

Research and development for the Rare Earth Element supply chain in Europe



Summary

This brochure is a product of the EURARE project, which was funded by the European Commission's Seventh Framework Programme to provide the basis upon which Europe could develop a secure supply of the rare earth elements (REE). The project ran from 2013–2017. This brochure provides a summary of European REE deposits, and describes the progress that the EURARE project has made in both improving the understanding of these deposits and processing the ores. The European value chain is also summarised, including uses and trade of the REE, and further reading suggestions are included. Further information about the project is available on the project website www.eurare.org

Introduction

The rare earth elements (REE) are important constituents of a range of modern technologies, including electric and conventional vehicles, communication technologies, and production and storage of renewable energy. The growing demand for REE is, at the time of writing, driven particularly by their use in neodymium-iron-boron magnets, which are extensively used in electric vehicles and wind turbines (Goodenough et al., 2017). Since the 1990s, China has dominated global REE production, and continues to produce approximately 95% of the world's REE (EC, 2017). Worldwide interest in the rare earths as a commodity intensified in 2010, when China introduced export quotas. This resulted in significant increases in REE prices, and led to an exploration boom (Paulick and Machacek, 2017). REE prices fell again from 2012, but the importance of an improved understanding of the REE supply chain had been demonstrated, paving the way for the development of research projects such as EURARE.

The EURARE project

The EURARE project began on the 1st of January 2013, and ran for five years (Balomenos et al., 2017). Its main goal was to set the basis for the development of a sustainable European REE industry. It aimed to safeguard the uninterrupted supply of REE raw materials and products crucial for sectors of the EU economy (including automotive, electronics, machinery and chemicals) in a sustainable, economically viable and environmentally-friendly way. The EURARE project was co-funded by the European Commission (EC) under the 2012 Cooperation Work Programme for Nanotechnologies, Materials and new Production Technologies and specifically the raw materials topic NMP.2012.4.1-1 'New environmentally friendly approaches in minerals processing'. The project brought together researchers from geological surveys, academia, consultancies and industry (Figure 1) to deliver a holistic approach to the European rare earth supply chain. This brochure summarises the different aspects of the REE supply chain, with a focus on Europe and the research carried out within the EURARE project.

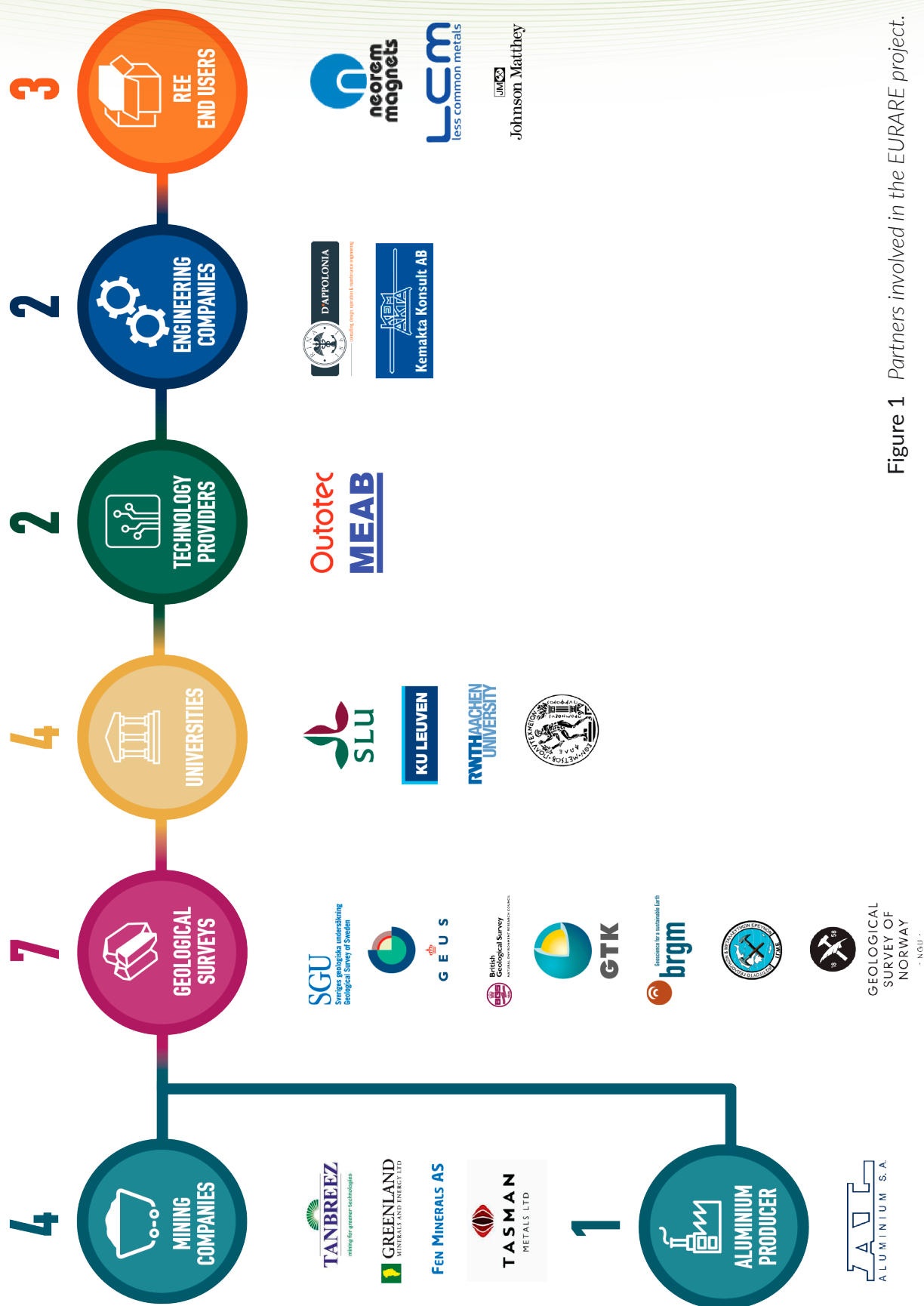


Figure 1 Partners involved in the EURARE project.

The REE: definitions

The REE are a group of 17 chemically similar, metallic elements that include the 15 lanthanides (lanthanum to lutetium), plus scandium and yttrium. The individual REE are difficult to separate, and so it was not until the 20th century that all of the REE were identified. This difficulty in separating the REE led to the misleading name 'rare earth'; the REE are actually relatively abundant in the Earth's crust, with a total concentration of about 180 ppm in bulk continental crust (Rudnick and Gao, 2003).

The REE are typically divided into two groups based on their atomic weights: (1) the light rare earth elements (LREE), which are here considered to include the elements lanthanum to samarium, and (2) the heavy rare earth elements (HREE), which here include the elements europium to lutetium, plus yttrium. The elements from samarium to terbium are sometimes described as the middle rare earth elements (MREE). The REE are mainly trivalent (Ln^{3+}), although cerium and europium can occur naturally in different oxidation states. Their trivalent electron configuration explains why the REE readily substitute for one another in mineral structures, and also gives them some of their more unusual magnetic and optical properties.

Name	Symbol	Atomic number	Atomic weight	Melting temperature (°C)	Crustal abundance (ppm)
Scandium	Sc	21	44.95	1541	14
Yttrium	Y	39	88.90	1522	21
Lanthanum	La	57	138.90	918	31
Cerium	Ce	58	140.11	798	63
Praseodymium	Pr	59	140.90	931	7.1
Neodymium	Nd	60	144.24	1021	27
Promethium	Pm	61	145.00	1042	–
Samarium	Sm	62	150.36	1074	4.7
Europium	Eu	63	151.96	822	1
Gadolinium	Gd	64	157.25	1313	4
Terbium	Tb	65	158.92	1356	0.7
Dysprosium	Dy	66	162.50	1412	3.9
Holmium	Ho	67	164.93	1474	0.83
Erbium	Er	68	167.26	1529	2.3
Thulium	Tm	69	168.93	1545	0.3
Ytterbium	Yb	70	173.04	819	2
Lutetium	Lu	71	174.97	1663	0.31

Table 1 Selected REE properties and abundance in the continental crust.

REE mineralogy

The REE do not occur in nature as native metallic elements, but as constituents in a wide range of mineral types, including phosphates (e.g. monazite and xenotime), carbonates (bastnäsite and synchysite), silicates (e.g. allanite and steenstrupine) and halides (e.g. fluocerite). They are most commonly found as minor or trace elements in rock-forming minerals, in which they substitute for the major ions, but there are also many minerals in which the REE are essential (Table 2). Rare earth-bearing minerals typically contain multiple REE in varying concentrations, but minerals tend to be biased towards either the LREE or HREE. Globally, the majority of REE resources are associated with just three minerals, bastnäsite, monazite and xenotime. However, in a European context, other complex rare earth-bearing minerals such as eudialyte and steenstrupine are important (Table 2), and the EURARE project has carried out extensive work on the beneficiation and processing of these minerals.



Figure 2 Image of alkaline igneous rock containing eudialyte (red mineral) from Kringlerne, Greenland. ©NERC.

REE-bearing mineral or mineral group*	Generalised formula	Typical REO (wt. %)	Typical deposit types	EU examples
Aeschynite*	REE(Ti,Nb) ₂ (O,OH) ₆	36	H	Galiñero, Spain; Ditrâu, Romania
Allanite*	(REE,Ca) ₂ (Al,Fe) ₃ (SiO ₄) ₃ (Si ₂ O ₇)O(OH)	30	A	Loch Loyal, Scotland; Misværdal, Norway; Třebíč, Czech Republic
Ancylite*	LREE(Sr, Ca)(CO ₃) ₂ (OH).H ₂ O	46	C	Sokli, Finland; Qaqarsuk, Greenland
Apatite*	Ca ₅ (PO ₄) ₃ (F,Cl,OH)	19	C; I-A	Silinjärvi, Finland; Kiruna, Sweden; Sokli, Finland; Kodal, Norway
Bastnäsite*	REE(CO ₃)F	76	C; H	Bastnäs, Sweden; Fen, Norway; Sokli, Finland;
Britholite*	(REE,Ca) ₅ (SiO ₄) ₃ (OH,F)	62	H	Norberg, Sweden; Korsnäs, Finland
Brockite	(Ca,Th,Ce)(PO ₄).H ₂ O	24	H	Kizilcaören, Turkey
Burbankite	(Na,Ca) ₃ (Sr,Ba,LREE) ₃ (CO ₃) ₅	11	C	Qaqarsuk, Greenland
Cerite*	(LREE,Ca) ₉ (Mg,Ca,Fe ³⁺)(SiO ₄) ₃ (SiO ₃ OH) ₄ (OH) ₃	75	H	Bastnäs, Sweden
Dollaseite*	CaLREE(Mg ₂ Al)(Si ₂ O ₇)[SiO ₄]F(OH)	32	H	Norberg, Sweden
Eudialyte*	Na ₁₅ Ca ₆ Fe ₃ Zr ₃ Si(Si ₁₆ O ₇₃)(O,OH,H ₂ O) ₃ (Cl,OH) ₂	10	A	Norra Kärr, Sweden; Kringlerne, Greenland
Euxenite*	(REE,Ca,Th,U)(Nb,Ta,Ti) ₂ O ₆	40†	A	Třebíč, Czech Republic
Fergusonite*	REENbO ₄	47	A	Ditrâu, Romania
Fluocerite*	REEF ₃	32†	H	Kizilcaören, Turkey
Gadolinite*	REE ₂ Fe ²⁺ Be ₂ O ₂ (SiO ₄) ₂	52	H; A	Norberg, Sweden; Mourne Mountains, Northern Ireland
Monazite*	REE(PO ₄)	71	C; P; H; A	Olserum, Sweden; Fen, Norway; Central Wales; Ditrâu, Romania
Parisite	CaLREE ₂ (CO ₃) ₃ F ₂	63	C	Fen, Norway
Perrierite*	REE ₄ (Mg, Fe,Ti) ₄ O ₈ (Si ₂ O ₇) ₂	40	P	Nettuno, Italy
Pyrochlore*	(Na,Ca) ₂ Nb ₂ O ₆ (OH,F)	3	C	Motzfeldt, Greenland; Delitzsch, Germany
Steenstrupine	Na ₁₄ LREE ₆ Mn ₂ Fe ³⁺ Zr(PO ₄) ₇ Si ₁₂ O ₃₆ (OH) ₂ ·3H ₂ O	30	A	Kvanefjeld, Greenland
Strontianite	Sr(CO ₃) ₃	–	C	Silinjärvi, Finland; Sokli, Finland
Synchysite*	CaREE(CO ₃) ₂ F	51	C; H	Sarfartoq, Greenland
Törnebohmite*	REE ₂ Al(SiO ₄) ₂ (OH)	62	H	Bastnäs, Sweden
Västmanlandite	Ce ₃ CaMg ₂ Al ₂ Si ₅ O ₁₉ (OH) ₂ F	26	H	Norberg, Sweden
Xenotime*	(Y,HREE)PO ₄	61	H; A; P	Olserum, Sweden; Galiñero, Spain; Ditrâu, Romania
Zircon	ZrSiO ₄	–	A	Katajakangas, Finland

Table 2 Table of the main REE-bearing minerals found in European deposits (Goodenough et al., 2016). Deposit types (H= hydrothermal deposits; C = carbonatite; A = alkaline igneous rocks; P = placers; I-A = iron oxide-apatite deposits). * indicates mineral groups. † indicates REO content stoichiometric calculation or REO content. REO contents from Castor and Hedrick (2006) and Mineralogical Society of America (2017)

Primary REE deposits in Europe

Primary REE deposits are those formed by natural geological processes, including high-temperature processes, such as magmatism and hydrothermal activity; and low-temperature processes operating at the Earth's surface, such as weathering, erosion and sedimentation. The EURARE project team has reviewed all the primary REE deposits and occurrences within the continent of Europe (Figure 3), and the data can be viewed in the project's Information Knowledge Management System (IKMS; <http://eurare.brgm-rec.fr/>). Organisations involved in this review included the Geological Survey of Denmark and Greenland (GEUS), the British Geological Survey (BGS), the Norwegian Geological Survey (NGU), the Swedish Geological Survey (SGU), the Geological Survey of Finland (GTK), the French Geological Survey (BRGM), and the Greek Institute of Geology and Mineral Exploration (IGME).

