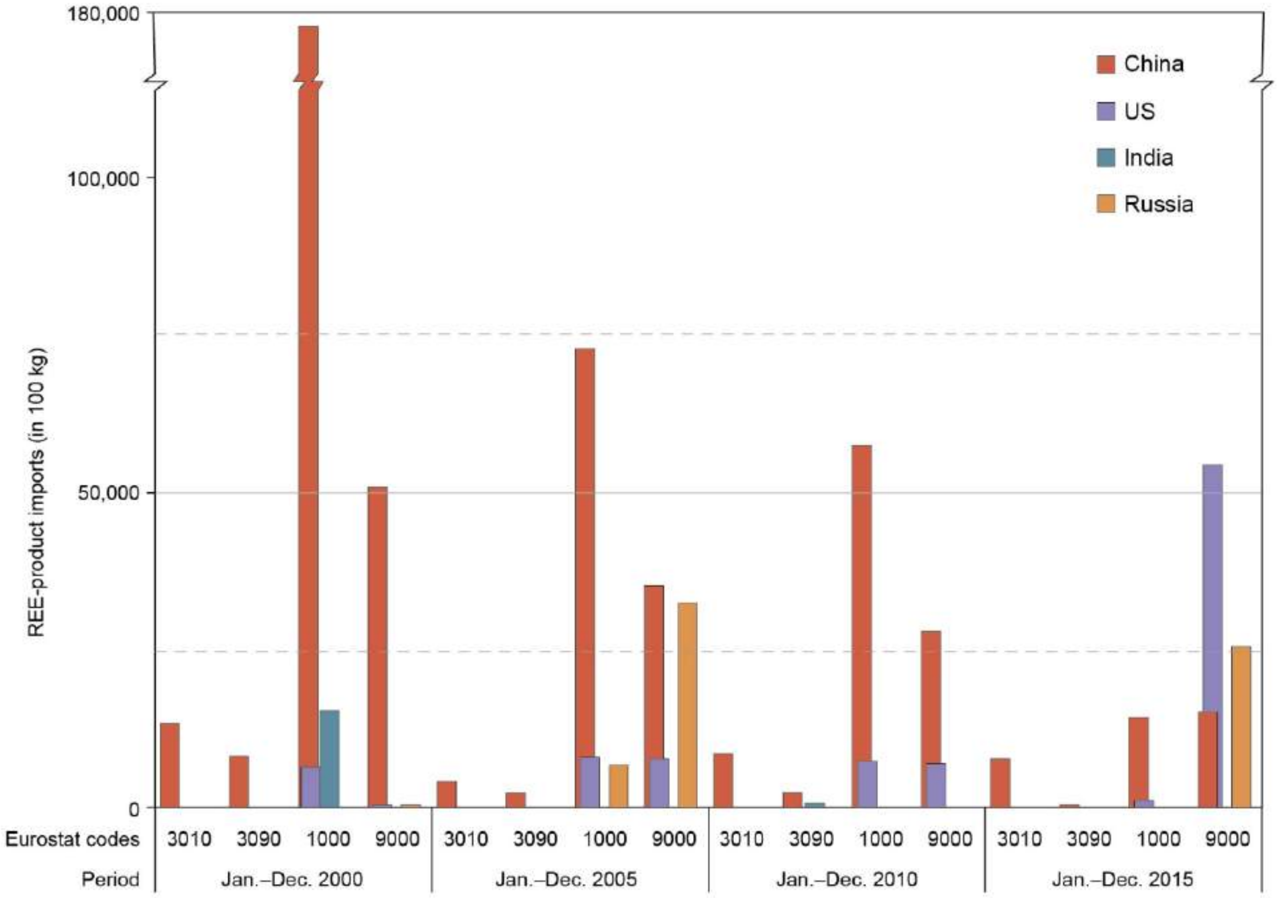


Figure 6.3. Detailed EU-imports of REE-metals and REE-compounds, 2000 – 2015.
Source: MiMa-GEUS, with data from Eurostat, 2016.
Note: The imports from China of product code 28461000 in the year 2000 equalled about 176,000 t.
The figure has also been created by enabling an overlapping presentation of the imports from different countries.

Table 6.1. Eurostat codes.

28053010	Intermixtures or interalloys of rare-earth metals, Scandium and Yttrium
28053020	Cerium, lanthanum, praseodymium, neodymium and samarium, of a purity of weight of &gt=95% (excl. intermixtures and interalloys)
28053030	Europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, and yttrium, of a purity of weight of &gt=95% (excl. intermixtures and interalloys)
28053080	Rare-earth metals, Scandium and yttrium, of a purity of weight of &gt=95% (excl. intermixtures and interalloys)
28053090	Rare-earth metals, Scandium and Yttrium (Excl. intermixtures or interalloys)
28461000	Cerium compounds
28469000	Compounds, inorganic or organic, of rare-earth metals, of Yttrium or of Scandium or of mixture of these metals (Excl. Cerium)
28469010	Compounds of lanthanum, praseodymium, neodymium, or samarium, inorganic or organic
28469020	Compounds of europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium or yttrium, inorganic or organic
28469090	Compound

Source: Eurostat (2016).

Figure 6.4 shows the disproportionally higher import into the EU of the product code ‘90000 - REE compounds’ (blue columns) when compared with the other three REE-product imports. It also illustrates the significant rise in the imports of REE-compounds in 2015. Further, it can be seen that the import of ‘1000 - cerium compounds’ (green column) occurs mostly in the first six months of the years examined, while the import of ‘3010 - intermixtures or interalloys of REM, Sc and Y’(orange column), and of ‘3090 - rare-earth metals, and Y’ (pink column), the former in significantly higher quantities than the latter, is more evenly divided between the first and the second half of the year.

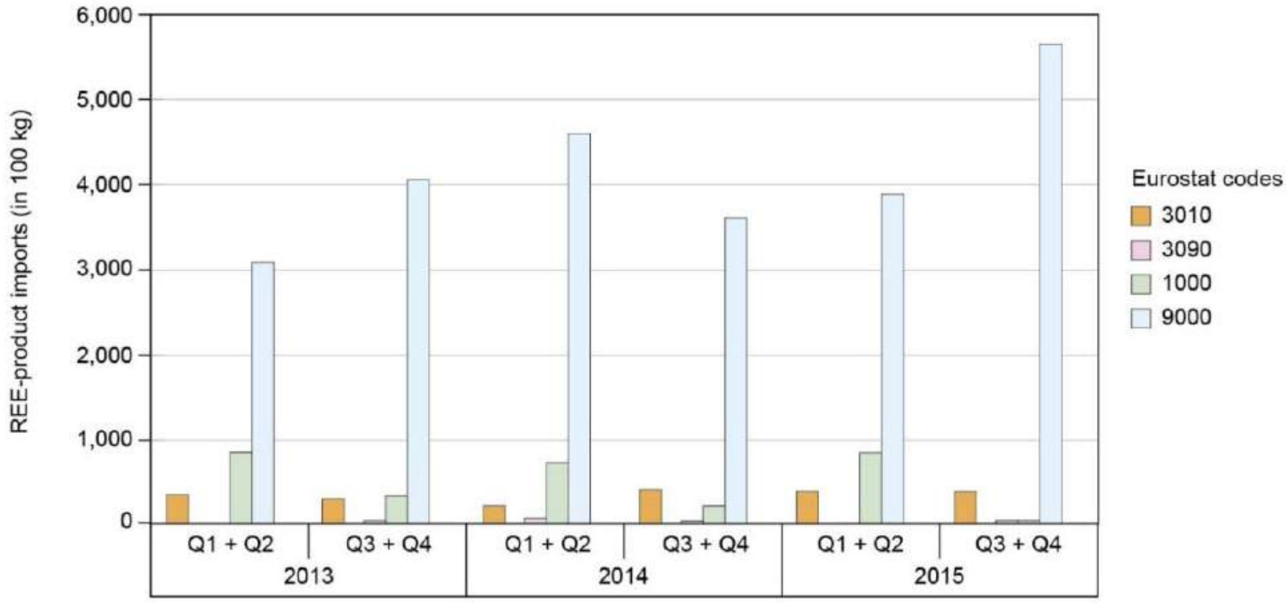


Figure 6.4. Product imports per quarterly division between 2013 and 2015.
Source: MiMa-GEUS, 2016 with data from Eurostat (2016).

For 2016, the available detail of REE-product codes has expanded from originally and previously discussed four product codes (held in white) in Table 6.1, to 12 product codes. The Eurostat (2016) product codes provide more detail on the individual REE imported. As will be described and illustrated in the following paragraphs, the nomenclature of these more detailed product codes comes with another set of challenges.

The first two quarters of 2016 reveal REE-product imports into the EU of ‘28461000 – Cerium compounds’ from Russia, and ‘28469010 – Compounds of La, Pr, Nd or Sm, inorganic or organic’ from China as shown in figure 6.5. While imports in January were comparatively rather low, they peaked in February 2016 during that six month period (Figure 6.5).

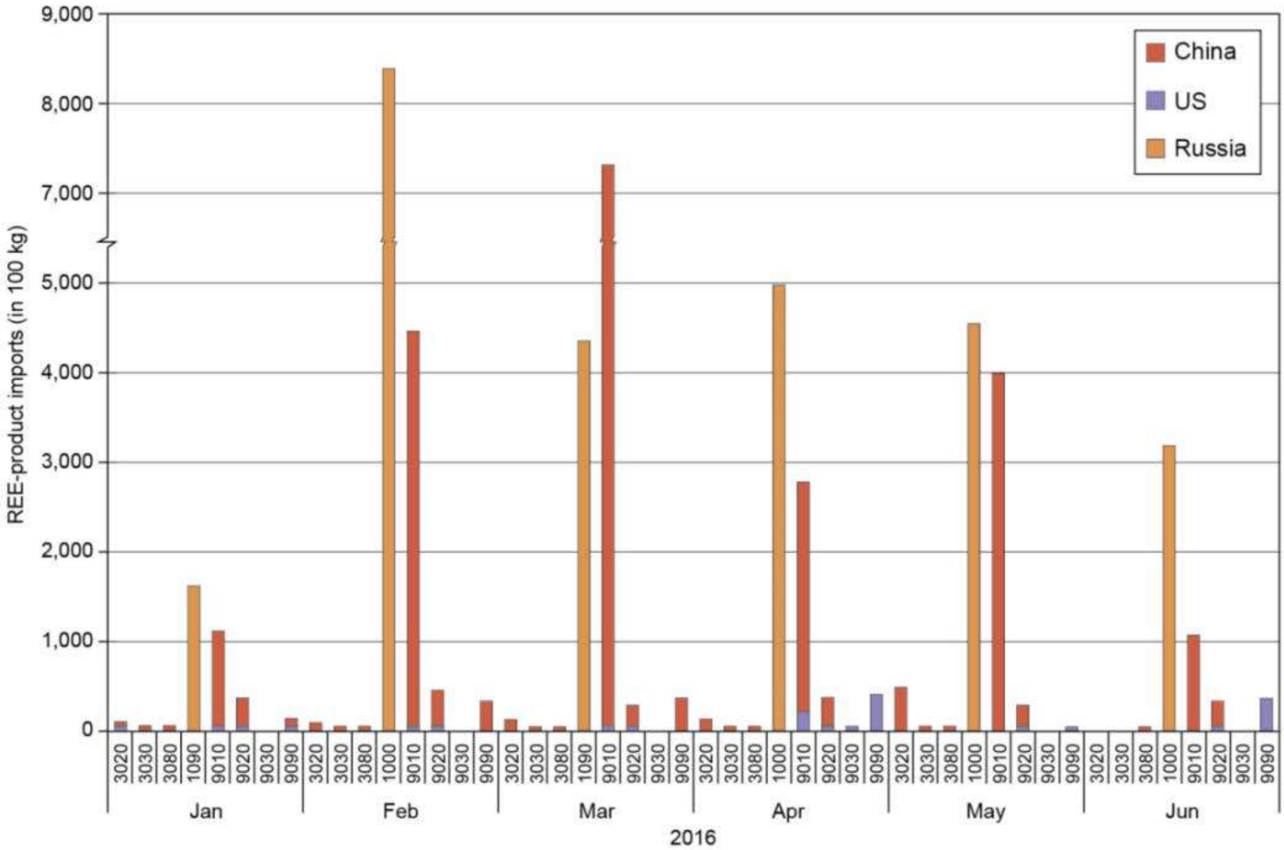


Figure 6.5. REE-product imports in 2016.
Source: MiMa-GEUS based on Eurostat, 2016.

Overall, the RE-compound and –metal product import structure over the first half year of 2016 also reveals more than 70% of imports of cerium compounds (product code '28461000'), followed by close to 25% RE-compounds (product code '28469010'), as shown in figure 6.6. These latter imports cannot be allocated to specific intermediate industrial sectors, as:

- the product code nomenclature, see table 6.1, continues to aggregate individual elements,
- and the use of the term 'compound' opens for various interpretations, such as to whether it refers to different types of compounds (metals, alloys, oxides, salts), and thus, REE that encompasses all types of compounds, or whether it refers to REM, as metals of individual elements in form of alloys.

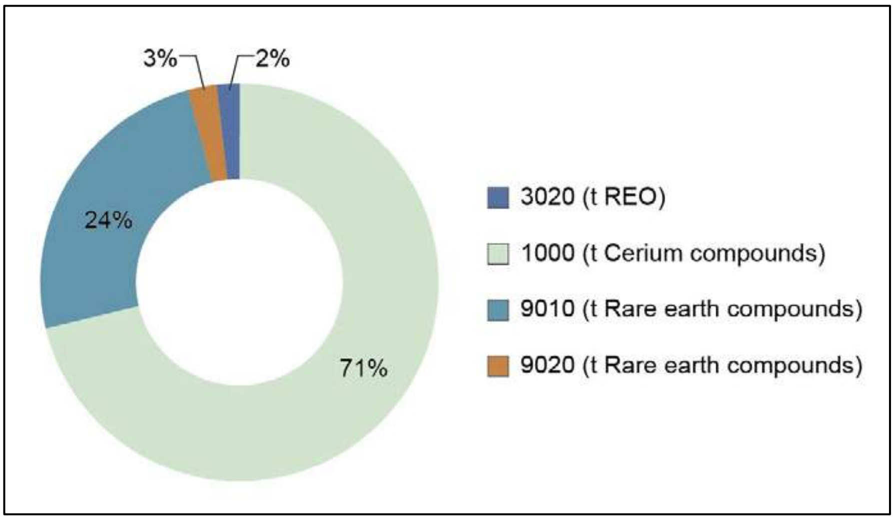


Figure 6.6. Share of REE-product type imports in 2016.
Source: Eurostat, 2016.
Note: January to June 2016 based on Eurostat, 2016; estimates for July to December, 2016.

Against these challenges described, the common methodology to derive approximate indications for individual intermediate sectoral uses of REE relies on the sectoral shares provided by ERECON (2014), shown in figure 6.7.

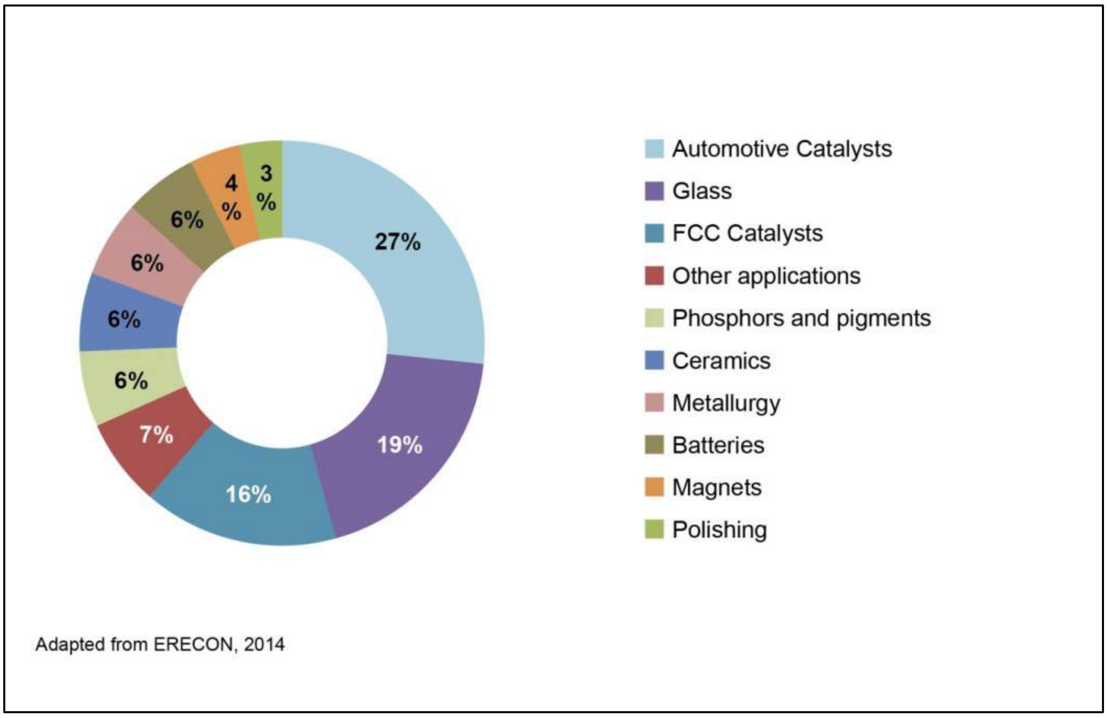


Figure 6.7. Intermediate REE-sectoral share in the EU.
Note: ERECON (2014) uses a 'Metal Alloy' sector specification, which we divide into 'Batteries' and 'Metallurgy', each of 6%. We also increased the 'Others' sector to 7% to align all sectors to a total of 100%.

Figure 6.8 draws on the sectoral shares of the previous pie chart and total REE-imports into the EU from Eurostat (2016) to construct the sectoral division of REE imports. From figure 6.8, a rather large rise in the total REE-product volume imports into the EU is visible for 2016 as compared to 2015, under the assumption that imports will be of equal volume or larger in the second part of the year as compared to the first (shown in fig. 6.5). This certainly, leaves a significant gap with a view to understanding the impact of Mountain Pass closure in the US, which was a major source for RE-imports into the EU in 2015 (see fig. 6.3)., but has also limited impact in the first half of 2016 (fig. 6.5). This development cannot be further analyzed at the time of finalizing this report (January, 2017). Further, the increase in REE-imports might also be a result of the application of new REE-product codes in Eurostat, yet this cannot be confirmed here.

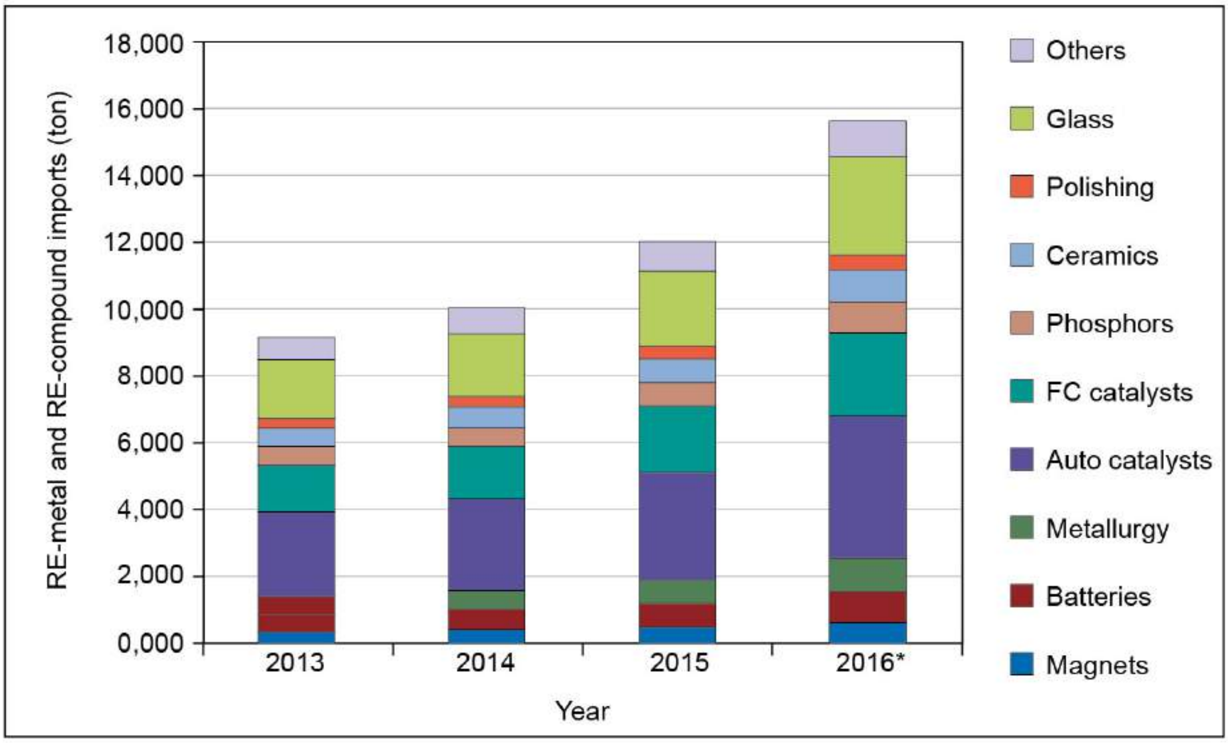


Figure 6.8. Indicative sectoral use of REE-imports into the EU between 2013 and 2016.
Source: compiled from Eurostat (2016).
Note: 2016* draws on the new product nomenclature and includes forecasts for the third and fourth quarter of the year which were derived by doubling the registered imports for the first and second quarter of 2016.

6.1 Supply chain segments served by firms in the EU

This sub-chapter provides a broad overview of the firms in the EU and their REE-related activity according to supply chain segment. With a view to the divergence in the industrial base of each EU-member state, it is important to specify REE-uses according to the respective material supply chain segment to gain an understanding of their significance for the particular EU-member country. This view focuses on firms operating in the particular segments of the supply chain, from processing and separation, intermediate-sectors and manufacturers to end-of-life product collection and recycling for some of the REE-using sectors. It is therefore highly simplified as these firms' operational reality is in a globalized economy, in which they have subsidiaries in countries outside the EU that might have different forms of ownership and are more or less organizationally integrated but geographically dispersed. This has also been demonstrated with the listing of the headquarters and subsidiaries at the end of the previous sub-chapter. In addition, the EU-based firms also source inputs into their operational activities (material components) from outside the EU.

At the upstream segments, the REE supply chain in the EU is restricted to exploration of REE-bearing mineral deposits, and technological consulting and research into technologies such as on solvent extraction (MEAB). On the European scale, exploration of REE-mineral deposits is being and has been conducted in numerous member states and regions of the EU (see 3.4.4). Beneficiation, extraction and separation technology and knowledge are hosted in Austria, Estonia, Finland, France, and Sweden.

On a commercial scale, the REE supply chain in the EU initiates at the chemical separation segment. The import of the feedstock for the chemical separation, the REE-bearing mineral concentrates, has, however, been restricted for a while:

- *First*, for regulatory reasons as legislation had mineral imports with radioactive content banned, which stopped the monazite imports from Mount Weld in Australia to La Rochelle in France in 1995[5]. Nonetheless, Molycorp Silmet imported REE-mineral concentrate from Mountain Pass into Estonia, and it seems to continue to source REE-mineral concentrate from Russia.
- *Second*, it has become challenging and costly to export less-processed mineral concentrates from China for chemical separation elsewhere (see export policies of China described in chapter 5).
- *Third*, low prices of the chemically separated products (e.g. REE oxides) in China cause chemical separation in the EU to be no longer continuously competitive (personal comm. Solvay). For these reasons, the activity of chemical separation in the EU is shifting to that of purchasing already chemically separated REE-products, to then engage in the purification of these to higher levels of purity, and to formulation according to detailed customer specifications.

In the case of Solvay, the tacit knowledge on the intricacies of chemically separating REE, which has been acquired over time in this family-owned business, has been used to close material loops by recycling REE-based phosphors. This project has been supported by EU-funding (LOOP, 2015). While the technological processes for the recycling of REE-phosphors are arguably readily available, recycling activity has reportedly been stopped in 2015, shortly after the end of project-funding. Low REE prices have been named as the reason that makes recycling no longer economically feasible (Solvay, 2015).

At the intermediate segments, the REE supply chain in the EU counts numerous firms. These firms use REE products as inputs into their operational activity, and are active in metal and alloy making,

[5] 'Between 1952 and 1995, Australia exported 265,000 ton of monazite with a real export value of $284 million in 2008 dollars (Australian Bureau of Statistics 2009). Most of the monazite was exported to France for REE extraction, but the monazite plant in France was closed because its operators were unable to obtain a permit for the toxic and radioactive disposal site.' (Commonwealth of Australia, 2015)

magnet manufacturing, process catalyst research and manufacturing, and automotive catalyst material research, among other.

Automotive- and process catalyst manufacturing and research occupy a significant role in the EU REE-intermediate segments: The chemical industry in the EU counts several players (including for instance BASF, Akzo Nobel, Johnson Matthey, Haldor Topsoe) which focus on specialty chemicals for different intermediate sectors.

The manufacturing of REE magnets is also among the important intermediate segments in the REE supply chain in the EU. Here, it is important to distinguish between manufacturing technologies applied for REE-magnets to paint a representative picture of the SME landscape in the EU. While sintered REE-magnet manufacturing is limited to a few firms in the EU of which one is significantly larger in size (Vacuumschmelze, and the integrated Neorem), and important particularly for the wind industry, also injection-bonded magnet manufacturing has a significant role to play for the SME landscape.

More than a dozen SMEs across the EU manufacture magnets with bonding as opposed to sintering technology, i.e. injection molding and compression-bonding. The sintering technology is used for magnets that are used in generators of certain wind turbine technologies, and in much smaller-sized magnets in the automotive industry. The bonded magnets, particularly injection-bonded magnets, are of strong interest to the automotive industry as the manufacturing method of injecting the magnet material into a form, allows for much more complex magnet shapes than sintering magnets. This is a considerable advantage in the automotive industry where magnets are used to reduce car weight, and up to 200 and more magnets are used in a single car, depending on car class. Further injection molding as opposed to compression bonding manufacturing technology enables the manufacturing of small magnets which vary between several millimeters and centimeters of size, and importantly, the material can be injected into particular, complex shapes which make this technology particularly interesting for customization.

Most of the EU magnet manufacturers supply to the automotive industry which represents their largest customer, with the rest of the customer base representing a rather diversified spectrum of industrial users. For most of the uses, it appears that REE-use is opaque in the EU, in other words, it is challenging to trace definitively which end-products contain REE. It appears that a share of REE-use in the EU, which is for obvious reasons rather challenging to estimate (Guyonnet *et al.*, 2015), occurs by means of importing components such as REE-containing electronics. These are used in further manufacturing of goods, but in many cases the importing firm will not be aware that the components contain REE. Also in the case of the intermediate segment of glass, REE might be imported contained in the glass, which might be redistributed for use in a range of different applications. This obscured use is particularly the case where EU regulation for hazardous material content declaration (e.g. for transportation) does not require the declaration of small material volume content. For instance, regulations such as RoHS Directive 2002/95/EC[6] and REACH[7] require the declaration from a particular level of minimum volume use.

Research on advanced materials with REE occurs in the EU, yet with small volumes. This includes research on REE use in magnets, in fluid cracking and automotive catalysts, fuel cells, and high-tech ceramics, and potential other ongoing activities. Notably, this small REE use might contribute to the development of new materials, to potentially be patented. Such development can be tracked retrospectively, via the Chemical Abstract Service (CAS) in which new materials are registered.

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[6]EU legislation restricting the use of hazardous substances in electrical and electronic equipment
[7]Registration, Evaluation, Authorisation and Restriction of Chemicals

At the end-use segments, the REE supply chain in the EU is vast, as the REE-containing components feed into uncountable end-uses from known REE-phosphor-coated fluorescent lamp bulbs or tubes, sintered REE-magnets used in some direct drive wind turbine generators but also in toys, household appliances and medical equipment (MRI), and lesser-known REE-uses as dopants in ceramics, such as piezoelectric ceramics (PLZT).

The following categorization is indicative and based on estimates on economic importance of the specific REE-sectors to the particular EU member states: REE use in the chemical industry is central for Germany, Belgium and France, and the Netherlands with firms such as BASF, Solvay, and Akzo Nobel. The UK and Denmark are centers for catalyst manufacturing, among other, with Johnson Matthey and Haldor Topsoe, respectively. REE-use is important to the UK and the health care industry, such as for the production of magnetic resonance imaging equipment. Further, Central Europe, particularly Germany, and Northern Europe, Denmark, Finland, and Sweden, as well as Italy jointly host numerous injection-bonded REE-magnet manufacturers in addition to the sintered magnet manufacturers – Vacuumschmelze and Neorem, owned by OMG (US) – which are of substantial size for Europe, and organizationally integrated while geographically dispersed. Slovenia is a recent addition to the magnet manufacturing base in the EU, including with scientific breakthroughs (The Slovenia Times, 2015).

Figure 6.9 illustrates the material supply chain segments from REE-mineral mining, beneficiation, extraction and separation, to processing to oxides, metals and alloys for uses by the intermediate REE-using sectors (numbered 1-9) by particular firms in the EU, and REE-component based end-use products. Further, the illustration indicates where material loops can (at least) technically be closed by recycling within the firm (‘in-process recycling’) such as for polishing media, or by collecting end-of-life (EoL) products for recycling at different other firms to be fed back into the supply chain.

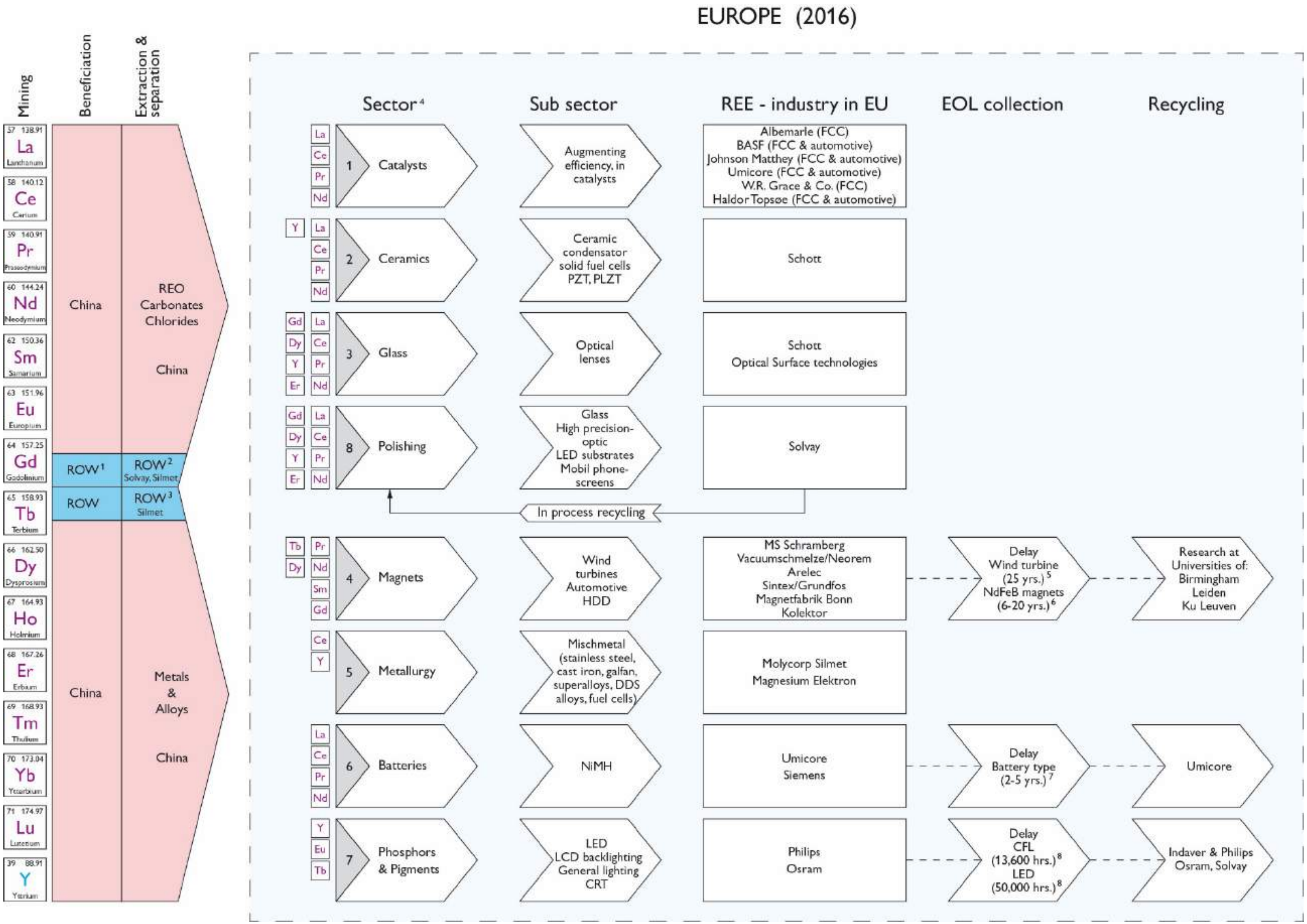

Figure 6.9. Stylized illustration of the REE supply chain segments.