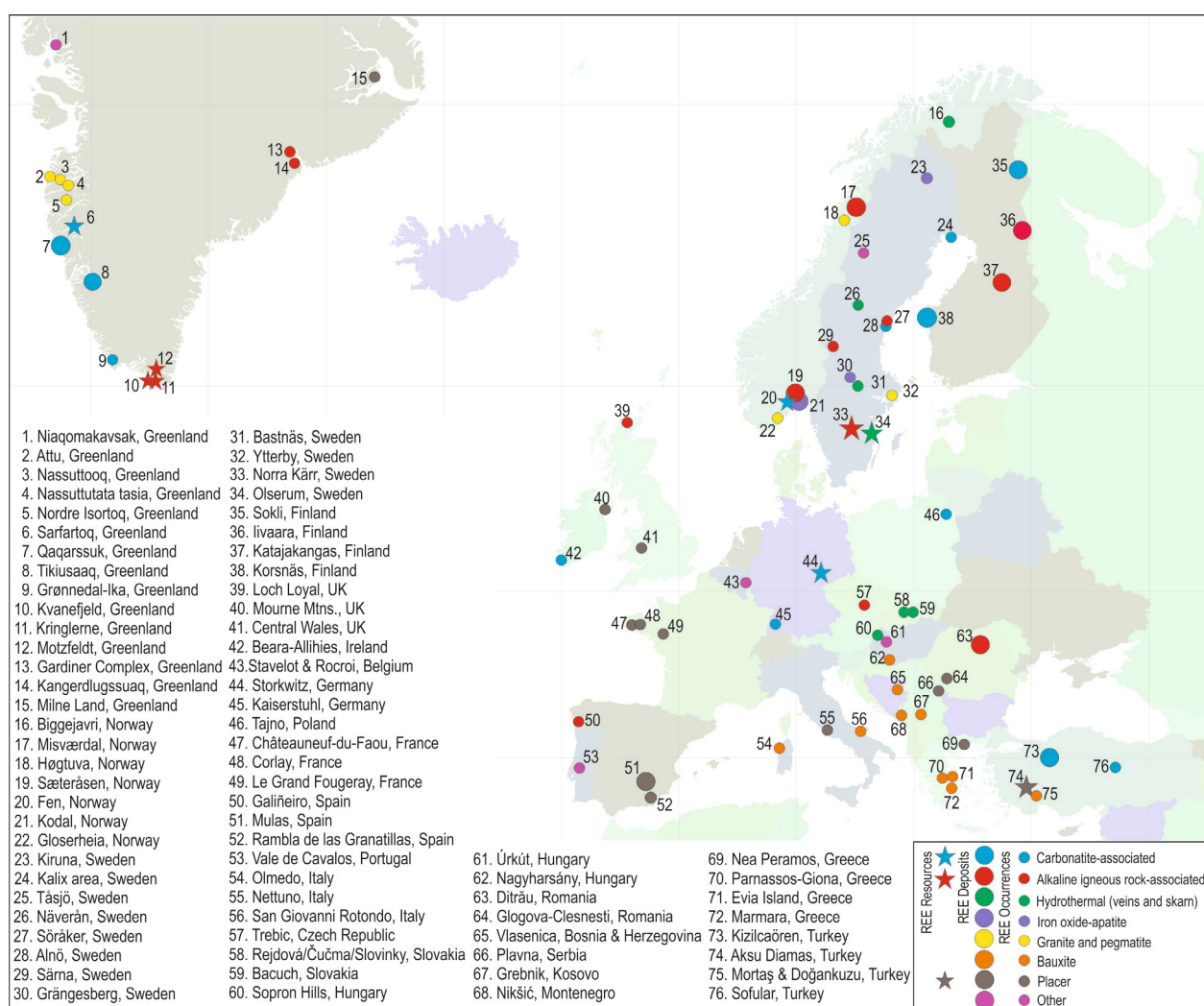


Figure 3 REE resources, deposits and occurrences in Europe recognised by the EURARE project.

Resources are those deposits that have been explored in enough detail to have publicly available resource estimates (Table 3). ©NERC.

Europe has many REE deposits and occurrences (Figure 3). Some of these have already undergone enough exploration to have public estimates of their contained REE resources (Table 3) whilst others have the potential to become economically viable deposits in the future, with further exploration work. The EURARE project has also investigated REE occurrences; REE mineralisation localities that are of geological interest but not likely to become economic on the basis of current evidence. European REE deposits and occurrences can be divided into eight main classes on the basis of how they were formed. The high-temperature deposit classes include deposits associated with alkaline igneous rocks; carbonatites; vein and skarn deposits formed by hydrothermal processes; iron oxide-apatite deposits; and granites and pegmatites. Low-temperature deposits in Europe are chiefly associated with either placers or bauxites, although some sedimentary layers such as phosphorites are also known to be REE-enriched.

Alkaline igneous rocks

Within Europe, the largest and best-known REE deposits associated with alkaline igneous rocks occur in south Greenland and Scandinavia (Goodenough et al., 2016). The deposits in south Greenland are part of the Gardar Province, a Precambrian alkaline igneous province formed during rifting at the margin of an ancient continent some 1.2 billion years ago (Figure 4). Erosion has now exposed the Gardar magma chambers, including the Ilímaussaq and Igaliko complexes, which are characterised by large volumes of unusual, very highly peralkaline igneous rocks that formed from volatile-rich magmas. These highly peralkaline compositions are termed agpaitic; they are enriched in sodium, potassium, high field strength elements (HFSE) such as niobium and zirconium, and REE, and they are characterised by unusual HFSE-rich minerals such as eudialyte and steenstrupine (Marks and Markl, 2017). Both the Kvanefjeld and Kringlerne deposits lie within the Ilímaussaq Complex. Kvanefjeld (and associated Sørensen and Zone 3 deposits) is currently under licence to Greenland Minerals and Energy, and has substantial resources of the REE (Table 3) as well as uranium and zinc, with steenstrupine as the main ore mineral. The Kringlerne project is under licence to TANBREEZ Mining Greenland, and has large resources of REE, zirconium and niobium; the ore mineral here is eudialyte. The nearby Motzfeldt Centre of the Igaliko Complex also hosts significant niobium, tantalum, zirconium and REE resources, and the licence is owned by Regency Mines. Ore minerals at Motzfeldt include pyrochlore, columbite, bastnäsite, monazite, eudialyte and zircon.



Figure 4 Overview of the Kringlerne REE deposit in the Ilímaussaq Complex, South Greenland. ©NERC.

In Scandinavia, the main known REE deposit associated with alkaline igneous rocks is the Norra Kärr complex in Sweden (Figure 3). This is a small (1300 x 400m) deformed Precambrian agpaitic syenite complex, in which eudialyte is the main ore mineral (Atanasova et al., 2017). It is under licence to Leading Edge Materials. Few other significant agpaitic intrusions are known in Europe, although the Kola Peninsula of Russia hosts some of the world's largest agpaitic complexes, and these are already exploited for their REE.

A number of other alkaline igneous complexes with REE enrichment have been identified across Europe, such as Misvaerdal in Norway (Ihlen et al., 2014), Katajakangas in Finland (Sarapää et al., 2013) and Loch Loyal in Scotland (Walters et al., 2013). These intrusions are typically of miaskitic type, in which the REE are disseminated in more common minerals such as allanite, titanite, zircon and apatite; there is no established processing path for recovering the REE from these minerals. One alkaline complex that has been studied in some detail by the EURARE project is the Ditrău Complex in Romania, in which REE-mineralised veins cross-cut the alkaline igneous rocks. The main ore minerals here are monazite and xenotime, with allanite, apatite and REE-carbonate minerals (Honour et al., 2017). In general, there has only been limited exploration of Europe's miaskitic intrusions for their HFSE and REE mineralisation, and significant exploration potential remains.

Carbonatites

The second largest class of European REE deposits is those associated with carbonatites, igneous rocks that comprise at least 50% carbonate minerals. Worldwide, carbonatites are major sources of both REE and niobium, and are characterised by significant enrichment in the LREE over the HREE. Carbonatites are typically formed in association with continental rifting, but may occur in isolation some distance from identifiable rift structures. Some carbonatites, but not all, are associated with alkaline igneous rocks. Individual carbonatite complexes are commonly characterised by sheeted or pipe-like early calcite and/or dolomite carbonatite intrusive bodies a few kilometres across, with later-stage ferrocarbonatitic and carbohydrothermal sheets and veins that typically host the REE mineralisation (Mitchell, 2015). At some localities, alkaline igneous rocks dominate but are cut by carbonatite dykes and sills that have high REE contents. The most important REE-bearing minerals in carbonatites are monazite and bastnäsite, but many other minerals may be present, including REE-carbonates such as ancylite, burbankite, parisite and synchysite.

A group of carbonatites along the west coast of Greenland includes the Sarfartoq and Qaqarssuk carbonatites, which have both been the subject of recent REE exploration. Scandinavia hosts the Fen carbonatite in Norway, the Alnö carbonatite in Sweden, and the Sokli carbonatite in Finland (Figure 3). The Fen Complex hosts significant REE resources spread across several different licence areas, including those currently held by Fen Minerals and REE Minerals, and has been studied in some detail by the EURARE project. The complex is about 3km across and comprises early calcite and dolomite carbonatites associated with alkaline silicate rocks, with later ferrocarbonatites that are locally affected by carbohydrothermal alteration (Ihlen et al., 2014). A zone of pervasive alkali metasomatism

(finitisation) occurs in the host rocks around the complex and provides evidence for extensive fluids emanating from the intrusions. The highest REE enrichments occur in the ferrocarnatites, particularly those affected by carbohydrothermal alteration (known as Rødbergite), and the REE minerals include monazite, bastnäsite, parisite and synchysite.



Figure 5 a) Overview of the Kizilcaören fluorite-barite-REE deposit, Turkey with visible drill pads and road cuttings ©NERC; b) Drilling at the Fen carbonatite, Norway. ©H Schiellerup. Carbonatites are typically poorly exposed, so drilling and trenching are required.

In central and southern Europe, carbonatites are relatively rare, and typically occur in association with alkaline silicate rocks. Two examples, the Delitzsch (Storkwitz) carbonatite in Germany and the Tajno intrusion in Poland, are buried and only known from drilling; REE resources have been estimated for Storkwitz (Table 3).

In Turkey, localised alkaline and carbonatite magmatism is associated with extensive barite-fluorite mineralisation at several localities. The most important of these for the REE is the Kizilcaören Complex, which includes alkaline igneous intrusions, carbonatite dykes, and lenses of fluorite-barite-bastnäsite ore that has likely been formed by carbohydrothermal processes.

Vein and skarn (hydrothermal) deposits

Vein and skarn REE deposits, formed by hydrothermal processes and not clearly related to igneous rocks, are rare in Europe. The most significant examples occur in Sweden, at Bastnäs, Norberg and Olserum. The Bastnäs-Norberg area is of great historical significance, as it provided many of the samples from which the individual REE were first isolated. In this area, the REE deposits largely take the form of skarns, formed where marble horizons have been extensively replaced by hydrothermal alteration. The hydrothermal fluids are considered to derive from coeval felsic magmatic activity in the area (Holtstam et al., 2014). The mineralisation in this area includes a wide range of REE minerals, such as cerite, ferriallanite, fluorbritholite, parisite, bastnäsite, and gadolinite, associated with many sulphide minerals (Holtstam and Andersson, 2007). Although this mineralisation has been mined in the past on a small scale, the mineralised zone is considered to be restricted in extent. The Olserum deposit in southern Sweden comprises hydrothermal veins that are rich in fluorapatite, monazite, xenotime and allanite. Resources have been estimated for this deposit (Table 3) but there has been little published study of the geology.

Iron oxide-apatite deposits

Sweden has the only known iron oxide-apatite deposits in Europe. The most important is the Kiirunavaara deposit which is exploited by LKAB in Europe's largest underground iron-ore mine. The genesis of these ores is still not well understood, with both magmatic and hydrothermal origins having been proposed, although recent research more strongly supports a hydrothermal origin (Westhues et al., 2017). The ores are composed predominantly of magnetite, but are also rich in fluorapatite, monazite, allanite and xenotime; these minerals are not currently processed as by-products of iron ore mining, and so are found in substantial quantities in the Kiruna tailings. They thus represent a potential REE resource, if appropriate processing methods are developed (Peelman et al., 2016).

Granites and pegmatites

Granites and pegmatites are recognised by EURARE as a separate deposit class where they are not found in association with alkaline igneous systems. The main examples of REE-enriched granites and pegmatites in Europe occur in Sweden and Norway, where they are associated with Precambrian orogenic belts. They include the Ytterby pegmatite field in Sweden, the Evje-Iveland, Froland and Glamsland pegmatites in Norway, and the Tysfjord and Høgtuva granites in Norway (Goodenough et al., 2016). Allanite and monazite are the most common ore minerals in these rocks although a wide range of other REE minerals may also occur.

Placers

Placers, or heavy mineral sands, are important sources of the REE in a global context. Placers are mineral deposits formed by the mechanical concentration of minerals that have been eroded from their parent rocks or sediments. The main types that are relevant in terms of REE deposits are coastal (beach sand) and alluvial (river deposit) placers. Whilst placers are most commonly found in unconsolidated sediments along modern coasts and river basins, palaeoplacers can also be found in the sedimentary record. The most common REE ore minerals are monazite and, more rarely, xenotime.

There has been no production of REE from placers in Europe but several placers have been explored. The Mulas placer in Spain is an example of an alluvial monazite placer, whilst coastal placers containing monazite and allanite occur in the Nea Peramos and Strymonikos Gulf areas of northern Greece. A particularly unusual placer occurs at Ramblas de las Granatillas in Spain; this is a garnet placer, which is likely to be enriched in HREE, but processing routes do not exist to obtain REE from garnet. In Italy and Turkey, there are some placers formed by accumulation of REE minerals that were deposited in volcanic ash and subsequently reworked. One such placer, the Aksu Diamas deposit in Turkey, has been studied by the EURARE project (Figure 6): it is a low-grade placer, rich in magnetite, but which also contains the REE ore minerals apatite, allanite, chevkinite, perrierite, bastnäsite and monazite.