Source: MiMa-GEUS, 2016 with material supply chain segments adapted from Golev *et al.* (2014, p. 54) and Machacek and Fold (2014, p. 55); intermediate sectors[4] as used and described in chapter 4 of this report, and adapted from Roskill, 2011 and Adamas Intelligence, 2014; firms identified by the authors, including with data from ERECON, 2015, and Roskill, 2011. [1]ROW processing of mineral concentrate in Russia, and ore from Russia in Estonia, among other (Adamas Intelligence, 2016). [2]Estonia and France host chemical separation facilities. [3]Estonia hosts also metal-making facilities (Adamas Intelligence, 2016). Data on REE recycling of wind turbines [5]Habib *et al.*, 2014; of NdFeB magnets [6]Sprecher *et al.*, 2013; Rademaker, Kleijn and Yang, 2013; of batteries [7]Terazono *et al.*, 2015, and of CFL and LED [8]Wilburn, 2012.

6.2 Firms of the EU rare earth industry

The member states of the EU absorb a small share of the global REE demand, but as has been illustrated earlier in this report, large volume use cannot be taken as the sole significant indicator in an industry where small volumes are highly appreciated for their specific function. In the following, a list of firms is provided that is known for their use of REE in their manufacturing activity, either directly as REE-products (preferred for the listing here) or indirectly in form of REE-containing components.

The selection of firms is based on their involvement in commercial REE-use and integration of REE-based components. Therefore, consultants are excluded. This list is not comprehensive but draws on examples that have been identified by inferences from their activities in specific sectors known for REE use, and in some cases by direct contact with the firm. Numerous other firms are assumed to use REE-containing components purchased as inputs for their manufacturing activity. Companies which have been mentioned in ERECON (2014, p.17) are marked (*). Traders including wholesalers of REE-products such as Auer-Remy (2016) are not listed here. Please note the different y-axis scales of the figures. A division between firms active in separating and further processing RE, and in manufacturing REE-containing components and end-products based on REE-components is made per country. This division is approximate and may be contested as some firms might have integrated activities that i.e. transcend from separating into the manufacturing of components.

EU countries considered are reported here below, along with 2015 imports and exports and citation of main players and if present, a short description of the potential reserves. A significant divergence between low imports and high exports may be indicative of either the use of locally sourced RE ores (as imports of ores are not taken into account in the figures) and/or the presence of processing industries to RE-compounds or metals (e.g. Russia, and Austria). High imbalance between high import and low export may be due to transformation industries, taking RE-compounds or metals to produce end- or intermediate-products (e.g. Germany, Netherlands). Importantly, geographical origins for the imported compounds or metals can be assumed but not established with certainty. Exports of REE-containing end-products are not shown in this graph, which explains also the seemingly low exports from China (as the country increasingly exports final consumer goods with REE-containing components).

Austria

In 2015 Austria imported 3176t of RE-compounds (including Ce- and other RE-compounds) and 493t of REMs. Exports in 2015 were about 9,000t of RE-compounds and 393t of REMs, globally more than 30% directed to Germany (COMTRADE database). The significant exports of RE-compounds require discussing in light of low imports of RE-compounds: Guyonnet *et al*. (2015, pp. 217) discuss the challenges in estimating REO import and export data, and mention the reporting stop of data by the significant player in Austria, Treibacher, since 2008. They also derived an estimate of above 3,000 t REOs imported by Austria from outside Europe, which they suggest could be explaining the divergence in total EU REO imports derived from Hedrick (2004) and USGS (12,500 t REO), and reported by POLINARES (2012) and Sievers and Tercero (2012) (10,000t REO) in 2010.

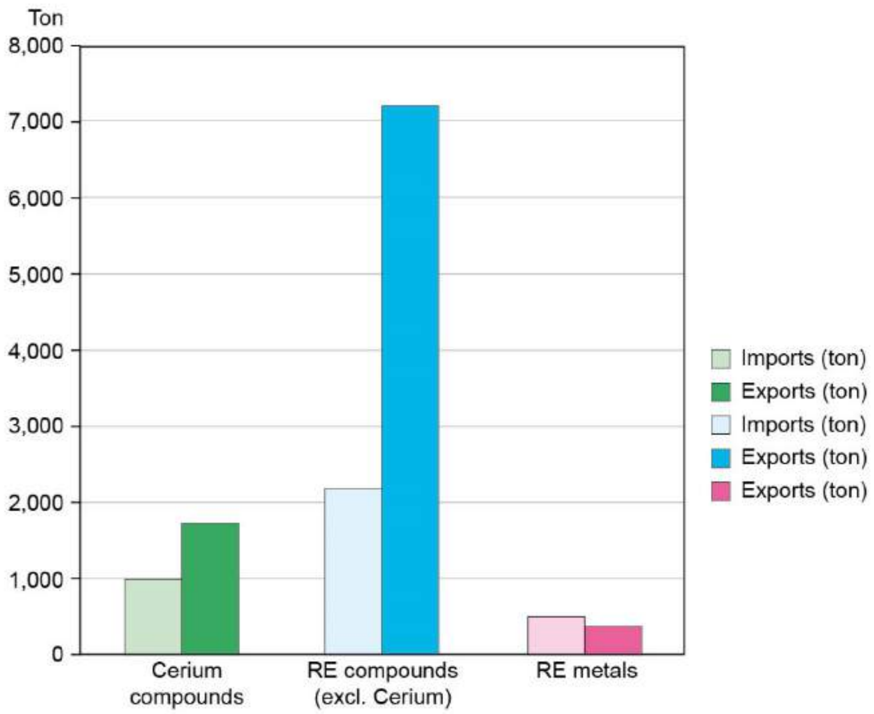

Figure 6.10. Austria imports and exports (t) of RE-compounds and metals in 2015.
Source: based on COMTRADE database.

Separation and Processing

- **Treibacher Industrie AG*** (2016) is a major chemical and specialist metal producer, and 'a market leader for rare earths' that supplies the basis for manufacturing high-quality products with very special properties. The firm offers REE as raw material for customer-specific processing and provides technological know-how for demanding new products in a range of application fields including catalysts, pigments, frits and ceramic stains, glass fusion and polishing agents, foundry industry, and flints.

Manufacturing

- **The Zumtobel Group** (2016) headquartered in Dornbirn, Austria, is a manufacturer and internationally leading supplier of professional indoor and outdoor lighting, lighting management systems and lighting components as well as LED and OLED technology with more than 60 years of tradition. The group has three sites in Austria, and numerous others in the world.

Belgium and Luxembourg

Belgium is important in the EU economy due to the presence of Umicore and its recycling facility, processing small volumes of REE (mainly Lanthanum). Belgian and Luxembourgian imports in 2015 are equal to 261t of RE-compounds (including Ce- and other RE-compounds) and 8t of REMs, while exports are equal to 347t of RE-compounds (including Ce- and other RE-compounds) and 53t of REMs.

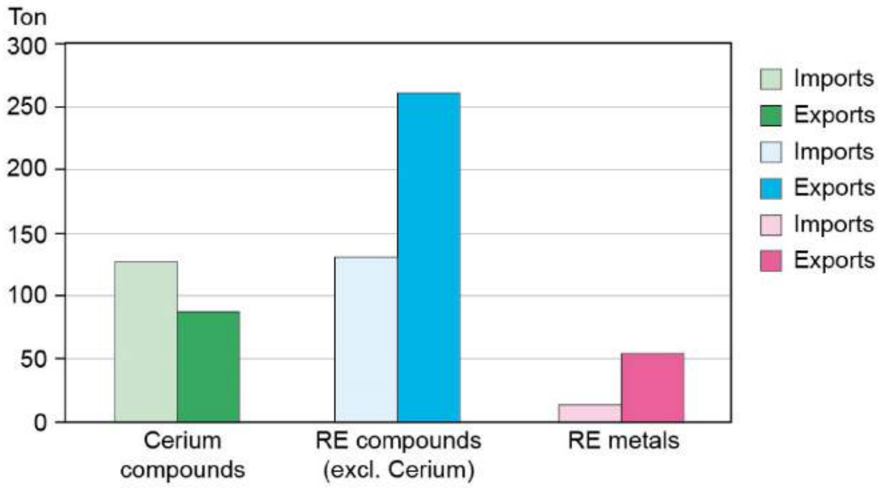

Figure 6.11. Belgium and Luxembourg imports and exports (t) of RE-compounds and metals in 2015.
Source: based on COMTRADE database.

Separation and Processing

- **Umicore** (2016) is a multinational material technology company that uses rare earths in the production of auto catalyst products which is to be consolidated until 2019 in three plants focused on emission control in light duty vehicles (Bad Säckingen, Germany; Nowa Ruda, Poland; Karlskoga, Sweden) as well as a dedicated operation in Florange, France, for catalysts mainly used in heavy duty diesel vehicles. At Hoboken, in Antwerp, Umicore also recycles REE rechargeable batteries into a rare earth concentrate (La, Pr, Nd next to nickel, copper, and cobalt) to be exported to Solvay (La Rochelle).

Denmark

Separation and Processing

- **Haldor Topsoe** (2016) is an engineering and manufacturing firm for advanced materials and it uses REE in the research on material development, both for catalysts and for fuel cells. Next to more than 150 different catalysts, their design and manufacture for specific tasks, Haldor Topsoe also makes equipment, components and consumables. In addition, the firm focuses on the improvement of battery materials.

Manufacturing

- **Danfoss** (2015) is active in the energy efficiency segment and manufactures compressors for water- and air-cooled air-conditioning systems, including with an oil-free, magnetic, variable speed compressor (Danfoss Turbocor) that uses REE. In the infrastructure segment, Danfoss is active in HVAC/R, district heating and cooling, commercial and residential buildings, construction, water and wastewater and mining and forestry.

- **Sintex-Grundfos** (2013) manufactures primarily pumps, and REE-magnets, latter by its subsidiary Sintex, to be used in these. Specifically the pumps Magna 3, Alpha 2, and MGE/MLE-SaVer models contain REE.

- **Siemens Wind Power** (2016) is a division of Siemens, headquartered in Germany, and created the world's first offshore wind power plant in 1991 in Denmark. Siemens Wind Power's strategy includes on- and offshore wind power plants. The firm uses REE-magnets, the manufacturing site of which is not publicly available.

- **Vestas** (2016) is exclusively working with wind energy as a manufacturer and installer of windmills with plants in Hammel and Randers, and some of its windmill generator models used REE-magnets (Garret and Rønde, 2013).

Estonia

In 2015 Estonia exported around 2,970t of RE-compounds (including Ce- and other RE-compounds) to US, Austria, France and Germany, counterbalanced by the imports of about 7,872t of RE-compounds (negligible amounts of Ce-compounds are included), mainly from US (67%) and Russia (32%). In Sillamäe there is the Molycorp Silmet complex, one of the main RE materials producers in Europe. The disparity between imports and exports of RE-compounds could be explained by the import of REE-mineral concentrates (which are not accounted for in the figure). This REE-mineral concentrate seemed to have been sourced both from Lovozero and from Mountain Pass in 2015.

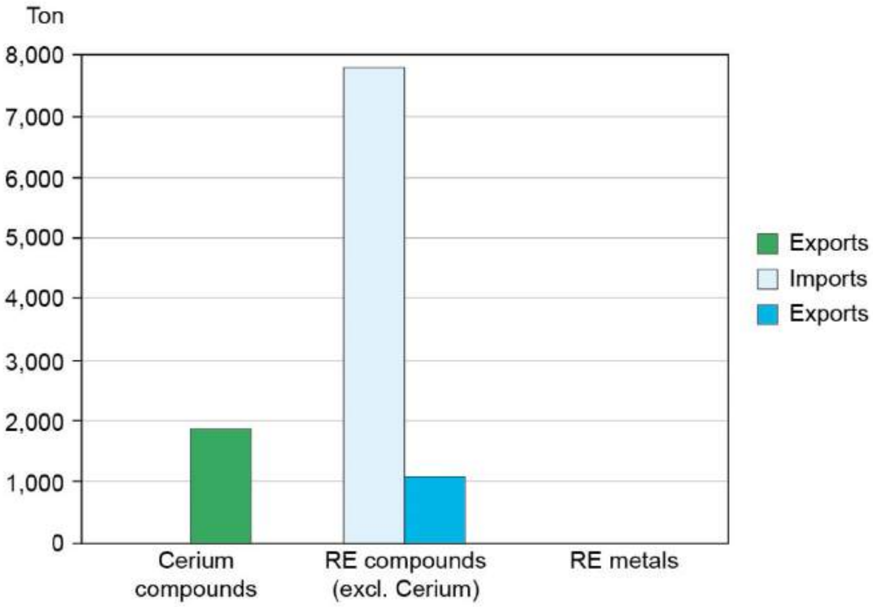

Figure 6.12. Estonia imports and exports (t) of RE-compounds and metals in 2015
Source: based on COMTRADE database.

Separation and Processing

- **Molycorp Silmet*** is part of US-controlled Molycorp, which developed the U.S. Mountain Pass mine in its mine-to-market strategy before it was declared bankrupt in 2015, which was approved in March 2016 (Brickley, 2016). Molycorp Silmet specializes in the production of tantalum and niobium, and is involved in extraction of

RE from mineral concentrate, rare earth separation and production of REM. It is among the largest rare metal and REM producers in Europe (MMTA, 2016).

Finland

Separation and Processing

- **Outotec Oy** is a globally operating firm that is active in minerals and metals processing technology, in industrial water treatment, the utilization of alternative energy sources, and the chemical industry.

Manufacturing

- **Neorem Magnets Oy*** (2014) (part of Vacuumschmelze which is subsidiary to an OMG company) in Ulvila is a manufacturer of large sintered NdFeB magnets and magnet pole elements for large electric motors and generators, particularly for renewable energy applications, for servo and linear motors and in mobile equipment.

France

France hosts the Solvay plant in La Rochelle (Rhodia Rare Earth Systems). In 2015, France exported around 907t of RE-compounds (excluded Ce-compounds) and 21t of REM. On the other side, imports in 2015 were 646t of RE-compounds (excluded Ce-compounds) and 163 t of REM. RE-compounds are mainly exported to markets in Germany, Italy, Japane and USA, while they are imported mainly from Austria, Japan, China and USA.

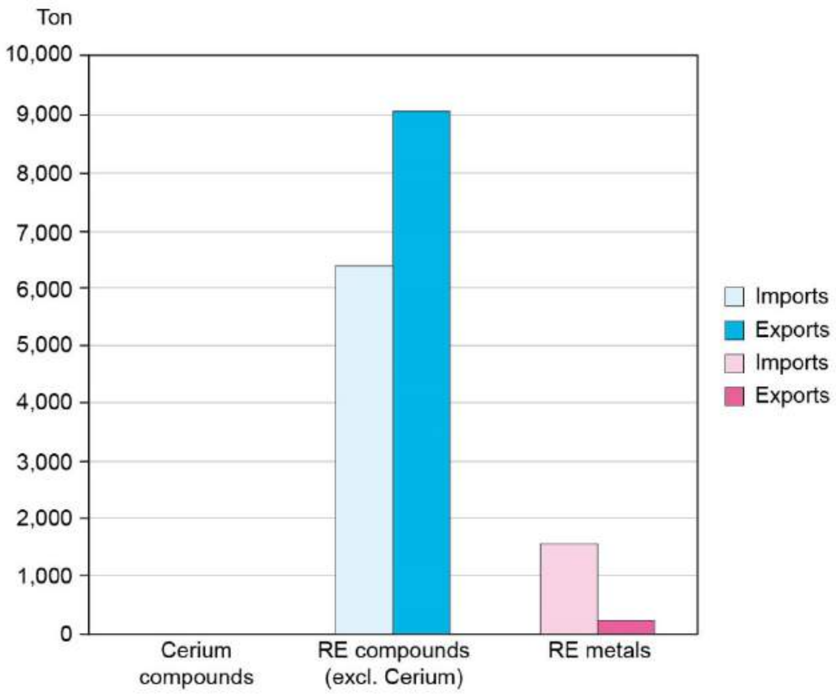

Figure 6.13. France imports and exports (t) of RE-compounds and metals in 2015.
Source: based on COMTRADE database.

Separation and Processing

- **Solvay*** (2016a) The REE separation branch of Solvay (ex Rhodia), located at La Rochelle, uses solvent extraction to separate mixtures of rare earth oxides (REO) into individual rare earths. Solvay offers REE-based high-technology products for various markets including automotive catalysis (emissions control for gasoline and diesel vehicles), lighting applications (phosphors for low-energy lamps) or electronic applications (LCD and plasma flat screens and precision optics). In 2012, Solvay launched a recycling unit for the recycling of REE from fluorescent lamp phosphors. Due to the low prices of REE, but also to the rapid replacement of fluorescent lamps by LEDs, Solvay announced in January 2016 that this unit was discontinued.

Manufacturing

- **Arelec** (2016) is a magnet manufacturer of injection-bonded magnets, and trades sintered magnets (NdFeB and SmCo) and bonded magnets (by injection, and compression bonding), also for sensor targets. It has plants in Pau (France), in Vitoria (Spain), and in Tunis.

Germany

Germany is one of the largest REEs importers in the world, importing 8,528 t of RE-compounds (including Ce- and other RE-compounds) and 297 ton of REM in 2015, mainly from China, Estonia, France, Japan and Korea. Exports in 2015 were 836 ton of RE-compounds (including Ce- and other RE-compounds) and 20 ton of REM. Main companies processing and using RE-compounds are BASF, W.R. Grace & Co, Vacuumschmelze, MS Schramberg and Siemens.

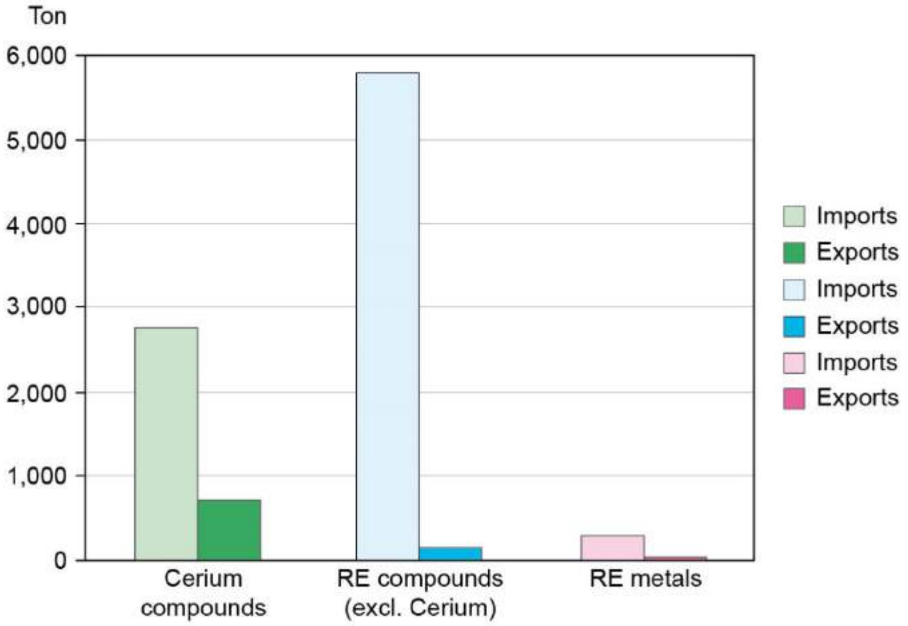

Figure 6.14. Germany imports and exports (tons) of RE-compounds and metals in 2015.
Source: based on COMTRADE database.

Separation and Processing

- **BASF** (2016) is a leading chemical company, including for auto- and FCC catalysts. In 2011, BASF signed an agreement to supply lanthanum-metal catalysts to the Lynas chemical separation plant in Malaysia. (The Chemical Engineer, 2011) BASF Catalysts Germany GmbH is one of the leading suppliers in vehicle exhaust after-treatment including with mobile emissions catalysts produced in Nienburg.

- **W. R. Grace & Co.** (Grace Division) manufactures FCC catalysts and other REE-products for the petroleum industry. A significant FCC catalyst production takes place in Germany (Worms) under the Grace Davison division. Under trade labels of REsolution™, REBEL™, REACTOR™, REMEDY™, and REduceR™, Grace Davison trades five zero and low REE containing catalysts.

- **Leuchtstoffwerk Breitungen GmbH** (2016), hereafter ‘LWB‘, was acquired by Treibacher in 2013 and produces phosphors for a wide range of fluorescent and pigment applications, including LED phosphors, phosphors for LCD backlighting and general lighting, fluorescent materials for cathode ray tubes, fluorescent materials for special purposes.

- **Magnequench** (2016) produces and trades REE-powders for bonded NdFeB magnet production, mostly for motors and sensors which come to use in numerous applications such as computer and office equipment, consumer electronics, in the automotive sector, and general industry. Magnequench International Europe (2016) is located in Tübingen.

Manufacturing

- **Kolektor Magnet Technology** (2016a, b) is a magnet manufacturer in Essen, including with a plant in Slovakia, and offers sintered NdFeB and SmCo magnets from affiliated companies in China, primarily for automotive and industrial applications, e.g. BLDC – motors and sensors.

- **Magnetfabrik Bonn** (2016) is a leading manufacturer of magnets of a wide range of material compositions, among other, polymer-bonded and sintered NdFeB magnets. The firm has significant development and production experience, and manufactures for the automotive industry and for machine and motor construction, as well as domestic electrical equipment.

- **Max Baermann Holding AG** (2016), a manufacturer of polymer-bonded REE-magnets known by its names Tromadur®, Tromaflex®, Tromadym®, and Tromamax® and used in micromotors, sensor magnets, armatures, computers and quartz watches. It has a production facility in Bergisch Gladbach.

- **MS Schramberg GmbH & Co KG** is a manufacturer of REE magnets and ferrite magnets. Originally, MS Schramberg manufactured only ferrite magnets. The NdFeB magnets are manufactured with the Hitachi Licence. Since the mid-1980s, the firm has moved on to manufacturing plastic bonded injection-molded and sintered NdFeB and SmCo magnets.

- **Osram** (2016) is a leading global firm for lamps, luminaires and lighting solutions for numerous market segments, and a product portfolio that extends from light sources to custom light management systems, in specialty and general lighting.’

- **Siemens AG** is a leading engineering and manufacturing conglomerate, and uses REE in the manufacturing of products that generate renewable energy such as wind turbines, water turbines, and photovoltaic cells, energy efficient generators, phosphors for lighting and medical equipment. Siemens has three bases in Germany: its headquarters in Berlin and Munich; Erlangen for the production of generators, motors and electronics.

- **Schott** (2016) is a multinational, technology-based group which manufactures specialized materials, components and systems in the glass and ceramic sector from small components for the electronics industry to large-scale optical glass for astronomy telescopes, specifically in defense, lighting and imaging, electronic packaging, home tech, pharmaceutical systems and flat glass. It is assumed that the group uses REE.

- **Vacuumschmelze GmbH & Co. KG*** (2016), hereafter 'VAC', and part of the OMG Group, is a leading global manufacturer of advanced magnetic materials and magnets, including through Neorem Magnets Oy in Finland. The VAC product range includes permanent magnets, magnet assemblies, materials such as VAC alloys, parts (punched and bent, sheet packages and screens), cores, inductive components.

Italy

Manufacturing

- **Cibas** (2016) is based in Milano, and develops and distributes permanent magnets and magnetic devices for a wide range of application fields including automotive, household appliances, industrial automation, security, green energy, medical, plasturgy, avionics, electronics, Hi-Fi Audio, water treatment and other. These magnets include NdFeB and SmCo.

Slovakia

Manufacturing

- **Vacuumschmelze** (2016) also has a subsidiary in Slovakia.

Slovenia

Manufacturing

- **Kolektor** (2016) has a subsidiary in Slovenia in which magnets are manufactured for automotive components and systems, energy and industrial technology, building technology and home products. In particular, Kolektor manufactures NdFeB, hard-ferrite and a mix of NdFeB and hard-ferrite by means of compressed molding and injection molding.

- **Magneti Ljubljana*** (2015) is a magnet manufacturer of permanent magnets and magnetic systems, with a focus on Cast AlNiCo magnets, sintered AlNiCo magnets, sintered SmCo magnets, sintered NdFeB magnets, bonded magnets and magnet systems. The magnetic systems include gripping/holing magnetic systems and systems used as components in different measurement and sensor systems and in different types of electric motors.

Spain

Glass and ceramics industries currently represent the most important demand sectors in Spain. Having no domestic production, Spain imported 256t and 266t of Ce- and other RE-compounds respectively, in 2015, mainly from China, Italy, France and Austria. Imports of REM reached instead 529t in 2015, showing a sharp growth rate over the last few years: this is essentially due to the increasing use of Pr metal in substitution to Pr compounds in glass and ceramics applications.

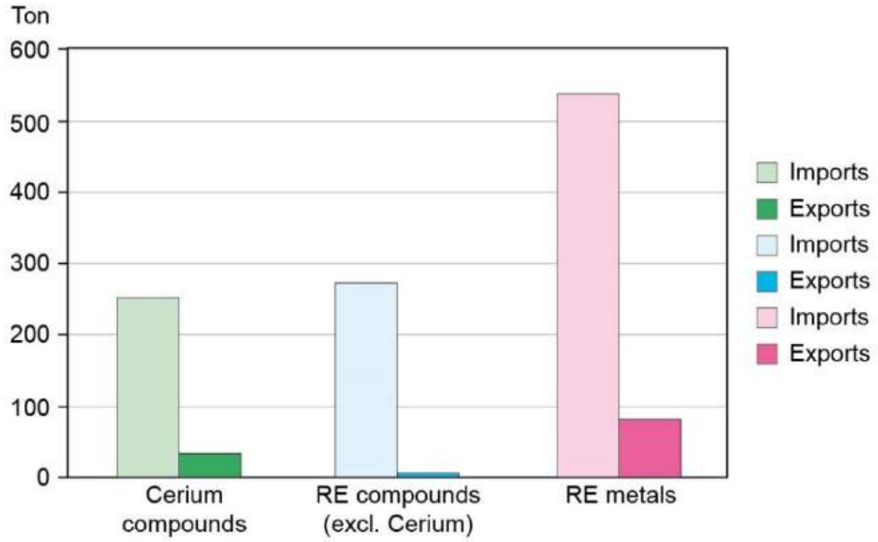

Figure 6.15. Spain imports and exports (t) of RE-compounds and metals in 2015.
Source: based on COMTRADE database.

Manufacturing

- **IMA** (Ingeniería Magnética Aplicada S.L.) (2016) in Mollet del Vallés, manufactures magnets including NdFeB and SmCo. The firm also has facilities in Italy, and China, and cooperates with the research institutes IMDEA Nanoscience (Spain) and IFE (Norway), and distributes through offices in Germany, Italy (Milan) and China (Ningbo).

Sweden

Manufacturing

- **Aura Light** provides businesses with lighting that is smart; sustainable, economical, long lasting and of high quality. The firm has a production site in Karlskrona, Sweden, where the Aura LED light sources are made. Aura Group AB is owned by FSN Capital and has subsidiaries in Sweden, Denmark, Finland, Norway, Germany, France, Italy, Portugal, Spain, UK, China and USA. Apart from our subsidiaries we also offer our products and solutions through our partner network around the world.

- **Sura Magnets** (2016a,b) is a magnet manufacturer in Sönderköping that manufactures a range of magnets, including plastic bonded injection-molded REE-magnets of SmCo, NdFeB, and SmFeN. Hard ferrite magnets are also part of the range. The firm delivers to the automotive- and medial sectors as well as general industry.

The Netherlands

The Netherlands is an international centre of REEs exchange. The country's port of Rotterdam functions as main entry port for REE product imports into the EU from which they are redistributed across the EU. This is also known as the 'Rotterdam effect' (Guyonnet *et al.*, 2015). To establish whether figure 6.17 accounts for the Rotterdam effect would require an empirical material supply chain study in the Netherlands, which was beyond the scope of this report. In 2015, exports accounted for 151t of RE-compounds (including Ce- and other RE-compounds) and 3202t of REM, while imports were equal to 475t of RE-compounds (including Ce- and other RE-compounds) and 165t of REM. The RE retained belongs mainly to Albemarle Catalyst Company.

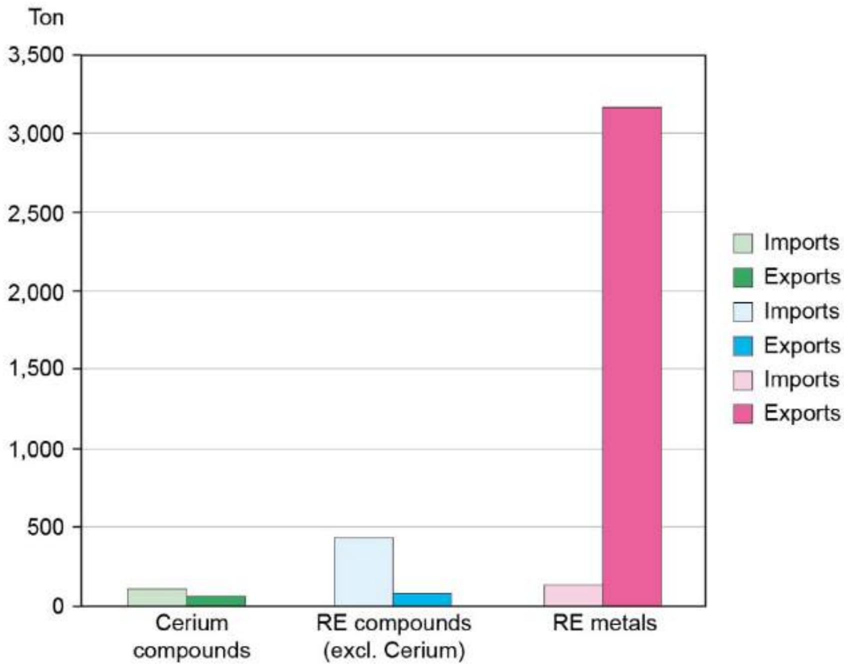

Figure 6.16. The Netherlands imports and exports (t) of RE-compounds and metals in 2015.
Source: based on COMTRADE database.

Separation and Processing

- **Albemarle Catalyst Company B.V.** is a leading global specialty chemical company with headquarters in the USA, and three plants in Amsterdam where research on and production of catalysts for use in the petroleum refining industry occurs. Specifically, one plant produces FCC, another hydro-processing catalysts, and a third has multiple functions producing isomerization, methyl chloride, methyl amine, melamine and oxychlorination catalysts.

Manufacturing

- **Koninklijke Philips Electronics N.V.,** in short 'Philips', is a technology company and has several manufacturing facilities in Europe which use REE in the production of MRI scanners, speakers and headphones, and LED televisions. Jointly with the Belgian waste-processing company Indaver, Philips Lighting developed a process for the recycling of phosphors from Philips' LFL. Philips has also prioritized the substitution of REE in LED (Halper, 2012).

United Kingdom

In 2015, imports were 737t and 599t of Ce-compounds and other RE-compounds, respectively, showing a slightly decrease in comparison to the previous years. While France, China and Estonia represent the main countries for cerium compounds' sourcing, the other RE-compounds are imported from Austria, Italy and Japan. Regarding REM, an overall amount of 47t was imported in 2015 mainly from China, the USA and the Netherlands. The REEs industries in UK are essentially involved in the production of specialty alloys and metals, polishing powders as well as catalysts. In particular, the main companies consuming REE are: Less Common Metals, Optical Surface Technologies, Johnson Matthey, Magnesium Elektron and MEL Chemicals.

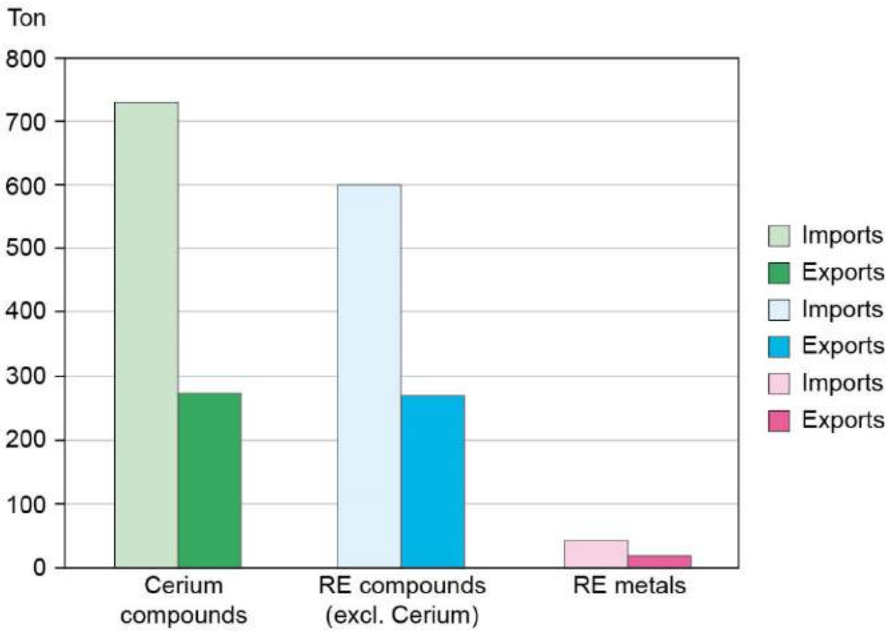

Figure 6.17. United Kingdom imports and exports (t) of RE-compounds and metals in 2015- Source: based on COMTRADE database.

Separation and Processing

- **Less Common Metals Ltd**.*, hereafter 'LCM' is a part of Canadian controlled Great Western Minerals Group (GWMG) and manufactures $SmCo_5$ and Sm_2Co_{17} powders, magnetostrictive materials, master alloys combining REE and non-REE metals, magneto-optic alloys (Tb-Fe-Co) and gadolinium-iron-cobalt (Gd-Fe-Co), lanthanum-nickel (La-Ni) alloys used in hydrogen storage, REE sputtering targets and super high grade (99.9999%-99.99998% purity) indium ingots. It is also a significant manufacturer of NdFeB alloys.

- **Optical Surface Technologies,** hereafter 'OST', is a leading European producer of polishing powders. OST is part of London and Scandinavia Metallurgical founded in 1937, which today is a subsidiary of Advanced Metallurgical Group N.V. (AMG) in the Netherlands.Regipol^{TM}. OST manufactures cerium oxide, aluminum oxide, and silica slurries for the polishing of glass components, both decorative and high-tech, plastic lenses, optical fibres and acryclic sheeting.

- **Johnson Matthey** is a chemical company producing with expertise in advanced material technologies in various sectors from environmental, automotive, chemical, pharmaceutical, recycling, oil, gas and refineries, and other industries including fuel cells, glass, jewelry, and food. The firm develops catalysts, precious metal and specialty chemical products. Catalysts are produced for the automotive, petroleum, pharmaceutical and fuel cell industries around the world. Ce oxide is used in several JM catalyst products as a reactive or supporting agent, including at its UK facilities.

- **Magnesium Elektron** (2016) is a **s**pecialist magnesium alloy producer (with REE content), as a division of the Luxfer Group same as below firm, a group of specialists in high performance engineering materials and supplies these alloys to healthcare applications, including pharmaceuticals, diagnostic equipment, orthopaedics and bioadsorbable implants. In the EU, alloys and other magnesium based products are manufactured at the UK Swinton facility, and the Czech Louka and Litvínova facilities.

- **MEL Chemicals Inc** (Roskill, 2011)
  A member of the Luxfer Group, MEL Chemicals Inc produces inorganic materials, mainly zirconium products in the UK (besides plants in the USA and Japan) for distribution in the EU and the world. These zirconium products are often doped with REE such as yttrium, cerium and lanthanum to make the compounds thermally stable. The products are used in numerous applications including automotive catalysis, electronics, structural and functional ceramics, paper productions, chemical catalysis, SOF cells, and water purification.

Manufacturing

- **Arnold Magnetic Technologies*** (2016), hereafter 'Arnold', is a subsidiary of U.S.-controlled Arnold Magnetic Technologies. Arnold manufactures custom SmCo magnets, Alnico, injection moulded NdFeB, and Flexmag rubber magnets for a wide range of applications. In addition, Arnold sources licensed NdFeB magnets from Asia.

Firms in the EFTA Member States

Norway

Separation and Processing

- **Yara International ASA** (Yara) Norwegian research facilities for metallurgical test-work. Yara, a post restructure subsidiary of Norsk Hydro, were chosen because they hold technology for the extraction of REE from apatite rock. Yara is a Scandinavian based organization that is considered to be a world leader in the manufacturer and marketing of fertilizer products (Arafura, 2005).

Switzerland

Manufacturing

- **Arnold Magnetic Technologies AG** (2016) has a subsidiary in Lupfig where REE-magnets are manufactured, as well as purchased from Asia, tested and distributed, if needed.

Firms in Other States

Russia

Currently there are two operating mines in Russia that are extracting REE influencing the trade balance, while Solikamsk Magnesium Works is the major firm processing REEs. As a consequence, balance is moved towards exports. In 2015, exports settled at 6,225t of RE-compounds (including Ce- and other RE-compounds), while imports were significantly lower, assessed at 1,862t of RE-compounds (including Ce- and other RE-compounds) and 56t of REM.

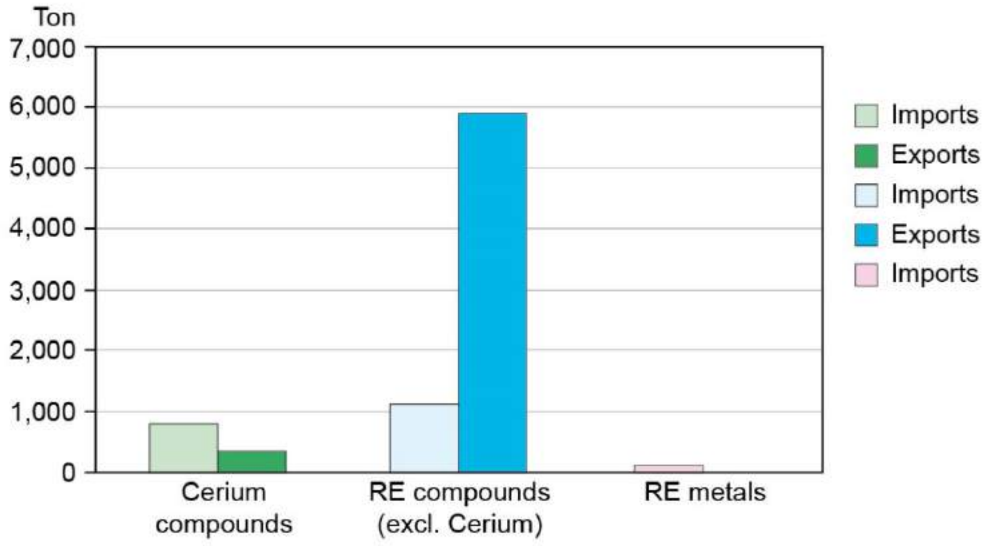

Figure 6.18. Russia imports and exports (t) of RE-compounds and metals in 2015.
Source: based on COMTRADE database.

The following section provides an outline of the local activities in the larger REE-using countries of some of the firms which have been identified in the description of the EU landscape of REE-using and REE-based component-using firms. This has arguably been in response to the growth potential in Brazil, India and China, as well as to the necessity to be present in markets known for high-tech development, such as Japan, and not least, for reasons of access to REE ore, and processed REE products, among other.

China

- Albemarle Chemicals (Shanghai) Company Limited
    - Albemarle Holdings Limited
    - Albemarle Management (Shanghai) Co., Ltd.
    - Ningbo Jinhai Albemarle Chemical and Industry Co., Ltd.
    - Shandong Sinobrom Albemarle Bromine Chemicals Company Limited
    - Shanghai Jinhai Albemarle Fine Chemicals Company Limited
- Arnold Pacific (Shenzhen, Guangdong, China)
- Baermann Magnets Suzhou Co. Ltd. (2016)
- BASF (2016, p. 19)
    - BASF Shanghai (R&D/Technical centre, Greater China HQ)
    - BASF Nanjing (Verbund sites)
    - BASF Hong Kong (Regional center)
- Cibas China / CS Magnets (Zhejiang, China)
- Grace China Ltd. (Headquarters), Shanghai
  Chinese offices and production plant
- Grundfos
- Haldor Topsoe Beijing Co., Ltd.
- IMA-NAFSA, Ningbo
- Johnson Matthey (9 subsidiaries in Shanghai, Yantai and Changzhou)
- Kolektor Automotive Nanjing Co. Ltd. (Jiangsu)

- LEHVOSS (Shanghai) Chemical Trading Co., Ltd. (Auer-Remy; Lehmann &Voss & Co.)
- Molycorp – Zibo (ZAMR)
- Molycorp – Jiangyin (JAMR)
- OSRAM China Lighting Ltd. (Foshan, Guangdong, China)
  - OSRAM Kunshan Display Optic Co., Ltd. (Jiangsu)
  - OSRAM Shanghai Rep. Office
  - OSRAM Sylvania Inc., PMC Shanghai Rep. Office
- Philips Lighting China Co., Ltd. (subsidiary of Koninklijke Philips N.V.)
  - Philips Innovation Campus Shanghai No. 1 Building
- Polyflex Magnets Ltd (Max Baermann)
- Siemens Centre Beijing (Headquarters)
- 2 Solvay-Rhodia plants
  - Baotou Solvay Rare Earth Co. Ltd.
  - Liyang Solvay Rare Earth New Materials Co. Ltd
- Treibacher Industrie AG Shanghai
  Pudong, Shanghai
- VACUUMSCHMELZE China Magnetics
  - Shanghai Sales Office
  - Beijing Office
  - Shenzhen Office
- Vestas (2016)
- Neorem Magnets Ningbo Co. Ltd.
- Outotec
  - Shanghai
  - Beijing
  - Suzhou

Japan

- Correns Corporation (Outotec)
- Intermetallics Japan
- Johnson Matthey Japan G.K. (Tokyo and Tochigi)
- Nikkei MEL (JV between MEL Chemicals and Nippon Light Metal)
- OSRAM Ltd. Yokohama, Japan
- Philips Japan
- Solvay-Rhodia plant
- Treibacher (Tokyo)
- VAC Magnetic Japan K.K. (Shinjuku-ku)

U.S.

- Arnold Magnetic Technologies
  - Flexmag Industries (OH & NE)
  - Alnico Division, Precision Thin Metals (Arnold Magnetics) (IL)
  - Corporate Headquarters (Rochester, NY)
  - Ogallala Electronics Division (NE)
- ACI Cyprus L.L.C. (Albemarle)
  - Albemarle Catilin Corporation
  - Albemarle Corporation
  - Albemarle Foundation
  - Albemarle Overseas Employment Corporation
  - Albemarle Virginia Corporation
- Baermann Magnetics Inc. (South Carolina)

- BASF North America (Freeport, Geismar (both Verbund sites), Florham Park (regional centre), and other)
- Grace China Ltd., Maryland, USA (World Headquarters)
- Haldor Topsoe, Inc. (Texas, Pasadena - Production plant, Orange, CA - Refining Technology Division)
- Johnson Matthey (numerous subsidiaries)
- LEHVOSS North America, LLC, Pawcatuck (Performance Compounding Inc,)
- Magnesium Elektron North America (Madison, Illinois)
- MEL Chemicals Inc
- Molycorp Materials and Alloys
  Outotec (Denver, Coeur d'Alene, Jessup, Cleveland)
- Philips North America
- Solvay-Rhodia plant
- VAC Magnetics LLC, NAFTA Headquarters (Elizabethtown, Kentucky), numerous subsidiaries

Others (Brazil, India, Malaysia)
Brazil

- Albemarle Brazil Holdings LTDA. and Albemarle Quimica LTDA
- Grace (São Paulo)
  Tracero Do Brasil (Johnson Matthey), Rio de Janeiro, Divisions: Process Technologies
- Johnson Matthey Brazil Ltda., São Paulo, Divisions: Precious Metal Products, Emission Control Technologies
- Paulo Viehmann Representacoes (Vacuumschmelze)
- Philips

India

- Albemarle Chemicals Private Limited
- Grace – Andhra Pradesh, Mumbai (Maharashtra), New Delhi, Chennai
- Haldor Topsoe India Pvt. Ltd (Haryana)
- Johnson Matthey India Private Ltd. (Haryana, Gurgaon)
    - Johnson Matthey Chemicals India Private Ltd. (Haryana; Maharashtra)
    - Johnson Matthey – Intercat Mumbai (Dist Vadodara)
- Magnaplast Technologies Ltd. *(Max Baermann)*
- Magnetic Meter Systems *(Max Baermann)*
- OSRAM Lighting India Private Limited (Head Office and Factory), Haryana
    - OSRAM Lighting India Pvt. Ltd. (Tamil Nadu)
    - Kolkata
    - Mumbai
    - Bangalore
    - Gurgaon
- Philips
- VAC India Office OMG Chemicals & Magnetics Pvt. Ltd. (Mumbai)

Malaysia

- Haldor Topsoe SDN. BHD. Kuala Lumpur
- BASF Kuantan (Verbund sites)

- Grace (Kuantan – Pahang)

- Johnson Matthey Sdn Bhd (Negeri Sembilan), *Emission Control Technologies*
- Tracero Asia (Petaling Jaya, Selangor), *Process Technologies*
- Johnson Matthey Oil, Gas & Syngas Office (Petaling Jaya, Selangor), *Process Technologies*
- OSRAM (Malaysia) Sdn. Bhd., Petaling Jaya
- Philips
- VAC Malaysia

7 Forecasting of REE-demand and supply

The REE market is significantly influenced by several economic, technological, political, environmental as well as social aspects which affect the balance between resources' demand and supply. We draw on different sources that present broader scenarios to account for this complexity as we forecast the future European and global REE market developments. Most of the data reported in sub-chapters 7.1 and 7.2 originate from elaborations by D'Appolonia, and are based on several sources to reflect different technological, economic, social and environmental aspects, both at the local and global scale. These sources are illustrated in Figure 7.1 and further described in the following two subchapters.

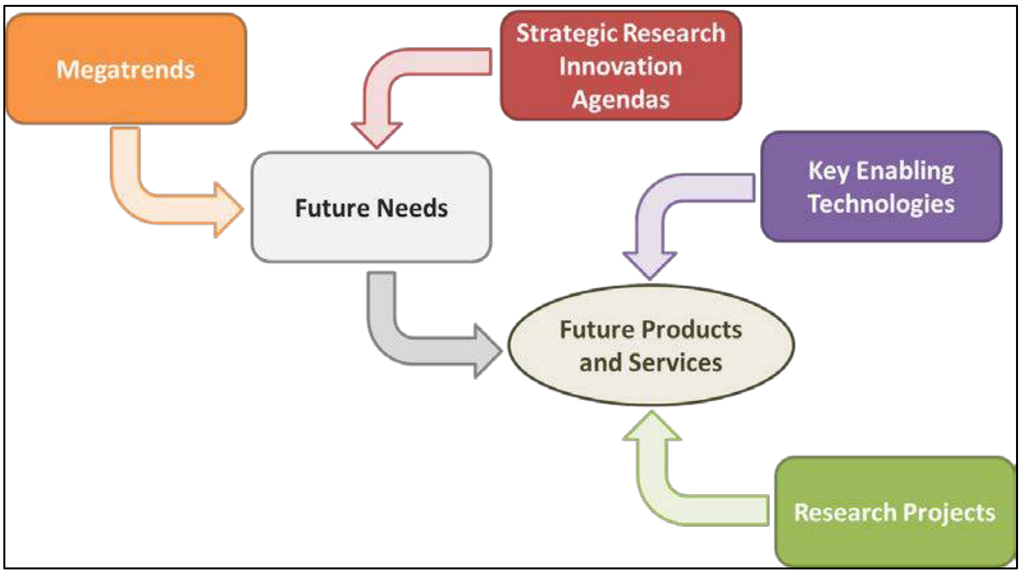

Figure 7.1. Illustration of the analysed sources
Source: D'Appolonia.

7.1 The global scenario

Megatrends are macro drivers for global development that impact on business, economy, society, environment, and more generally on lifestyle of the people. They provide a general and qualitative vision on different mid- and long term phenomena, identifying for example consumptions and needs of the humanity in the future. These trends can be grouped into three fundamental pillars of forecast developments (see Figure 7.2):

1. *Biosphere and natural resources*: scarcity of water, higher demand for materials and energy, climate change triggering migrations, new lifestyles and new technologies for environment protection.
2. *Demography and society*: along with a forecasted growth in global population (estimated 8.4 billion people in 2030), society will be older, multi-racial and urbanized; Alzheimer and Parkinson will be more commonly occurring; public health and pension systems will be increasingly under pressure.
3. *Globalized economy, new technologies*: emerging countries will continue to industrialize; economy will increase its own social aspects, together with the diffusion of new types of ownership (sharing economy) and smart accessories for smart economy; collaborative

knowledge (Wikinomics) will expand; innovative technologies (Key Enabling Technologies) will impact society.

The information and data included in this subchapter are originally extracted from different documents and further elaborated by D'Appolonia in other studies. Such sources are: Vodafone, "Future Agenda - The World in 2020"; L.C. Smith, "The World in 2050: Four Forces Shaping Civilization's Northern Future"; V. Raisson, "2033: atlas des futurs du monde - 2033"; KPMG, "Future State 2030"; Roland Berger, "Trend Compendium 2030"; Frost & Sullivan, "Top 20 Global Megatrends and Their Impact on Business, Culture and Society". Where sentences or data are directly reported, the source is cited within the text.

Figure 7.2. Three fundamental pillars of megatrends
Source: D'Appolonia.

Globalization will continue to unfold in the years to come. Productive (manufacturing) activity will augment particularly in BRIC[8] countries, which GDP is anticipated to grow annually by almost 6% up to 2030, as well as Next11[9], MINT[10] and MIST[11] countries, which GDP is projected to annually grow between 6.4% and 6.9% up to 2030 (Roland Berger, 2014). Firms in these countries are involved in the upstream segments of the REE value chain: Next to China, some examples of other REE producers are Brazil, India, Russia and Vietnam (Kable Intelligence Limited, 2014). However, political and regulatory instability may affect the economic performance of these countries, including the availability of their exports and supply chains for REE products.

To sustain future raw materials supply, the adoption of more sustainable solutions along the line of "Life Cycle Thinking" are needed as resource access and mining is met by constraints related to i.e. economic, political, environmental, social, technological issues, and resource depletion. These solutions focus on the end-of-life phase of products (e.g. "eco-design"), improvements in recycling processes, as well as new, high performance products and technologies with lower energy and raw material consumption. In particular, efforts are to develop solutions requiring less critical materials,

[8] Brazil, Russia, India, China
[9] Bangladesh, Egypt, Indonesia, Iran, Mexico, Nigeria, Pakistan, Philippines, Turkey, South Korea and Vietnam
[10] Mexico, Indonesia, Nigeria, Turkey
[11] Mexico, Indonesia, South Korea, Turkey

and to substitute the latter with alternative resources (European Commission [EC], 2014a), without compromising the quality of the products themselves.

Global primary energy demand will increase by 23% by 2030, with most of the world's primary energy demand to still be met by fossil fuels. Along with a growing demand for green power generation, anti-pollution technologies able to limit climate-changing emissions will continuously be improved. REE used for permanent magnets in some wind turbine generator technologies or REE-based phosphors and ceramics for devices in solar power generation are only some of the potential applications where REE could play a strategic role in the coming years. In addition, and with fossil fuels prevailing as principal energy source at least until 2030, the demand for high performance catalysts for automotive and FCC (i.e. fluid catalytic cracking) will remain, together with subsequent need for REE (mainly cerium and lanthanum) used in their formulation.

Within an overall growth in REE requirement, the demand will not grow uniformly for individual REEs, but rather depends on growth in the markets for derivative products of the individual REEs (MIT, 2016). This will emphasize the critical supply of such raw materials, accelerating the diffusion of solutions aiming to recovery, reuse or recycle secondary raw materials containing REE. The EC plans to achieve an overall recycling target of 70% by 2030 (Roland Berger, 2014): however, the current recycling rate for REM is still around 1% (see for instance Binnemans, 2014; Binnemans and Jones, 2014), thus developments and improvements in this field are being addressed and discussed (see Machacek *et al.*, 2015), also in order to establish Europe-based technologies and processes.

The second pillar "Demography and society" is concerning mainly health and sociologic issues of the future such as for example: in 2030 there will be 8.4 billion persons; society will be older, multi-racial and urbanized; there will be a boom of Alzheimer and Parkinson; public health and pension systems will be under pressure. It affects only indirectly the technology development, while it influences the other two dimensions ("Biosphere and natural resources", "Globalized economy, innovation and new technologies") which megatrends are directly correlated to the technology development and thus the potential use and consumption of REE in the future.

Megatrends and consequences related to "Biosphere and natural resources" and "Globalized economy, innovation and new technologies" potentially affecting the use and consumptions of REEs are summarized in the following tables, Table 7.1 and Table 7.2.

Table 7.1: Megatrends "Biosphere and natural resources" - REEs consumption

Biosphere and natural resources		
Challenges: scarcity of water, higher demand of materials, energy, climate change-driven migrations, new lifestyles and -technologies for environment protection		
Megatrends	**Consequences and actions**	**Aspects potentially impacting on RE market**
CO_2 emissions: Rise by 27% up to 2030 *Global primary energy demand:* Increase 23% by 2030, mostly by demand in non-OECD countries	Reduction of CO_2 emissions by companies to comply with legal requirements. Business opportunities arising from new eco-friendly products and technologies.	Boost towards more efficient and cleaner technologies, including for example energy production or automotive sector

Change in energy supply landscape: Boom of shale gas and tight oil exploitation with US to become energy self-sufficient by 2035. *Fossil fuels:* Extensive reserves (942 Gtoe) and resources (12,706 Gtoe). *Sun:* Excessive energy availability *Economic development and growth:* Continued dependence on raw materials such as metals. *Recycling:* Option for decreasing dependence on primary raw materials; EC has a 70% recycling target for 2030.	Environmental friendliness as a company target for their reputation and brand value. Optimization of production and logistics to reduce CO_2 emissions. Competitive edge from green energy production, sustainable industry processes and green consumer goods. Energy efficiency crucial for a sustainable energy system and for maintaining competitiveness Resource-saving production processes/Resource-conscious product design. Diversification of specific resource uses, including by substitution of critical resources. Self-sufficient energy-production by companies. Life Cycle Thinking approach.	Aim to reduce CO_2 emissions both from vehicles and transport sector, and from stationary plants Increase of recycling and recovery solutions from the final products, aiming at reducing the requirements of raw materials Research for alternative raw materials or new product formulations to develop more economically and environmentally sustainable technological solutions

Source: D’Appolonia.

Table 7.2: Megatrends “Global economy, innovation and new technol.” - REEs consumption

Globalized economy, innovation and new technologies		
Challenges: booming emerging countries, Social economy: New type of ownership, sharing economy, collaborative knowledge (Wikinomics). Impact of innovative technologies (Key Enabling Technologies). Smart accessories for smart economy. Transport: electric cars and boom of trains, ships and aircraft in emerging countries		
Megatrends	**Overall consequences**	**Aspects potentially impacting on RE market**
Significant GDP growth: BRIC countries, Next11, MINT and MIST (Roland Berger, 2014). *Growing global middle class:* from within Asian Next11 (Roland Berger, 2014). *Increasing importance of technology:* faster adoption of new technologies; shorter innovation cycles (Roland Berger, 2014).	Rising demand for international brands triggered by economic growth in many developing countries. Companies to focus on those markets, yet while analysing and evaluating political, social and cultural aspects.	Economic growth of China and of several developing countries to potentially impact raw materials supply Wide diffusion of ICT solutions, electronic devices (e.g. smartphones, computers and tablets)

Geographically diversified, fast technology diffusion and smart connections: Central & Latin America, Central & Eastern Europe and Asia & Pacific (Roland Berger, 2014). *Worldwide online devices:* 50 billion by 2020, to double by 2030 (Roland Berger, 2014). *New cyber reality by 2030:* New hardware and sensors embedded in e.g. clothes, glasses, cars. *Implementation of the KETs*. *Strong growth in aircraft fleet*: Asia Pacific region The real great transformation, the biofuel, will be in the decades *China:* Extensive infrastructure investment; highly automated airports facilitated by ICT *World's naval fleet*: to double by 2020. *Automotive market trends:* anticipated 20% hybrid cars; 10% electric dependent on policy choices in US and China. France and Japan among global technology leaders.	Increasing demand for clean technologies (using traditionally REEs). Use scenario planning. Upon identifying new, marketable technologies, companies should set up an innovation roadmap to implement new business models and technologies. Extend R&D activities by establishing or joining cooperative research partnerships and networks. Use both traditional (e.g. capital ventures) and innovative (e.g. crowdfunding) funding raising instruments for Research & Innovation activities.	Increase hybrid and electric car market Large implementation of KETs and clean technologies

Source: D'Appolonia.

7.2 European Technology Platforms, related Organizations and other EU forecast

Numerous European Technology Platforms and technological communities exist, gathering and representing the interest, the vision and the aims of different technological fields: many of such organizations concern REE-using applications. For an overview on the REE demand and supply in Europe, strategic documents of the most relevant European Technology Platforms have been consulted. Table A.1. lists these documents. The complete list of the analyzed documents is available in Appendix A.

The analysis made it possible to extract specific development paths that influence the future use of REE. In the following sub-section, the technological development scenarios that increase the consumption of REE, are extracted and reported. In the framework of these scenarios, the second sub-section shows possible paths for limiting REE-consumption and dependency (e.g. recovery, recycling, substitution).

7.2.1 Technological development scenarios

As reported in the Strategic Research Agenda of SmartGrids TP, *"by 2050 wind power will provide more electricity than any other technology in the "High Renewables" scenario";* in addition, *"in the medium term, wind from the coastal areas [from the Northern Seas and the Atlantic sea basin] and solar power from the Mediterranean countries could deliver substantial quantities of electricity"* (ETP SmartGrids, 2012). In this context, permanent magnets for wind turbines and consequently REE used in their production (mainly Nd, Pr, Dy, which are to-date mainly sourced from China) represent one of the most promising and developing sectors.

This scenario is further supported by considering that in 2030 none of the existing turbines will be probably operational, since the lifespan of onshore and offshore wind turbines currently amounts to between 20 and 25 years respectively: new generations of wind turbines with improved performance are being developed in the coming years, thus allowing beyond 30% of total European electric energy demand to be met by wind (ETP Wind Energy, 2014). Considering the European leadership in the manufacturing of wind turbines and their components (Haymarket Media Group, 2015), extensive investments and efforts are likely in this technological sector.

More sustainable, energy-efficient and environmental-friendly solutions are being implemented, relating i.e. to the diffusion of solid-state lightings (LEDs and OLEDs) to substitute incandescent and fluorescent lamps, as well as to foster the "*limitation of standby power consumption in consumer products*" (ENIAC, 2010). LEDs are mainly based on semi-conductors and phosphor use, which often depend on REE (mainly Y, Ce, La, Eu and Tb). ENIAC (2010) "Multi-Annual Strategic Programme" reports, for example, that *"only 13% of the global semiconductor production capacity is located in Europe, while 20% of the worldwide semiconductor products are consumed in Europe. This implies that Europe is a net importer of semiconductors. The centre of gravity for semiconductor production has moved from Japan, the USA and, more gradually, Europe to Asia Pacific, which now has more than 50% of the worldwide capacity. The main reasons for this are the move of the semiconductor market to this region and particularly the unfavorable cost structures of manufacturing facilities in Japan, the USA and especially Europe"*. Europe has many players involved in the lighting industry, including lamps and LED manufacturers, as well as several suppliers of materials, equipment and electronic components (ETP Photonics21, 2010).

In addition, as highlighted within EPoSS "Strategic Research Agenda" *"there is a window of opportunity for smart systems during this replacement period, as new functions offered by smart systems can enhance consumer willingness to invest in new devices. However, once LED lighting is fully installed, the opportunity for smart systems will decrease because the next replacement bulb will not be needed for another 30-50 years (the lifetime of the LED). Market predictions indicate moderate near term growth for lighting, followed by a period of lower market growth (or even decline). The emergence of OLED lighting may provide additional growth in the medium term"* (EPoSS, 2013).

Taking into consideration that LEDs are foreseen to lead the lighting market for the coming years due to their longer lifetime, demand for Eu, Tb and Y will be probably significantly affected, with the subsequent necessity to look for and develop new applications for these elements: specialty ceramics for Y and magnets for Tb (as substitute for Dy) represent some possible solutions to limit the consequences of a drop in the demand for these REE. However, because the market for Eu is almost exclusively based on lighting applications, this REE could be subject to an oversupply in the next years (ERECON, 2014).

The push towards more sustainable materials and processes, both from a technological and an environmental point of view, entails also the increasing request for improved solutions for the automotive and transport sector. This is the case of light and long-life La-NiMH batteries, as well as of high performance catalysts, whose formulation REE (mainly Ce, but also La, Nd and Pr) currently play a relevant role, which have to operate at lower temperature, but preserving deactivation phenomena or generation of polluting compounds. This is particularly due to *"internal combustion engines (i.e. ICE) vehicles [which] will remain the main type of vehicles on the roads for a long period as the market for electric vehicles and hybrid electric vehicles develops"*, thus *"the fuel-efficiency and emissions performance of ICE vehicles must be continuously improved"* (SusChem, 2015b). Within this framework, research is also focusing on permanent magnets able "to assure high efficiency and high power density that is compact, electrical motors" (ERTRAC, EPoSS and SmartGrids, 2012). However, no alternative solutions will be ready to substitute NdFeB magnets for motors at industrial level for at least ten years from now (ERTRAC, EPoSS and SmartGrids, 2012): thus, Dy, Nd and Pr, will remain relevant in this sector.

All these considerations have been further confirmed by ERECON. The report "Strengthening the European Rare Earths Supply Chain" states that *"by 2017, REE demand is projected to increase by more than 20% compared to 2014, and could be 50% higher by 2020"*, particularly considering that *"as the world moves towards a cleaner, greener future, demand for rare-earth-based materials will continue to increase. Hybrid cars, wind turbines, and ultra-efficient lighting and appliances can't function without REE; next-generation technologies such as electric vehicles and magnetic cooling technology could also require large quantities of rare earths"* (ERECON, 2014).

7.2.2 How to reduce the consumption of primary raw materials?

Considering the issues related to the REE supply with the high dependence on imports (mainly from China) and variables of availability and costs, different Technology Platforms points out the need for finding alternative sources for such elements, e.g. by enhancing REE recycling processes, or to investigating and identifying metals and materials other than REE.

To limit raw materials consumption, improvement in process efficiency, particularly of hydrometallurgical processes, is indicated by SusChem as one of the most relevant routes to increasing overall sustainability of the chemical industry: along with reducing raw materials and energy requirements, with a consequent drop in production costs, it would impact also on waste generated. Considering that several chemical processes are currently strictly dependent on critical raw materials (e.g. REE and platinum group metals), actions toward developing more efficient and sustainable technologies for processing, recycling or reducing the amounts of materials used represent a feasible solution to tackle supply issues of such materials, at the same time maintaining, or even improving, process performances and overall competitiveness of the European industry (SusChem, 2015a).

Within "life-cycle thinking", further technological developments are still required to reach well-demonstrated environmental and economic benefits during the entire life cycle of the products, by comparing recovery and recycling of materials – among these also the REE – with the supply of primary raw materials. In this approach, considering the end-of-life phase from the design stage of the products (eco-design), without affecting final performances of the products themselves, would significantly facilitate recycling and further reuse of target components and elements: excellent examples to be used as benchmarks already exist and are efficiently applied at large scales (e.g. glass, steel, aluminum industry). Indeed, as reported in ETP SMR's "Policy Document", starting from its leadership *"with regard to recycling of base metals and a number of other raw materials"*, Europe has the ambition both to reinforce its leading role in these technological fields and to reach also a leading position in recycling of critical, technology and toxic metals in general, including gallium, indium, germanium, REE, tantalum, arsenic, tungsten, and vanadium metals. In particular, ETP SMR sets mid and long term objectives for the EU industry (ETP SMR, 2011):

- Recycling rates of critical metals from wastes at least above 10% by 2020 (ETP SMR, 2013);
- Recycling rates of critical metals at least above 25% by 2050;
- 10% increase of recycling rates for all other metals by 2050.

In the framework of the establishment of the European Innovation Partnership on Raw Materials, ETP SMR's contribution (ETP SMR, 2012) indicated some potential secondary sources for the recovery of REE: by-products from iron ore mining, electronic wastes and low-energy electric bulbs, combustion flue dusts and residues, magnets and magnetic materials, solid state lighting.

The 2011 REE-price crisis pointed to the necessity to reduce the dependence on China's exports, during which innovative solutions have been developed for improving process efficiency and resource recovery, e.g. by reusing REE-rich processing wastes like magnet swarfs and polishing powders. However, ERECON (2014) reports that *"REE recycling rates are still very low (<1%), and while it is technically feasible to recycle REE from many applications, only the recycling of fluorescent light bulbs and batteries have been commercialized so far. Key obstacles to increase rates of recycling include the lack of information about the quantity of REE materials available for recycling, insufficient and often non-selective collection rates, and recycling-unfriendly designs of many REE-containing products"*(Binnemans *et al.*, 2013a). To that, the limited interaction between various companies which operate at different REE-processing and REE-using segments of the value chain for the purpose of exchanging material information is added (Machacek *et al.*, 2015).

In the same context, several opportunities exist for REE magnets recycling, e.g. by direct alloy reprocessing, especially *"for hard disk drives and specific assemblies in automotive, where magnets are relatively large and economies of scale can be achieved"* (Sprecher *et al.*, 2014). Thus, *"offshore wind turbines and hybrid and electric vehicles are likely to become key targets for future REE recycling; currently, however, their potential is still limited due to low market penetration and relatively long lifetimes"*.

The EURARE project is well-inserted within this framework, aiming to foster the creation of EU-based REE value chains and to develop innovative and sustainable solutions for downstream processing of REE containing ores. Considering that, as reported by ERECON (2014), "there are no markets for mixed REE concentrates outside China", a full scale demonstration project should entail the entire value chain from exploration phase and ore mining, up to obtaining REE compounds and end-products. In doing so, the environmental (associated for example to radioactivity issues) and economic feasibility of the developed solutions should be assessed, by means of viable business models and sustainable processes. Moreover, the different REE separation processes developed within the EURARE project integrate with recommendations by ERECON (2014).

The search for REE substitutes focused on magnets and lightings sectors. Regarding magnets for motors, studies are being carried out to precisely identify in which cases high-performances are strictly requested, thus requiring NdFeB magnets, and where lower-performance ferrites can be used instead. However, for several high-grade products for which high energy density is required (e.g. disc drives, fast-moving motors for robots, consumer electronics) the NdFeB substitution for REE will remain unlikely.

Recently, policy focus was on the transition from filament incandescent light bulbs to fluorescent lamps, joined by a market-driven on-going substitution of the latter with solid-state lightings. Following a first growth in REE demand for phosphors associated with the diffusion of fluorescent lamps, the switch to LED-technology has resulted in an overall decrease in REE-use for this sub-sector (a.o. Eu, Tb and Y) requirement, due to LEDs' lower phosphors content. Nevertheless, improvements in REE recovery and recycling from e.g. discarded fluorescent lamps would allow enhancing the sustainability of supply chains, by reducing requirements of raw materials as well as dependency on imports. Provided no downgrading is taking place.