Figure 6 Exposures in the REE placer at Aksu Diamas, Turkey. ©NERC.

Many of Europe's Palaeozoic sedimentary basins are characterized by unusual, localised concentrations of authigenic nodular monazite. In Wales, France and Belgium, these nodular monazites are found in the original sedimentary successions, and are considered to have formed by remobilization of the REE during diagenesis of the sediments. These sedimentary features are unlikely to be of economic interest, but higher grades are achieved where the monazites have been eroded and concentrated into placers. In Brittany, such monazites have been concentrated into alluvial placers, such as that at le Grand-Fougeray. In Portugal, Palaeozoic quartzites that are rich in monazite are thought to represent an example of a palaeoplacer. Similar quartzite palaeoplacers occur in the Västervik region in Sweden.

Bauxites

Karst bauxites, such as those that occur in the circum-Mediterranean region, are known to contain REE-bearing minerals. Karst bauxite forms where there is intense lateritic weathering of residual clays that accumulate in topographic lows on limestone surfaces. Examples of REE-enriched bauxites include the Parnassus-Giona bauxite in Greece, and the Mortaş and Doğankuzu bauxites in Seydişehir in Turkey (Deady et al., 2016). Bauxites are typically mined for aluminium, and processed using the Bayer process. Where REE-enriched bauxites are processed into alumina, the REE have 100% conveyance through to the red mud. There is potential for the REE to be extracted from red muds and this has been investigated in the EURARE project. Project partners have characterised red muds from both Greece and Turkey (Deady et al., 2016) and tested extraction mechanisms using ionic liquids (Davris et al., 2016).

Other deposits

Other types of deposits known worldwide include those formed by weathering and sedimentary processes, such as laterites, ion adsorption clays and phosphorites. Such deposits are rare in Europe, with one exception being REE-rich phosphorite layers at Tåsjö in Sweden. Phosphorites are also known to occur in Eastern Europe, but there has been little study of their REE potential.

Deposit	Country	Reporting code	Measured resource	Indicated resource	Inferred resource	Cut-off	Source of data
Katajakangas	Finland	n/a			0.46 Mt @ 2.4% TREO	n/a	Sarapää et al. (2013)
Storkwitz	Germany	JORC			4.4 Mt @ 0.45% TREO (total indicated + inferred)	n/a	http://rohstoff.de/wp-content/uploads/2013/01/2013-01-31-Meldung-SES_e_final.pdf
Kringlerne	Greenland	n/a			4700 Mt @ 0.65% TREO	n/a	http://tanbreez.com/en/
Kvanefeld (including Sørensen, Zone 3)	Greenland	JORC	143 Mt @ 1.21% TREO	308 Mt @ 1.11% TREO	559 Mt @ 1.07% TREO	0.015% U ₃ O ₈	GMEL (2015)
Motzfeldt (Aries)	Greenland	JORC			340 Mt @ 0.26% TREO	n/a	Ram-Resources (2012)
Sarfartoq (ST1)	Greenland	NI-43-101		5.88 Mt @ 1.77% TREO	2.46 Mt @ 1.59% TREO	1% TREO	Druecker and Simpson (2012)
Fen (REE Minerals licence area)	Norway	n/a			84 Mt @ 1.08% TREO	0.8% TREO	Lie and Østergaard (2014)
Norra Kärr	Sweden	NI-43-101		31.1 Mt @ 0.61% TREO		0.4% TREO	Short et al. (2015)
Olserum	Sweden	NI-43-101		4.5Mt @ 0.6% TREO	3.3Mt @ 0.63% TREO	0.4% TREO	Reed (2013)
Aksu Dıamas	Turkey	NI-43-101			494 Mt @ 0.07% TREO		Cox et al. (2013)

Table 3 The REE deposits in Europe that have been explored sufficiently to have publicly available resource estimates. Those that are reported against the JORC and NI-43-101 codes have been signed off by an independent Competent Person. Inferred resource estimates are made with relatively low confidence levels; indicated resource estimates have a reasonable level of confidence. A measured mineral resource is an economic deposit with a high level of geological confidence and confirmed geological continuity. TREO = total rare earth oxides, typically including yttrium.

Mining methods

Europe does not currently have any REE mines, but extensive exploration and research work has been carried out. This section discusses potential methods that may be used in future for mining of Europe's REE resources.

Surface mining

Large, low-grade, near-surface ore deposits are amenable to open-pit mining methods. These methods typically involve the removal of overburden, extraction of the ore by digging or blasting, and the removal of the ore by conveyor belt or truck for stockpiling prior to processing. Open-pit mining operations can reach depths of several hundred metres, although in reality they rarely exceed 100 metres. Within Europe, the large deposits associated with alkaline igneous rocks, such as Kvanefjeld in Greenland and Norra Kärr in Sweden, are proposed to be mined by open-pit methods.

Land-based placer deposits are amenable to strip mining using scrapers, bulldozers and loaders to collect and transport the typically poorly consolidated ore to the processing plant. Drilling and blasting are typically not required, except in deposits where materials have become cemented. Hydraulic mining methods can also be used to extract ore from loosely consolidated placer deposits. High-pressure water cannons (monitors) are used to dislodge the ore, and pipelines are used to transport the resulting slurry to the processing plant. Large, loosely consolidated placer deposits, such as Aksu Dıamas in Turkey, are particularly amenable to hydraulic mining methods.

Mining typically leads to the extraction of waste rock which is commonly stored in stockpiles at the mine area. Subsequent processing also produces waste (tailings) which has to be stored. The EURARE project has studied the tailings produced by processing testwork, to investigate possible environmental issues associated with this waste material (see later section).

Underground mining

Underground mining techniques are usually employed when surface mining methods become too expensive, for example if the ore deposit becomes too deep. Another important factor in the decision to use underground mining methods is the waste to ore ratio, or strip ratio. Once the strip ratio becomes large, open-pit mining methods become uneconomic. However, underground mining operations typically require extensive mine development, including shaft sinking, de-watering, ventilation, geo-technical support and ore handling (transport). REE Minerals have proposed that they may use underground mining methods to mine their licence area in the Fen Complex.

In underground operations, ore is typically blasted and then transported by conveyor belt, train or truck to the processing plant. Room and pillar is a common underground mining

method where mining progresses in a horizontal direction by developing a number of stopes, or rooms, leaving pillars of material behind to support the roof. A less common method of underground mining is sublevel caving, which is employed at LKAB's Kiruna mine in Sweden. Here, the orebody is steeply dipping, and the process works by creating cavities in the orebody through drilling and blasting, which allows the ore to fall down into an underlying level from where it is loaded for transport. Waste rock above the orebody collapses down to fill the cavity; this creates a depression at the surface above the mine.

By-product mining

The rare earth elements are rarely mined as the only or primary product of a mine. For example, REE extraction at Bayan Obo in China is actually a by-product of iron ore extraction and loparite production in Russia is actually a by-product of titanium extraction. Within Europe, there is significant potential for by-product REE production. For example, rare earth-bearing minerals (e.g. allanite, chevkinite and apatite) are found in the Aksu Dıamas placer deposit in Turkey, which has primarily been worked for magnetite. Iron oxide-apatite deposits, such as Kiirunavaara in Sweden, which are principally exploited for their iron ore also contain rare earth-rich apatite, monazite, allanite and xenotime that could potentially be extracted as by-products (Peelman et al., 2016). Mediterranean bauxite deposits exploited for their aluminium content are also enriched in rare earth carbonates such as bastnäsıte and parisite, which end-up in waste bauxite residue (red mud) after processing. Extraction of the REE from these red muds could make a significant contribution to European REE demand (Deady et al., 2016).

Processing of REE-bearing ore

The current state-of-the-art processes for REE extraction require complex, energy and resource intensive technologies. These include a beneficiation stage for the production of a rare earth-rich concentrate, leaching/purification to produce mixed rare earth compounds, separation into individual high purity rare earth solutions, precipitation as individual rare earth compounds, and finally production of rare earth metals or alloys through metallothermic reduction or fused-salt electrowinning. A European REE industry will require cost-effective, and resource-efficient processing methods that are appropriate for European primary REE resources and for European health, safety, and environmental standards. Currently, Europe does not have industrial-scale REE beneficiation or leaching, but has some capability for REE separation: this includes the Solvay plant at La Rochelle in France, and the Silmet plant in Estonia (Guyonnet et al., 2015). At the time of writing, activities at both plants are limited, due to the concentration of the REE separation industry in China (Wall et al., 2017). A new demonstration plant for REE separation is currently under construction in Norway by the company REEtec, which has previously carried out REE separation at pilot-scale.

The EURARE project has worked towards developing appropriate processes for a number of target European deposits – the processing routes for REEs are highly dependent on the REE-bearing phase in question and there is no one-size-fits-all solution. Figure 7 summarises the work carried out by the EURARE project towards development of processing paths for Europe’s primary REE resources.

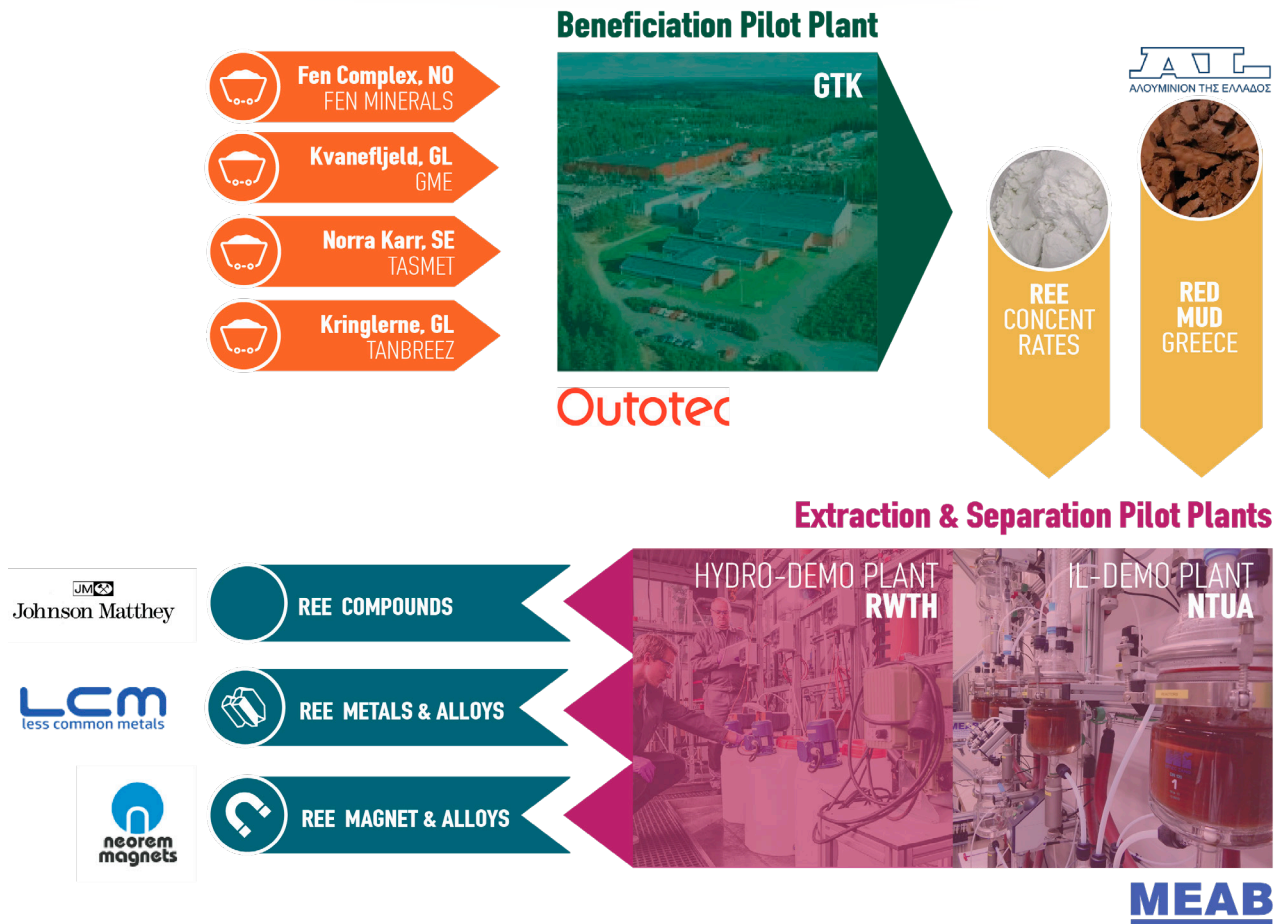


Figure 7 A summary of the processing research carried out within the EURARE project.

Beneficiation

Beneficiation is the term used for the processing of the raw ore to remove gangue minerals, producing an REE concentrate that can then be shipped for further processing. Once a deposit has been mined, the rock is crushed and ground at the entry point of the processing plant. This liberates the target minerals so that they can be separated from the tailings during the beneficiation process.

The optimal beneficiation methods vary according to the grain size, mineralogy and texture of the ore (Figure 8). These characteristics are different for every REE deposit, and therefore each ore has to be carefully characterised before testing. Where the ore has a coarse grain size, it can be crushed coarsely and it may be possible to concentrate

the minerals using physical methods such as gravity or magnetic separation. Finer grained rare earth minerals need to be separated using methods such as froth flotation, in which a specific collector is adsorbed onto the surface of the rare earth minerals to allow a physical separation. Complex ores may not be suitable for physical beneficiation and may require direct, whole of ore leaching in order to recover the REE.