In addition to the Strategic Research Agendas, the EC (2009) identified some Key Enabling Technologies (KET) which are "knowledge intensive and associated with high R&D intensity, rapid innovation cycles, high capital expenditure and highly-skilled employment". They have a strategic relevance for development and innovativeness, especially in research, development and innovation. The KETs pointed out by EC are:

i. Advanced materials (catalysts, batteries, semiconductors)
ii. Nanotechnology (nanophotonics)
iii. Micro- and Nano-electronics ((nano-)semiconductors)
iv. Industrial biotechnology
v. Photonics (photonics for solar/photovoltaics, solid-state lightings)

In addition, EC stated that in the supply chain of such KETs, vi. Advanced manufacturing systems or technologies should be pursued. KETs currently form one of the pillars on which Horizon 2020 framework programme is built and KETs are among the priority action lines of European industrial policy (EC, 2011). Considering the cross-sectorial features of such strategic technologies, REE find applications in different fields associated with KETs, with a subsequent high market potential for REE (see content of parentheses in KET list above).

Moreover, in 2012, the EC launched a study on the cross fertilization of KETs (EC, 2014c) since combinations of KETs offer even greater possibilities to foster innovation and create new markets because the integration of different KET creates value beyond the sum of the individual technologies. This study resulted in the identification and the definition of a shortlist of 117 key innovation fields of industrial interest with the highest potential for answering market, industry and society demands from cross-cutting KETs developments, which constitute the nodes of the roadmap for 2020 and beyond future developments.

The global roadmap is organized according to 13 cross-sectoral domains. Among the above cross-sectoral domains, three domains, namely electronics and communication systems; chemical processes, chemicals, chemical products and materials; and manufacturing and automation (including robotics) can be distinguished from the other, as being themselves enablers of applications in other domains. These three domains are suppliers of general purpose technology to other domains and highly pervasive.

The other domains, for which a dedicated roadmap is built, relevant for REE are:
- Energy (including energy generation, storage, transmission and distribution);
- Transport and mobility (including road, rail, marine and air transport as well as logistics, besides space);

- Construction;
- Civil security (including dual use applications);
- Mining, quarrying and extraction;
- Environment (including water supply, sewerage, waste management and remediation);
- Health and healthcare

As an example, the overall development roadmap related to the *Energy domain* is illustrated in Figure 7.3.

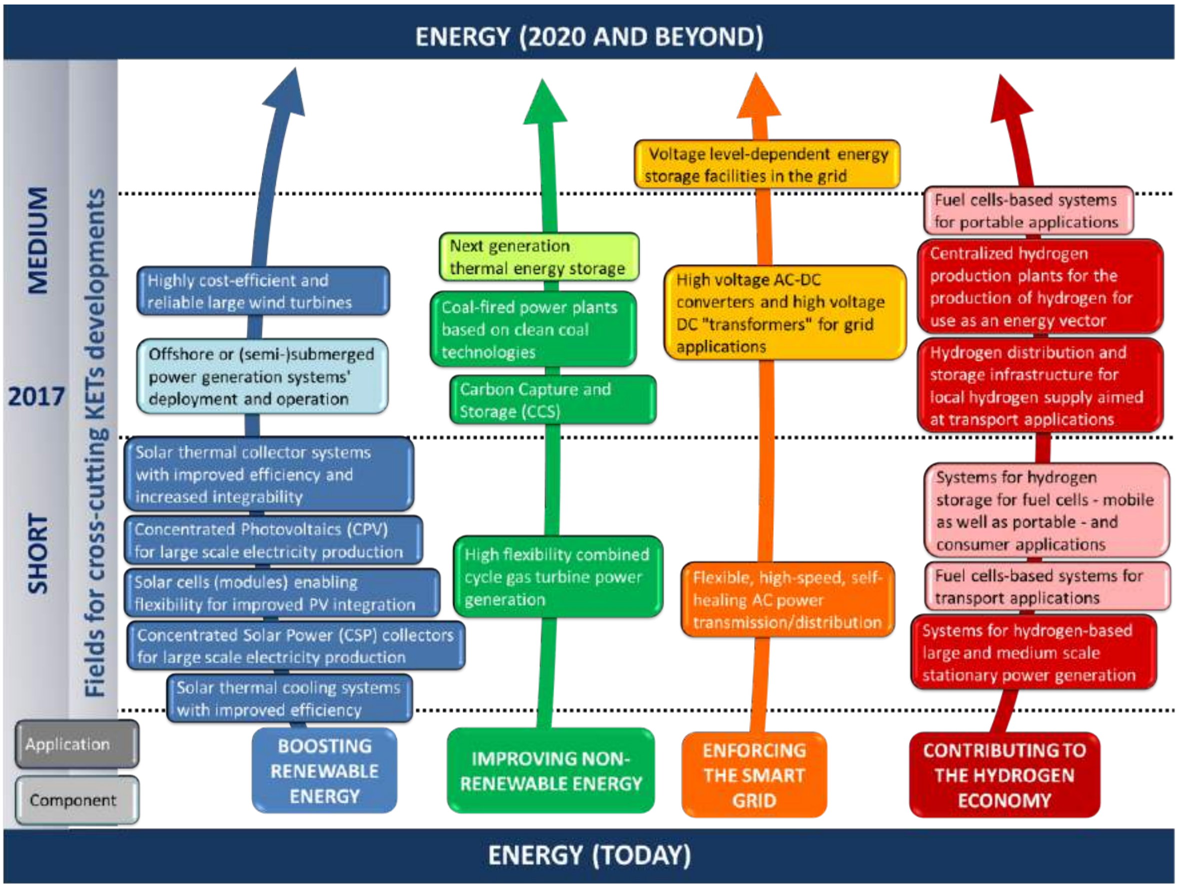

Figure 7.3. Energy KETs roadmap
Source: RocKETs project, 2014.

The complete list of available roadmaps is available here[12].
Reading and analysing the roadmaps, it can be deduced that the development of future technologies will hardly be restrained by the need of REE.

In conclusion, megatrends, supported by KETs identified by the EC, confirm the general direction of the global and European industry indicated also by the different European Technology Platforms. Within these trends, REE, such as other critical raw materials, are mostly foreseen to increase their strategic role in several markets and applications, thus requiring further interventions to foster the

[12] https://ec.europa.eu/growth/industry/key-enabling-technologies/eu-actions/ro-ckets_en

creation of new or improved value chains based on REE: it is in this framework that EURARE and similar research projects (e.g. REEcover[13], REE4EU[14]) have been developed.

7.3 Development scenarios according to relevant EU policy

This chapter serves to delineate assumptions for the development of the sectors and technologies described in Chapter 4 by elaboration of scenarios for these sectors. These scenarios are constructed on three time horizons - 2020/25/30 - and with REE-volume estimates for the sectors.

7.3.1 Policies affecting the REE-using sector related to wind energy for electricity

'Variable renewable energy sources (solar and wind) reach around 19% of total net electricity generation in 2020, 25% in 2030 and 36% in 2050, demonstrating the growing need for flexibility in the power system. Wind onshore is expected to provide the largest contribution (EC, 2016f, p.5). Present drive train technologies can be divided into three major groups: Geared drive train, *d*irect *d*rive *w*ind *t*urbine (DDWT) technology and hybrid (see Table 7.3). Geared drive train types operate without REE. Latter operates without a gearbox, and therefore has less moveable parts and requires generally less maintenance. This is useful for off-shore mills for which maintenance is costly.

Some DDWT technology might use REE-permanent magnets (REE-PM), while other DDWT might use electrically-separately excited PM-generators (see Enercon) and hybrid technology).[15] For instance, PM excited synchronous direct drive (PMSG-DD) use REE-PM, while DD- and hybrid technology-HTS use no magnet but nonetheless Y, La, Ce. Overall, the technologies that use REE-PM are the PMSG-DD, and the hybrid PMSG-SG, as well as the hybrid PMSG-MG. Further, the technologies are divided according to their use as onshore and offshore installations. DD technology, due to the cost-advantages pertaining to less maintenance requirements, is the technology of choice for offshore installations. Global total offshore wind capacity amounted to over 12 GW in 2015, of which 11 GW were installed off the coast of eleven European countries, led by the UK, followed by Germany, and Denmark, Belgium, Netherlands and Sweden (GWEC and UTS, 2016).

At the end of 2015, the EU combined wind power installations amounted to 142 GW, which is to be viewed in perspective of global wind power installations of about 433 GW in 2015 (Global Wind Energy Council [GWEC], and UTS 2016, p. 11). For comparison, this installed capacity is exceeded by China's cumulative wind power installations of 145 GW at the end of 2015 (GWEC and UTS, 2016). In Europe, 17 countries had more than 1 GW installed in 2015, whereas Germany, Spain, the UK and France belong to the 10 GW club. In Denmark, more than 40% of electricity is produced from wind turbines (GWEC and UTS, 2016, p. 8).

Discrepancies in the geographical spread of the new wind power capacity installations of 2015 across the EU can be observed: 47% occurred in Germany, and 73% in the top four markets, a trend which was also observed in 2014, yet not in the years prior. A list of largest capacities installed looks as follows (GWEC and UTS, 2016, p. 12; numbers rounded): Germany (45 GW), Spain (23 GW), UK (14 GW), France (10 GW), Italy (9 GW), Sweden, Denmark, Poland and Portugal (each >5 GW).

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[13] http://www.reecover.eu/
[14] http://www.ree4eu.eu/
[15] *Four European wind turbine firms (Gamesa, Enercon, Siemens, Winergy; Vestas; ABB) range among the top 10 with 38% market share, mainly using hybrid or PMDD (Enercon only) or both technologies and are vertically integrated turbine manufacturers. (…)* (CRM-Innonet, 2014, p. 31).

Table 7.3. Generator typologies and their REE-consumption.

Wind turbine	Gearbox	Generator	Permanent magnet	Rare Earths
Geared drive train	Single stage	Induction (IG)	-	-
	Multistage	Wound rotor induction (WRIG)	-	-
		Squirrel cage (SCIG-MG)	-	-
		Doubly fed induction (DFIG-MG)	-	-
Direct drive	-	Electrically excited synchronous (EESG-DD)	-	-
		Permanent magnet excited synchronous (PMSG-DD)	650 kg/MW	250 kg/MW (Nd, Dy, Pr, Tb)
		High-temperature superconducting (HTS)	-	0.1 kg/MW (Y, La, Ce)
Hybrid	Single stage	Permanent magnet synchronous (PMSG-SG)	160kg/MW	45 kg/MW (Nd, Dy, Pr, Tb)
		High-temperature superconducting (HTS)	-	0.02 kg/MW (Y, La, Ce)
	Multistage	Permanent magnet synchronous (PMSG-MG)	80 kg/MW	25 kg/MW (Nd, Dy, Pr, Tb)

Source: Barteková, 2016, p. 156.

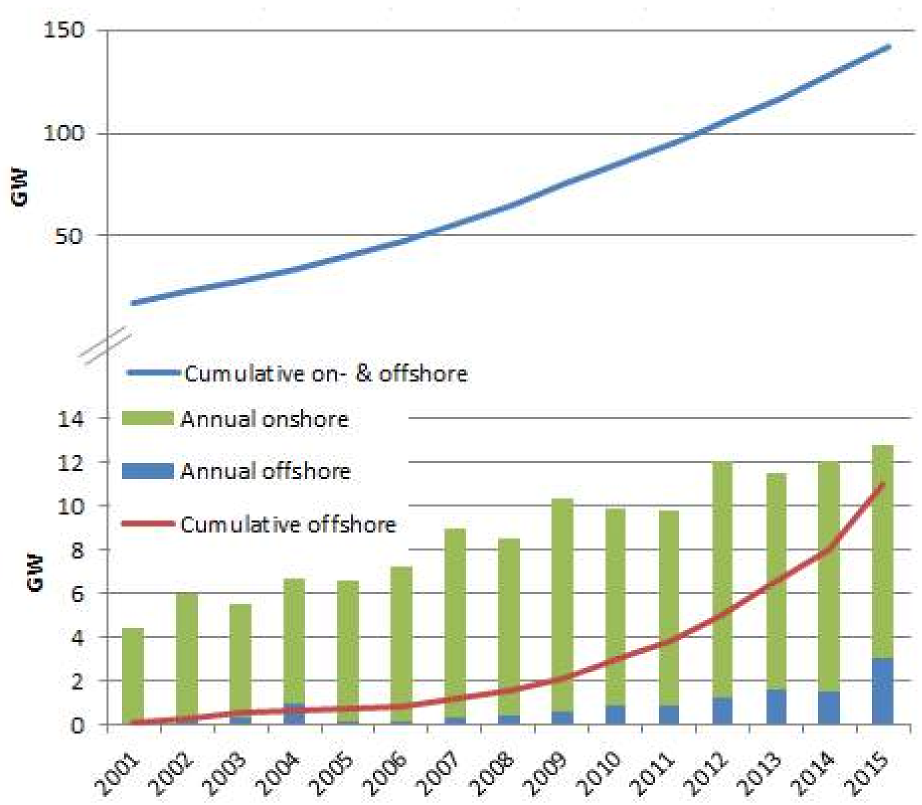


Figure 7.4. Annual onshore and offshore, and cumulative installations (GW) in the EU
Source: adapted from EWEA (2016; 2015)

The developments of the installations of wind turbine capacity in GW from 2001 to 2015 are summarized in Figure 7.4. These developments are shown in annual onshore- and offshore wind turbine installations, combined annual onshore and offshore installations, cumulative offshore and cumulative on-and offshore installations. The spilt of annual installations in 2015 was 25% offshore, 75% onshore. A total of 12 GW was added in the period 2014 - 2015.

Offshore installations rose by 108% from 2014 to 2015: in 2015, a total of 3.019 GW offshore capacity was installed through 754 new offshore wind turbines. In 2012, 2013, and 2014 the annual installations were 1.1 GW, 1.5 GW and 1.4 GW respectively (EWEA, 2016). The average offshore wind turbine size was 4.2 MW, a 13% increase from 2014. The deployment of 4-6 MW turbines seen in 2015 will be followed by the gradual introduction of 6-8 MW turbines closer towards 2018 (EWEA, 2016).

Further, the EU capacity (GW) of joint annual on- and offshore installations rose from 4 GW in 2001 to 13 GW in 2015, whereby the annual offshore installation amounted to 3 GW. The cumulative offshore installations were at 11GW in 2015, and the cumulative on- and offshore installations were at 140 GW in 2015. Overall, while the cumulative offshore installations appear to rise significantly, annual onshore installations experienced an overall rather steady growth rate.

The regional breakdown of each of the four scenarios - New Policies, 450, Moderate and Advanced Scenario - and their results for 2020 and 2030 elaborated by the GWEC and UTS (2016), is illustrated in figure 7.5. The IEA New Policies Scenario is based on an assessment of current national and international energy and climate policies, even if not yet implemented or enacted in law such as the emission reduction targets adopted in Paris in 2015, numerous commitments to renewable energy and efficiency at national and regional levels and commitments made at the G8 and G20, as well as the Clean Energy Ministerial (GWEC, 2016). Three different scenarios are considered:

(i) The *450 Scenario* dates back to the IEA's World Energy Outlook in 2010, and reflects an energy pathway centred on a 50% chance of limiting the global increase in average temperature to 2ºC which has been estimated to require a limitation of the greenhouse gas concentration in the atmosphere to about 450 parts per million (ppm) of carbon-dioxide equivalent (ppm CO_2-eq.). Instead of policy action-influenced projections, this 450 Scenario works with plausible energy pathways to achieve the described objective, and policy assumptions until 2020 draw on measures described in the WEO Special Report on Energy and Climate (GWEC, 2016).

(ii) The *Moderate Scenario* has been elaborated by the GWEC and is centred on many of the factors laid out and used in the New Policies Scenario, namely the policy measures to support renewable energy that are already enacted or being planned in the world, while simultaneously assuming that commitments for emissions reductions agreed at COP21 in Paris in 2015 will be implemented by the participating governments, yet modestly. Existing and planned national and regional targets for the uptake of renewable energy (both general and for wind energy) are accounted for, and in the case of planned targets, they are assumed to be met (GWEC, 2016). On this point, the Moderate Scenario matches the EURARE Scenario that we elaborate and describe later in this sub-chapter.

(iii) The *Advanced Scenario* has also been elaborated by the GWEC and as its name suggests, is constructed on highest ambitions, including '*unambiguous commitment to renewable energy in* *line with industry recommendations, the political will to commit to appropriate policies and the political stamina to stick with them'* (GWEC, 2016, p. 16). Contrary to the IEA scenarios (namely the New Policies and the 450 Scenario), this scenario does not work with the assumption of extensive roll-out and investment in new-build nuclear technologies or large carbon capture and storage (CCS) technologies. This Scenario further builds on the assumption of clear government-driven enactment of policies on carbon emission reductions in line with the objective of limiting global mean temperature rise below 2ºC (GWEC, 2016).

The forecasts are summarized in Table 7.4. The OECD share of global total wind power capacity installed is estimated to range between 25 to 28% in 2020, and between 17 to 25% in 2030. Importantly, while the New Policies Scenario for 2020 and 2030 is at the lower end of the estimates, the Advanced Scenario is at the higher end of the estimates on installed wind power capacity, with the 450 Scenario and the Moderate Scenario in the medium range. The range of forecasts for installed capacity of wind power for the OECD Europe is from 181 to 220 GW (average 195 GW) in 2020, and from 311 to 360 GW (average 330 GW) in 2030. A fifth scenario 'EURARE' has been elaborated that has also relevance for EU 28. The construction of this scenario is explained below. The EURARE scenario exceeds slightly the Advanced Scenario.

Table 7.4. Installation forecast for scenarios, regional breakdown of capacity (in GW)

	2020			2030		
	EU 28	OECD share of Global Total	Global Total	EU 28	OECD share of Global Total	Global Total
New Policies Scenario	181	28%	639	311	25%	1.260
450 Scenario	182	28%	658	329	23%	1.454
Moderate Scenario	200	25%	797	320	19%	1.676
Advanced Scenario	220	25%	879	361	17%	2.110
EURARE Scenario	213			380		

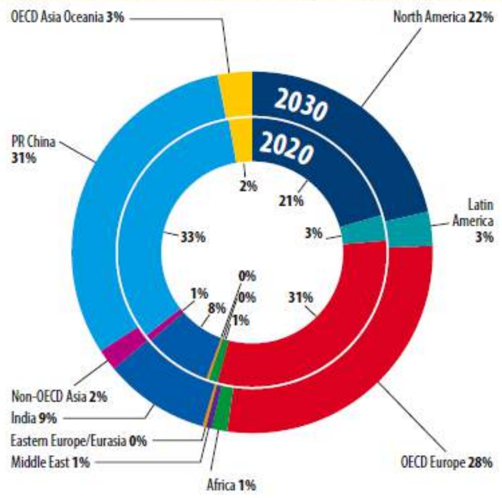
Source: Compiled from GWEC and UTS, 2016.

Note: For the EURARE scenario, the OECD share of the global total (in %) and the global total (in GW) of 2020 and 2030 have not been estimated separately.

7.3.2 The EURARE Scenario

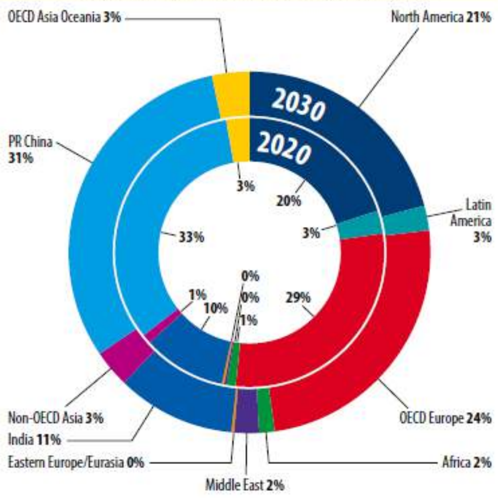
The 'EURARE-Scenario' is constructed on the basis of EU2020 renewables target scenario for wind and sintered REE-magnet use in offshore direct-drive wind turbines. The EU2020 renewables target foresees 20% energy consumption based on renewable sources by 2020. EU countries have committed to reaching their own national renewables targets ranging from 10% in Malta to 49% in Sweden (EC, 2016a). Wind energy is to supply 14% of the EU's electricity consumption in 2020 (corresponding to 495 TWh of electricity gained from the estimated installed wind power capacity of 213 GW within the EU).

REGIONAL BREAKDOWN: NEW POLICIES SCENARIO



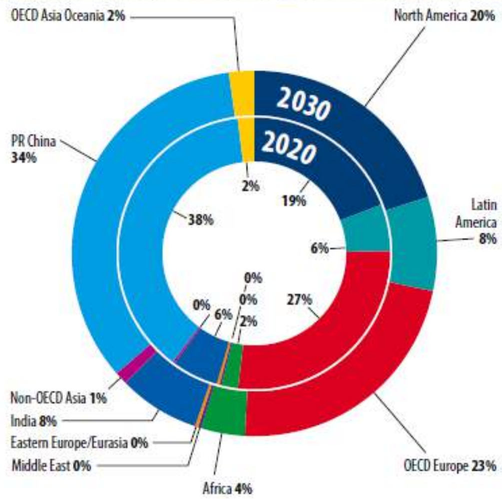
	2020	2030
North America	126,961	252,784
Latin America	18,749	36,196
OECD Europe	186,878	323,091
Africa	6,575	15,908
Middle East	1,072	8,009
Eastern Europe/Eurasia	668	1,117
India	50,063	111,938
Non-OECD Asia	5,213	21,796
PR China	201,178	364,801
OECD Asia Oceania	15,322	34,598
Global Total / MW	**639,478**	**1,259,974**

REGIONAL BREAKDOWN: 450 SCENARIO



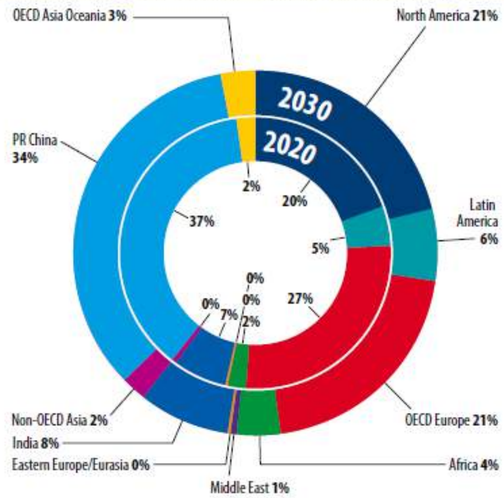
	2020	2030
North America	131,659	303,322
Latin America	18,913	35,830
OECD Europe	190,855	355,769
Africa	7,207	23,005
Middle East	1,501	30,124
Eastern Europe/Eurasia	722	1,982
India	67,098	155,736
Non-OECD Asia	6,411	49,250
PR China	216,806	452,081
OECD Asia Oceania	16,836	47,295
Global Total / MW	**658,009**	**1,454,395**

REGIONAL BREAKDOWN: MODERATE SCENARIO



	2020	2030
North America	149,120	318,390
Latin America	42,997	129,491
OECD Europe	207,955	358,554
Africa	16,805	60,852
Middle East	777	4,995
Eastern Europe/Eurasia	644	1,895
India	44,734	116,257
Non-OECD Asia	2,344	14,842
PR China	291,439	541,577
OECD Asia Oceania	13,364	32,887
Global Total / MW	**797,028**	**1,675,624**

REGIONAL BREAKDOWN: ADVANCED SCENARIO



	2020	2030
North America	165,181	413,970
Latin America	38,203	124,494
OECD Europe	227,217	398,691
Africa	18,337	72,229
Middle East	1,017	10,234
Eastern Europe/Eurasia	650	2,835
India	56,297	163,473
Non-OECD Asia	4,296	41,659
PR China	313,061	666,500
OECD Asia Oceania	17,242	57,084
Global Total / MW	**879,446**	**2,110,161**

Figure 7.5. Scenario results presented in the Global Wind Energy Outlook, 2016
Source: GWEC, 2016, pp. 20

National action plans
The National Renewable Energy Action Plan, in short 'NREAP', specifies EU countries' plans for meeting their 2020 renewable energy obligations. Distinctive paths for each of the EU member states reflect each of their unique energy market and different available resources to meet the legally binding 2020 targets. These national action plans include an outline of the planned mix of different renewables technologies. (EC, 2016b)

For the purpose of forecasting REE demand in direct drive and hybrid- wind turbine technology, we have used the estimates of the NREAP which specify wind (onshore and offshore) as a separate category next to electricity from hydro, geothermal, solar (photovoltaic, concentrated solar power), and biomass (solid, biogas, bioliquids), and the attainable objective of GW installed and GWh generated in 2020. In addition, the estimated capacity in GW is divided into on- and offshore installations. Since these estimates were prepared in 2010, we referred to the 2015 progress reports[16]. The most recent progress reports were published in 2015 and contain data for 2014 by each member state on installed MW (EC, 2016c) from which the total GW capacity between 2015 and 2020 can be derived.

Assumptions
Several assumptions underpin this scenario:

- Only offshore wind turbines will use REE-PM.
- We conceptualize offshore capacity to comprise the following mix and share of technology:

Table 7.5. Offshore technology split with PM content of Pr, Nd, Tb and Dy

		Share in offshore technology	REE (kg)/MW*	Pr (kg) (corr. to 4% of REE content)	Nd (kg) (95%)	Tb (kg) (0,99%)	Dy (kg) (0,01%)
Direct drive	PMSG-DD	75%	250	10	237.5	2.5	0.025
Hybrid	PMSG-SG	12.5%	45	1.8	42.75	0.4	0.0045
	PMSG-MG	12.5%	25	1	23.75	0.2	0.0025

Source: MiMa-GEUS; technologies and REE (kg)/MW and individual RE content by Barteková (2016).
Note: REE volumes require conversion to enable a comparison with other policy scenarios presented in REO.

- According to the NREAP progress report of 2015, total installed wind power capacity in the EU member states amounted to approximately 132 GW in 2014 which is forecast to rise to 213 GW in 2020 (EC, 2016a). This estimate lies above the average of the four scenarios put forward in GWEC and UTS (2016), and positions the NREAP between the Moderate and Advanced GWEC Scenarios for 2020. To reach this estimate, a cumulated capacity of about 80 GW requires installing between 2014 and 2020 in EU member states.[17]

[16] EU countries publish reports every two years to show their progress towards the EU's 2020 renewables goals.
[17] Please note that the NREAP refer to the EU member states, while the scenarios in table 7.5 indicate the OECD share of the global total, and our EURARE scenario also works with EU member state data, yet with orientation from OECD.

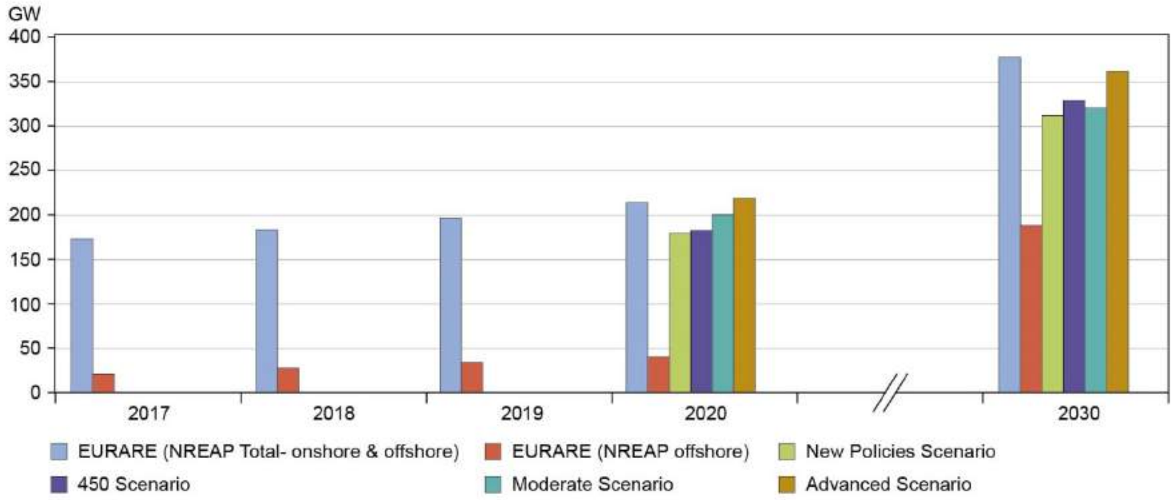


Figure 7.6. Modelled forecast scenarios until 2030, including NREAP.
Source: NREAP for 2030 calculated by MiMa-GEUS (2016), all other scenarios compiled from GWEC and UTS, 2016.

- Offshore DDWT installations are likely to play a significant part in the projected installations based on observed growth in this type of installation in the EU (GWEC and UTS, 2016), and the declared EU member state forecasted offshore capacity to be installed, amounting to 34 GW (of the total installation projected of 80 GW). It is likely that DD- and hybrid-WT technology might also be applied onshore by 2020.

- In our rough calculations we assumed that member states which have provided data for the generic 'wind' category without a division into on- or offshore capacity, are assumed to install 50% of the onshore capacity as offshore (with the symbolic understanding that the type of technology applied will contain REE-PM as per the DD- or hybrid WT technology offshore technology share indicated in table 7.6).This assumption lifts the forecast of offshore capacity to be installed between 2015 and 2020 to about 40 GW. The EURARE forecast scenario based on the NREAP can be summarized as follows:

Table 7.6. Forecast scenarios of capacity installations
.

Wind power capacity	GW to be installed btw 2015 and 2020	GW to be installed btw 2020 and 2030
On- and offshore	80	376
of which offshore	34	188
Offshore including +50% of NREAP 'onshore'	**40**	**146**

Source: MiMa-GEUS, 2016.

- We also forecast how the EU-NREAP scenario would develop up to 2030, using the average cumulative growth rate of 8.5% per annum between 2014 and 2020. According to this forecast that follows from the EURARE scenario, the anticipated total installation onshore and offshore capacity would amount to about 380 GW in 2030. This scenario corresponds closest to the estimates of the advanced scenario for the EU which is estimated at about 360 GW, see figure 7.6. The extended NREAP scenario amounts to about 188 GW in 2030 offshore installations. This requires offshore installations of about 146 GW between 2020 and 2030.

Results

Thus, according to the EURARE scenario, from cumulatively installed offshore 11 GW in 2015, installations of about 40 GW are to be effectuated by 2020, lifting the required REE content for the magnets to be used in forecast installations of DD- and hybrid-WT between 2015 and 2020 to an estimated rounded total of about 367 t Pr_2O_3, 8,695t Nd_2O_3, 89t Tb_4O_7 and 900t Dy_2O_3. These volumes would correspond to 73,5 t Pr_2O_3, 1,739 t Nd_2O_3, 17,9 t Tb_4O_7 and 182 t Dy_2O_3 in annual demand between 2015 and 2020. See table 7.7 for a detailed split-up.

Table 7.7. Forecast of REO demand for the 40 GW installations until 2020

40 GW to 2020	REE-PM	GW division acc. to techn. split	t (REM)/GW				t (REO)/GW			
			Pr	Nd	Tb	Dy	Pr_2O_3	Nd_2O_3	Tb_4O_7	Dy_2O_3
Direct drive	**PMSG-DD**	30	300	7,125	75	0,7	351	8,307	86	0,87
Hybrid	**PMSG-SG**	5	9	213	2	0,023	11	249	3	0,025
	PMSG-MG	5	5	118	1	0,013	6	139	1	0,015
		40	314	7,456	78	0,7	367	8,695	89	0,9
P.a. demand			62.8	1,491	15.6	0.147	**73.5**	**1,739**	**17.9**	**0.182**

Source: MiMa-GEUS, 2016; REE to REO conversion factors from Tasman Metals NI 43-101 report.
Note: It has been assumed that the indications in Table 7.5 of REE (kg)/MW refer to REM.

The 146 GW of offshore technology installations amount to an estimated rounded total volume of about 1,340 kt Pr_2O_3, 31,737 kt Nd_2O_3, 326 kt Tb_4O_7, and 3 kt Dy_2O_3 between 2020 and 2030. This corresponds to average forecast annual demands specified in Table 7.8.

Table 7.8. Forecast of REO demand for the 146 GW installations until 2030

146 GW to 2030	REE-PM	GW division acc. to techn. split	t (REM)/GW				t (REO)/GW			
			Pr	Nd	Tb	Dy	Pr_2O_3	Nd_2O_3	Tb_4O_7	Dy_2O_3
Direct drive	**PMSG-DD**	110	1095	26.006	273	2,7	1281	30323	312	3,17
Hybrid	**PMSG-SG**	18	32	780	7,3	0,082	38	909	9,3	0,091
	PMSG-MG	18	18	433	3,6	0,046	21	505	5	0,055
		146	1,145	27,219	283,9	2,8	1340	31737	326	3
P.a. demand			114	1721	28.39	0.28	**134**	**3,173**	**32.6**	**0.331**

Source: MiMa-GEUS, 2016; REE to REO conversion factors from Tasman Metals NI 43-101 report.
Note: It has been assumed that the indications in Table 7.5 of REE (kg)/MW refer to REM.

7.3.3 Policies for energy efficient lighting affecting REE-based phosphors

Seven technologies exist in general lighting: incandescent lamps, halogen lamps, linear fluorescent lamps (LFL), compact fluorescent lamps (CFL), high-intensity discharge (HID) lamps, light emitting diodes (LED) and organic light emitting diodes (OLED) (McKinsey & Company, 2012).