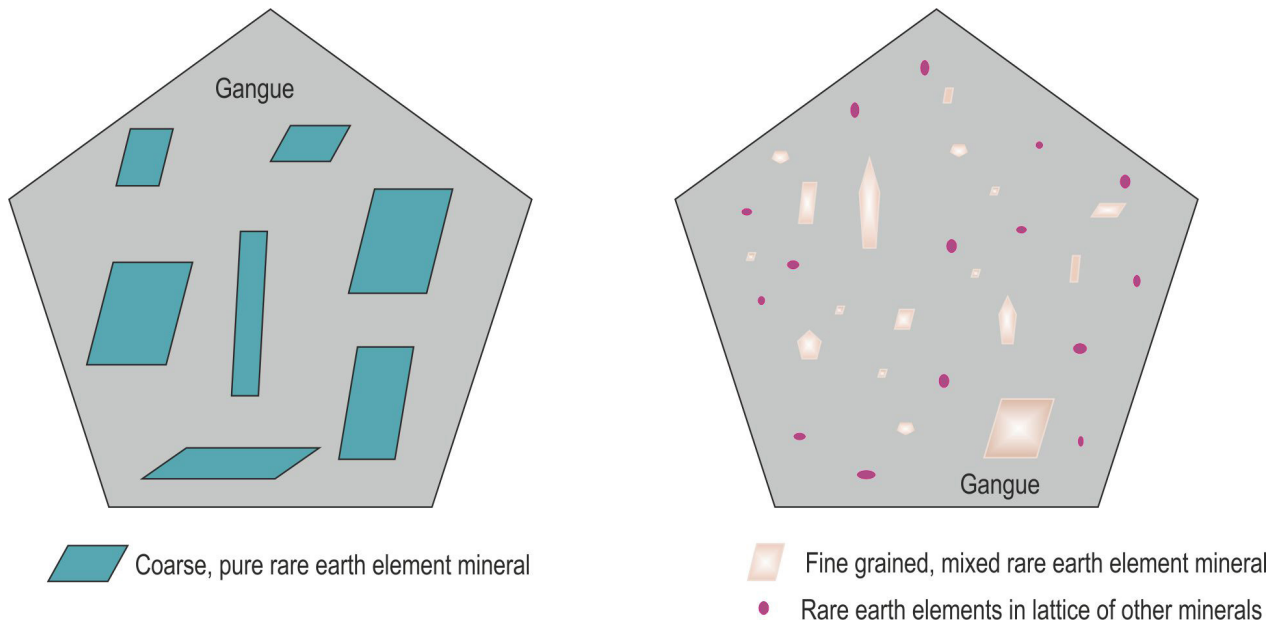


Figure 8 Illustration of two different hypothetical ore materials. The ore on the left is likely to be relatively easy to beneficiate, whilst the ore on the right is much more challenging. ©D Krebs.

One of the aims of the EURARE project was to optimise beneficiation for European REE ores and to minimise the environmental impacts. Beneficiation testwork and pilot plant studies were carried out at the Geological Survey of Finland (GTK) and at IGME in Greece. A variety of beneficiation methodologies were tested on the following deposits: Kringlerne and Kvanefjeld (Greenland), Norra Kärr and Olserum (Sweden), Fen (Fen Minerals, Norway) and the Nea Peramos placer (Greece). These deposits contain a wide range of ore minerals including eudialyte, steenstrupine, monazite, xenotime and allanite (Table 4).

Development and optimisation of a successful beneficiation methodology for each of the ore types involved several steps (Figure 9). For each of the ore types, representative samples were prepared and the mineralogy was quantitatively analysed using a mineral liberation analyser at GTK. Once the ores were characterised, bench-scale tests using kilograms of material were used to trial the beneficiation techniques and develop appropriate flowsheets (Table 4). Finally, beneficiation of selected ores (Kvanefjeld, Kringlerne and Norra Kärr) was carried out on a pilot plant scale (with tonnes of material) at the GTK pilot plant in Finland.

Deposit	Ore Mineral	Beneficiation Method	Concentrate REO grade	Leaching	Rare Earth product and grade
Kvanefjeld	Steenstrupine	Flotation	15%	Atmospheric Sulphuric	Mixed REE carbonate 58% REO
Kringlerne	Eudialyte	Magnetic Separation	1.5%	Hydrochloric Acid dry digestion process	Mixed REE carbonate 40% REO
Norra Kärr	Eudialyte	Magnetic Separation	1.5%	Hydrochloric Acid dry digestion process	Mixed REO carbonate 30% REO
Olserum	Monazite, Xenotime	Flotation	18%	Acid Bake	Not performed
Fen (Fen Minerals)	Complex mineral assemblage	Direct leaching	1.5%	Atmospheric Hydrochloric, Ionic Liquids	Mixed REO carbonate 25% REO
Nea Peramos	Allanite	Magnetic separation	1.5%	Not performed	Not performed
Greek red muds	n/a	Ionic Liquid leaching	0.1%	Ionic Liquids	Mixed REO carbonate 0.7% REO

Table 4 Summary of beneficiation and leaching testwork carried out in the EURARE project.

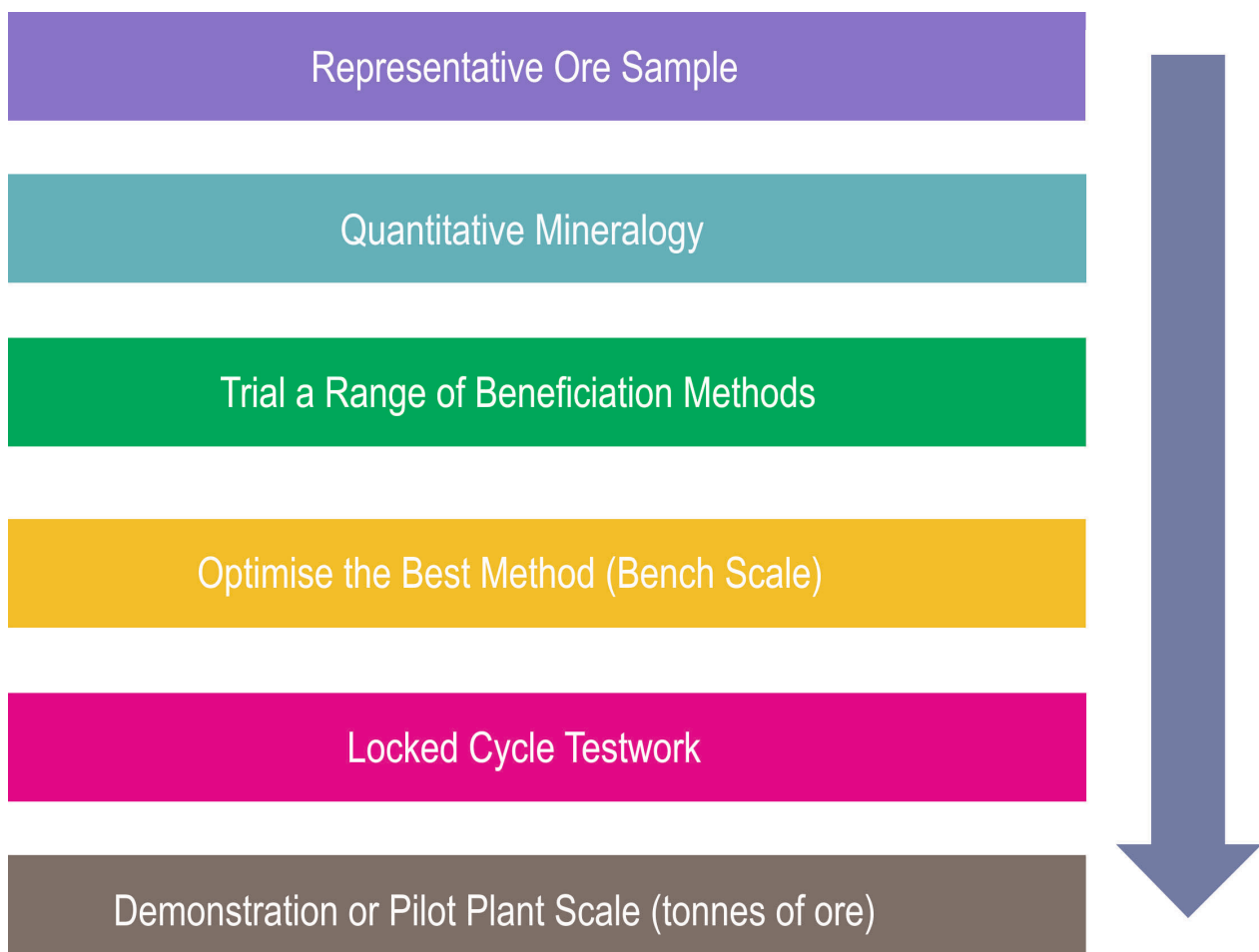


Figure 9 Steps in developing a successful beneficiation flow sheet. ©GTK.

The main physical beneficiation processes tested include gravity and magnetic separation and flotation. Minerals are separated based on parameters such as magnetic susceptibility, density and surface charge. Physical beneficiation has been shown to be successful for many REE-bearing minerals, such as eudialyte, monazite, xenotime and allanite, although individual flowsheets are needed for each deposit due to variations in mineralogy and texture (Jordens et al., 2013). Bench scale beneficiation of eudialyte ore from the agpaitic igneous rocks of Norra Kärr was achieved, using the magnetic properties of the mineral. Development of the flotation process for steenstrupine in ore from Kvanefjeld was significantly advanced through three pilot studies and the completion of a Feasibility Study Design. The project also optimised the flotation of monazite and xenotime from hydrothermal veins at the Olserum deposit; flotation of monazite and xenotime was achieved to a high level with over 70% recovery of the REE-bearing phases. Allanite hosted in the Nea Peramos heavy mineral sand deposit was beneficiated using magnetic separation at lab-scale to concentrate 80% of the REO into 20% of the mass; this process could be used as a pre-concentration step in a processing flow sheet.

Leaching

Once the ore minerals have been concentrated through beneficiation, they are leached to dissolve the rare earths from the minerals, using acid or alkaline solutions. Hydrometallurgical treatment is well developed for some of the commonly processed rare earth minerals such as monazite (Kumari et al., 2015) but more work was needed to optimise such techniques for the key minerals for EURARE. Steenstrupine concentrate from Kvanefjeld was successfully treated using sulphuric acid at pilot plant scale at the Outotec laboratories in Finland, producing mixed rare earth carbonates. For both Kringlerne and Norra Kärr, the main ore mineral is eudialyte, which can be challenging to leach (Davris et al., 2017). Digestion leads to a high silica concentration in solution forming a gelatinous mass of silica that is unfilterable (Davris et al., 2017; Voßenkaul et al., 2017). The formation of silica gel has been inhibited through development of a patented methodology for stabilising the silica (Friedrich et al., 2016). Utilising this methodology, EURARE project researchers have developed a two-stage treatment for eudialyte that resulted in an easily filterable silica precipitate with more than 90% REE recovery into pregnant solution (Davris et al., 2017).

Not all European ores are susceptible to beneficiation techniques. Where ore and gangue minerals have similar physical properties, or where the ore has a complex chemistry or contains minerals that are refractory in nature, direct leaching can be applied. Beneficiation of each of the ore types from the Fen carbonatite (Fen Minerals) proved to be challenging due to their fine-grained nature and complex, disseminated, mixed REE mineralogy. As part of the EURARE project, the ores from Fen were treated with a variety of leaching techniques in order to dissolve the REE. Conventional acid leaching as well as combined treatment of smelting and slag leaching of Rødberg ore was successfully used to recover REE. Rødberg ore was also leached using unconventional solvents called ionic liquids, i.e. room-temperature molten salts that consist entirely of ions. Leaching with the ionic liquid HbetTf₂N recovered good levels of REE into solution

(Davris et al., 2018). The REE were then stripped from the ionic liquid using acid, and the ionic liquid regenerated and reused (Figure 10).



Figure 10 Ionic liquid leaching of Rödberg bastnäsite ore and red mud (or bauxite residue) (Balomenos et al., 2017). ©NTUA.

Direct leaching is also the main method used to extract REE from bauxite residue (red mud). Previous work has trialled a number of acids for red mud leaching, and has shown good recoveries of the REE, but with significant amounts of co-dissolved iron into solution (Borra et al., 2015). The EURARE team at the National Technical University of Athens (NTUA) has used HbetTf2N in direct leaching experiments to selectively dissolve REE, achieving up to 80% of REE recovery with only <3% iron dissolution (Davris et al., 2016).

REE separation

The typical product of the leaching step is a mixed REE carbonate or other compound, and the next step is the separation of the individual REE from each other. This is conventionally achieved using solvent extraction, which is the only REE separation process currently used at an industrial scale (Wall et al., 2017; Xie et al., 2014).

The EURARE project partners MEAB Chemie Technik GmbH (MEAB), Germany; Katholieke Universiteit Leuven (KUL), Belgium; and the Swedish University of Agricultural Sciences (SLU) have worked on different approaches for REE separation. MEAB have studied the separation of REE through conventional solvent extraction employing standard organic phases, whereas the KUL team have developed innovative solvent extraction using ionic liquids as both diluents and a source of coordinating anions. Researchers at SLU have investigated REE separation using nanoparticles.

Solvent extraction

Solvent extraction (SX) in hydrometallurgy is an important process for separating and obtaining the REE. First, a leaching solution of dissolved elements (aqueous phase) is forcibly mixed with an immiscible organic solvent (organic phase), which can extract an element or group of elements from the solution. This separation takes place in equipment known as mixer settlers, and an industrial plant for REE separation may contain hundreds of these (Xie et al., 2014). The research carried out in the EURARE project aimed to optimise these methodologies for the mixture of REE found in European ores.

At MEAB, where the researchers worked with REE carbonate produced from hydrometallurgical studies, the separation of heavy (HREE: dysprosium-lutetium (Dy–Lu), Y), medium (MREE: samarium-terbium (Sm–Tb)) and light (LREE: La–Nd) rare earth elements was achieved. Y was separated from the HREE fraction and a mixture of praseodymium (Pr) and Nd was separated from the LREE fraction. Finally, Y was successfully separated from the LREE fraction (Balomenos et al., 2017). The main process uses bases for conditioning the organic phase and controlling the pH of the aqueous phase. It used acidic extractants

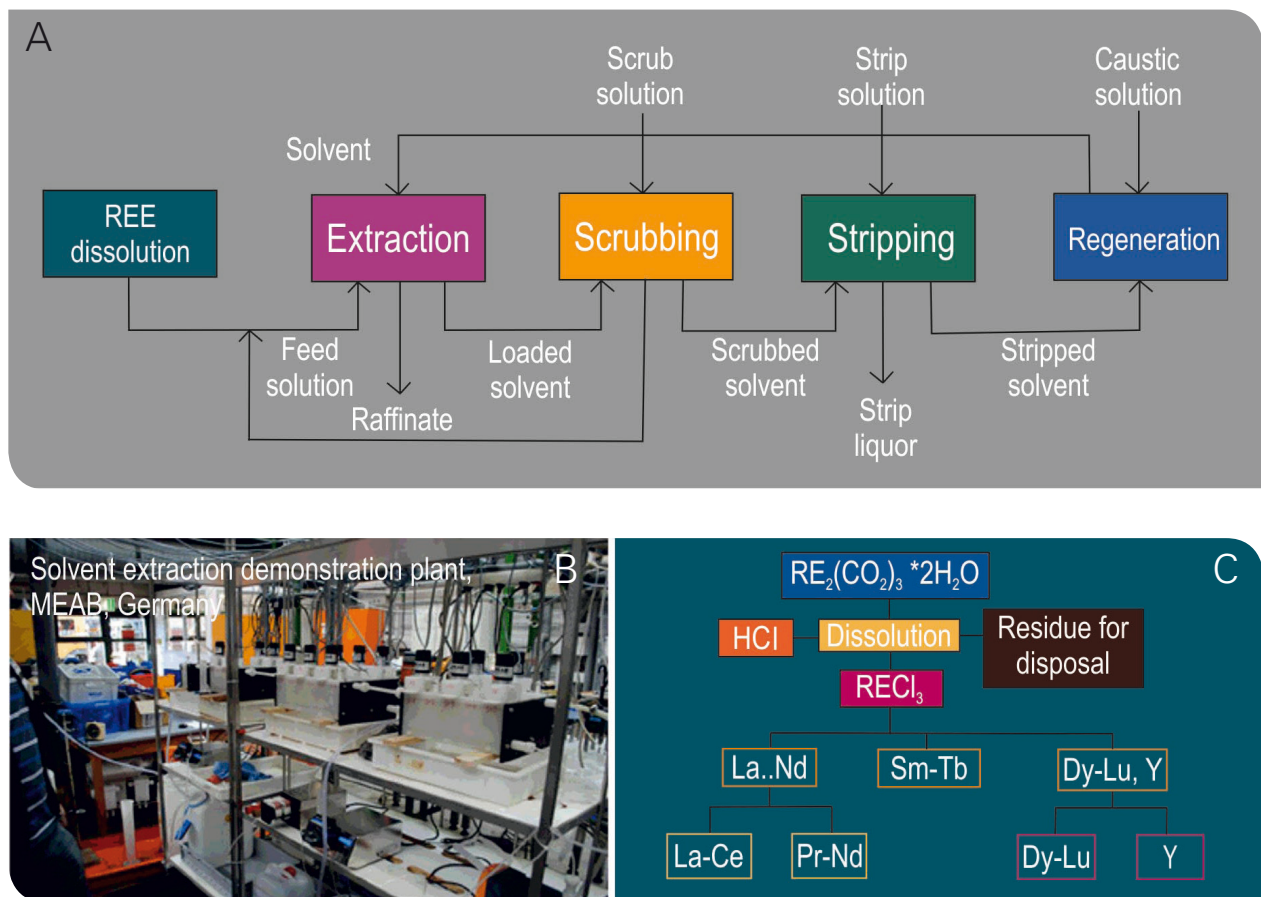


Figure 11 The solvent extraction process for REE separation. A) Generic flowsheet; B) The MEAB solvent extraction pilot plant for EURARE; C) Block diagram demonstrating REE separation. Starting from a mixed REE carbonate concentrate, separate streams of pure REE compounds are produced. ©MEAB.

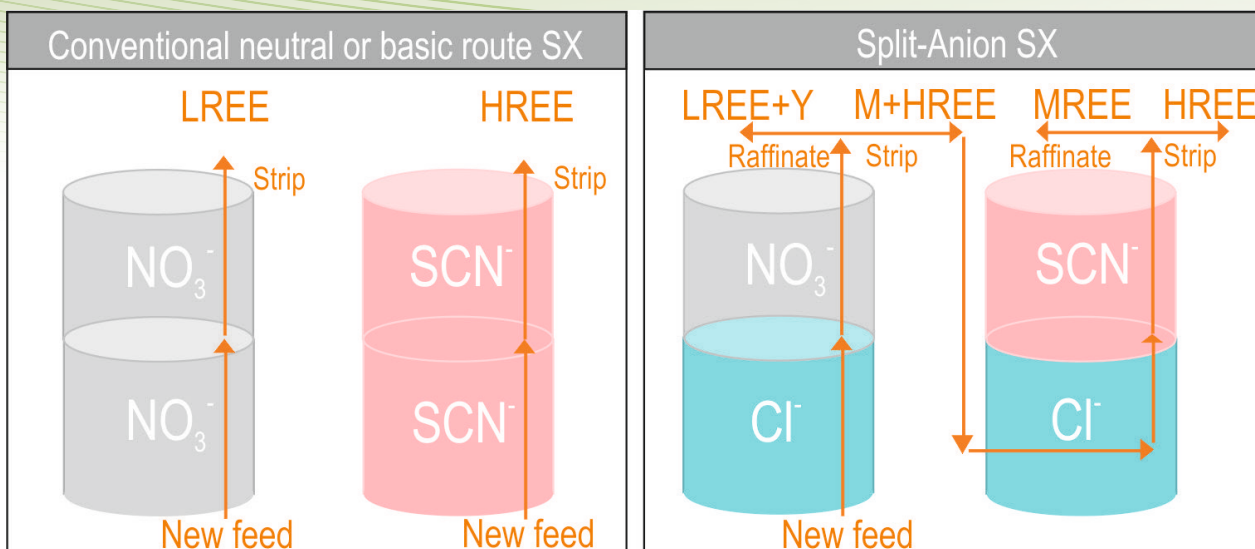


Figure 12 Comparison of conventional and split-anion solvent extraction for REE separation. ©KUL.

for extracting the targeted REE into the organic phase, 0.5–1.5 M hydrochloric acid (HCl) for scrubbing unwanted REE from the organic phase at high organic:aqueous volume ratios, and 4 M HCl for stripping the required REE from the organic phase. The process was tested by MEAB in continuous extraction demonstration tests using a multistage arrangement of mixer settler units (Figure 11).

Researchers at KUL used fluorine-free ionic liquids (Figure 12) instead of the conventional organic diluents (kerosene, toluene). Use of ionic liquids has potential to improve the sustainability of the process, as these liquids are non-volatile and non-flammable. The separation process is termed ‘split-anion extraction’ (Larsson and Binnemans, 2015). A range of ionic liquids have been tested by the EURARE project and have been shown to achieve REE separation.

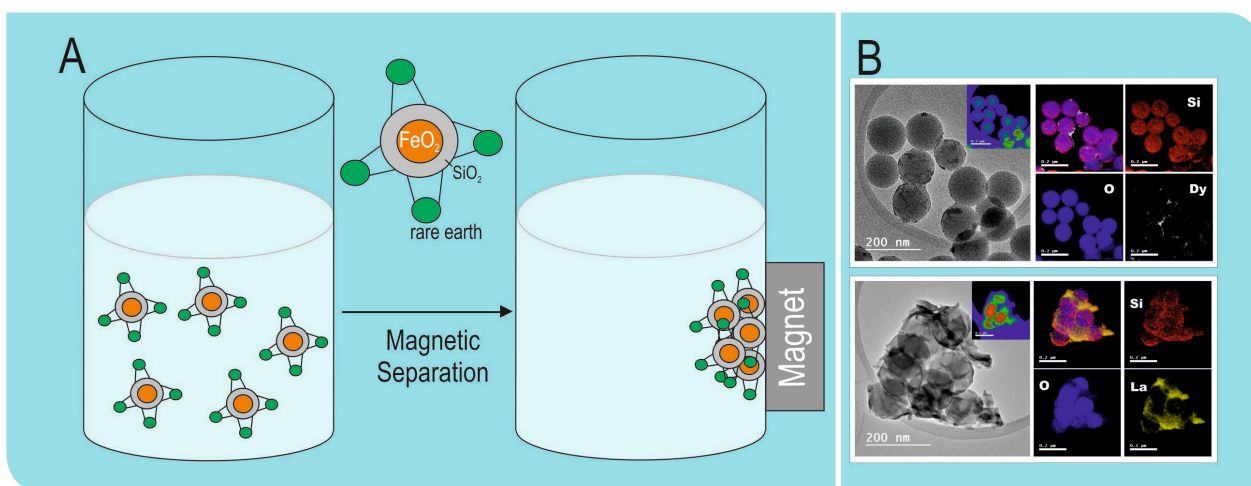


Figure 13 BF-TEM images and elemental mapping by EFTEM of SiO_2 nanoparticles bearing induced crystallized REE. The individual EFTEM elemental maps of Si (red), O (blue), Dy (white) and La (yellow) and the overlay of all elements for each sample are shown (Polido Legaria et al., 2017). ©SLU.

Nanoparticles

A novel, nanoparticle, extraction technique has been developed by project partners SLU (Polido Legaria et al., 2017). This work developed magnetic silica nanoparticles, which have a large surface area that is covered in organic molecules. Typically, these nanoparticles are added to a REE-bearing solution where they bind selectively to REE, causing crystallisation of REE on the surface (Figure 13). The group further developed the methodology by testing adsorption of REE to nanoparticles at different pH, in this case by adding ammonium hydroxide. The group found that uptake of REE could be increased by as much as 20% where pH was elevated. Furthermore, as the nanoparticles developed are magnetic, these could be separated easily from the REE and reused. Significantly, this technique could be applied to low grade or low concentration REE concentrates where other techniques would be uneconomic.

Metal production by salt electrolysis

Once the REE have been separated, the remaining step is the electrowinning of high-purity REE metal. Nd and Pr can be produced separately, or as an alloy (didymium), using an oxy-fluoride molten salt electrolysis process. The technology is similar to aluminium electrolysis, but the setup and size differs. Rare earth oxides (REO) provide the raw material to a fluoride-based electrolyte, which is fed into a closed steel cell operated under inert argon atmosphere (Figure 14). The system contains a hollow carbon ring anode and a tungsten (or molybdenum) cathode, and is heated to around 1050 °C. Oxidation occurs at the anode, where oxygen reacts with carbon to produce CO and CO₂ gases. Simultaneously, the reduction reaction occurs on the cathode where the neodymium/didymium metal is produced. The working temperature is slightly above the melting point of the metal/alloy and this allows the liquid metal to drop into the tungsten crucible positioned below the cathode. Where the 'anode effect' occurs, when the concentration of REO in the solution

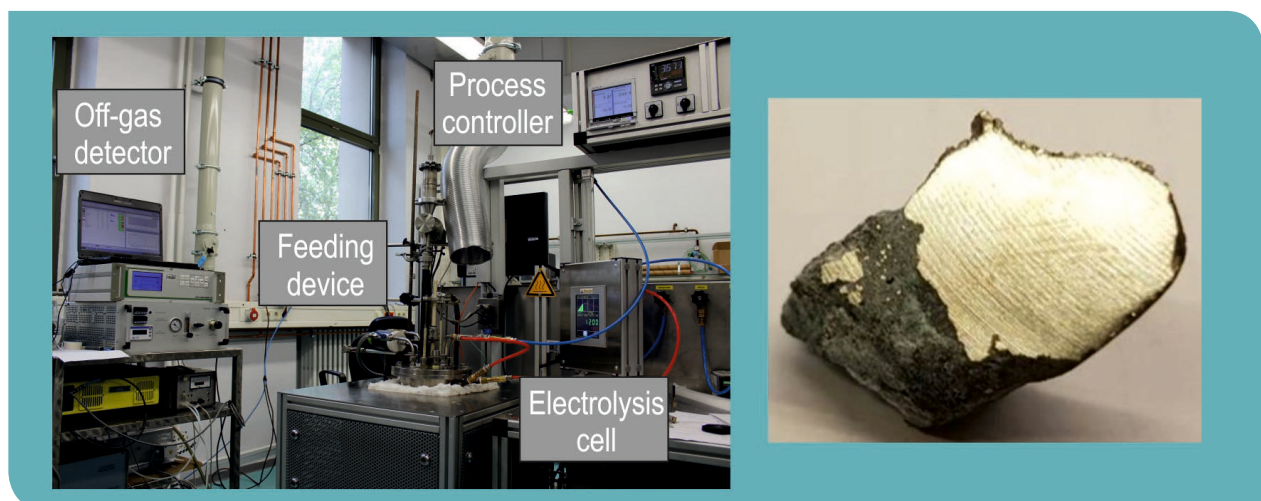


Figure 14 Setup for molten salt electrolysis of neodymium and didymium at RWTH Aachen; (cell, FTIR-spectrometer, controller) and obtained didymium with purity >99 %. ©K Milicevic.

drops off and results in the production of perfluorocarbons (PFCs) from the anode, CF_4 and C_2F_6 are emitted, which have a global warming potential 6500 and 9200 times of CO_2 , respectively (Green, 2007). PFCs production shoots up, current density is interrupted and metal production is stalled when the anode effect occurs.

The challenges of developing a successful REE molten-salt electrolysis method under European environmental standards led researchers at RWTH, Aachen, to develop an automated new cell design (closed system). The main goal was to improve current molten salt technology by reducing energy losses, improving cost efficiency and reducing impurity interferences.

Multiple electrochemical techniques were used to determine the process window and recognise the mechanisms ongoing in the system, in order to both produce metal efficiently and prevent the production of PFCs. A breakthrough point of the project was the process automation, leading to a reduction of greenhouse gas production. Emission of these gases depends on oxide concentration and other process parameters, such as potential and current density, which were regulated by an installed controller, and a Fourier-transform infrared (FTIR) spectroscope was used to measure off-gases. As soon as the above-mentioned parameters reach critical values, the resulting emission of PFCs are detected, triggering an alarm and a dosing of REO, preventing the full anode effect. Through the EURARE project the fundamentals behind electrolysis of neodymium and didymium were investigated and the optimal process parameters were established. Furthermore, the fully automated process control was installed based on critical potential and current values as well on off-gas concentrations leading to a high efficiency in metal production and reduction of PFC greenhouse gases.