Incandescent lamps create light by heating a suitable material (usually metal filament wire) to a high temperature until it glows. The technology has a relatively low luminous efficacy (~ 10 - 19 lumen per watt) and a short lifetime (750 - 2,500 hours). The lamps have a high color quality (~ 97 CRI), are quick to switch on and are dimmable.

Halogen lamps have a tungsten filament just like incandescent lighting, but the bulb is filled with halogen gas. Halogen results in a longer lifetime and a cleaner bulb wall for the light to shine through. Halogen lamps have a luminous efficacy of between 11 and 20 lumen per watt, and a lifetime of 2,000 - 3,500 hours. These lamps are characterized by high color quality (~ 99 CRI) and a fast turn-on time.

Linear fluorescent lamps (LFLs) are gas-discharge lamps that use electricity to excite mercury vapor. LFL has a relatively high luminous efficacy (~ 35 - 87 lumen per watt) and a lifetime of 7,500 - 20,000 hours with T8 as an example. LFLs take a couple of seconds to turn on. The luminous efficacy of LFLs is high, but the color quality is low (~ 52 - 90 CRI), and the color tends to be cold.

Compact fluorescent lamps (CFLs) contain a gas that produces invisible ultraviolet light (UV) when the gas is excited by electricity. The UV light hits the white fluorescent coating material inside the bulb and the coating changes it into visible light. CFLs have a luminous efficacy of 40 - 70 lumen per watt and a lifetime of ~ 10,000 hours. The color quality has traditionally not been as good as incandescent even though it is improving, and has already achieved CRIs in the low 80s. The turn-on time of CFLs is usually slow.

High-intensity discharge (HID) lamps are a type of arc lamp. The technology produces light by establishing an arc between two electrodes in a gas-filled tube, which causes a metallic vapor to produce radiant energy. A metal halide HID lamp, for instance, has high luminous efficacy and output (~ 50 - 115 lumen per watt) as well as a long lifetime (~ 3,000 - 20,000 hours), but relatively low color quality (~ 65 - 70 CRI). There are some other types of HID, such as mercury vapor lamps and high-pressure sodium lamps, and characteristics vary among these sub-technologies.

Light emitting diodes (LED) are a semiconductor light source. A LED is often very small (less than 1 mm^2), and integrated optical components may be used to shape its radiation pattern. LEDs have a relatively high luminous efficacy (~ 60 - 120 lumen per watt) and a lifetime of 12,000 - 50,000 hours. The CRI is approximately 44 - 90. The technology is characterized by having tunable and flexible color and almost instant turn on time.

Organic light emitting diodes (OLEDs) are LEDs where the emissive electroluminescent layer is a film of organic compounds emitting light in response to an electric current. OLEDs have a luminous efficacy of 25 - 75 lumen per watt and a lifetime between ~ 14,000 and 30,000 hours. OLED technology is still emerging.

EU2020 energy efficiency scenario for phosphor-based lamps

The EU2020 energy savings are to be 20% lower than projected for 2020, this corresponds roughly to turning off 400 power stations (EC, 2016d). Lighting is a targeted product group among the energy efficient products: Inefficient bulbs are expected to be replaced by 2020 (EC, 2016e). This shift has peaked with a replacement of incandescent light bulbs to compact- and linear fluorescent light [CFL and LFL] bulbs and LEDs. Phosphor powders in these energy-efficient lamps are based on REE, and as such this energy efficiency target affects also the use of REE, if only in small volumes.

Phosphor manufacturers buy a concentrated REE product (oxides or compounds, see Lynas Corporation, 2014) for direct use in producing various patented phosphor powder compositions (Wilburn, 2012). Estimates partially produced from primary data suggest that REE use in phosphors accounted for 11% of total REE market demand in 2013 and for 19% of REE market demand value in the same year (derived from Adamas Intelligence, 2014). The 11% phosphors are divided among various phosphor using applications (Adamas Intelligence, 2014), with an estimated 90% for phosphors in energy-efficient lamps, and 10% for TVs and screens (Balachandran, 2014).

REE-based phosphor powders use varying amounts of REE, resulting in a wide variety of powder compositions (Ronda, Jüstel & Nikol, 1998), but primarily phosphor powders contain some proportion of Y, Eu and Tb is used to generate red, green and blue phosphors (Balachandran, 2014). Almost all global supply of about 85% of Tb and close to 77% of Y are used for phosphors (Moss *et al.*, 2013; Tan, Li, & Zeng, 2014).

REE content varies in CFLs, LFLs and LEDs, see Table 7.9. The data related to the elemental composition of phosphors contained in LFL, CFL and LED has been derived from Castilloux (2014) for phosphor (g), and Wu, *et al.* (2014) for REE composition in standard tricolor phosphor. The estimated phosphor composition for all these three lamp types is shown in the following table:

Table 7.9. Approximate REO content (g/unit) of various energy-efficient light types

	Y_2O_3 (g)	**Eu_2O_3(g)**	**Tb_4O_7 (g)**
Range of content	**46.9-51.2%**	**3.9-4.4%**	**2.2-2.6%**
LFL	1.0975-1.1981	0.0913-0.103	0.0515-0.06084
CFL	0.7035-0.768	0.0585-0.066	0.033-0.039
LED	0.0047-0.0051	0.0004-0.0004	0-0

Sources: Castilloux, 2014; range of content from Wu *et al.*, 2014, p. 23.
Note: Contents of La_2O_3 and CeO_2 were derived from forecasts in Adamas Intelligence (2016, p. 763).

In this model we use McKinsey & Company (2012) data on general lighting applications (which encompasses lighting in residential applications and six professional applications, namely office, industrial, shop, hospitality, outdoor and architectural) on the number of lamp types, both new installations and replacements, from 2015 to 2020 for Europe with an estimated share of 23% in 2020 and of 15% in 2030 of the global market. The number of lamps is multiplied with the averaged total REO (g) as per lamp type in Table 7.9. to estimate the final demand of Y_2O_3, Eu_2O_3 and Tb_4O_7 for these three energy-efficient lamp types.

Figure 7.7 illustrates estimates of the share per lamp type for the European alongside the global lighting market. The estimate for 2030 includes an assumption that the European share of the global lighting market will continue to fall to about 15%. It is also assumed that the share of LED as compared to other lamp types will further augment, both in the global lighting market as well as in the European market.

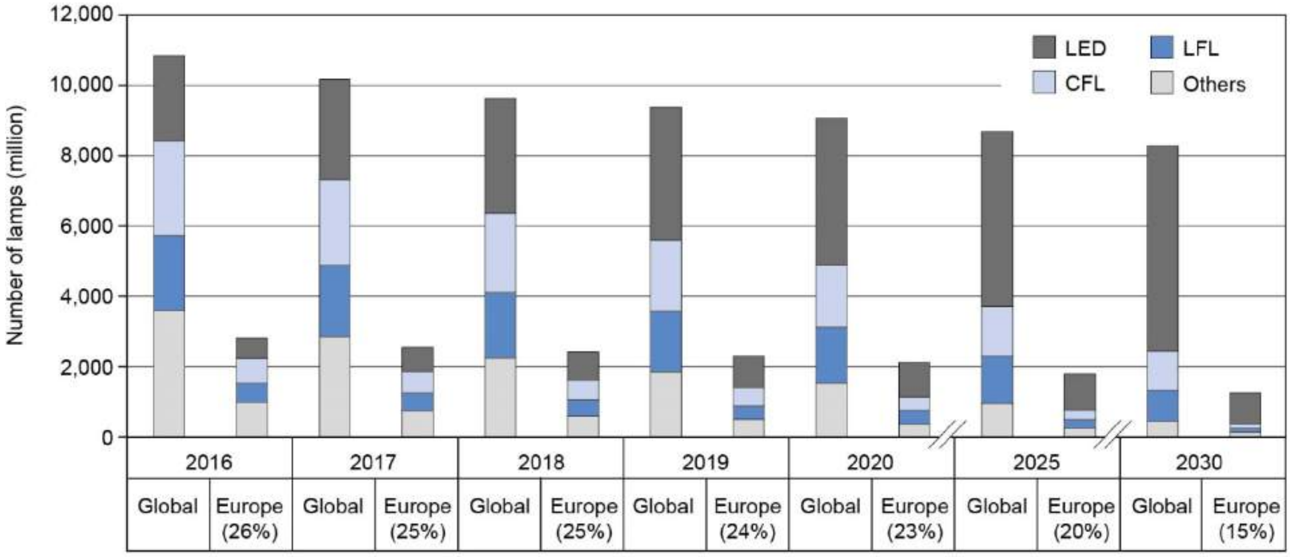


Figure 7.7. Forecast, global and European lighting market and lamp type shares.
Source: MiMa-GEUS.

The estimates for individual REE element demand anticipated in Europe, are shown in Figure 7.8. These reveal an anticipated demand in 2020 of 92t La_2O_3, 46t Ce_2O_3, 723t Y_2O_3, 61t Eu_2O_3 and 35t Tb_4O_7.

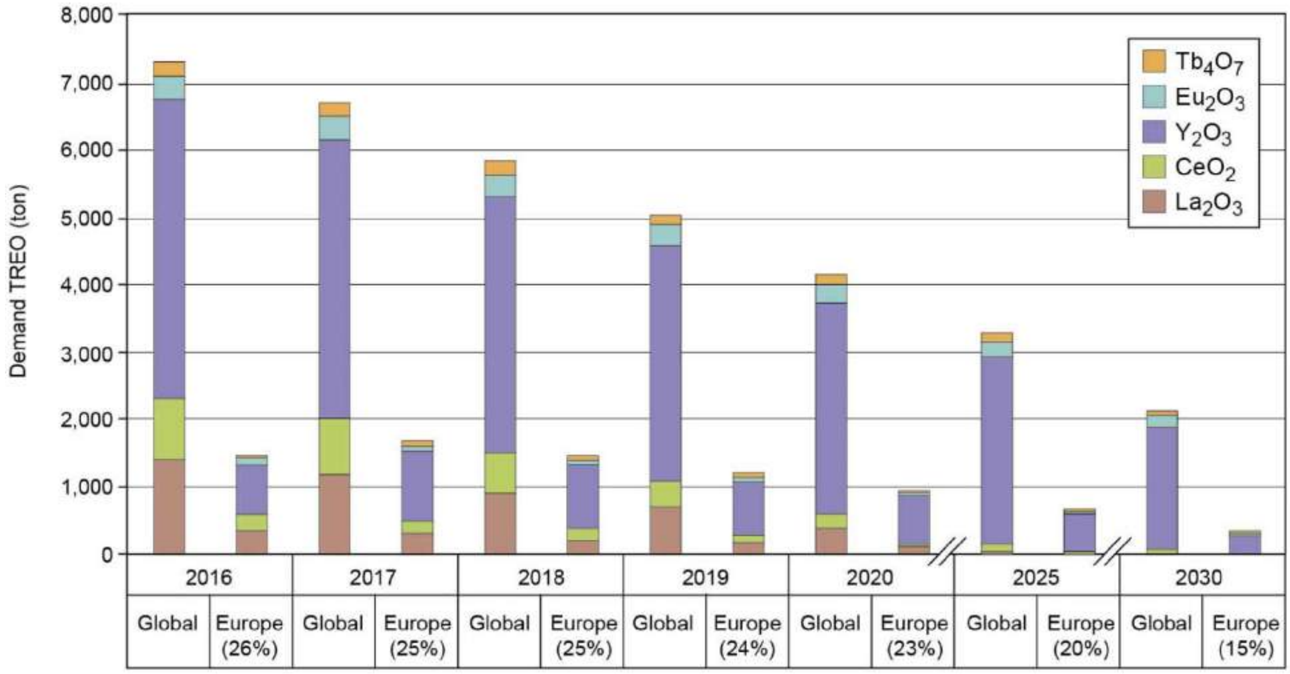


Figure 7.8. Forecast global and European lighting market demand for the five REOs.
Source: MiMa-GEUS.

7.3.4 Policies in the transport sector – REE use in components and consumables

The scenario in this chapter describes a forecast of developments in the automotive market until 2020, 2025, and 2030, with a focus on the effects of these forecasts for REE-use in passenger cars. About 16 mio. units of cars have been manufactured in the EU in 2015, corresponding roughly to a quarter of the worldwide manufacture of cars (ACEA, 2016a, p. 10). Passenger cars constituted more than 85% of the EU motor vehicle production, as illustrated in figure 7.9., and they have therefore been selected as focus of this chapter. Further, in 2016, about 14 mio. cars were newly registered in the EU (ACEA, 2016a).

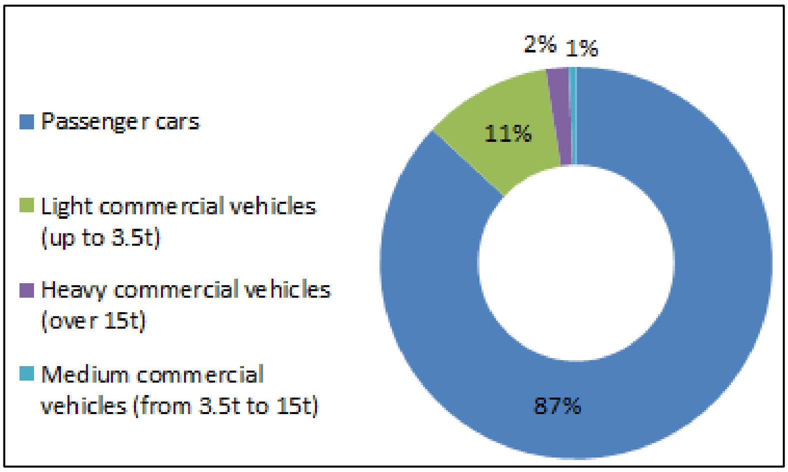


Figure 7.9. EU motor vehicle production by type.
Source: ACEA, 2016d.

The automotive sector has seen rapid changes triggered by technological advances in recent years. In the following, the vehicle types are described that are at the forefront of these changes: *Diesel and gasoline cars* are conventional car technologies at this point in time. The diesel engine (correctly compression-ignition [CI] engine) is an internal combustion engine in which ignition of the fuel that has been injected into the combustion chamber is caused by the high temperature which the air achieves when greatly compressed. Diesel engines work by compressing only the air which increases its temperature inside the cylinder to such a high degree that it ignites atomized diesel fuel that is injected into the combustion chamber. This is in contrast to *spark-ignition engines* such as a petrol (gasoline) engine or gas engine (using a gaseous fuel), which use a spark plug to ignite an air-fuel mixture.

Electric vehicles (EV), such as e-Bikes, electric cars or high-speed rail, are propelled by electric motors, (i) powered by *electricity* from sources outside the vehicle, or (ii) self-contained with a *battery or generator* to convert fuel to electricity. This propulsion is distinct to conventional vehicles that use *internal combustion engines*. *Hybrid electric vehicle* (HEV) derives its name from combining a fossil-fuel energy source with electric propulsion.

Plug-in electric vehicle (PEV) refers to a vehicle that is charged by any external source of electricity, alongside *all-electric or battery electric vehicles* (BEVs), *plug-in hybrid vehicles* (PHEVs), and electric vehicle conversions of hybrid electric vehicles and conventional internal combustion engine vehicles.

Fuel cell is a technology that enables the *conversion of a fuel* (its chemical energy) *into electrical energy*. In contrast to a battery, a fuel cell requires *constant sourcing* from a source of fuel and oxygen or air to uphold the chemical reaction.

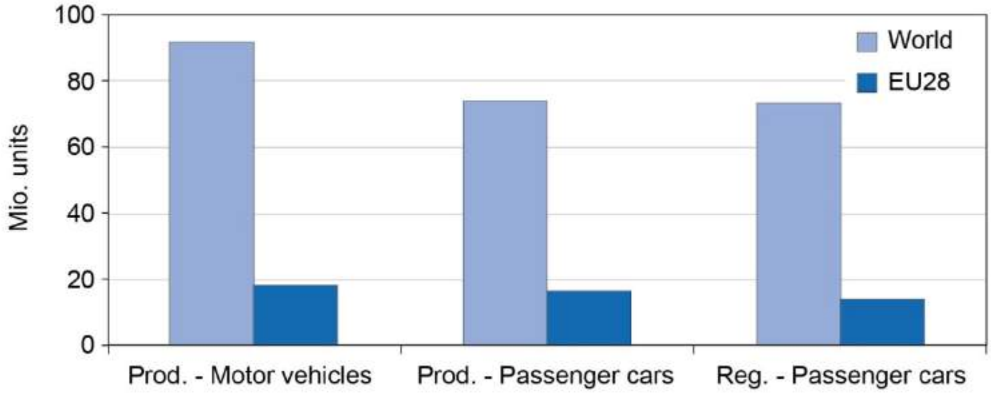


Figure 7.10. Motor vehicle and passenger car production and passenger car registration in 2015
Source: ACEA, 2016.
Note: 'Prod.' is short for 'production' and 'Reg.' is short for 'registration'. Production refers to the volume of car units manufactured worldwide and in the EU, while registration describes the number of cars that entered into and are from then on, part of the car fleet, globally and in the EU.

Figure 7.10. shows EU production of motor vehicles and passenger cars next to world production, and the registration of passenger cars in the EU as compared to the world in 2015. Between 2004 and 2015, EU passenger car production was between 14 and 16 mio. with the exception of production in 2009 which was around 13.5 mio. cars. From 2013 to 2014, a growth from about 14 mio. passenger cars to 16 mio. passenger cars could be noted. (ACEA; 2016) The cumulated average growth rate in EU passenger car production between 2004 and 2014 was 2.5%. (ACEA, 2016)

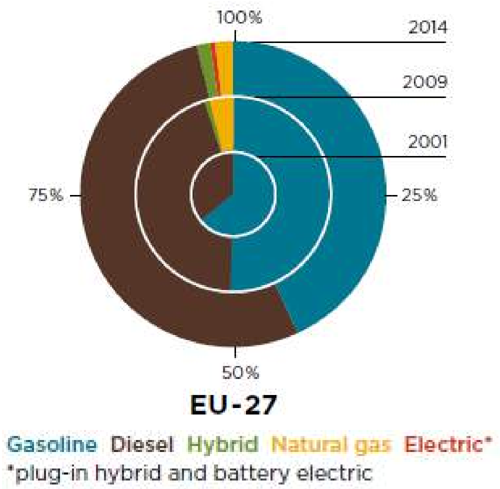


Figure 7.11. EU-27 division of car technologies on the market in 2014
Source: Mock, 2015, p. 40.

Diesel dominates the passenger car market in the EU; in 2014, 53% of all newly registered cars were powered by diesel engines and about 43% by gasoline engines as shown in Figure 7.11. Hybrid, natural gas, and electric cars (which includes plug-in hybrid and battery electric) accounted jointly for about 4% of the technologies on the market. The market share of hybrid-electric vehicles alone was at 1.4 % of all new car sales in the EU in 2014. As ever, there is significant variation among EU member states. *‘While in 2001 only two hybrid vehicle models were offered in the EU, and only about 2,000 were sold, more than 30 hybrid and plug-in hybrid models are now on offer and more than 200,000 are sold. In Japan, every fifth car sold is a hybrid. For Toyota, one-fourth of all new vehicles sold in the EU are hybrid-electric.’ (Mock, 2015, p. 40)*

REE-uses in a car are manifold and different vehicle technology types are to be considered for REE-market demand forecasts.

a) **Car components** (Source: SAE Off-Highway Engineering Online)
   - Magnets
     - REE-magnets in (hybrid-electric) motor and generator using Pr, Nd, (Dy; Tb), Sm
     - 25 and even more electric motors throughout the vehicle using REE-magnets with NdFeB or SmCo alloys, thus Pr, Nd, (Dy; Tb), Sm
   - NiMH battery
     - REE-metal alloy with La and Ce
   - Fuel cell
     - Ce; Nd (Antolini and Perez, 2011)
   - Catalytic converter
     - Ce; La
   - UV cut glass
     - Ce
   - LCD screens
     - Ce, Eu, Y

b) **Consumables**
   - during car component manufacturing
     - glass and mirrors polishing powder of Ce
   - during the refinery of raw oil to diesel and gasoline
     - La, and, if needed, Ce, Pr and Nd, are used in the production of fuel cracking catalysts (FCC catalysts) used in the production of diesel and gasoline

Scenarios

Total passenger car fleet

In the following, the development of the passenger car fleet is estimated based on estimates from the EC (2016f).

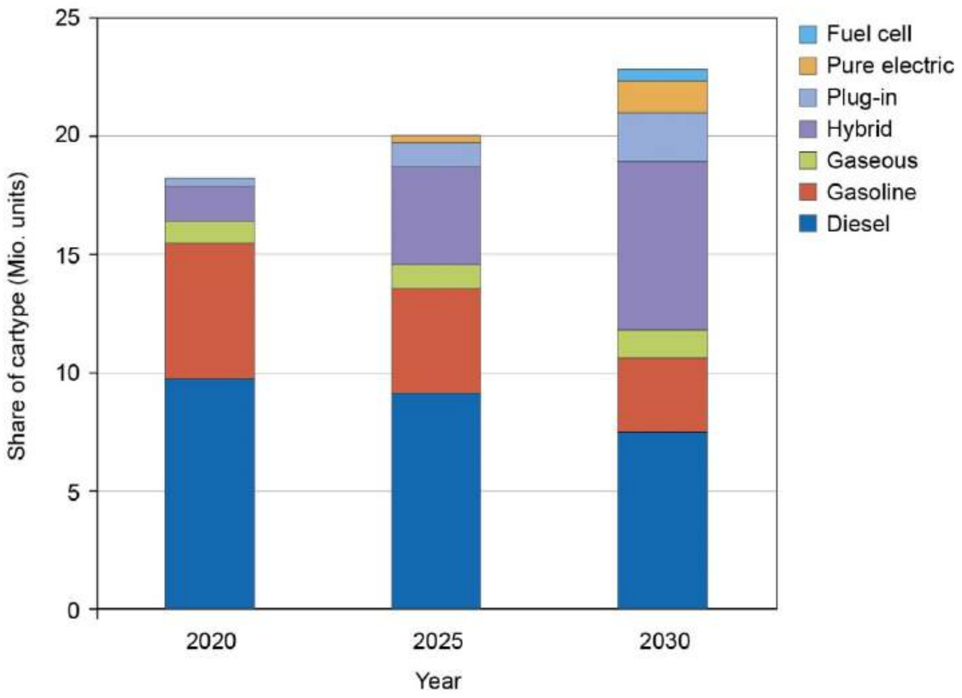


Figure 7.12. Technology types among the EU production of passenger cars
Note: Calculation based on EC estimates on market share development.
Source: EC, 2016f, p. 21.

- *Magnets*

It was estimated that a conventional car contains between 70 and 150 REE magnets, and executive car classes up to 220 REE magnets. The content of these magnets in small motors and sensors was estimated at 250g NdFeB and 10 to 20g SmCo (Legranger, 2014). Further estimates stipulated a total of 20,000t NdFeB contained in the 80 mio. conventional cars that were sold in 2013, with the automotive industry thus accounting for an estimated third of global NdFeB production in 2013. (Benecki, 2013)

With roughly 90 mio. vehicles produced worldwide in 2015, the estimated use of NdFeB is at about 22,500t NdFeB, of which consumption by manufacturing 16 mio. cars in the EU is estimated to have amounted to 4,000t NdFeB. At an estimated 30% content of Nd and 0% Dy in an average NdFeB magnet alloy, the volume of Nd metal used amounted to approximately 1,200t. (Dy content information from Dubus, 2016)

With a historically cumulated annual growth rate of 2.45% as point of departure for estimating future car production in the EU, the estimated passenger car production in the EU will augment to about 18 mio. units in 2020, 20 mio. units in 2025, and 22 mio. units in 2030, as shown in figure 7.12. Using the assumptions on REE-magnet content from above, these increases are anticipated to result in Nd metal demand of 1,350t in 2020, 1,500t in 2025, and 2,650t in 2030 in the EU.

- *NiMH battery in electric (hybrid) vehicle car share*

Based on percentage forecasts on the development of passenger car production in the EU by the (EC, 2016f), we estimate that the share of hybrid vehicles will augment from 1.4 mio. units manufactured in 2020 to 4.1 mio. units in 2025 and to 7.1 mio. units in 2030, as shown in figure 7.12. These estimates have implications for the use of several REE used in the manufacturing of the alloys for batteries.

In NiMH batteries, the hydrogen storage alloys are based on REM, Ti, Zr, Fe and other, and they are extensively studied. However, only REE-based so called AB_5-type and transition metal based AB_2-type alloys have reached the stage of mass production and commercialization. At the same time, as a reversible gas storage material, only AB_5-type alloys can operate at moderate temperatures (from -20°C up to +60°C), while the AB_2-type ones require additional heating.

In the AB_5 alloy, 'A' refers to a mixture of REM of lanthanum, cerium, neodymium and praseodymium, while 'B_5' refers to a mixture of nickel, cobalt, manganese, and/or aluminum (Adamas Intelligence, s. 100). About 7% REE-content is typical for NiMH batteries, which amounts to about 2kg for a HEV battery. (Roskill, 2016) These 2 kg might be roughly composed of about 50% La; 30% Ce; 10%Nd; 3% Pr[18] (adapted and rounded from Lota, Sierczynska, Acznik and Lota, 2014, p. 661, based on commercial AB_5-type alloy of Treibacher Industrie AG), as shown in figure 7.13.

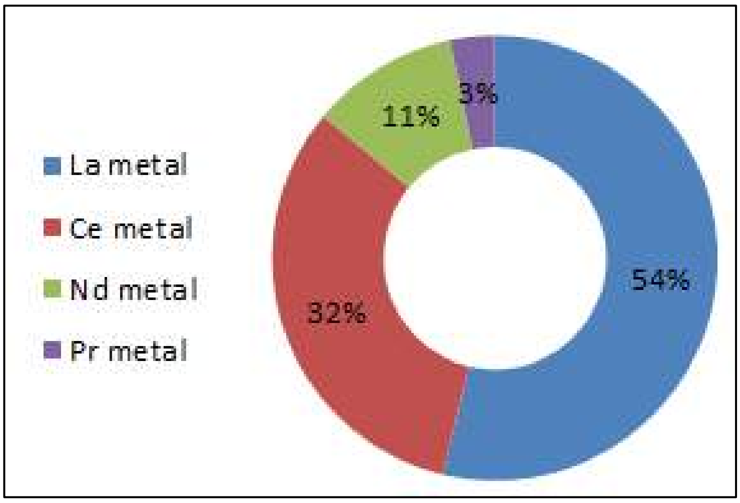


Figure 7.13. Example of battery alloy based on commercial AB_5-type alloy
Source: adapted and rounded from Lota, Sierczynska, Acznik and Lota, 2014, p. 661
Note: The values indicated in the figure are related to the content, in kg, of each RE metal of a battery of 2kg in a HEV.

The forecasted demand for different REE metal content in batteries for HEV vehicles has been calculated from the share of hybrid electric vehicles indicated in figure 7.12. The total REE-metal content anticipated to be needed in 2020 for hybrid vehicle production in the EU is above 2,000t, of which a little more than half of the volume corresponds to La metal, followed by 840t Ce metal, 280t Nd metal, and about 80t Pr metal. For 2030, a significant rise in hybrid vehicles is forecast which will have an effect on REE-metal demand. This could rise to about 7,000t La metal, about 4,300t Ce metal, close to 1,500t Nd metal and about 430t Pr metal.

[18]Among the rare earths typically employed in the formulation of the AB_5 alloy, lanthanum accounts for 63%, cerium for 26%, neodymium for 8% and praseodymium for 3% (Roskill, 2016).

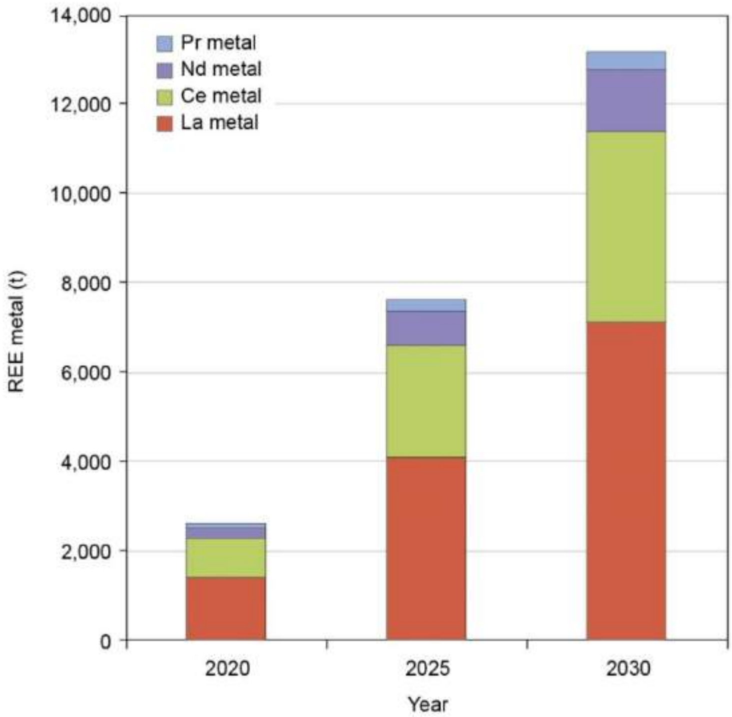


Figure 7.14. Forecast REE metal content (kg) in HEV roll-out between 2020 and 2030
Source: authors based on EC, 2016f, Lota, Sierczynska, Acznik and Lota, 2014, and Roskill, 2011.

It needs mentioning that Li-ion battery types are distinguishable by the cathode material used, allowing for a differentiation between LCO ([lithium cobalt oxide], dubious as to safety and high cost), NMC ([nickel-manganese-cobalt], mostly discussed at this point in time), LFP ([lithium iron phosphate], mainly for busses), and NCA ([nickel cobalt aluminum], only Tesla uses this material). (Spurk, 2016) In light of the anticipated growth of the e-drive car fleet, major significance is attributed to the development of the nickel price, and it has been emphasized that recycling of cobalt will be essential to obtain sufficient supply for anticipated demand. (Spurk, 2016)

- *Catalytic converter (except for pure electric car)*

EU manufacturing standards for cars ensure a clean, safe and quiet fleet: in 2015, about 75% of the car fleet emitted less than 130g CO_2 per kilometer. (ACEA, 2016b) The automotive catalyst is sprayed with precious metals, which, as they are warmed, clean the hazardous particles from the emissions. If the catalyst does not contain many precious metals, e.g. if it is not ‘properly alloyed’, there will be higher amounts of emissions containing the undesired/hazardous emissions (Dehca, 2016).
About 2% of the catalytic converter material used in an average car corresponds to cerium oxide, which amounts to about 20g per catalyst. (Adamas Intelligence, 2014) At a vehicle production of 90 mio. units in 2015, the cerium oxide consumption in catalytic converters amounted to approximately 1,800t cerium oxide. In the EU manufacturing of passenger cars, the volume of cerium oxide used was about 320t in 2015. The estimated passenger car production in the EU is about 18 mio. units in 2020, 20 mio. units in 2025 and 22 mio. units in 2030, and it is forecast to require 360t of cerium oxide in 2020, 400t in 2025, and 440t in 2030.

- *UV cut glass and LCD screens*

No estimates are produced for these two product categories as the content of REE in these product groups for car applications is unknown.

<u>REE use as consumable</u>

'The tax-incentivized dieselization trend has significantly contributed to a fundamental change in the EU road fuel demand structure. The shift from gasoline to diesel began some 25 years ago and led to major gasoline demand decline as well as a shortage of diesel production in the EU.'(Wood Mackenzie in Cooper, p. 14) Figure 7.15 illustrates the decline in gasoline demand at about 75Mt, while diesel demand is augmenting, having reached a total demand of 200 Mt in 2014.

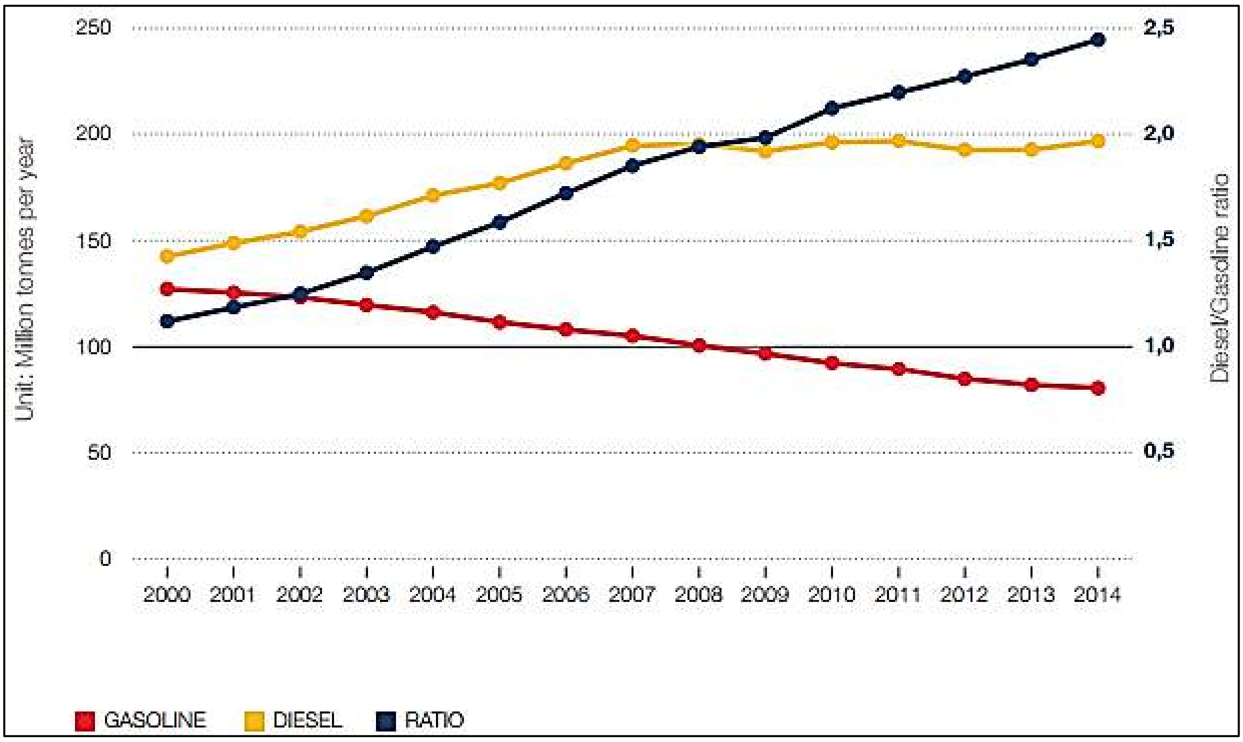


Figure 7.15. Road fuel demand in the EU, 2014
Source: Wood Mackenzie in Cooper, p. 14

A total of 81 refineries were operating in the EU in 2014 at an annual refining capacity of about 680 Mt. (Cooper, 2015) In 2013, the utilization rate of these refineries was at about 80% compared to 2012, and it was anticipated that this rate would drop further in the adjustment to the diesel-gasoline balance, shown in figure 7.15. The average refinery output by product type in OECD Europe includes 39% diesel/gasoil and 19.2% gasoline (OECD in Cooper, 2015, p. 13) among many other product outputs, as illustrated in figure 7.16.