The developed cell (Figure 14) resulted in process parameter optimisation, automation, reduction of greenhouse gas emissions, and high purity metal production for Nd and didymium (Nd-Pr) metals. Elucidation of the process of didymium metal production was a significant breakthrough led by the EURARE project, as previously this information did not exist in the literature. Automation of the process has led to high metal production efficiency and reduction in PFC greenhouse gas production.

Separately, Nd electrodeposition in a copper substrate has been achieved in a process developed by NTUA researchers at ambient temperature, using ionic liquids as electrolytes. The type of cations and anions changes several properties of the ionic liquids, such as melting point, chemical and thermal stability, ionic conductivity and broad electrochemical window. The deposition of metallic Nd was confirmed by XPS (X-ray photoemission spectroscopy) analysis and scanning electron microscopy.

Environmental considerations

The EURARE project has successfully developed resource-efficient REE processing technologies specifically tailored for European REE ore deposits. The entire production chain, from the mining of REE ores to production of didymium metal is now possible in Europe. European law is well developed for protecting the environment from mining and industrial processes, emissions and wastes (Keith-Roach et al., 2016). A strong legislative framework is particularly important in light of the impacts of past REE mining and processing activities in Brazil, China, Malaysia, and the United States (Ali, 2014).

Although REE ores often contain naturally-occurring radioactive materials (NORM), eudialyte (Norra Kärr and Kringlerne) and red mud are of low radioactivity and the processes, wastes and products would not require regulation as NORM (2013/59/Euratom.) The U in Kvanefjeld ore is a by-product, which can be considered as adding value to the ores, and this ensures that the radioactive risks will be managed explicitly.

An important aspect of the EURARE project was to scrutinise the tailings produced as waste from the beneficiation processes. Each waste material was closely monitored and mineralogically characterised. This had a twofold benefit; it allowed the investigation of any potential environmental impacts and provided a quality control measure on the efficiency of the beneficiation method. The REE-bearing ores studied under EURARE generally do not contain sulphide minerals, therefore the wastes from the ores tested do not produce acid mine drainage (AMD). The radioactivity of the waste materials was also carefully monitored and tested; generally, these were low but in some cases were slightly elevated above background.

The EURARE project has also focused on developing greener technologies. The major advances include:

- A large scale industrial waste, red mud, has been demonstrated to be a useful REE resource, potentially reducing the environmental footprint of the metallurgical industry
- Eudialyte ore (as found at Norra Kärr, Sweden and Kringlerne, Greenland) can be beneficiated using magnetic techniques, avoiding the need for large quantities of flotation chemicals
- A successful mineral acid leaching method has been developed, avoiding the need for toxic, bioaccumulative perfluorinated surfactants
- Ionic liquid extraction, separation and electro-winning techniques have been developed. These techniques are potentially more environmentally friendly than traditional methods.
- A highly efficient and stable SiO_2 -based magnetic nanoparticle REE separation technique has been developed. The nanoparticles adsorb high concentrations of REE, and selective desorption of Dy, Nd and Y produces high purity, single REE products. The technique avoids the use of organic solvents and concentrated acids, and the magnetic nanoparticles can easily be removed from solution for repeated re-use.

Uses of the REE

The REE have a wide range of uses that are of particular importance for modern technologies such as smartphones, wind turbines and electric cars (Figure 15).

Magnets

Rare earth elements, in particular neodymium and dysprosium, are important constituents in permanent magnets, such as those found in motors in electric vehicles, hard disk drives, loudspeakers and wind turbines. The permanent magnet sector consumes almost 23% of global REE supply (Machacek and Kalvig, 2016). There are two main types of rare earth-bearing permanent magnet: (1) NdFeB (neodymium-iron-boron) magnets and (2) SmCo (samarium-cobalt) magnets. Both types of magnet can contain up to 36% REE by weight. Sometimes Pr, Gd and Ce are used in the manufacture of permanent magnets in place of Nd, although they generally produce weaker magnets. Similarly, Tb and Ho can be used in place of Dy in NdFeB magnets to improve magnetic strength at high-temperature (Machacek and Kalvig, 2016). The wind turbine sector is one of the largest consumers of rare earth-bearing permanent magnets, because a typical direct drive (gearless) wind turbine can contain up to 1200 kilograms of rare earth-bearing magnets. However, the forecast growth in demand for electric vehicles is likely to be the main driver of increased demand for NdFeB magnets in the coming decades (Goodenough et al., 2017).

Catalysts

Rare earth elements (cerium, lanthanum and neodymium) are primarily used in two different types of catalytic application: (1) automotive catalysts that convert pollutants in engine exhaust gases into non-toxic compounds; and (2) catalysts used in petroleum refining, or fluid catalytic cracking (FCC) (Machacek and Kalvig, 2016). Automotive catalysts account for about 20–25% of total REO demand in the catalyst sector. The use of cerium and cerium compounds (e.g. cerium carbonate) in auto-catalysts is advantageous as it improves oxidation efficiency by allowing the catalyst to operate at higher temperatures. This has led to a reduction in the amount of platinum and other precious metals used in auto-catalysts, and has thus reduced costs (Lusty and Walters, 2011). REE-based catalysts used in FCC account for about 65–70% of the total REO demand in the catalyst sector. Fluid catalytic cracking is used to obtain light fraction petroleum products (e.g. LPG) from high-molecular weight hydrocarbons. Lanthanum-based catalysts are used to improve the thermal stability and selectivity of zeolites used in the cracking process. Lanthanum-based catalysts also improve (increase) the yield compared to rare earth-free zeolite catalysts.

Phosphors

The REE are commonly used in phosphors, which are important in televisions, computer monitors, fluorescent lighting and light emitting diodes (LEDs). Approximately 2% of

global REE production is consumed in the manufacture of phosphors and pigments, of this about 80% is used to produce phosphors (Machacek and Kalvig, 2016). REE-based phosphors emit luminescence with specific colours when activated by light-energy. For example, Y and Eu compounds are used to produce red phosphors; green phosphors contain Tb compounds, while blue phosphors are cerium based. The use of REE-based phosphors in modern lighting applications (i.e. LEDs) has led to more energy efficient lighting that has a much longer lifespan. For example, an LED uses almost 80% less energy than a fluorescent tube and on average lasts five times as long (Machacek and Kalvig, 2016).

Ceramics

Rare earth elements are used to produce three broad types of ceramic: (1) refractory ceramics used in furnace linings; (2) electronic ceramics used to manufacture capacitors; and (3) engineering ceramics used in high-temperature, high-wear applications. About 6% of global REE production is consumed in the production of ceramics. Yttrium and cerium are the most commonly used REEs in the production of ceramics, although neodymium, gadolinium, samarium and lanthanum are also utilised. The addition of REE in ceramics typically improves strength, wear resistance and high-temperature performance. For example, yttrium-bearing refractory ceramics are used to line furnaces and crucibles used in metallurgical industries. Rare earth oxide-bearing ceramics are used in electrical applications, such as the manufacture of resistors, capacitors and thermistors, in which they typically improve the capacitance and dielectric properties. Engineering ceramics can contain up to 6 wt% Y_2O_3 , these high-performance ceramics are used in demanding environments such as gas turbines and car engines, or in the manufacture of high-speed cutting tools and high-performance bearings (Machacek and Kalvig, 2016).

Metallurgical uses

The use of REE in the production of metals and alloys (e.g. super alloys and stainless steel) accounts for about 8% of global REE consumption. In metallurgical applications the rare earths typically take the form of mischmetal (an alloy of Ce, La, Nd, Pr and Fe), or REE-silicide (an alloy of REEs, Si and Fe). However, the use of rare earths in metallurgy has shown a recent decline. For example, REEs used to remove impurities during casting are increasingly being substituted for less expensive metals, such as Mg and Ca (Machacek and Kalvig, 2016). The rare earths are primarily added to alloys to: (1) increase their strength at high temperature; (2) improve their resistance to oxidation and/or corrosion; and (3) improve ductility (i.e. workability). The amount of REE added to cast steels, and high strength low alloy (HSLA) steels is low, typically less than 1%. However, the amount added to some high-performance stainless steels, and to magnesium- and aluminium-based, alloys can be as high as 5%. These lightweight alloys are generally used in the automotive sector to manufacture vehicle frames and engine blocks; they are also widely used in the aerospace sector (Machacek and Kalvig, 2016).

Batteries

The use of rare earths (La, Ce, Nd and Pr) in the manufacture of batteries accounts for about 8% of global rare earth consumption. This is predominantly the use of La-mischmetal in the manufacture of rechargeable nickel-metal hydride (NiMH) batteries, in which the REEs form part of the anode assembly. NiMH batteries are used in portable tools, consumer electronics and in hybrid electric vehicles (HEV). In terms of the battery sector, the use of NiMH batteries in HEVs is the single largest consumer of rare earths, with a large NiMH battery containing up to 17% REE by weight (Machacek and Kalvig, 2016).

Glass and polishing

Glass and polishing applications collectively account for about 19% of global REE consumption. Rare earth oxides of Nd, Pr, Er and Ce are used to impart red, green, pink or yellow-brown colours to glass products; they may also be used to remove impurities (e.g. iron oxides) from clear glass that may otherwise cause unwanted colouration (Gupta and Krishnamurthy, 2005; Lusty and Walters, 2011). REE-oxides of La, Gd, and Y are applied to optical glass products as coatings that increase the refractive index and reduce dispersion. For instance, La_2O_3 is commonly used in the manufacture of camera lenses, in which low dispersion and a high refractive index are desirable properties. Cerium-based compounds are typically added to glass bottles and sunglasses lenses to reduce the effects of UV-radiation (sunlight). The most commonly used rare earth-based polishing compound is CeO_2 , used to finish the surface of a number of glass products, for example display panels, flat glass, optical glass and glass used in consumer electronics (Machacek and Kalvig, 2016). Cerium-oxide is favoured as a polishing compound because it removes glass by both chemical dissolution and mechanical abrasion making it more efficient than silica- or zirconia-based compounds (Lusty and Walters, 2011).

Other applications

Minor amounts of the rare earths are used in many niche applications, including: microwave devices; lasers; shielding in nuclear reactors; magnetic refrigeration; synthetic gemstones; textiles; and paints. These applications collectively account for about 10% of global REE consumption, although cerium is the most widely rare earth in many of these applications. Laser, microwave and gemstone applications tend to utilise HREE, such as Y, Gd, Er and Yb, whilst many of the other applications listed (i.e. textiles and paints) are heavily reliant on the light rare earth elements (e.g. La, Ce and Nd). For example, the addition of rare earths (Ce, La, and Nd) to paint improves resistance to fading, but also reduces paint drying times. The rare earths are also used in some biological applications, for instance medicines, fertilisers and water treatment. Examples include: (1) cerium- and neodymium-based medicines used to treat conditions such as motion sickness and thrombosis; (2) the use of cerium and lanthanum in fertilisers to increase crop yield (Xiangsheng et al., 2006); and (3) the use of cerium and lanthanum to remove phosphate during water treatment (Lusty and Walters, 2011; Machacek and Kalvig, 2016).



Figure 15 Different uses of the REE. Size of the box is proportional to market share using data from Machacek and Kalvig (2016). ©NERC.

The REE supply chain

Production and resources

There are currently no REE producing mines in Europe, and estimated global production figures for the REE vary slightly between providers. The British Geological Survey estimates that 154 000 t of rare earth oxides (REO) were produced globally in 2015, the most recent year for which data are available. Of this, 140 000 t were produced by China (Brown et al., 2017). Slightly different figures are provided by the USGS (Figure 16). The

imposition of REE export quotas by China, in 2010, led to a REE price spike and a short-lived global REE exploration boom (Paulick and Machacek, 2017) and the recognition of the REE as ‘critical metals’ (EC, 2017). Global REE supply was diversified by the development of the Mt Weld mine in Australia and the reopening of Mountain Pass in California, although Mountain Pass subsequently closed again in 2015 as REE prices fell. China’s dominance of REE production thus continues, but the defined REE mineral resources outside China have now more than doubled, from 40Mt in 2011 to 98Mt in 2016 (Paulick and Machacek, 2017). In Europe, significant resources of the REE have now been recognised (Table 3), and projects such as EURARE have greatly improved our understanding of REE deposits (Goodenough et al., 2017). The most advanced REE exploration project in Europe at the time of writing is the Kvanefeld deposit in southern Greenland, under licence to Greenland Minerals and Energy, which has completed a feasibility study and has announced a maiden ore reserve.