To produce gasoline and diesel from raw oil, fluid cracking catalysts are used. About 40% of commercially available FCC catalysts are produced from REE. These catalysts are produced by including La, even though Ce, Pr and Nd can also be used in small amounts if La is not available. In 2010, when the diesel demand was at about 200 Mt, it was estimated that about 12,000 to 12,500t La oxide were used in the production of FCC catalysts, next to about 500 to 1,000t Ce oxide. (Roskill, 2011)

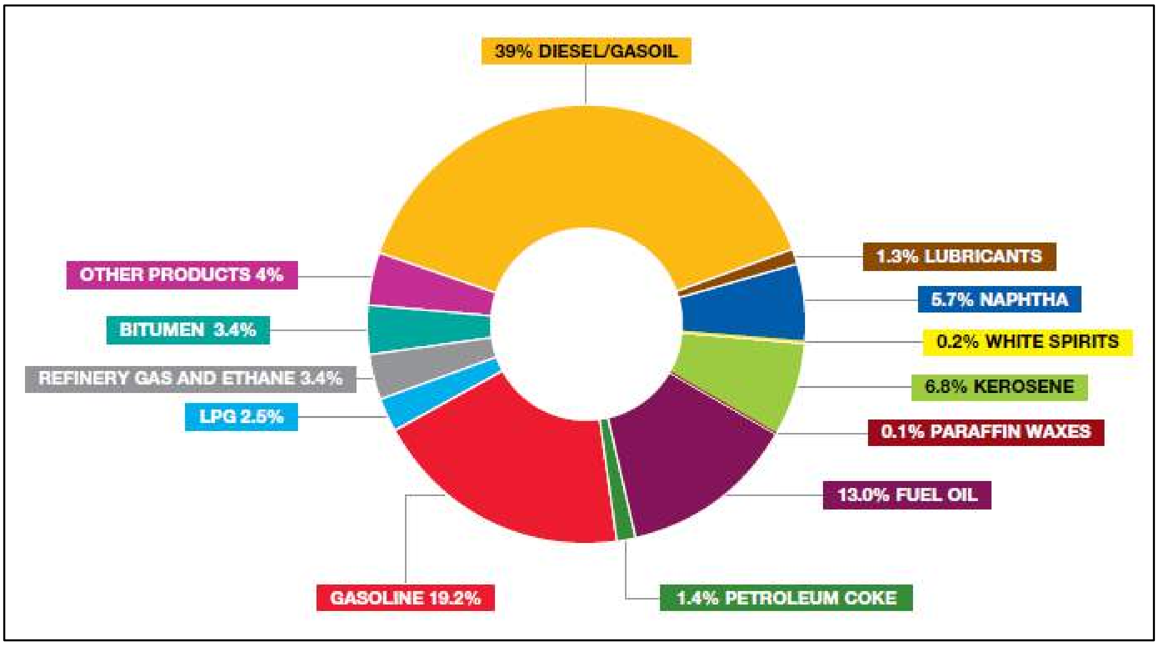


Figure 7.16. Average refinery output by product type in OECD Europe.
Source: OECD in Cooper, 2015, p. 13.

In 2014, the EU diesel car share was at 53% of a total passenger car fleet of 16 mio. cars, as described earlier, thus about 8.5 mio. cars were using diesel, and the diesel demand for road fuel was 200Mt. This equals about 23,500 litres per year, and La oxide and Ce oxide use is estimated to equal that of 2010.

The peak of the diesel car share in the EU car fleet production is estimated for 2020 at 9.8 mio. cars. Up until then, a slight increase in La and Ce use for FCC catalysts production might be forecasted. Between 2020 and 2025, the share of diesel cars in EU production is forecast to decrease, to 9.1 mio. cars in 2025, and more significantly to 7.5 mio. cars by 2030, when this share makes room for hybrid car production. It can thus be anticipated that the volumes of REE used in FCC catalysts production might decrease until 2030.

7.3.5 REE-recycling from end-of-life vehicles

From an environmental resource use perspective of closing material loops, the EC End-of-Life (EoL) Vehicle Directive ('ELV Directive') is important to address in material use forecasts: the Directive puts forward targets for the treatment of EoL Vehicles. As of January 01, 2015, a 95 wt% target for reuse and recovery of EoL Vehicles is in place, alongside a 85 wt% target for material reuse and recycling (Directive 2000/53/EC).
Specifically, the Directive requires the Member States to set up a system for the collection, treatment and recovery of EoL vehicles, according to which the presentation of a Certificate of Destruction (CoD) is a condition for de-registration (Directive 2000/53/EC, Art. 5(3)). Findings from examining the effectiveness of the Directive have found that vehicles disappear due to the existence of an illegal market (see Figure 7.17), deregistration is possible without Certificates of Destruction and no parts data are (made) available for reuse of parts. (Egara, 2016; Öko-Institut e.V., 2016)

As discussed earlier in this subchapter, cars contain many REE-magnets in different applications. At their end of life, they are therefore a source for REE-magnet materials. However, recycling of REE-magnets continues to be hampered by numerous reasons which were identified in a recent study as part of the MORE Project (Hörnig, 2015): the export of EoL cars to third-countries (Extra-EU28 used car export in Figure 7.17), a comparatively laborious disassembly for comparatively small magnets, a lacking infrastructure for the collection, disassembly and reworking on a large-scale without which no buyer of EoL material can be found, or efforts maintained to increase the collected amounts. Further, contrary to Cu, magnet scrap material cannot be sold at 90% of the new material price, and a technical analysis is needed in the collection of the scrap magnet material as magnet types are not marked (Hörnig, 2015).

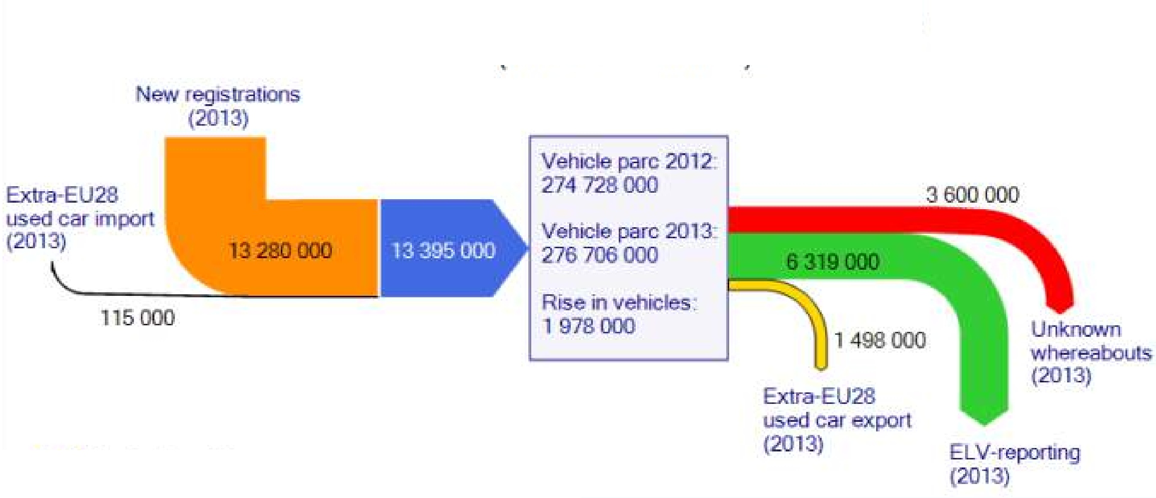


Figure 7.17. Vehicle park development in Europe – 2013.
Source: Öko-Institut e.V., 2016.

With a view to the lacking infrastructure, the European Group of Automotive Recycling Associations [EGARA, 2016] provides useful insights: National Associations of automotive recyclers are known to exist in nine EU member states, Norway and Switzerland, as listed in table 7.10. Rather alarming is the low information on the percentage of ELV handled in column G: of the nine member states, four report no percentage on ELVs handled, suggestive of a significant waste of resources that are contained in ELV, including of REE-containing components.

Table 7.10. Countries with a National Association of Automotive Recyclers.

Country	Acronym of Nat. Assoc. (NA)	No. of members in NA	No. of authorized dismantlers	No. of ELVs in the country (total p.a.)	No. of ELVs handled by NA members	% of ELVs handled
Denmark	DAG	45	210	95,000	25,000	26
Estonia	NGO ELV	29	0	0	0	0
Finland	SAL	64	0	0	0	0
France	CNPA	405	1,200	1,300,000	845,000	**65**
Ireland	IMVRA	29	200	175,000	20,000	9
Netherlands	STIBA	135	550	230,000	170,000	**74**
Norway	NBF	69	136	147,000	102,000	**70**
Poland	FORS	220	690	1,000,000	?	?
Sweden	SBR	122	286	190,000	142,500	**75**
Switzerland	VASSO	23	45	210,000	100,000	48
UK	MVDA	147	1,300	1,800,000	0	0

Source: European Group of Automotive Recycling Associations [EGARA], 2016.
Note: The no. of authorized dismantlers refers to the total known for each country.

REE-components contained in REE-using applications used in the EU, and entering their end-of-life (EoL) stage at various points in time, constitute significant sources for raw material supply. Given the described risks attached to investing into building and maintaining a material supply chain from REE-mine to market outside of China, it is considered justified to examine the contained secondary REE-material flows in the EoL applications. Especially so under the condition of existing legislation that could enable, through specific targets and checks, and well-governed collection systems, the closing of material loops through reuse and remanufacturing with recycling. The valuation of these materials, however, in the context of the different players participating and interacting in this material supply chain requires careful consideration, along the insights a value chain analysis can deliver. Overall, closing material loops might not be left to a pure cost-price evaluation, but to one worthy for the relative improved predictability of material supply.

8 Discussion: Potential EURARE effect on future REE market scenarios

The EU-based supply chain of REE is based on imported REE-products given that Europe currently has no mine supply of the REE. However, more than 60 REE-occurrences and deposits are known in Europe, and thus carry the potential for future REE-mining. The EURARE project (WP1) identified the REE-mineral potential in Europe (see the EURARE website (http://www.eurare.eu/countries/home.html) and the EURARE portal (http://eurare.brgm-rec.fr/). A brief review of the European REE resources potential is outlined by Goodenough *et al.* (2016), and detailed in chapter 3. The European REE resources include alkaline igneous rocks such as those found in the Gardar Province, Greenland hosting the two advanced exploration projects Kvanefjeld and Kringlerne advanced exploration projects and within the Fennoscandian Shield, hosting the carbonatites of Fen in Norway and Sokli in Finland, as well as the advanced exploration project Norra Kärr in Sweden. Four of these REE-deposits and exploration projects are partners in the EURARE: Kvanefjeld, Kringlerne, Norra Kärr, and Fen. Additionally, the European REE-resource potential includes secondary placer deposits such as those in Greece and Serbia.

The EURARE partner-projects Kvanefjeld, Kringlerne and Norra Kärr all state that they have reached the advanced stage of development, and thus, could be put into production around 2020 and ramping up over a few years. In this case they will potentially be new suppliers to the European REE-market with various types of REO-products. In addition to the uncertainty regarding their materialization, it should be emphasized that the geographical location of each of these projects does not give any indication about the geographical location of the market. E.g. a REE-mine in Greenland may supply a market in China and a mine in China may supply a market in Europe. All three projects are envisaged to last for 20 plus years.

In addition to the primary resources, the potential of the red mud waste from alumina plants has been investigated to assess the technical possibilities for exploiting the REE-content of these resources. These types of resources are large but low grade; the global annual red mud production is about 150 Mt, and carries the potential to generate up to about 172,500 tpa TREO (Deady *et al.* 2016); the authors find it realistically, that at the most only a minor share of the REE-supply will be supplied from this type of material.

The non-conventional mineralogy associated with deposits of Kringlerne and Norra Kärr (eudialyte), and Kvanefjeld (steenstrupine) require development of tailored beneficiation flow-sheets. EURARE (WP2) has contributed in both bench-scale and pilot-scale tests to the beneficiation studies with more efficient flow-sheets as a result. Further, beneficiation studies have been undertaken on the ore from the Fen Complex.

Separation of the individual REE from a mixed compound is one of the bottlenecks in the REE-supply-chain, and the development of *new separation technologies* has been a high priority in the EURARE (WP3 and 4), and as a result new separation technologies have been developed by the EURARE partners. This technology needs to be viewed in the context of the described global and EU-REE-industry developments: China continues to be the major player in the industry, and policy developments suggest that environmental performance targets to which mining and separation firms will have to adhere, are *likely to be effectively implemented* over the short- to medium term alongside industrial consolidation. Effective and cheap technology for the separation is of crucial importance to establish a European REE supply chain that is to be independent of China. As ERECON (2014, p. 65) pointed out, '*opening a state-of-the-art REE mine, without processing operations in Europe,* *North America or Australia would require an investment of anywhere between several hundred million dollars to slightly over a billion dollars, depending on the size of the operations and the complexity of the project (these numbers are based on available preliminary economic assessments and feasibility studies of major exploration projects today).'*[19]

The EURARE project initiated in 2013, in the aftermath of the REE price peaks of 2011 when the effects of the sudden price increase were still in the recent memories of the REE-using industries in the EU, and the criticality of REE featured also prominently in political debates about maintaining and securing stable access to REE-products. Some individual REE-prices surged by up to +600% within a period of a few months. These prices have since returned to pre-2011 prices, or decreased even further, as illustrated in figure 8.1. This had the effect that investment in REE exploration as well as in other parts of the REE supply-chain has diminished, and many exploration projects have been put on hold.

Outside China, Lynas Corp. remains the only partially integrated mining firm with access to REE-supply from Mount Weld in Australia, and chemical separation in Malaysia, with strong financial support by the Japanese government, that has been tested in a debt restructuring process which was initiated in August 2015. This negative investment climate is also affected by the rapid dynamics within technological development and replacements, which creates uncertainties about the future demand for REE. This is for instance the case with Eu, and Y as fluorescent lamps are rapidly replaced by LEDs, while Tb functions as a substitute for Dy in NdFeB magnets, if required. It has been proposed that the original US Department of Energy (DOE, 2010) list of CREOs that comprised Nd, Dy, Tb, Eu and Y, is amended to a 'neo-CREOs' list in which Nd, Dy, Tb remain and are joined by La and Pr in reflection of anticipated shortfalls in supply of these elements by 2025 (Adamas Intelligence, 2016).

For Nd, Pr, Dy, a shortage in supply by 2025 is possible as a result of NdFeB magnet use in renewable power generation, energy-efficient technologies and electric mobility, while Tb could substitute for Dy. The wide use in catalytic converters and rechargeable batteries as well as thermal stabilizer of poly-vinyl chloride (PVC) to reduce lead use are mentioned as reasons for a potential La shortage by 2025 (see Adamas Intelligence, 2016 for details). Further on in this chapter, we summarize the results of our forecasts on particular REE-using sectors which lead us to conclude that a shortfall in Nd supply is most likely, while a shortfall in Dy and Tb might be probable, but could be circumvented by technological development. We are skeptical as to the potential shortfall in La supply, but this view is limited to our transport sector scenario, and therefore not comprising a complete range of technologies using La.

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[19] *'For comparison this is the value of a handful of Airbus 330s52, one or two large, state-of-the art hospitals, a few dozen kilometers of high-speed railway, or a larger bridge or tunnel. In the capital intensive mining industry these are relatively modest sums: in 2013, the world's 40 largest listed mining companies alone invested $130 billion, with the largest greenfield mines costing tens of billions of dollars.'* (ERECON, 2014, p. 66)

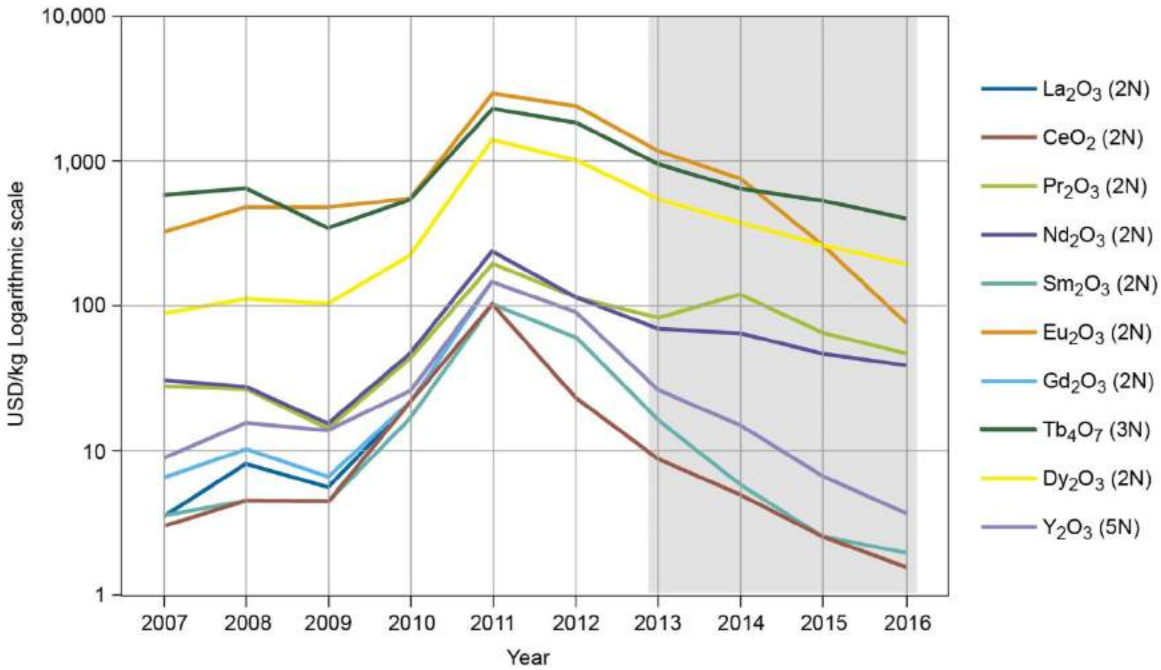

Figure 8.1. Developments of FOB China prices from 2007 to 2016.
Source: adapted from Adamas Intelligence, 2016.
Note: The grey-highlighted area marks the EURARE project period. With the exception of Tb4O7 at a purity of 3N and Y2O3 at 5N, all other REOs are shown at a purity of 2N. These two elements only have industrial use at these purities.

Whether the challenges for establishing REE-mining and processing activities outside China are a troublesome development for EU-based industrial activity, such as for the automotive industry, that relies on REE-input, needs to be placed in the context of the global interconnectedness of REE-using firms based in the EU. Most of the firms that have been named in this report to paint a broadly representative picture of the EU REE-using industry, are part of globally connected value chains in which they negotiate their REE-product input and prices with (vertically integrated) subsidiaries, including from within China.

However, it is the view of the authors, that access to REE-raw material in China through subsidiaries should not be considered as a secure and stable source of supply, as raw material access in China is subject to increasing regulation, and the REE-quota allocations to joint ventures with foreign companies might be revised, and/or attached to requirements of relocating downstream activities to China – with implications for the future of value-added manufacturing.

From this perspective, and given anticipated growing demand for REE in several REE-using sectors, it appears that REE-producers might need to adopt emerging technological developments, namely to select the individual REE from a REE-bearing mineral in the separation process to minimize the balance problem. While the targeted selection for separation appears to have potential for a less costly process, it is important to highlight that the implementation of REE-projects outside China (see Figure 8.2) will need not only a viable feed source, a reliable process and industrial off-takers, but a strategy for how to address the fluctuations in REE-prices which are, not only market-driven. Rather, the REE-prices are also reflective of significant subsidization and controlled by the Chinese government through industrial policy, and operate next to a significant illegal REE-supply that finds its way out of China to separation plants in South-East Asia.

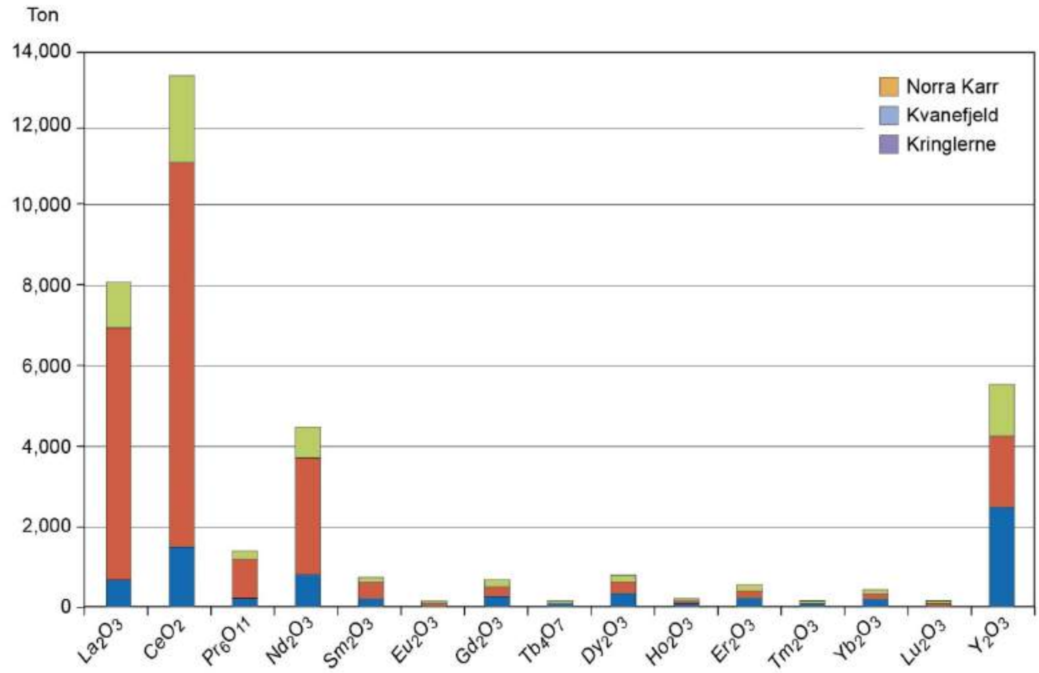

Figure 8.2. Estimated annual TREO production from EURARE partner projects.
Source: The three projects have reported to initiate production in 2020, and the ramping-up period is assumed to be about 3-5 years. Thus this production should fit to the output in 2025.

As per 2015 November more than 60 REE-exploration projects outside China were being developed, although this number is assumed to have decreased since due to low REO-prices. In addition to the three advanced EURARE-partner projects (Kringlerne, Kvanefjeld and Norra Kärr, see Figure 8.2), six projects outside China and Europe are considered potential TREO-producers in 2025 (see Figure 8.3). Figure 8.4 combines the potential EURARE partner and ROW production of the six projects in Figure 8.3.

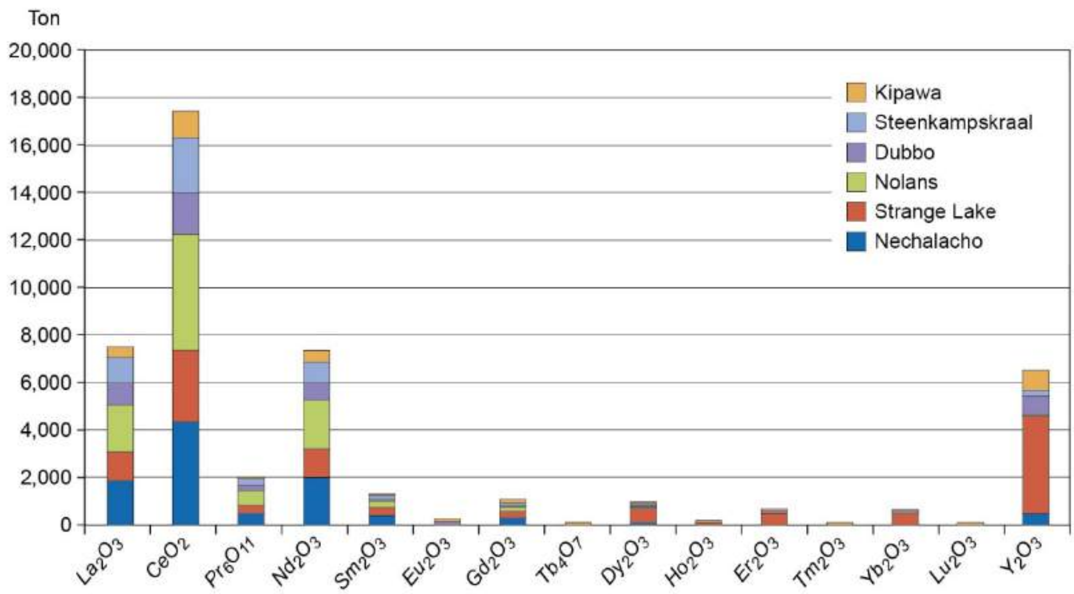

Figure 8.3. Estimate of the annual TREO production from six global projects.
Source: MiMa-GEUS, 2016.
Note: The selection of global advanced projects is based on Machacek and Kalvig, 2016.

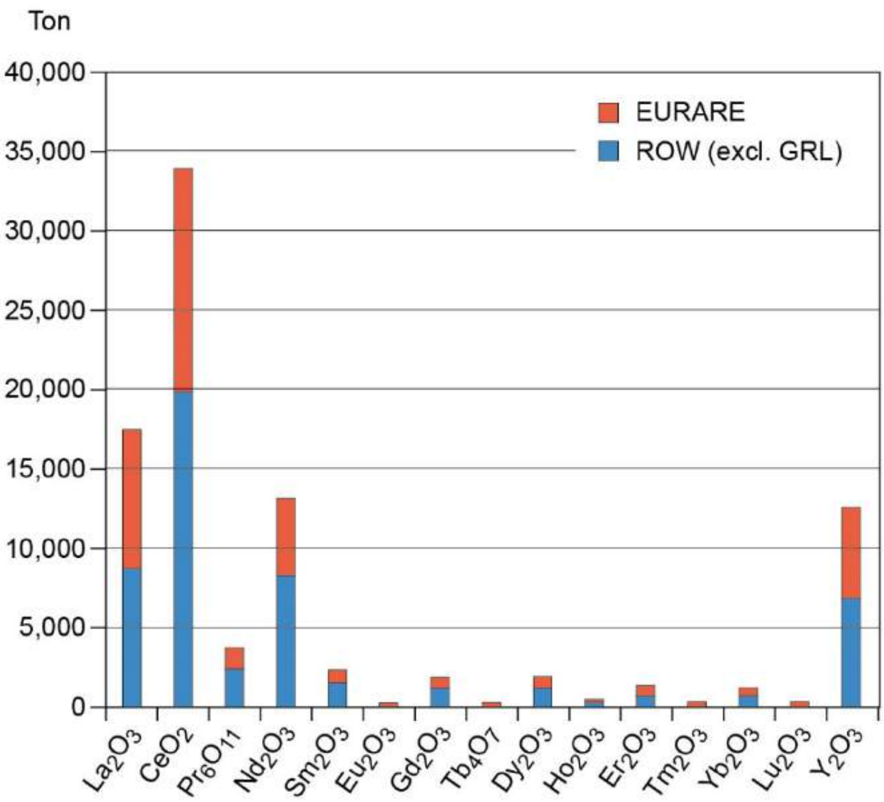

Figure 8.4. Estimated annual TREO production EURARE and global advanced projects.
Source: MiMa-GEUS, 2016.
Note: One or several of these projects may be put into operation by 2025 and contribute to the TREO-world-market.

The relatively limited demand for REE-products by the European industry is inadequate to absorb the REE-products from even one of the three advanced REE-projects; new European REE-producers will require off-takes outside Europe. The Eurostat import codes for REE-products are used to elaborate REE-market scenarios, despite the reporting codes remain too vague to draw clear-cut conclusions as to the volume and type of the imported REE-products. The elaborated REE market scenarios are the following:

- Increasing demand for REE-materials in the deployment of REE-permanent magnet driven generators of wind turbines, especially in offshore technology, for the achievement of renewable energy targets in the EU
- Changes in general lighting technology carry along reduced demand for the REE-phosphors
- The content of REE-permanent magnets contained in numerous small motors in the car will grow alongside REE-use in alloys of catalyst converters due to general rises in car demand. As the share of diesel and gasoline driven passenger cars makes way for hybrid cars towards 2030, increasing demand for light REE in alloys of batteries will be noted.

The developed scenarios for (i) wind energy generation sector, (ii) phosphor-based general lighting, and (iii) the transport sector is considering the impact this may have on the industries for REE-permanent magnets, REE-use in catalytic converters, and REE-use in FCC of oil refining for automotive passenger cars. The derived forecasts are then viewed in the context of plans for REE-mineral mining of the three advanced REE-mining projects within Europe (Kvanefjeld, Kringlerne and Norra Kärr) from 2025, as illustrated in Figure 8.5.

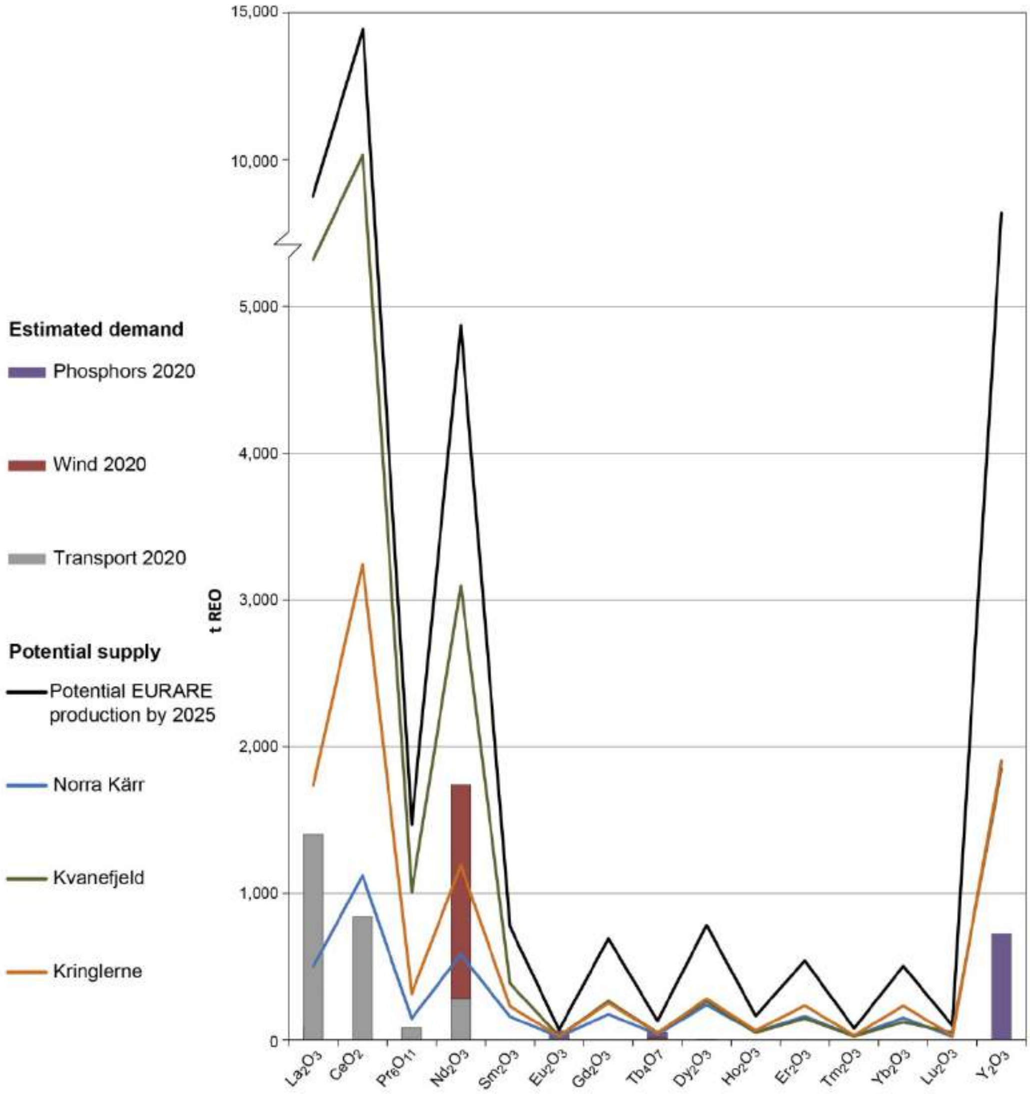

Figure 8.5. Comparison of REE-demand forecast and potential European REO production
Source: MiMa-GEUS, 2016.