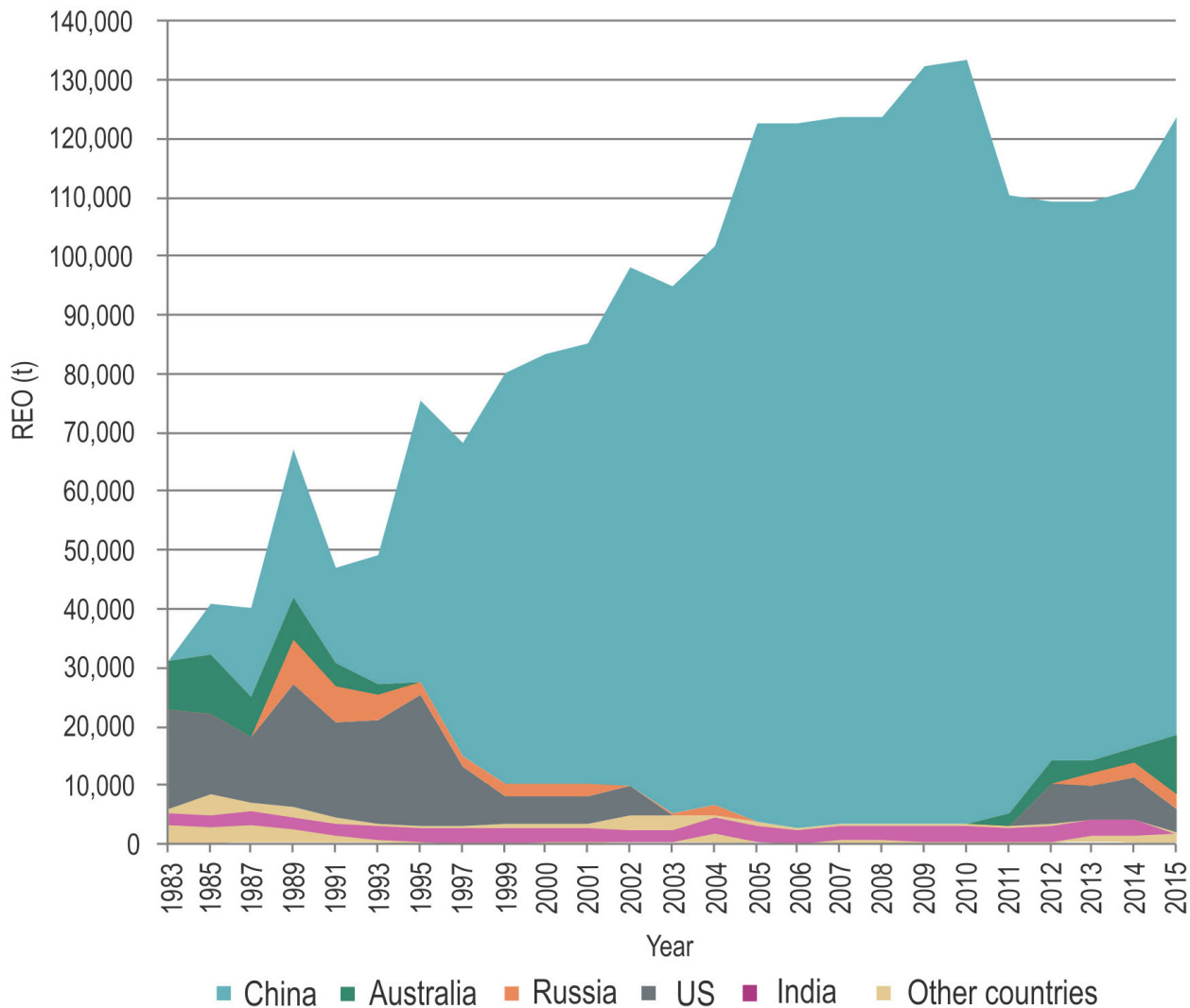


Figure 16 Global rare earth oxide production 1983–2015 (Machacek and Kalvig, 2016). ©NERC.

EU trade

The EURARE project has produced a detailed survey of the REE market in the EU (Machacek and Kalvig, 2016) and key points from that report are summarised here. The European REE market begins at the stage of REE separation from mixed REE compounds, and so the EU is entirely dependent on imports of rare earth metals and rare earth compounds to meet demand. However, recent (2015) trade data indicate that imports of rare earth products to the EU have more than halved since the year 2000, a decrease from 27 290 tonnes to just under 12 000 tonnes over a fifteen-year period (Figure 17), which can be attributed to an increasing focus of manufacturing operations that use REE in China. The EU sources most of its rare earth products from three countries, namely China, the United States and Russia. Of these, China has historically been the largest supplier. However, in the period from 2010–2015, the EU imported more rare earth products from the United States than from China, because of the import of mixed REE compounds from Mountain Pass to the Silmet separation plant in Estonia; this import ceased after the closure of Mountain Pass in 2015. The data also show that exports from Russia to the EU have been on the rise. The EU also imports small quantities of rare earth products from other countries including India, Vietnam, Malaysia, Brazil and Australia.

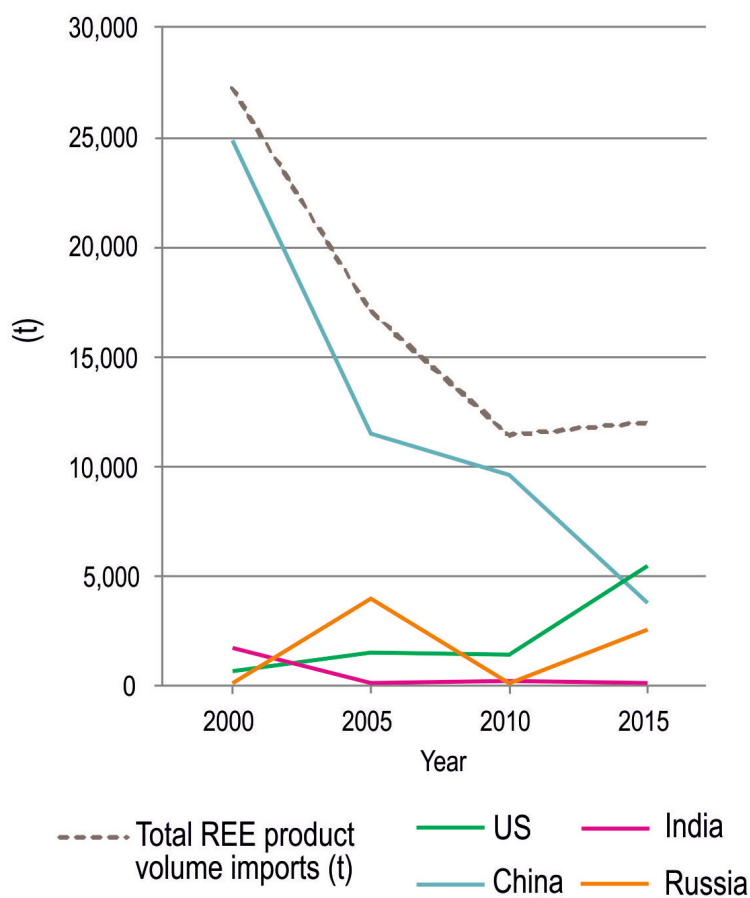


Figure 17 Total EU import of rare earth metals and rare earth compounds (2000–2015) (Machacek and Kalvig, 2016).

©NERC.

Imports of rare earth products into the EU are dominated by cerium compounds, and organic or inorganic mixed rare metal compounds (excluding cerium). The import of compounds is strongly affected by the activities at the relatively small number of plants in Europe that carry out REE separation, particularly the Solvay plant in France and the Silmet plant in Estonia. China dominates the REE separation industry and so is the primary supplier of mixed rare earth alloys and pure metals to the EU manufacturing industry.

The majority of rare earth products imported into the EU are used in the manufacture of glass (19%) and automotive catalysts (27%), and in fluid catalytic cracking (FCC) (16%). The remaining 38% is shared fairly equally between numerous applications, which include metallurgy, ceramics, batteries, magnets, phosphors, pigments and polishing. A breakdown of rare earth usage by sector, during the period 2013–2016, shows that demand in many sectors (i.e. magnets, batteries, metallurgy, polishing and phosphors) has been quite consistent. However, demand in the auto catalyst, FCC and glass sectors has increased slightly year on year (Figure 18).

Overall, it is evident that although European manufacturers need the REE and products produced from them, the European value chain is highly dependent upon China. Proposals have been put forward for development of a more diversified and sustainable supply chain for Europe (ERECON, 2015) but at the time of writing the dependence upon China remains.

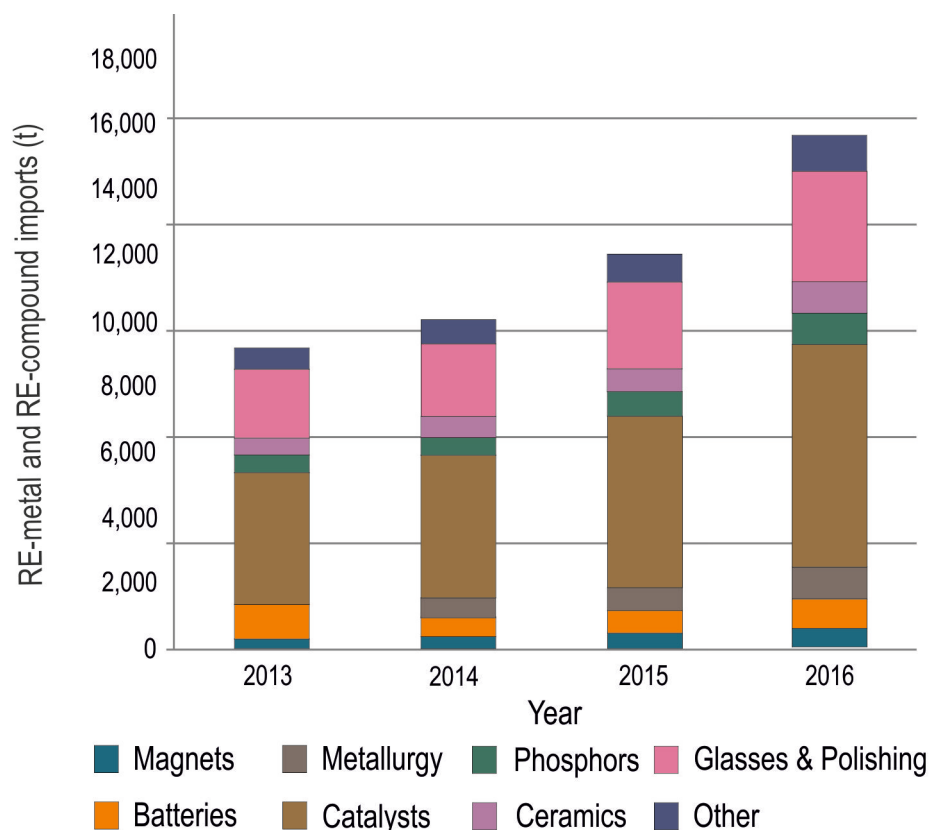


Figure 18 Indicative use of rare earth imports by sector in the EU between 2013 and 2016 (Machacek and Kalvig, 2016). ©NERC.

Recycling and substitution

Recycling rates for the REE are very low for end of life (EoL) products, potentially as low as 1% (Bio by Deloitte, 2015; UNEP, 2013). However, recycling rates for pre-consumer scrap, or 'new scrap' as it is also known may be higher. Closed-loop recycling of new scrap, derived from the production of magnets, was the only form of REE recycling for many years, although details about the actual processes involved are scant (Binnemans et al., 2013). These low recycling rates are largely due to technological challenges, inefficient collection and a lack of incentives (Binnemans et al., 2013). A large amount of lab-scale research has been undertaken to try to overcome some of the technological challenges in recycling EoL products (i.e. magnets), such as how small amounts of strongly bonded REE can be recovered from highly stable, complex compounds. A number of options are potentially available for recovering REE from EoL products; however, their commercialisation will depend on REE demand, favourable economics, and technological advances (Yang et al., 2017). One particularly attractive option is the direct re-use of permanent magnets. In many applications, the contained magnets have a much longer lifespan than the products in which they are found (e.g. hard disk drives), meaning there is potential for the magnets to be recovered and re-used in their current form/shape (Binnemans et al., 2013). Some of these options, and their respective pros and cons, are summarised in Table 5..

Recycling method	Pros	Cons
Direct re-use in current form/shape	• Low energy • Chemicals not required • No waste generated	• Only suitable for large, easily accessible magnets (e.g. in wind turbines) • Large quantities of these magnets are typically not available as scrap
Reprocessing of 'new scrap' to form magnets after hydrogen deprecation	• Lower energy than hydro- or pyrometallurgical processes • No waste generated • Well suited to hard disk drives	• Not suited to oxidised magnets • Doesn't cope with mixed feeds (i.e. magnets of differing compositions)
Hydrometallurgical	• Suitable for all types of magnets • Similar processing steps to those for extracting REE from primary ores	• Large volumes of chemicals required • Generation of large volumes of waste water • Complex process route
Pyrometallurgical	• Suitable for all types of magnets • No generation of waste water • Simpler process route than hydrometallurgy • Can directly produce metallic REE, or REE alloys	• Energy intensive • Not suited to oxidised magnets • Generation of large volumes of waste
Gas-phase extraction	• Suitable for all types of magnets • No generation of waste water	• Consumption of large volumes of chlorine gas • Use of toxic chemicals (e.g. aluminium chloride)

Table 5 Summary of recycling methods and their associated pros and cons (Binnemans et al., 2013).

In Europe, studies have been undertaken to assess the current recycling situation, with a focus on the status of research, current barriers to recycling and recommendations about future priorities (Bio by Deloitte, 2015; ERECON, 2015). Currently in Europe only batteries and fluorescent light bulbs are recycled on a commercial scale for their REE content. However, EoL magnets from hard disk drives have been identified as a potentially important source of REE (Binnemans et al., 2013; ERECON, 2015). Barriers to recycling identified by these studies include a lack of information about the quantity of REE materials available for recycling, inefficient and non-selective collection of EoL products and product design that does not support REE recycling (ERECON, 2015).

An alternative approach that has been suggested to reduce dependency on REE imports for manufacturing is substitution. There are two types of substitution: (1) element to

Application	REE material	Alternative materials/applications
Magnets High-strength permanent magnets	Nd ± Pr; Dy; Tb	Ce; Co; Sm; Fe-nitride (Fe_{16}N_2); hexagonal ferrites (e.g. $\text{BaFe}_{12}\text{O}_{19}$)
Metallurgy Al-alloys Mg-alloys Iron and steel	Sc Ce; Nd Ce; La	Titanium boride (TiB_2) ** Mg
Polishing Glass polishing	Ce	Alumina (Al_2O_3); iron oxide (Fe_2O_3)
Phosphors Compact fluorescent lights (CFL) Light emitting diodes (LED)	La; Ce; Eu; Y; Er; Tb La; Ce; Eu; Y; Er; Tb	** Organic-LEDs; gallium-zinc-oxynitride (GaZnON); boron-carbon-oxynitride (BCNO)
Glass Digital camera applications Plate glass	La Ce	** **
Batteries Nickel metal hydride (NiMH)	La; Ce; Nd; Pr	Mg-Ni-Ti-Al intermetallic compound. In the future Li-ion batteries may also compete with NiMH.
Ceramics Structural ceramics Electronic ceramics	Y La; Ce; Pr; Nd	** Other REE-free ceramics (e.g. lithium niobate, barium stannate, etc.)
Catalysts Fluid-catalytic cracking (petroleum) Catalytic convertor (automotive)	La; Ce; Pr; Nd Ce	†† La; Nd; Pr

Table 6 REE substitutes. †† indicates applications where the amount of REE used has been significantly reduced, or where REE-free alternatives have been developed. ** indicates applications for which suitable substitutes are not known. Information compiled from (CRM_InnoNet, 2015; Halme et al., 2012; Machacek and Kalvig, 2016).

element substitution, in which one element is simply swapped for another in a given application or (2) application to application substitution, where a completely new material may take the place of the one currently in use. In many cases, substitutes for the REE are either unknown or they provide inferior performance. The REE are typically used in highly specialised applications, for example in the production of permanent magnets for electric motors, or as coloured phosphors in computer monitors. For applications where substitutes have been identified the substitutes are generally critical raw materials themselves, or more expensive (Lusty and Walters, 2011). For example, magnesium can substitute for cerium and lanthanum in some foundry steel applications (Skaland, 2003; van der Eijk et al., 2009) (Table 6); however, magnesium, like the REE, is also a critical metal. Sometimes substitution requires the development of a completely new material or product that excludes REE altogether. For example, iron nitride (Fe_{16}N_2) is showing promise as an alternative to REE-based permanent magnets (Widmer et al., 2015) (Table 6). Current research is focussed on developing new REE-free materials, or on reducing the amount of REE used in key applications such as magnets. Whilst some success has been achieved in developing high-strength magnets with reduced Dy content, it is evident that Nd is still an important component for high-performance magnets (Widmer et al., 2015). In Europe, a number of studies (CRM_InnoNet, 2015; Halme et al., 2012; Machacek and Kalvig, 2016) have been undertaken to assess the status of substitution research. However, as has been shown by the EURARE project, there is no shortage of REE resources within Europe; the challenge lies in developing all the steps in the supply chain within Europe. The EURARE project has carried out research along the length of the supply chain and greatly increased our understanding of all aspects.