It is in this light, that the raw material base of REE-components contained in REE-using applications used in the EU, and entering their end-of-life (EoL) stage at various points in time, present themselves as a significant source for raw material supply, under the condition of existing, targeted legislation that promotes, through specific targets and checks, and well-governed collection and recycling systems which use might not be left to a pure cost-price evaluation, but to one of a value that is measured in predictability.

Numerous initiatives have already been supported to develop recycling technologies, including by EC-funded projects, such as of hard-disc drives (e.g. at University of Birmingham), REE-containing magnets from motors in electric vehicles (e.g. at KU Leuven), yet what remains to be addressed is how these technologies link with the socio-economic organization and structure of the European society. This includes a discussion of requirements to implement these technologies and of how the recycled secondary material streams may become relevant for manufacturing activity that to-date draws on primary material sourcing.

9 Conclusion

The EURARE project aims to address the entire European REE-material supply chain from ore to final product. It was funded to *'set the basis for the development of a European REE industry that will safeguard the uninterrupted supply of REE raw materials and products crucial for the EU economy industrial sectors, such as automotive, electronics, machinery and chemicals, in a sustainable, economically viable and environmentally friendly way'* (EURARE, 2013). With this background it is noteworthy that the EU-based material supply chain of REE does not comprise REE-mining but initiates at the REE-separation segment.

This market report was written with the purpose of elucidating EU-based REE-industrial activities and market scenarios, considered in the context of the global REE-market, to set the scene and explain the broader context for technological process development within the EURARE project. Specifically, this report has outlined particular aspects around mining and processing of REE, delineated the intermediate REE- industrial sectors, described the EU and global REE markets, and provided forecast scenarios for 2025 and 2030 for the REE-demand in various industrial sectors. These scenarios have been developed with a view to EU2020 renewable energy targets which affect REE-consuming technologies.

In the context of described REE-market developments, the EURARE REE-projects (Kvanefjeld, Kringlerne and Norra Kärr) could potentially be in production by 2025. In addition, six projects outside China and Europe are considered potential TREO-producers in 2025. However, the relatively limited demand for REE-products by the European industry is inadequate to absorb the REE-products from even one of the three advanced REE-projects; new European REE-producers will need to find markets outside Europe. This is especially so in the context of the scenarios developed in this report, for REE use in components for the wind energy generation sector, phosphor-based general lighting, and the transport sector. These scenarios aimed to forecast REE-demand and provide context for plans for mining at the three advanced REE-mining projects within Europe by 2025. The comparison showed that none of these three projects will supply exactly the anticipated volume demand of each of the REE.

In contrast, REE-recycling allows targeting of the particular individual REE of interest. Several pathways to REE recycling exist, namely in-process-recycling, recycling of tailings from mineral processing and recycling of REE from components in end-user applications. Further, in the EURARE project, by-product production of REE from red mud waste of alumina plants has been explored. Recycling technologies are being developed for specific end-user applications, including for instance for REE-based phosphors from lamps. However, an available, commercialized technology is not sufficient to operate a recycling process: What is needed, as we have outlined in this report, is an understanding of the interactions that underpin business exchanges and determine how prices are derived and negotiated among different business partners, and importantly, where along the material supply chain (i.e. at which firm) information on prices is lacking to close material loops.

This finding clearly stipulates a pathway for future research: While primary sources for REE-supply will continue to be needed, closing material loops with recycling of different material streams is an important pathway for material supply. Thus, gaining an understanding of the information - price formation dynamics that drive the material supply, including under high government-influence, will be essential to target and design future research and respond to material supply challenges.

10 References

ACEA (2016a) Statistics. Registration Figures. Consolidated Registration Figures. Consolidated Registrations – by Manufacturer. Retrieved on December 07, 2016 from http://www.acea.be/statistics/tag/category/by-manufacturer-registrations

ACEA (2016b) About the Automobile Industry. Passenger Cars. Retrieved on December 07, 2016 from http://www.acea.be/automobile-industry/passenger-cars

ACEA (2016c) Statistics. Key Figures. Retrieved on December 07, 2016 from http://www.acea.be/statistics/tag/category/key-figures

ACEA (2016d) The Automobile Industry Pocket Guide 2016, 2017. Retrieved on December 09, 2016 from http://www.acea.be/uploads/publications/ACEA_Pocket_Guide_2016_2017.pdf

ACI Cyprus L.L.C. (Albemarle) Company profile. Retrieved from https://www.sec.gov/Archives/edgar/data/915913/000119312513062728/d437520dex211.htm

ACREI (2016b) Argus 2016 International Rare Earth Conference, Hangzhou, October 25-27, 2016. Retrieved from http://www.ac-rei.org.cn/portal.php?mod=view&aid=5561

Adamas Intelligence (2016).Rare Earth Market Outlook Update: Supply, Demand, and Pricing from 2016 through 2025, edited by R. Castilloux.

Adamas Intelligence (2014). Rare Earth Market Outlook: Supply, Demand and Pricing from 2014 - 2020, edited by R. Castilloux. Published on October 1, 2014.

Allied Market Research (2016). Lithium-Ion Battery Market by Material Type (Cathode, Anode, Electrolytic solution, Foils, Binders, Separators) and Industry Vertical (Smartphones, UPS, Cars, Aircraft, Busses, Trucks, Mining equipment, Smart Grid, Games, Gardening tools) - Global Opportunity Analysis and Industry Forecast, 2015-2022. Retrieved on February 10, 2017 from https://www.alliedmarketresearch.com/lithium-ion-battery-market

Al Ani, T and Sarapää, O. 2013. Geochemistry and mineral phases of REE in Jammi carbonatite veins and fenites, southern end of the Sokli complex, NE Finland. *Geochemistry: Exploration, Environment, Analysis*, v. 13:217–224.

American Elements (2017) Retrieved from https://www.americanelements.com

Åmli, R. 1975. Mineralogy and rare earth geochemistry of apatite and xenotime from the Gloserheia granite pegmatite, Froland, southern Norway. *American Mineralogist*, 60:607–620.

Andersson, U B (ed.). 2004. The Bastnäs-type REE mineralisations in north-western Bergslagen, Sweden. *SGU Rapporter and Meddelanden.* 119: 34 pp.

Antolini, E. and Perez, J. (2011) The use of rare earth-based materials in low-temperature fuel cells. *International Journal of Hydrogen Energy 36* (24), 115752-15765.

Arafura (2005) ASX Announcement. Interim metallurgical test results Nolans Bore. Released on April 20, 2005.

Auer-Remy (2016) Specialist for rare earth and zirconium compounds. Retrieved on March 18, 2016 from http://www.auer-remy.de/en/home/

Aura Light (2016) Sustainable lighting for business. Accessed on December 29, 2016 and retrievable from http://www.auralight.com/

Baermann Magnets Suzhou Co. Ltd. (2016). Retrieved on November 7, 2016 from http://www.baermann-magnets.com/about.html

Balachandran, G. (2014). Case Study 1 - Extraction of Rare Earths for Advanced Applications. In S. Seetharaman (Ed.), *Treatise on Process Metallurgy* (pp. 1291–1340). Boston: Elsevier. Retrieved May 20, from http://www.sciencedirect.com/science/article/pii/B9780080969886099831

Barteková, E. (2016) The role of rare earth supply risk in low-carbon technology innovation In Borges de Lima, I. and Filho, W.L. (2016) *Rare Earths Industry. Technological, Economic, and Environmental Implications*. Oxford, UK and Waltham, USA: Elsevier.

BASF (2016) Source: https://www.basf.com/documents/corp/en/about-us/publications/reports/2016/BASF_in_Greater_China_Report%202015.pdf

BASF (2017) Retrieved on February 8, 2017 from http://www.refiningonline.com/EngelhardKB/crep/TCR4_23.htm

Bauer, D., Diamond, D., Li, J., McKittrick, M., Sandalow, D., Talleen, P. (2011) Critical Materials Strategy. US Department of Energy. Retrieved from http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf on November 28, 2016

Bergfald, B. (2016) Personal communication per email on January 12, 2017.

Binnemans, K. (2015). Rare earths: essential elements for the transition to a low-carbon economy. *Bauxite Residue Valorisation and Best Practices*, Leuven (Belgium), 5-7/10/2015.

Binnemans, K. and Jones, P.T. (2015) Rare Earths and the Balance Problem. *Journal of Sustainable Metallurgy 1*, 29-38.

Binnemans , K. (2014a) Rare earth recycling and the balance problem. Presentation at the EREAN Summer School, KU Leuven, August, 2014.

Binnemans, K. (2014b). Economics of rare earths: the balance problem. Proceedings from ERES2014: 1st European Rare Earth Resources Conference, Milos, 04-07/09/2014.

Binnemans, K. and Jones, P.T. (2014) Perspectives for the recovery of rare earths from end-of-life fluorescent lamps. *J. Rare Earths 32* (3), 195-200, http://doi.org/10.1016/S1002-0721(14)60051-X.

Binnemans, K., Jones, P. T., Acker, K., Blanpain, B., Mishra, B., Apelian, D. (2013a) Rare-earth economics: the balance problem. *JOM 65 (7)*, pp. 846-848, http:// doi.org/10.1007/s11837-013-0639-7

Binnemans, K., Jones, P.T., Blanpain, B., Van Gerven, T., Yang, Y., Walton, A., Buchert, M. (2013b). Recycling of rare earths: a critical review. *J. Clean. Prod. 51*, 1-22, http://doi.org/10.1016/j.jclepro.2012.12.037.

Binnemans, K., Jones, P.T. (2013). Rare-Earth Element Recycling: Challenges and Opportunities. Presentation within the framework of the COST Association, TU Delft, 19-11-2013. Retrieved on February 8, 2017 from www.cost.eu/download/Day2Recycling

Biswas DI (2013) Potential for recovery of cerium contained in automotive catalytic converters: U.S. Geological Survey Open- File Report 2013-1037. Retrieved from http://pubs.usgs.gov/of/2013/1037

Browne, D.J., de Faoite, D., Chang-Díaz, F.R., Stanton, K.T. (2012). A review of the processing, composition, and temperature-dependent mechanical and thermal properties of dielectric technical ceramics. *Journal of Materials Science*, Volume 47, issue 10, pp. 4211-4235. DOI: 10.1007/s10853-011-6140-1

Brown, T.J., Wrighton, N.E., Raycraft, E.R., Shaw, R.A., Deady, E.A., Rippingale, J. and Bide, T. (2016): World Mineral Production; 2010-2014. British Geological Survey. file:///C:/Users/pka/Downloads/WMP_2010_2014%20(1).pdf

Castilloux, R. (2014) Emerging End-Uses of REEs that could transform the market prior to 2020. Retrieved January 10, 2015 from http://www.techmetalsresearch.com/

CEC (2015). Environmentally Sound Management of End-of-Life Batteries from Electric-Drive Vehicles in North America. Montreal, Canada: Commission for Environmental Cooperation. 103 pp.

Chaubey, A.K., Mohapatra, S., Jayasankar, K., Pradhan, S.K., Satpati, B., Sahay, S.S., Mishra, B.K., Mukherjee, P.S. (2009). Effect of cerium addition on microstructure and mechanical properties of Al-Zn-Mg-Cu alloy. *Transactions of The Indian Institute of Metals*, Volume 62, Issue 6, pp. 539-543. DOI: 10.1007/s12666-009-0090-1

CN Stock (2016) Retrieved on November 04, 2016 from http://news.cnstock.com/industry/sid_rdjj/201607/3832493.htm)

Cooper, J. (2015) Fuels Europe. Refining products for our everyday life. Statistical report 2015. Retrievable from https://www.fuelseurope.eu/uploads/Modules/Resources/fuelseurope-statistical-report-2015.pdf

CRM-Innonet (2014) CRM-Innonet Project. Internal report summarizing the results of energy sector analysis. Edited by A. Brunot, V. Charreyron. Institut Liten and Commissariat à l’ énergie atomique et aux énergies alternatives [CEA]. Grenoble: CEA; Liten.

Danfoss (2015) Global Danfoss 3/15. A stakeholder publication. English edition.

Davris, P., Stopic, S., Balomenos, E., Panias, D., Paspaliaris, I., Friedrich, B. (2016) Leaching of rare earth elements from eudialyte concentrate by suppressing silica gel formation. *Minerals Engineering* (Article in press, January 2017).

Deady, E.A., Mouchos, E., Goodenough, K., Williamson, B.J., Wall, F. (2016) A review of the potential for rare-earth element resources from European red muds: examples from Seydişehir, Turkey and Parnassus-Giona, Greece. *Mineralogical Magazine, 80 (1)*, 43-61.

Deady, E.A., Mouchos, E., Goodenough, K., Williamson, B.J., Wall, F. (2014) Rare Earth Elements in Karst-Bauxites: A novel untapped European resource? ERES 2014; European Rare Earth Resources Conference, Milos 04-07 September, 2014.

Dubus, J.-M. (2016) Presentation in the session ‘E-Drives for Mobility and Automation. Current status and future needs’ at the EIT expert forum on Materials and Technologies for Future Mobility, Darmstadt, 9th December 2016

European Commission (2014a) Report on critical raw materials for the EU.

European Commission (2014b) Communication on the review of the list of critical raw materials for the EU and the implementation of the Raw Materials Initiative. 26 May 2014.

European Commission (2014c) Study on cross-cutting KETs (Ro-cKETs). https://ec.europa.eu/growth/industry/key-enabling-technologies/eu-actions/ro-ckets_en.

EC (2016d) Topics. Energy Efficiency. Saving energy, saving money. Retrieved on October 20, 2016 from https://ec.europa.eu/energy/en/topics/energy-efficiency

EC (2016e) Energy. Energy efficient products. Lighting. Retrieved on October 20, 2016 from https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-efficient-products

EC (2016f) EU Reference Scenario 2016. Energy transport and GHG emissions. Trends to 2050. Main results. EC DG for Energy, DG for Climate Action and DG for Mobility and Transport. Retrieved from https://ec.europa.eu/energy/sites/ener/files/documents/20160712_Summary_Ref_scenario_MAIN_RESULTS%20(2)-web.pdf on November 28, 2016

EC (2013) Critical Metals on the Path towards the Decarbonisation of the EU Energy Sector. EC, 244p.

European Commission (2011) Key Enabling Technologies. https://ec.europa.eu/growth/industry/key-enabling-technologies_en.

European Commission (2009) Preparing for our future: Developing a common strategy for key enabling technologies.

EC, 2000. Directive 2000/53/EC on the end of life vehicles. Retrievable from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=CONSLEG:2000L0053:20050701:EN:PDF

EGARA, 2016. Our members. EGARA members. Retrievable from http://www.egaranet.org/

Elgallad, E.M., Doty, H.W., Alkahtani, S.A., Samuel, F.H. (2016). Effects of La and Ce Addition on the Modification of Al-Si Based Alloys. *Advances in Materials Science and Engineering*, Volume 2016, Article ID 5027243, 13 pages. DOI: 10.1155/2016/5027243

ENIAC (2010) Multi-annual strategic programme.

EPoSS (2013) Strategic Research Agenda.

ERECON (2014) Strengthening the European rare earths supply chain: Challenges and policy options. Kooroshy, J., G. Tiess, A. Tukker, and A. Walton (eds.) Retrieved from http://reinhardbuetikofer.eu/wp-content/uploads/2015/03/ERECON_Report_v05.pdf

ERTRAC, EPoSS and SmartGrids (2012) European Roadmap Electrification of Road Transport.

ETP Photonics21 (2010) Lighting the way ahead - Photonics SRA.

ETP SmartGrids (2012) Strategic Research Agenda for Europe electricity networks of the future.

ETP SMR (2011) Securing a sustainable raw materials supply basis for Europe.

ETP SMR (2012) WP 1 – Developing new innovative technologies and solutions for sustainable raw materials supply.

ETP Wind Energy (2006) Wind Energy: a vision for Europe in 2030.

EURARE (2016) Welcome to EURARE. Project website retrievable from eurare.eu.

Eurostat (2016). Your key to European statistics. Database > Data Navigation Tree > Database by themes > International Trade > International trade detailed data (detail) > EU trade. Retrieved October 26, 2016.

EWEA (2016) The European offshore wind industry – key trends and statistics 2015. February 2016. A report by the European Wind Energy Association.

EWEA (2015) Wind in power. 2015 European statistics. EWEA: February 2016. Retrieved on November 22, 2016 from https://windeurope.org/wp-content/uploads/files/about-wind/statistics/EWEA-Annual-Statistics-2015.pdf

Falconnet, P. (1985) The economics of rare earths. *J. Less Common Met. 111 (1),* 9-15.

Garrett, P. and Rønde, K. (2012) Life cycle assessment of wind power: comprehensive results from a state-of-the-art approach. *Int. J. Life Cycle Assess. 18*, 37-48.

Global Market Insights Inc. (2017). Permanent Magnet Market Size, Industry Share Report - 2024. Report ID: GMI1113. Retrieved on February 10, 2017 from https://www.gminsights.com/industry-analysis/permanent-magnet-market

GMEL (2015) Kvanefjeld Feasibility Study Completed. Study Highlights. Company Announcement, May 25th, 2015. Retrieved on September 20, 2016 from http://www.ggg.gl/docs/ASX-announcements/Kvanefjeld-Feasibility.pdf

GME (2015) https://www.google.dk/search?q=greenland+minerals+energy+pfs&ie=utf-8&oe=utf-8&client=firefox-b-ab&gws_rd=cr&ei=2g1sWJ_TNYf_swHmn7TABg#q=greenland+minerals+energy+feasibility+study Kvanefjeld_Feasibility 2015.

Goodenough, K.M., Schilling, J., Jonsson, E., Kalvig, P., Charles, N., Tuduri, J., Deady, E.A., Sadeghi, M., Schiellerup, H., Müller, A., Bertrand, G., Arvanitidis, N., Eliopoulos, D.G., Shaw, R.A., Thrane, K., Keulen, N. (2016) Europe's rare earth element resource potential: An overview of REE metallogenetic provinces and their geodynamic setting. *Ore Geology Reviews 72,* 838-856.

Goonan, T. G. (2011) Rare Earth Elements – End Use and Recyclability. Scientific Investigations Report 2011-5094. US Department of the Interior, USGS. Retrieved on March 14, 2016 from http://pubs.usgs.gov/sir/2011/5094/pdf/sir2011-5094.pdf

Grace China Ltd. (2016) Company website. Retrieved from https://grace.com/en-us/welcome-to-grace-china-english

Grand View Research, Inc. (2014). Permanent Magnets Industry Trends and Market Segment Forecasts to 2020. Retrieved on February 10, 2017 from http://ireport.cnn.com/docs/DOC-1112999

Green Living Ideas (2015) Retrieved on February 8, 2017 from http://greenlivingideas.com/2015/02/19/the-true-cost-of-light-bulbs-led-cfl-incandescent/

Guj, P. and Trench, A. (2013) An Introduction to Mineral Finance. In *Mineral Economics*, 2nd ed. Monograph 29. AusIMM The Minerals Institute. Carlton Victoria: Australia.

Gupta, C.K. and Krishnamurthy, N. (2004): Extractive Metallurgy of Rare Earths. CRC Press. 484 pp.

Guyonnet, D., Planchon, M., Rollat, A., Escalon, V., Tuduri, J., Charles, N., Vaxelaire, S., Dubois, D., Fargier, H. (2015). Material flow analysis applied to rare earth elements in Europe. *J. Clean Prod. 107*, 215-28.

Guyonnet, D., Dubois, D., Escalon, V., Fargier, H., Rollat, A. Material flow analysis for identifying rare earth element recycling potentials in the EU-27. R. Cossu and R. Stegmann. SARDINIA-2013, Fourteenth International Waste Management and Landfill Symposium, Sep 2013, Cagliari,Italy. Cisa Publisher, 10 p., 2013. <hal-00805340>

GWEC and UTS (2016) Global Wind Energy Outlook 2016. October 2016. FWEC and UTS: Institute for Sustainable Futures.

GWEC (2015) Global Wind Report. Annual market update.

GWMG (2012) Company presentation from February 22, 2012.

Habib, K. and Wenzel, H. (2016) Review. Reviewing resource criticality assessment from a dynamic and technology specific perspective – using the case of direct-drive wind turbines. *J. of Clean. Prod. 112*, 3852-3863.

Habib, K. and Wenzel, H. 2014. Exploring rare earths supply constraints for the emerging clean energy technologies and the role of recycling. *J. of Cleaner Prod. 84*, 348-359.

Habib, K., Schibye, P.K., Vestbø, A.P., Dall, O., and Wenzel, H. (2014) Material flow Analysis of NdFeB Magnets for Denmark: A Comprehensive Waste Flow Sampling and Analysis Approach. *Environmental Science & Technology 48*, 12229-12237.

Hassan, A. (2001) Rohstoffeinsparung durch Kreislaufführung von verbrauchten Katalysatoren aus der chemischen Industrie", TU Berlin, UBA-Texte 21/01, Berlin März 2001.

Hatch, G. (2012) Chinese Rare-Earth Mining Quotas for 2012. Retrieved on November 07, 2016 from http://www.techmetalsresearch.com/2012/05/chinese-rare-earth-mining-quotas-for-2012/

Haxel, G.B., Hedrick, J.B. & Oris, G.J. (2002): US. Geological Survey: http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/

Haymarket Media Group (2015) Ten of the biggest and the best manufacturers. Wind Power. 30 June 2015. http://www.windpowermonthly.com/article/1352888/ten-biggest-best-manufacturers.

Hedrick, J.B. (2004) Rare Earths. U.S. Geological Survey Minerals Yearbook – 2004.

Henriques, C. (2012). Catalysis by Zeolites. EUCHEME 11/08/2012. Retrieved on February 8, 2017 from http://d7.unicam.it/eucheme/sites/d7.unicam.it.eucheme/files/files/doc/Prof.%20Carlos%20M.%20F.%20B.%20Henriques%201.pdf

Herraiz, E. (2015). Rare Earth Elements in Agriculture. EREAN project. Retrieved on February 10, 2017 from http://erean.eu/wordpress/rare-earth-elements-in-agriculture-2/

Hörnig, G., 2015. Recycling von NdFeB-Magneten aus elektrischen Antrieben – das Projekt MORE, pp. 219-232.

IMA (1995) Definition of a mineral. Source: http://www.ima-mineralogy.org

IMC [Innovation Metals Corp.] (2016a) Innovation Metals Corp. Announces Successful Testing of Proprietary Low-Cost Rapid Solvent Extraction Process. Released on February 18, 2016 by info@innovationmetals.com

IMC (2016b) IMC Announces the Successful Separation of High-Value Rare-Earth Elements from Mineração Serra Verde Concentrate Using the RapidSXTM Process. Retrieved from http://www.innovationmetals.com/news/imc-announces-the-successful-separation-of-high-value-rare-earth-elements-from-mineracao-serra-verde-concentrate-using-the-rapidsx-process/ on September 15, 2016.

Inframat Advanced Materials (2017). Retrieved on February 10, 2017 from http://www.advancedmaterials.us/

Innocenzi V., Ferella, F., De Michelis, I., and Vegliò, F. (2014) Treatment of fluid catalytic cracking spent catalysts to recover lanthanum and cerium: Comparison between selective precipitation and solvent extraction, *Journal of Industrial and Engineering Chemistry, 24* (25), pp. 92–97. DOI: 10.1016/j.jiec.2014.09.014

Investorintel (2016a) Lynas debt amendment to provide an estimated $70 million in interest savings. Retrieved on November 09, 2016 from http://investorintel.com/technology-metals-intel/lynas-corporation-reaches-agreements-major-lenders/

Investorintel (2016b) Lynas Corporation Limited: Amendments to Debt Facilities. Retrieved on November 07, 2016 from http://investorintel.com/technology-metals-news/lynas-corporation-limited-amendments-debt-facilities/

Izatt, S. R., McKenzie, J. S., Izatt, N. E., Bruening, R. L., Krakowiak, K. E. and Izatt, R. M. (2016). Molecular Recognition Technology: A Green Chemistry Process for Separation of Individual Rare Earth Metals. White Paper on Separation of Rare Earth Elements. February 20, 2016. Retrieved on September 19, 2016 from http://ucore.com/documents/WhitePaper_REE_Separations.pdf

Jha, A.R. (2014). Rare Earth Materials: Properties and Applications. CRC Press - Taylor & Francis Group. ISBN 978-1-4665-6402-2

Jiangxi Xinji Metals Co. Ltd (2017). Retrieved on February 8, 2017 from http://jxmetals.diytrade.com/

Jordens, A., Cheng, Y. P. and Waters, K. E. (2013) A review of the beneficiation of rare earth element bearing minerals. Minerals Engineering 41, pp. 97-114.

Kable Intelligence Limited (2014) Scarce supply - the world’s biggest rare earth metal producers. mining-technology.com. 3 July 2014. http://www.mining-technology.com/features/featurescarce-supply---the-worlds-biggest-rare-earth-metal-producers-4298126/.

Kingsnorth, D. J. (2016). Curtin University publication on the rare earth industry in 2016.

Kleijn, R., and van der Voet, E. (2010) Resource constraints in a hydrogen economy based on renewable energy sources: an exploration. Renew. Sustain. *Energy Rev. 14*, 2784-2795.

Kolektor Automotive Nanjing Co. Ltd.. (2016) Company website. Retrieved from http://www.kolektor.com/en/firms-in-group/kolektor-automotive-nanjing.

Largo Resources Ltd (2017). Retrieved on February 10, 2017 from http://www.largoresources.com/

Larsson, K. and Binnemans, K. (2015) Process for extraction and separation of rare earths by split-anion extraction with ionic liquids. Patent publication number WO2015106324 A1.

Leading Edge (2017) http://leadingedgematerials.com/download/norra-karr-information/ Norra Karr_PFS_(43-101)-2016.pdf

Leveque, A. (2014) Extraction and separation of rare earths. In: Proceedings of the EREAN Summer School, Leuven, Belgium.

Lim, Y.P., Yeo, W.H. (2015). Effect of Yttrium on the Microstructure of Gravity Die Cast A356 Alloy. *Proceedings of the World Congress on Mechanical, Chemical, and Material Engineering* (MCM 2015). Barcelona, Spain - July 20-21, 2015. Paper No. 123.

Lin, S.L., Huang, K.L., Wang, I-C., Chou, I-C., Kuo, Y.M., Hung, C.H., Lin, C. (2016). Characterization of spent nickel–metal hydride batteries and a preliminary economic evaluation of the recovery processes.

Journal of the Air & Waste Management Association, Volume 66, Issue 3, pp. 296-306. DOI: 10.1080/10962247.2015.1131206

Liu, H. (2016): Rare Earths: Shades of Grey. Can China Continue to fuel our global clean and smart future. China Water Risk 2016. June, 2016.

Lota, G., Sierczynska, A., Acznik, I. and Lota, K. (2014) AB_5-type hydrogen storage alloy modified with carbon used as anodic materials in borohydride fuel cells. *International Journal of Electrochemical Science* 9, 659-669.

Lusty, P.A.J. and Gunn, A.G. (2015) Challenges to global mineral resource security and options for future supply. In Jenkin, G.R.T., Lusty, P.A.J., MacDonald, I., Smith, M.P., Boyce, A.J. and Wilkinson, J.J.(eds) 2015. *Ore Deposits in an Evolving Earth*. Geological Society, London, *Special Publications, 393*, 265-276. Doi: dx.doi.org/10.1144/SP393.13

Lynas Annual Report (2013). The Path From Here (Annual Report).

Machacek, E. and Kalvig, P. (2016). Assessing advanced rare earth element-bearing deposits for industrial demand in the EU. *Resources Policy 49*, 186-203. DOI: 10.1016/j.resourpol.2016.05.004

Machacek, E., Richter, J.L., Habib, K. and Klossek, P. (2015). Recycling of rare earths from fluorescent lamps: Value analysis of closing-the-loop under demand and supply uncertainties. *Resources, Conservation & Recycling 104*, 76-93. DOI: 10.1016/j.resconrec.2015.09.005

Mackowski, S. (2016) Technology Metals Review – Is it really all about culture? Article published on October 28, 2016 on Investorintel.com. Retrievable from http://investorintel.com/technology-metals-intel/technology-metals-review-really-culture/

Magnesium Elektron North America (2016) Company profile. Retrieved from http://www.magnesium-elektron.com/about-us/business-units/magnesium-elektron-north-america

Magnetic Component Engineering (2017). Retrieved on February 10, 2017 from http://www.mceproducts.com/

MarketsandMarkets (2013). Permanent Magnet Market By Types (NdFeB, Ferrite, SmCo, AlNiCo), End User Industry (Consumer Electronics, General Industrial, Automotive, Medical Technology, Environment & Energy, Aerospace & Defense, Others) & Geography - Trends & Forecast To 2018. Report Code: AD 1270. Retrieved on February 10, 2017 from http://www.marketsandmarkets.com/PressReleases/permanent-magnet.asp

McKinsey & Company (2012). *Lighting the Way: Perspectives on the global lighting market* (No. 2nd ed.). Retrieved on February 8, 2017 from http://www.mckinsey.com

MEL Chemicals Inc. (2016) Company profile. Retrieved from http://www.zrchem.com/company-profile/mel_chemicals_inc.asp

Metall Rare Earth Ltd. (2017) Retrieved on February 8, 2017 from http://www.metall.com.cn/

Mintek (2013). Email correspondence regarding REE processing steps with informant.

MIT (2016). The future of strategic natural resources, 2016. Retrievable from http://web.mit.edu/12.000/www/m2016/finalwebsite/elements/ree.html

Mock, P., ed. (2015). European vehicle market statistics – Pocketbook 2015/16. Retrieved from the International Council on Clean Transportation [ICCT]: http://www.theicct.org/sites/default/files/publications/ICCT_EU-pocketbook_2015.pdf

Molycorp (2016a). Our facilities. Molycorp Silmet retrieved from http://www.molycorp.com/about-us/our-facilities/molycorp-silmet/ on March 01, 2016

Molycorp (2016b). About Molycorp. Retrieved from http://www.molycorp.com/about-us/about-molycorp on March 03, 2016

Moss, R. L., Tzimas, E., Willis, P., Arendorf, J., Espinoza, L. T. (2013) Critical Metals in the Path towards the Decarbonisation of the EU Energy Sector, Retrieved March 14, 2016 from www.Reeminerals.no/images/Marketing/Presseartikler/Critical_Metals_Decarbonisation_small.pdf

MSE Supplies (2017) Retrieved on February 8, 2017 from https://www.msesupplies.com/

Neorem Magnets Ningbo Co. Ltd. (2016) Company website. Retrieved from http://www.neorem.com.cn/introduction.htm

NERC (2016) What are Rare Earth Elements? Retrieved on September 19, 2016 from http://www.eurare.eu/RareEarthElements.html

Nikkei Meil (2016) Company website. Retrievable from http://www.zrchem.com/company-profile/nikkei_mel.asp

OECD (2010) Export restrictions on strategic raw materials and their impact on trade and global supply. In *The Economic Impact of Export Restrictions on Raw Materials.* OECD Trade Policy Studies. DOI: 10.1782/9789264096448-en

Öko Institut (2011) Study on Rare Earths and Their Recycling. Final Report for The Greens/EFA Group in the European Parliament.

Öko-Institut (2016). Assessment of the implementation of Directive 2000/53/EC on end-of life vehicles (the ELV Directive) with emphasis on the end-of life vehicles with unknown whereabouts. Retrievable from http://elv.whereabouts.Öko.info/

OICA (2015), Retrieved on February 8, 2017 from http://www.oica.net/category/production-statistics/2015-statistics/

OSRAM China Lighting Ltd. (2016) Company Website. Retrieved from http://www.osram.com.cn/osram_cn/

OSRAM Ltd. Yokohama, Japan (2016) Company website. Retrieved from http://www.osram.jp/osram_jp/

Osram Malaysia (2016) Company profile. Retrieved from http://www.osram.asia/osram_asia/

Otto, R. and Wojtalewicz-Kasprzak, A. (2012) February 2, 2012. Method for recovery of rare earths from fluorescent lamps. Retrieved from http://www.google.com/patents/US20120027651.

Panadyne Abrasives (2012-2016) All Products. Cerium Oxide 99.9% Purity <6um - 1 Lb. Retrieved on September 19, 2016 from http://www.panadyneabrasives.com/Cerium-Oxide-999-Purity-6um-1-Lb-Ce99O1Lb.htm

Philips Brazil (2016) Company profile. Retrieved from http://www.philips.com.br/

Philips India (2016) Company profile. Retrieved from http://www.philips.co.in/

Philips Malaysia (2016) Company profile. Retrieved from http://www.philips.com.my/

Philips North America (2016) Company profile. Retrieved from http://www.usa.philips.com/a-w/about-philips/company-profile/local-management/brent-shafer.html

Piekoszewski , J., Barlak, M., Werner, Z., Sartowska, B., Waliś, L., Starosta, W., Kierzek, J., Kowalska, E., Wilhelm, R.A., Pochrybniak, C., Woźnica, M. (2012). High-temperature oxidation resistance in yttrium implanted stainless steel. Nukleonika, Volume 57(4), pp. 473-476.

POLINARES (2012) Fact Sheet: Rare Earth Oxides (REO) (POLINARES working paper no. 7) European Commission, Brussels. Retrievable from http://www.polinares.eu

Polyflex Magnets Ltd (2016) Company website. Retrieved from http://www.22090.tradebig.com/

Rademaker, J.H., Kleijn, R. and Yang, Y. (2013). Recycling as a strategy against Rare Earth Element Criticality: A Systemic Evaluation of the Potential Yield of NdFeB Magnet Recycling. *Environmental Science & Technology 47*, 10129-10136.

Rare Earth Technology Alliance (2014) The Economic Benefits of the North American Rare Earths Industry. American Chemistry Council.

REEtec AS (2016) REEtec in brief. Retrievable from http://reetec.no/reetec-2/

RFC Ambrian (2016). Neodymium (Nd) & Praseodymium (Pr) Primer. The Alchemist, Issue 28, 1-5.

Rhodia (2015). Brochure. Diesel solutions. Imagine a world where mobility is in harmony with nature, p. 8 Retrieved on March 16, 2016 from file:///C:/Users/em/Downloads/Rhodia_TDS_ALUMINAS.pdf

Rhodia (2015b) Brochure on Luminostar™ Green A. Retrieved on March 16, 20156 from file:///C:/Users/em/Downloads/Rhodia_TDS_LUMINOSTAR%20GREEN%20RANGE.pdf

RM Research (2016) Greenland Minerals & Energy Limited; Shenghe placement…Kvanefjeld development moves a step closer. 29. Nov. 2016. Retrieved from http://www.ggg.gl/

Rollat, A., Guyonnet, D., Planchon, M., Tuduri, J. (2016). Prospective analysis of the flows of certain rare earths in Europe at the 2020 horizon. Waste Management, Volume 49, pp. 427-436. DOI: 10.1016/j.wasman.2016.01.011

Roskill Ltd (2016) Rare Earths: Global industry, markets and outlook to 2026. ISBN 9781910922187.

Roskill Ltd (2015) Rare Earths: Global industry, markets and outlook to 2020. ISBN 9780862146184.

Roskill Ltd (2011) Rare Earths & Yttrium: Market Outlook to 2015, Fourteenth Edition, 2011. ISBN 978 0 86214 565 1.

Rudnick, R.L. and Gao, S. 2003: Chemical composition of the Continental Crust. Elsevier, 1-64. ISBN 0-08-043751-6 SAE Off-Highway Engineering Online. http://www.sae.org/automotive/

Schott (2016a) Products and Applications: Our Portfolio at a Glance. Retrieved on March 18, 2016 from http://www.us.schott.com/english/products/index.html

Schott (2016b) Brochure 'Defense and Security. Designed to serve.' Retrieved on March 18, 2016 from http://www.us.schott.com/defense/english/download/schott_defense_us_2010_low.pdf

Schott (2016c) Glass products for the automotive sector. Retrieved on March 16, 2016 from http://www.us.schott.com/lightingimaging/english/automotive/datacom/index.html

Siemens Centre Beijing (2016) Company website. Retrieved from https://www.siemens.com/history/en/countries/China.htm

Siemens Wind Power and Renewables. Retrieved on November 07, 2016 from http://www.siemens.com/about/en/businesses/wind-power-and-renewables.htm

Sievers, H. and Tercero, L. (2012) European Dependence on and Concentration Tendencies of the Material Production (POLINARES working paper No 14), p. 11, retrievable from www.polinares.eu.

Solvay (2016a) Rare Earths and Metal Compounds. Retrieved on March 16, 2016 from http://www.solvay.com/en/markets-and-products/chemical-categories/index.html

Solvay (2016b) La Rochelle. Retrieved on March 16, 2016 from http://www.solvay.fr/fr/implantations/la-rochelle/index.html

Solvay (2015) Aluminas. Retrieved on March 16, 2016 from http://www.rhodia.com/en/markets_and_products/product_finder/product_details.tcm?productCode=90054471&productName=ALUMINAS

Sparky (2016a) Sparky Group. Products. Retrieved on March 18, 2016 from http://sparkygroup.com/products.html

Sparky (2016b) International Offices. Retrieved on March 18, 2016 from http://sparky.eu/distributors/worldwide-offices.html#

Speirs, J., Houari, Y., and Gross, R. (2013) Materials Availability: Comparison of Material Criticality Studies – Methodologies and Results. Working Paper III. UK Energy Research Center. Available at http://www.ukerc.ac.uk/publications/materials-availability-comparison-of-material-criticality-studies-methodologies-and-results-working-paper-iii.html

Sprecher, B., Kleijn, R., Kramer, G. J. (2014) Recycling Potential of Neodymium: The Case of Computer Hard Disk Drives. Environmental Science and Technology, 48, p. 9506–9513.

Sprecher, B., Xiao, Y., Walton, A., Speight, J., Harris, R., Kleijn, R., Visser, G., Kramer, G.J. (2014) Life Cycle Inventory of the Production of Rare Earths and the Subsequent Production of NdFeB Rare Earth Permanent Magnets. *Environmental Science & Technology 48* (7), 3951-3958.

Spurk, P. (2016) Presentation in the session 'Batteries for Mobility. Current status and future needs' by Umicore at the EIT expert forum on Materials and Technologies for Future Mobility, Darmstadt, 9th December 2016.

SusChem (2015a) Strategic Innovation and Research Agenda.

SusChem (2015b) SusChem SIRA published: 2015 Stakeholder event registration opens soon. Suschem. [Online] 16 March 2015. Retrieved from http://suschem.blogspot.it/2015/03/suschem-sira-published-2015-stakeholder.html

Tanbreez (2017) Distribution of Rare Earths. Retrieved from http://tanbreez.com/en/project-overview/distribution-of-rare-earths/?page=1

Tasman Metals (2015) Prefeasibility Study. Retrieved on September 23, 2016 from http://www.sedar.com/CheckCode.do

TMR (2015) Advanced Rare Earth projects index, http://www.techmetalsresearch.com/metrics-indices/tmr-advanced-rare-earth-projects-index/

Terazono, A., Oguchi, M., Iino, S. and Mogi, S. (2015) Battery collection in municipal waste management in Japan. Challenges for hazardous control and safety. *Waste Management 39*, 246-257.

Terra Pacific USA Inc. (2014), Retrieved on February 8, 2017 from http://terrapacificusa.com/wp-content/uploads/2014/08/Comparison-Chart-LED-vs-CFL-vs-Incandescent-Bulbs.pdf

The Guardian (2015) China scraps quotas on rare earths after WTO complaint. Retrieved on November 07, 2016 from https://www.theguardian.com/world/2015/jan/05/china-scraps-quotas-rare-earth-wto-complaint

Treibacher (2016). Rare earths and chemicals. Retrieved from http://www.treibacher.com/en/business-units/rare-earths-and-chemicals.html on March 01, 2016.

Treibacher (2013) Treibacher Industrie AG aquires Leuchtstoffwerk Breitungen GmbH. Retrieved on November 07, 2016 from http://www.treibacher.com/en/company/news/treibacher-industrie-ag-acquires-leuchtstoffwerk-breitungen-gmbh.html

Trigueiro F.E., Falabella Sousa-Aguiar, E., Zotin, F.M.Z. (2013). The role of rare earth elements in zeolites and cracking catalysts. Catalysis Today, Volumes 218–219, pp. 115–122. DOI: 10.1016/j.cattod.2013.06.021

Tse, P-K. (2011) China's Rare-Earth Industry. Open-File Report 2011-1042. US Department of the Interior and USGS. Reston, Virginia: USGS.

UBI Research (2016) Bae, O. (ETnews, 01/12/2016). Competitions between Rigid OLED and LTPS LCD to Start in Earnest in Markets for Middle-Grade Smartphones. Source: UBI Research. http://english.etnews.com/20161201200001

Umicore (2016) Battery Recycling. Retrieved from http://www.umicore.com/en/bu/umicore-battery-recycling

Umicore (2011) Umicore and Rhodia develop unique rare earth recycling process for rechargeable batteries. Retrieved from http://www.umicore.com/storage/migrate/20110616REErecyclingEN.pdf on March 14, 2016.

USGS (2016) Rare earth mineral fact sheet. Retrievable from http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/2016

Vacuumschmelze GmbH & Co. KG (2016). Firm data accessible from http://www.vacuumschmelze.com/

VAC Magnetic Japan K.K. (2016) Company website. Retrieved from http://www.vacuumschmelze.com/en/contact/international-contact/asia.html

Vestas (2016) Company website. Retrieved from https://www.vestas.com/en/media/~/media/aa393fd6e6854f9cae7a82751b6620a0.ashx

Visentin, M., Baraldi, S. (2011). Rare Earths in the Ceramic Industry. Presentation at the *6th Workshop of T.A.C.E.C. Programme*. http://www.federchimica.it/docs/default-source/6-ws-tacec/Marco_Visentin_e_Sabina_Baraldi.pdf?sfvrsn=0

Walter, P. (2011). Rhodia recovers rare earths. Chemistry & Industry, Issue 3. 07/07/2011. http://www.soci.org/chemistry-and-industry/cni-data/2011/3/rhodia-recovers-rare-earths

Wilburn, D.R. (2012) *Byproduct Metals and Rare-Earth Elements Used in the Production of Light-Emitting Diodes – Overview of Principal Sources of Supply and Material Requirements for Selected Markets.* U.S. Geological Survey Scientific Investigations Report 2012–5215, 15 p., at http://pubs.usgs.gov/sir/2012/5215/.

Wall, F. (2014) Rare earth elements. In: Gus Gunn (edit): Critical Metals Handbook, Wiley, BGS.

Weng, Z., Jowitt, S.M., Mudd, G.M., and Haque, N. (2015) A Detailed Assessment of Global Rare Earth Element Resources: Opportunities and Challenges. *Economic Geology 110*, pp. 1925-1952.

Wolfram, P., German, J., Mock, P., Tietge, U. (2016) Deployment of passenger car technology in Europe and the United States. Working Paper 2016-19. The International Council on Clean Transportation [ICCT]. Retrievable from http://www.theicct.org/sites/default/files/publications/EU%20US%20PV%20Tech_working-paper_ICCT_27102016.pdf

WTO (2015) China – Rare Earths (DS431, 432, 433). One page summary retrieved on November 07, 2016 from www.wto.org/english/tratop_e/dispu_e/cases_e/1pagesum_e/ds431sum_e.pdf

Wu, Y., Yin, X., Zhang, Q., Wang, W., & Mu, X. (2014). Review: The recycling of rare earths from waste tricolor phosphors in fluorescent lamps: A review of processes and technologies. *Resources, Conservation & Recycling, 88*, 21–31. http://doi.org/10.1016/j.resconrec.2014.04.007

Yes2Renewables.org (2016) Renewable technologies, wind farms. Rare earth magnets: not all new turbines are using them. Retrieved on November 22, 1016 from https://yes2renewables.org/2012/03/06/rare-earth-magnets-not-all-new-turbines-are-using-them/

Zhang, J., Zhao, B., and Schreiner, B. (2016) *Separation Hydrometallurgy of Rare Earth Elements.* Switzerland: Springer International Publishing. ISBN 978-3-319-28233-6.

Zhang, L., Guo, Q., Zhang, J., Huang, Y. and Xiong, T. (2015) Did China's rare earth export policies work? – Empirical evidence from USA and Japan. *Resources Policy 43*, 82-90.

Zhang, Q., Su, G., Li, A., Liu, K. (2011). Electrochemical performances of AB_5-type hydrogen storage alloy modified with Co3O4. *Transactions of Nonferrous Metals Society of China*, Volume 21, pp. 1428-1434. DOI: 10.1016/S1003-6326(11)60877-7

Zhao Z. Qui, Z., Yang, J., Lu, S., Cao, L., Zhang, W. Xu, Y. (2017) Recovery of rare earth elements from spent fluid catalytic cracking catalysts using leaching and solvent extraction techniques. *Hydrometallurgy, 167*, pp. 183–188. DOI: 10.1016/j.hydromet.2016.11.013

Žilinska, N., Zālīte, I., KrastIņš, J. (2011). Investigation of Production of Fine-grained SiAlON Ceramics from Nanopowders. *Material Science (Medžiagotyra)*, Volume 18, Issue 3, pp. 275-279. DOI: 10.5755/j01.ms.18.3.2439

Zumtobel (2016) About Zumtobel. Retrieved on December 29, 2016 from http://www.zumtobel.com/com-en/company.html#1628

Appendix I

Table A.1. List of consulted documents published by different European organizations linked to potential REE application fields

Technological sector	European Organization	Reference document used for consultation	Version of the document	Relationship with REE markets
Communication and Electricity Networks	eMobility - Mobile and Wireless Communications TP	Strategic Applications Research Agenda	July 2010	Low
	SmartGrids - TP for Electricity Networks of the Future	Strategic Deployment Document	April 2010	Low
		Strategic Research Agenda	March 2012	Medium
Construction and Buildings	ECTP - Construction TP	Strategic Research Agenda	December 2005	Low
	EeB PPP - PPP on Energy-efficient Buildings	Roadmap	2010	Low
Electronics	ARTEMIS - Industrial Association on Embedded & Cyber-Physical Systems	Strategic Research Agenda	March 2016	Low
	ENIAC - Nanoelectronics Initiative Advisory Council	Strategic Research Agenda	November 2007	Low
		Multi-Annual Strategic Plan	November 2010	Medium
	EPoSS - TP on Smart Systems Integration	Strategic Research Agenda	September 2013	Medium
	ARTEMIS, ENIAC and EPoSS - Associations representing ICT Components and Systems Industries	High Level Strategic Research and Innovation Agenda	April 2012	Low
	Photonics21 - TP on Photonics	Strategic Research Agenda	January 2010	Medium
	SPARC - PPP for Robotics	Strategic Research Agenda	2014	Low
Industry and Energy Production	EBTP - TP on Biofuels	Strategic Research Agenda	2010	Low
	ESTEP - TP on Steel	Strategic Research Agenda	May 2013	Low
	ETPIS - TP on Industrial Safety	Strategic Research Agenda	January 2006	Low
	SNETP - TP on Sustainable Nuclear Energy	Strategic Research and Innovation Agenda	February 2013	Low

Technological sector	European Organization	Reference document used for consultation	Version of the document	Relationship with REE markets
	SusChem - TP for Sustainable Chemistry	Strategic Innovation and Research Agenda	March 2015	High
	ZEP - TP for Zero Emission Fossil Fuel Power Plants	Strategic Research Agenda	November 2006	Low
Materials and Manufacturing	EuMaT - TP for Advanced Engineering Materials and Technologies	Roadmap	June 2006	Low
		Strategic Research Agenda	2012	
	EURATEX - Apparel and Textile Confederation	Strategic Research Agenda	June 2006	Low
	Manufuture - TP on Manufacturing	Strategic Research Agenda	July 2006	Low
		Presentation on “Next Generation Manufacturing - Manufacturing 2030”	2011	Low
Renewable Sources	ESTTP - TP on Solar Thermal	Strategic Research Agenda	2008	Low
	EUPVTP - TP on Photovoltaic	Strategic Research Agenda	September 2011	Medium
	PV-TRAC - PV Technology Research Advisory Council	Vision report.	2005	Low
	RHC - TP on Renewable Heating and Cooling	Strategic Research Agenda	2013	Low
	TPWind - TP on Wind Energy	Vision document	2006	Medium
		Document titled “The Way Forward”	March 2009	Low
		Strategic Research Agenda	March 2014	High
Resources Supply Chains	ERECON - Rare Earths Competency Network	Report on EU Rare Earths Supply Chain	2014	High
	ETP SMR - TP on Sustainable Mineral Resources	Document “WP1 - Developing new innovative technologies and solutions for sustainable raw materials supply”	January 2012	High

Technological sector	European Organization	Reference document used for consultation	Version of the document	Relationship with REE markets
		eMINEnt - European Minerals Network: Document "WP3 - Improving Europe's raw materials regulatory framework, knowledge and infrastructure base"	July 2011	High
		Document "Framework of Action for the Development of the Mineral Resources Sector in ACP Countries"	October 2011	Medium
		Policy Document	November 2011	Medium
		Strategic Research and Innovation Agenda	2013	High
	WssTP - TP for Water Supply and Sanitation	Strategic Research Agenda	2010	Low
Transportation and Space	ACARE - Advisory Council for Aviation Research and Innovation	Strategic Research and Innovation Agenda	September 2012	Low
	ERRAC - Rail Research Advisory Council	Strategic Rail Research and Innovation Agenda	October 2014	Low
	ERTRAC - Road Transport Research Advisory Council	"Scenario 2030" and Executive Summary	October 2009	Low
		Strategic Research Agenda - Technical Document	October 2010	Medium
		Strategic Research Agenda - Executive Summary	October 2010	Low
		Research and Innovation Roadmaps	September 2011	High
		Roadmap for Electrification and Road Transport	June 2012	High
	ESTP - TP on Space	Strategic Research Agenda	July 2006	Low
	WATERBORNE - TP on Waterborne Transport and Operations	Strategic Research Agenda	May 2011	Low

Appendix II – Overview of the European REE occurrences and deposits

Extract from the IKMS: http://eurare.brgm-rec.fr/ (Feb. 2017)

					REE Resource/reserve classification				
Country	**Deposit name**	**Develop. Status**	**Main REE minerals**	**Main commodity type**	**Est. Grade (TREO%)**	**Est. Ton. Ore (Mt)**	**Est. TREO (t)**	**Ressource category type**	**Mine status**
BA	Vlasenica	occurrence	goyazite-Nd						Abandoned
BE	Stavelot & Rocroi massifs	occurrence	monazite						null
CZ	Trebic	occurrence	allanite, monazite, aeschynite, euxenite						null
DE	Kaiserstuhl	occurrence	apatite						null
DE	Storkwitz	prospect	parisite, rontgenite, apatite			4		indicated and Inferred	Green field
ES	Fuerteventura	occurrence	Britholite Allanite Pyrochlore Monazite						Not operating
ES	Galineiro	occurrence	Allanite Bastnaesite Parisaite Monazite Zircon Xenotime						Not operating
ES	Mulas	prospect	Monazite			<12			Brown-field
ES	Ramblas de las Granatillas	deposit	Monazite Xenotime						Not operating
FI	Jokikangas	occurrence	Fergusonite-(Y) Allanite Columbite	Nb					null
FI	Karhukoski	occurrence	monazite	Th					null
FI	Katajakangas	occurrence	Fergusonite-(Y) Allanite Columbite	Nb	2,4	0,46	12.400		null
FI	Kontioaho	occurrence	Fergusonite-(Y) Allanite Columbite	Nb	0,45	7,69	45.000		null
FI	Korsnas	deposit	Apatite Monazite	Pb	0,85	0,9	7.650		abandoned
FI	Kovela	occurrence	monazite	REE	1	0,1		Inferred	null
FI	Kymi	occurrence	Monazite-(Ce), allanite-(Ce), bastnäsite-(Ce), xenotime-(Y)	Be					null
FI	Sokli Kaulus	occurrence	Ancylite-(Ce), bastnäsite, allanite	P					Greenfield
FR	Le Gras	deposit							
FR	Plouguerneau	deposit							
FR	Sainte Tr├®phine	deposit							
FR	Coz Porz	deposit							
FR	Evisa	deposit							

FR	Capette	deposit							
FR	Ch├óteauneuf-du-Faou	occurrence							
FR	Corlay	occurrence							
FR	Ch├óteaubriant	occurrence							
FR	Craon	occurrence							
GB	Central Wales	occurrence	monazite						null
GB	Loch Loyal	occurrence	allanite, apatite						null
GB	Mourne Mountains	occurrence	allanite, fergusonite-(Y), gadinolite-(Y), monazite-(Ce)						null
GL	Attu	occurrence	Allanite						No activity
GL	Gardiner complex	occurrence	Apatite Perovskite Titanite						Null
GL	Grønnedal-Ika Jernhatten	occurrence	Bastnaesite						null
GL	Ilimaussaq, Kvanefjeld	deposit	Steenstrupine	REE	1,21	143	########	Measured	Brown field
GL	Ilimaussaq, Sørensen	deposit	Steenstrupine	REE	1,11	242	########	Inferred	Brown field
GL	Ilimaussaq, Zone 3	deposit	Steenstrupine	REE	1,16	95	########	Inferred	Brown field
GL	Kangerdlugssuaq Alkaline Intrusion	occurrence	Allanite Astrophyllite Catapleiite Chevkinite Eudialyte Lavenite Perovskite Titanit zircon						Brown field
GL	Kringlerne	deposit	Catapleiite Eudialyte Nacreniobsite	REE	0,7	4700	########	Inferred	Brown field
GL	Kap Simpson Bjørnedal	occurrence	Bastnaesite Columbite Euxenite Fergusonite Monazite						Null
GL	Milne Land	occurrence	Anatase Monazite Xenotime Zircon						No activity
GL	Motzfeldt centre - Aries Prospect	deposit	Bastnaesite Columbite Eudialyte Hydropyrochlore	Nb		340		Inferred	No activity
GL	Motzfeldt, Motzfeldt South East/Drysdale	deposit	Bastnaesite Columbite Hydropyrochlore	Nb					No activity
GL	Motzfeldt, Storeelv East/Voskop	deposit	Bastnaesite Columbite Hydropyrochlore	Nb					No activity
GL	Nassuttooq	occurrence	Monazite						No activity
GL	Nassuttutatasia	occurrence							No activity
GL	Niaqonakavsak	occurrence	Allanite Bastnaesite Monazite						No activity
GL	Nordre Isortoq	occurrence							No activity

GL	Qaqarssuk	deposit	Ancylite Burnakite Huanghoite Qaqarssukite	REE					No activity
GL	Sarfartoq	deposit	Pyrochlore	REE	1,51	14	213.000	Indicated	No activity
GL	Tikiusaaq Carbonatite complex	deposit	Monazite	REE					No activity
GL	Werner Bjerge Alkali Granite subcomplex	occurrence	Monazite Perovskite Rutile Zircon						Null
GR	Steni Arahovis - Prossorema	occurrence	Rhabdophane, florencite, churchite, xenotime, zircon, anatase, bastnäsite		0,38				
GR	Nafpactos	occurrence	Anatase, zircon	Al	0,06				
GR	Smerna	occurrence	Anatase, zircon	Al	0,02				
GR	Pylos	occurrence	Anatase, zircon	Al	0,02				
GR	Atalandi	occurrence	Anatase	Al	0,06				
GR	Amorgos	occurrence	Anatase,rutile	Al	0,06				
GR	Glifa	occurrence	Anatase	Al	0,02				
GR	Panormos - Skopelos island	occurrence	Alunite,rutile	Al	0,04				
GR	Petralona	occurrence	Anatase	Al	0,05				
GR	Aghios Ioannis (Nissi)	occurrence	Bastnaesite	Ni	0,73				
GR	Lokrida (Marmeiko)	occurrence	Bastnaesite, monazite	Ni	0,71				
GR	Nea Peramos	deposit	Monazite, allanite, titanite, uraninite, zircon, apatite		0,83				
GR	Sarakiniko	deposit	Monazite, allanite, titanite,uraninite, zircon, apatite		0,82				
GR	Esochi	occurrence	Monazite, xenotime, allanite,apatite, zircon		0,02				
GR	Vrondero	occurrence	Bastnaesite, monazite	Al,Ni	0,12				
GR	Fanos	occurrence	Monazite, allanite, parisite, apatite, thorium phosphate, zircon		0,02				
GR	Samotrace	occurrence	Monazite,allanite,apatite, titanite, zircon		0,02				
HU	Nagyharsány	occurrence	Monazite						unknown
HU	Sopron Hills	occurrence	Monazite, florencite, xenotime						null
HU	Úrkút	occurrence	bastnäsite						Green field
IE	Beara-Allahies	occurrence							historic
IT	Nettuno	occurrence	Monazite, chevkinite, perrierite						null
IT	Olmedo	occurrence	bastnäsite						Operating

IT	San Giovanni Rotondo	occurrence	bastnäsite, monazite						abandoned
ME	Niksic	occurrence	hydroxyl-bastnäsite-(Nd), hydroxyl-bastnäsite-(La)						Operating
NO	Biggejavri	deposit	Davidite Loveringite Xenotime Monazite Synchysite Parisite	Sc	0,2	0,05	100	Inferred	null
NO	Bjortjørn	occurrence	Calciosamarskite Allanite Monazite Xenotime Yttrotantalite	REE					historic
NO	Fen	deposit	Fluorcalciopyrochlore Monazite Bastnaesite Parisite Synchysite Fluorapatite	REE	1,08	84	907.200	Inferred	historic
NO	Gloserheia	occurrence	Monazite Xenotime Allanite Fluorapatite Zircon Euxenite Uraninite Thorite	REE	0,002	4	80	Inferred	historic
NO	Høgtuva	deposit	Zircon Gadolinite Allanite Monazite Fergusonite	Be	0,15	0,35	525	Inferred	null
NO	Kodal	deposit	Fluorapatite	P	0,12	49	58.680	Inferred	brownfield
NO	Langesundsfjord	occurrence	Eudialite Wohlerite Rosenbuschite Catapleiite Pyrochlore	REE					null
NO	Misværdal	deposit	Fluorapatite	P	0,07	30	21.000	Inferred	null
NO	Sæteråsen	deposit	Euxenite Fluorcalciopyrochlore Fergusonite Fluorapatite	REE	0,53	8	42.400	Inferred	null
PO	Tajno	occurrence	kukharenkoite series						null
PT	Vale de Cavalos	occurrence	Monazite Zircon			<2.4			Not operating
RO	Ditrau	prospect	Allanite Bastnaesite Synchysite Monazite Xenotime						Brown-field
RO	Glogova-Clesnesti	prospect	Monazite						Brown-field
RS	Plavna	prospect	monazite						null
SE	Kiruna	Deposit	Fluorapatite, monazite-(Ce)	Fe	0.99	2000			operating
SE	Leveäniemi	Deposit	Fluorapatite	Fe	0.50	390			operating
SE	Malmberget	Deposit	Fluorapatite	Fe	0.95	840			operating

SE	Tåresåive Mo-REE	occurrence	Monazite-(Ce), allanite-(Ce), xenotime-(Y), REE-fluorocarbonates	Mo					abandoned
SE	Flakaberget	occurrence	Xenotime-(Y), polycrase-(Y), fergusonite-(Y), allanite sensu lato	Quartz and feldspar					null
SE	Reunavaare	occurrence	Thalénite-(Y) - yttrialite-(Y), gadolinite-(Y), fergusonite-(Y)	Quartz and feldspar					abandoned
SE	Kalix (Storö)	occurrence							null
SE	Gräddmanshällan	occurrence							null
SE	Tåsjö	deposit	Fluorapatite	U, REE	0.15-0.27	75-150		Inferred	Greenfield
SE	Kvarnån	occurrence	Fluorapatite	U, REE					Greenfield
SE	Åkersjön	occurrence	Bastnäsite-(Ce), REE-carbonate, pyrochlore group mineral						null
SE	Näverån	occurrence	Monazite-(Ce), xenotime-(Y), allanite	REE	0.07-0.8				Greenfield
SE	Båräng (Alnö)	occurrence	Fersmite	Sövite					abandoned
SE	Smedsgården (Alnö)	occurrence	Fersmite	Sövite					abandoned
SE	Finnbo pegmatitbrott	occurrence	Gadolinite-(Y), allanite	Quartz and feldspar					abandoned
SE	Kårarvet	occurrence	Gadolinite-(Y), allanite	Quartz and feldspar					abandoned
SE	Rista	occurrence	Gadolinite-(Y)? Allanite-(Ce)?	Quartz and feldspar					abandoned
SE	Idkerberget	deposit	Fluorapatite	Fe		11		inferred	abandoned
SE	Holmtjärnsgruvan (Flintgruvan)	occurrence	Yttrialite-(Y), keiviite-(Y)	Quartz and feldspar					abandoned
SE	Bredåsen (Finnsbo)	occurrence	Allanite-(Ce), REE-fluorocarbonates, gadolinite-(Y), fluorite,	Fe, Cu, Au					abandoned
SE	Bäckbergsgruvan	occurrence	Allanite-(Ce)	Fe					abandoned
SE	Blötberget	deposit	Fluorapatite, allanite-(Ce), monazite-(Ce), xenotime-(Y)	Fe		16		inferred	abandoned
SE	Östanmossgruvan	occurrence	Dollaseite-(Ce)	Fe					abandoned
SE	Grängesberg	deposit	Fluorapatite, monazite-(Ce), xenotime-(Y), allanite-(Ce), REE-fluorocarbonates	Fe		280		inferred	abandoned
SE	Knutsbo Haggruvan	occurrence	Allanite sensu lato	Fe					abandoned
SE	Gruvhagen	occurrence	Allanite sensu lato	Fe					abandoned
SE	Johannagruvan	occurrence	Dollaseite-(Ce), cerite-(Ce)	Fe					abandoned

SE	Södra Hackspiksgruvan	occurrence	Bastnäsite-(Ce), törnebohmite-(Ce), alanite sensu lato	Fe					abandoned
SE	Malmkärragruvan	occurrence	Västmanlandite-(Ce), fluorbritholite-(Ce), gadolinite-(Y), gadolinite-(Nd)	Fe					abandoned
SE	Aspgruvan	occurrence		Fe					abandoned
SE	Plåtäng	occurrence	Allanite sensu lato	Fe					abandoned
SE	Morens Östergruva	occurrence		Fe					abandoned
SE	Stora Långgruvan	occurrence	Allanite sensu lato	Fe					abandoned
SE	Stora Högforsgruvan	occurrence	Cerite-(Ce), allanite-(Ce), västmanlandite-(Ce)-analogue	Fe					abandoned
SE	Stålklockan	occurrence	Fluorbritholite-(Ce), dollaseite-(Ce)	Fe					abandoned
SE	Östra Älgtorpsgruvan	occurrence		Fe					abandoned
SE	Storgruvan 4	occurrence	Allanite-(Ce), Cerite-(Ce)	Fe					abandoned
SE	Bastnäs (Cerit- and Sankt Göransgruvan)	Deposit	Cerite-(Ce), ferriallanite-(Ce), bastnäsite-(Ce), törnebohmite-(Ce)	REE					abandoned
SE	Lerklockan	occurrence	Allanite-(Ce), törnebohmite-(Ce)	Fe					abandoned
SE	Persgruvan	occurrence		Fe					abandoned
SE	Myrbacksfältet	occurrence	Allanite sensu lato	Fe					abandoned
SE	Timansberg	occurrence		Fe					abandoned
SE	Blankagruvan	occurrence		Fe					abandoned
SE	Östra Gyttorpsgruvan	occurrence	Allanite-(Ce), hingganite-gadolinite-(Y)	Fe					abandoned
SE	Rödbergsgruvan	occurrence	Cerite-(Ce), ferriallanite-(Ce)	Fe					abandoned
SE	Ytterby	occurrence	Gadolinite-(Y), fergusonite-(Y), yttrotantalite-ishikawaite-(Y), allanite-(Y)	Quartz;feldspar					abandoned
SE	Dalkarlsberg (Vretgruvan)	occurrence		Fe					abandoned
SE	Sveafallen	occurrence	Monazite-(Ce)	Fe					abandoned
SE	Bojgruvan	occurrence	Monazite-(Ce), xenotime-(Y)	Fe					abandoned
SE	Tybble	occurrence	Fluorapatite, Allanite-(Ce), monazite-(Ce)	Fe					abandoned
SE	Gullebo	occurrence	REE-fluorocarbonate?	Fe					abandoned
SE	Norra Kärr	occurrence	Eudialyte		0,59	31			Greenfield

SE	Hylleled	occurrence	Xenotime-(Y), monazite-(Ce)	Fe					abandoned
SE	Djupedalsgruvan	occurrence	Fluorapatite, monazite-(Ce), xenotime-(Y), allanite-(Ce)	Fe					abandoned
SE	Bersummen	occurrence	Fluorapatite, monazite-(Ce), xenotime-(Y)						abandoned
SE	Olserum Fe-mines	occurrence	Fluorapatite, monazite-(Ce), xenotime-(Y), allanite-(Ce)	Fe					abandoned
SE	Olserum deposit	deposit	Fluorapatite, monazite-(Ce), xenotime-(Y), allanite-(Ce)	REE	0,6	8			Greenfield
SE	Källhagen (Brotorp)	occurrence	Allanite sensu lato	Fe					abandoned
SE	Trostad	occurrence	Monazite-(Ce)	REE, U					abandoned
SE	Klockartorpet	occurrence		REE, U					abandoned
SE	Gränsö	occurrence	Monazite-(Ce), xenotime-(Y)	Fe					abandoned
SE	Balltorp (RA-granite)	occurrence	Allanite sensu lato, monazite-(Ce), Chevkinite-(Ce)?	REE, Be, Zr, F	0.65-0.88				Greenfield
SK	Bacúch	occurrence	monazite-(Ce), monazite-(Nd), xenotime-(Y), hingganite-(Y)						historic
SK	Čučma	occurrence	Xenotime-(Y), monazite-(Ce) to monazite-(Nd), fluorapatite						null
SK	Rejdová Prospect area	occurrence	unknown						Green field
SK	Slovinky	occurrence	unknown						green field
TR	Aksu Diamas	deposit	Allanite, chevkinite		0,1	494	344.812	Inferred	Green field
TR	Kizilcaoren	deposit	bastnäsite, brockite, florencite, monazite	Ba, F	0,3	4	1.200	Poorly Estimated	Green field
TR	Mortas & Dogankuzu	occurrence	cerianite						Operating
TR	Sofular	occurrence	britholite			0,001		Poorly Estimated	
XK	Grebnik	occurrence	bastnäsite, synchysite (Nd)						Abandoned