Figure 19 *The EURARE partners at the meeting in Santorini.*

Acknowledgments

This brochure was written by Eimear Deady, Richard Shaw and Kathryn Goodenough of the British Geological Survey, with contributions from many members of the EURARE project team including Thymis Balomenos, Panagiotis Davris, Miranda Keith-Roach, Damien Krebs, Erika Machacek, Ksenija Milicevic, and Elizabeth Polido-Legaria. The research leading to these results received funding from the European Community's Seventh Framework Programme EURARE ([FP7/2007-2013]) under grant agreement n°309373. This brochure was designed by Amanda Hill and Deborah Rayner at the British Geological Survey.

References

- Ali, S. 2014. Social and Environmental Impact of the Rare Earth Industries. *Resources* 3, 123.
- Atanasova, P, Marks, M A W, Heinig, T, Krause, J, Gutzmer, J, Markl, G. 2017. Distinguishing Magmatic and Metamorphic Processes in Peralkaline Rocks of the Norra Kärr Complex (Southern Sweden) Using Textural and Compositional Variations of Clinopyroxene and Eudialyte-group Minerals. *Journal of Petrology* 58, 361–384.
- Balomenos, E, Davris, P, Deady, E, Yang, J, Panias, D, Friedrich, B, Binnemans, K, Seisenbaeva, G, Dittrich, C, Kalvig, P. 2017. The EURARE Project: Development of a Sustainable Exploitation Scheme for Europe's Rare Earth Ore Deposits. *Johnson Matthey Technology Review* 61, 142–153.
- Binnemans, K, Jones, P T, Blanpain, B, Van Gerven, T, Yang, Y, Walton, A, Buchert, M. 2013. Recycling of rare earths: a critical review. *Journal of Cleaner Production* 51, 1–22.
- Bio by Deloitte. 2015. *Study on Data for a Raw Material System Analysis: Roadmap and Test of the Fully Operational MSA for Raw Materials (Final Report)*
- Borra, C R, Pontikes, Y, Binnemans, K, Van Gerven, T. 2015. Leaching of rare earths from bauxite residue (red mud). *Minerals Engineering* 76, 20–27.
- Brown, T J, Idoine, N E, Raycraft, E R, Shaw, R A, Deady, E A, Hobbs, S F, Bide, T. 2017. *World Mineral Production 2011–2015*. British Geological Survey, Keyworth, Nottingham
- Castor, S B, Hedrick, J B. 2006. Rare earth elements. *Industrial minerals volume, 7th edition: Society for mining, metallurgy, and exploration, Littleton, Colorado*, 769–792.
- Cox, J J, Masun, K M, Fayram, T. 2013. *Technical Report on the Aksu Dıamas Rare Earth Element and Minor Metals, Isparta District, Southwest Turkey* RPA Inc., Toronto
- CRM_InnoNet. 2015. Critical raw materials substitution profiles – Rare Earth Elements [online].
- Davris, P, Balomenos, E, Panias, D, Paspaliaris, I. 2016. Selective leaching of rare earth elements from bauxite residue (red mud), using a functionalized hydrophobic ionic liquid. *Hydrometallurgy* 164, 125–135.

Davris, P, Marinos, D, Balomenos, E, Alexandri, A, Gregou, M, Panias, D, Paspaliaris, I. 2018. Leaching of rare earth elements from 'Rödberg' ore of Fen carbonatite complex deposit, using the ionic liquid HbetTf₂N. *Hydrometallurgy* 175, 20–27.

Davris, P, Stopic, S, Balomenos, E, Panias, D, Paspaliaris, I, Friedrich, B. 2017. Leaching of rare earth elements from eudialyte concentrate by suppressing silica gel formation. *Minerals Engineering* 108, 115–122.

Deady, É 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, 43–61.

Druecker, M, Simpson, R G. 2012. *Technical Report on the Sarfartoq Project, West Greenland*. Hudson Resources Inc, Vancouver http://www.hudsonresources.ca/files/hudson_43-101_30may12.pdf

EC. 2017. *Communication from the Commission on the 2017 list of Critical Raw Materials for the EU*. European Commission, Brussels

ERECON. 2015. *Strengthening the European rare earths supply chain: Challenges and policy options*.

Friedrich, B, Hanebuth, M, Kruse, S, Tremel, A, Vossenkaul, D. 2016. Method for opening a eudialyte mineral. Google Patents.

GMEL. 2015. *Kvanefjeld Feasibility Study*. Greenland Minerals and Energy <http://www.ggg.gl/docs/ASX-announcements/Kvanefjeld-Feasibility.pdf>

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.

Goodenough, K M, Wall, F, Merriman, D. 2017. The Rare Earth Elements: Demand, Global Resources, and Challenges for Resourcing Future Generations. *Natural Resources Research*.

Green, J A. 2007. *Aluminum recycling and processing for energy conservation and sustainability*. ASM International.

Gupta, C K, Krishnamurthy, N. 2005. *Extractive Metallurgy of Rare Earths*. CRC Press.

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. *Journal of Cleaner Production* 107, 215–228.

Halme, K, Piirainen, K A, Vekinis, G, Sievers, E U, Viljamaa, K. 2012. *Substitutionability of Critical Raw Materials*.

Holtstam, D, Andersson, U B. 2007. The REE minerals of the Bastnäs-type deposits, south-central Sweden. *The Canadian Mineralogist* 45, 1073–1114.

Holtstam, D, Andersson, U B, Broman, C, Mansfeld, J. 2014. Origin of REE mineralization in the Bastnäs-type Fe-REE-(Cu-Mo-Bi-Au) deposits, Bergslagen, Sweden. *Mineralium Deposita* 49, 933–966.

- Honour, V C, Goodenough, K M, Shaw, R A, Radulescu, I G, Hirtopanu, P. 2017. *The evolution of REE mineralisation within the Ditrău Alkaline Complex, Romania: interplay of magmatic and hydrothermal processes* <https://eartharxiv.org/2fdct/>
- Ihlen, P M, Schiellerup, H, Gautneb, H, Skår, Ø. 2014. Characterization of apatite resources in Norway and their REE potential – A review. *Ore Geology Reviews* 58, 126–147.
- Jordens, A, Cheng, Y P, Waters, K E. 2013. A review of the beneficiation of rare earth element bearing minerals. *Minerals Engineering* 41, 97–114.
- Keith-Roach, M, Grundfelt, B, Hoglund, L O, Kousa, A, Pohjolainen, E, Magistrati, P, Aggelatou, V, Olivieri, N, Ferrari, A. 2016. Environmental Legislation and Best Practice in the Emerging European Rare Earth Element Industry, in: Lima, B, Filho, L. (Eds.), *Rare Earths Industry, Technological, Economic and Environmental Implications*. Elsevier.
- Kumari, A, Panda, R, Jha, M K, Kumar, J R, Lee, J Y. 2015. Process development to recover rare earth metals from monazite mineral: A review. *Minerals Engineering* 79, 102–115.
- Larsson, K, Binnemans, K. 2015. Separation of rare earths by split-anion extraction. *Hydrometallurgy* 156, 206–214.
- Lie, A, Østergaard, C. 2014. *The Fen Rare Earth Element Deposit, Ulefoss, South Norway*. 21st North, Svendborg, Denmark http://www.reeminerals.no/en/about-us/geology_reports/
- Lusty, P A J, Walters, A. 2011. *Rare Earth Elements*. British Geological Survey, Nottingham
- Machacek, E, Kalvig, P. 2016. *EURARE European REE market survey. Roadmap for the REE material supply autonomy in Europe*. <http://www.eurare.org/publications.html>
- Marks, M A W, Markl, G. 2017. A global review on agpaitic rocks. *Earth-Science Reviews* 173, 229–258.
- Mineralogical Society of America, 2017. Handbook of Mineralogy.
- Mitchell, R H. 2015. Primary and secondary niobium mineral deposits associated with carbonatites. *Ore Geology Reviews* 64, 626–641.
- Paulick, H, Machacek, E. 2017. The global rare earth element exploration boom: An analysis of resources outside of China and discussion of development perspectives. *Resources Policy* 52, 134–153.
- Peelman, S, Sun, Z H I, Sietsma, J, Yang, Y. 2016. Hydrometallurgical Extraction of Rare Earth Elements from Low Grade Mine Tailings, in: Alam, S, Kim, H, Neelameggham, N R, Ouchi, T, Oosterhof, H. (Eds.), *Rare Metal Technology 2016*. Springer International Publishing, Cham, pp. 17–29.
- Polido Legaria, E, Rocha, J, Tai, C.-W, Kessler, V G, Seisenbaeva, G A. 2017. Unusual seeding mechanism for enhanced performance in solid-phase magnetic extraction of Rare Earth Elements. *Scientific Reports* 7, 43740.
- Ram-Resources, 2012. *Maiden Inferred Resource of 340 Million Tonnes for Aries Project* <http://www.asx.com.au/asxpdf/20120427/pdf/425vdqmzhqgxp0.pdf>

- Reed, G C. 2013. *Amended and Restated Technical Report for Olserum REE deposit, southern Sweden* Tasman Metals, Vancouver https://www.sec.gov/Archives/edgar/data/1474547/000094935313000119/exh99-1_olserum.htm
- Rudnick, R L, Gao, S. 2003. Composition of the Continental Crust, in: Rudnick, R L. (Ed.), *Treatise on Geochemistry Vol 3: The Crust*. Elsevier-Pergamon, Oxford, UK.
- Sarapää, O, Al Ani, T, Lahti, S I, Lauri, L S, Sarala, P, Torppa, A, Kontinen, A. 2013. Rare earth exploration potential in Finland. *Journal of Geochemical Exploration* 133, 25–41.
- Short, M, Apelt, T, Moseley, G, Mounde, M, La Touche, G. 2015. *Amended & Restated Prefeasibility Study – NI 43-101 – Technical report for the Norra Kärr Rare Earth Element Deposit*. GBM Minerals Engineering Consultants Ltd <http://leadingedgematerials.com/download/norra-karr-information/>
- Skaland, T. 2003. Ductile iron shrinkage control through graphite nucleation and growth. *International Journal of Cast Metals Research* 16, 11–16.
- UNEP, 2013. *Metal Recycling – Opportunities, limits and infrastructure. A Report of the Working Group on the Global Metal Flows to the International Resource Panel*.
- van der Eijk, C, Grong, Oslash, ystein, Haakonsen, F, Kolbeinsen, L, Tranell, G. 2009. Progress in the Development and Use of Grain Refiner Based on Cerium Sulfide or Titanium Compound for Carbon Steel. *ISIJ International* 49, 1046–1050.
- Voßenkaul, D, Birich, A, Müller, N, Stoltz, N, Friedrich, B. 2017. Hydrometallurgical processing of eudialyte bearing concentrates to recover rare earth elements via low-temperature dry digestion to prevent the silica gel formation. *Journal of Sustainable Metallurgy* 3, 79–89.
- Wall, F, Rollat, A, Pell, R S. 2017. Responsible Sourcing of Critical Metals. *Elements* 13, 313–318.
- Walters, A S, Goodenough, K M, Hughes, H S R, Roberts, N M W, Gunn, A G, Rushton, J, Lacinska, A. 2013. Enrichment of Rare Earth Elements during magmatic and post-magmatic processes: a case study from the Loch Loyal Syenite Complex, northern Scotland. *Contributions to Mineralogy and Petrology* 166, 1177–1202.
- Westhues, A, Hanchar, J M, Voisey, C R, Whitehouse, M J, Rossman, G R, Wirth, R. 2017. Tracing the fluid evolution of the Kiruna iron oxide apatite deposits using zircon, monazite, and whole rock trace elements and isotopic studies. *Chemical Geology* 466, 303–322.
- Widmer, J D, Martin, R, Kimiabeigi, M. 2015. Electric vehicle traction motors without rare earth magnets. *Sustainable Materials and Technologies* 3, 7–13.
- Xiangsheng, L, Jiachen, W, Jun, Y, Yubin, F, Yanping, W, He, Z. 2006. Application of Rare Earth Phosphate Fertilizer in Western Area of China. *Journal of Rare Earths* 24, 423–426.
- Xie, F, Zhang, T A, Dreisinger, D, Doyle, F. 2014. A critical review on solvent extraction of rare earths from aqueous solutions. *Minerals Engineering* 56, 10–28.
- Yang, Y, Walton, A, Sheridan, R, Guth, K, Gauss, R, Gutfleisch, O, Buchert, M, Steenari, B-M, van Gerven, T, Jones, P, Binnemans, K. 2017. REE Recovery from End-of-Life NdFeB Permanent Magnet Scrap: A Critical Review. *Journal of Sustainable Metallurgy* 3, 122–149.