A REPORT BY THE EUROPEAN RARE EARTHS COMPETENCY NETWORK (ERECON)

STRENGTHENING THE EUROPEAN RARE EARTHS SUPPLY-CHAIN

Challenges and policy options

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FOREWORD

Rare earth elements (REE) have become a political buzzword, surging to prominence in recent years. However, these 17 critical elements in the periodic table have long been on the European Commission's radar screen. They are, after all, essential to helping Europe build an efficient, high-tech, and competitive economy, which can spur a renaissance of European industry.

Many of today's sophisticated technologies – including those in the automotive, renewables and defence sectors – depend on rare earths. With their unique properties, rare earths increase efficiencies and performance. In this context, they can play a key role in helping the European Union achieve its industrial, climate and energy targets.

With Europe depending entirely on imports, supply of these critical materials has come under pressure. Changing production patterns and increasing export restrictions have made the availability of rare earths more volatile.

The European Commission and particularly the Directorate-General for Enterprise and Industry, under the leadership of Vice-President Antonio Tajani, has taken the lead in tackling the challenges facing Europe's sustainable supply of rare earths.

In addition to holding intensive raw materials dialogues with countries in Latin America, engaging in trilateral cooperation with the U.S. and Japan, and undertaking several trade initiatives, DG Enterprise has also convened a select group of Europe's best and brightest into a European Rare Earths Competency Network (ERECON). Bringing together experts from industry, academia and policy-making, ERECON has over the last two years looked at ways to improve the security of Europe's rare earth supply. With its three Working Groups, ERECON has focused on opportunities for primary supply in Europe, closing the loop through resource efficiency and recycling, and staying ahead of the curve by identifying future supply trends and challenges for Europe's end-user industries.

This excellent report is the culmination of their work and dedication to Europe's rare earths supply. With its valuable recommendations, it makes an important contribution to the further development of Europe's raw materials strategy and plays an integral part in the European Raw Materials Innovation Partnership.

Reinhard Bütikofer
Member of the European Parliament

EXECUTIVE SUMMARY FOR POLICY MAKERS

RARE EARTHS MARKETS AFTER THE HYPE: CONTINUED SUPPLY SECURITY CONCERNS

By 2017, REE demand is projected to increase by more than 20% compared to 2014, and could be 50% higher by 2020. 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 REEs; next-generation technologies such as electric vehicles and magnetic cooling technology could also require large quantities of rare earths.

The supply crunch of 2010/2011 served as a wake-up call to businesses and governments, highlighting the fact that future rare earths should not be taken for granted. Tightening export restrictions by near-monopolist China put rare earths in the headlines and set off a speculative rally that drove up prices by between four and nine times in less than a year. Some European manufacturers were forced to fly supplies from one plant to another to avoid production outages.

Three years after the crisis, prices have dropped, resource efficiency has improved, and supply has begun to diversify, with China's share in global output dropping from 95% in 2010 to 80% in 2015. Since the bubble burst in the second half of 2011, prices have dropped by over 80% compared to their mid-2011 peak – although they are still higher than they were prior to the crisis. Innovations that were developed in response to the crisis have improved resource efficiency, e.g. through re-using REE processing wastes, such as magnet swarfs and polishing powders. After long delays, mines and processing facilities under development in Australia, Malaysia and the U.S. are now slowly ramping up their production.

Yet competitive, reliable and sustainable access to rare earths is still far from secured, and a repeat of the 2010/11 supply crisis remains a distinct possibility. Questions remain about the commercial sustainability of rare earths suppliers outside of China; and if these operations were to fold, the supply structure would again resemble the situation prior to the crisis. Also, China's monopoly on the production of heavy rare earths remains unbroken (over 95% of mine output outside China consists of light rare earths). Despite recent WTO rulings, companies within China still access REEs at a significant discount. Strategic downstream manufacturing such as magnet making continues to move to China, where access to REEs remains cheapest and most secure.

Rather than focusing on admonishing China over its REE policy, European industry and policy-makers must consider what they are prepared to do to support the development of a more diversified and sustainable supply chain. China has nurtured its REE industry over decades at a great expense, and will continue to try to capitalize on the opportunities this offers for developing high-tech industries. In the meantime, volatile prices and insecure rare earths access threaten to undermine European innovation and competitiveness and may slow the diffusion of priority technologies, such as electric vehicles and offshore wind.

OPTIONS FOR DEVELOPING A DIVERSIFIED AND SUSTAINABLE REE SUPPLY CHAIN FOR EUROPE

Substitution can help to mitigate supply pressures, however it does not offer a panacea to the rare earths challenge. Currently, the development of LEDs, lithium-ion batteries, and solid state drives is rapidly reducing the use of REEs in lighting, battery and data storage applications. Targeted research efforts have also helped to alter the REE composition in permanent magnets, reducing their reliance on the most critical REEs. However, demand continues to grow as rare earths remain the material of choice for many key technologies, such as electric motors and turbines, and new REE applications are likely to emerge in the future.

The development of new sources of heavy rare earths outside of China and greater recycling from priority waste streams must therefore remain an urgent priority for Europe. In the current market environment, however, such alternative sources may not emerge without public support. Under a business-as-usual scenario, investors will remain hesitant to commit to future mining and recycling as they face high barriers to entry, large externalities, regulatory hurdles, and the threat of discontinuities in China's export policy.

Recycling could provide a valuable source of rare earths for Europe, but several challenges have to be overcome for commercially viable, large-scale REE recycling. End-of life (EOL) recycling could offer a significant and secure alternative REE source for Europe, as one of the world's largest producers of REE-containing wastes. But REE recycling rates are still very low (<1%), and while it is technically feasible to recycle REEs from many applications, only the recycling of fluorescent light bulbs and batteries have been commercialized so far. Key obstacles to increasing 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.

A case-by-case assessment of the most promising products and recycling strategies is key to overcoming bottlenecks and improving the economics of REE recycling. In the near term, opportunities for EOL recycling of REE magnets are largest for hard disk drives and specific assemblies in automotives, where magnets are relatively large and economies of scale can be achieved. Direct alloy reprocessing routes could offer a cost-effective strategy for recycling the REE magnets contained in these products. 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.

In contrast to public perception, there is also serious potential for European REE mining, particularly in Sweden and Greenland. With adequate funding and permitting, mining could begin before 2020 and secure European REE supply for decades. Assessments regularly rank a small number of existing advanced projects in Northern Europe among the most attractive in the world. The most advanced projects that are currently being explored are of the size and grade that could add substantially to global output. These projects have completed extensive geological, hydrometallurgical and environmental R&D. With adequate funding and permitting, they could begin mining REE concentrates before the end of the decade.

Key obstacles for bringing REE mines into production, in Europe and elsewhere, include developing a viable business model for downstream processing, environmental permitting, and lack of access to cornerstone equity capital. There are no markets for mixed REE concentrates outside of China, and aspiring miners must either attempt to develop their own capital-intensive and technically complex separation plants or cooperate with existing facilities. Outside of China, such facilities currently exist only in France, Estonia, Malaysia, Japan, and the U.S. Equally, demonstrating that adequate safeguards are in place to mitigate environmental impacts, including radioactivity issues, is a key challenge for exploration projects, particularly those with high uranium and thorium concentrations.

POLICY RECOMMENDATIONS: AN AGENDA FOR ACTION

1. **Maintaining and strengthening the European REE skills and knowledge base through research funding, science and technology education and international cooperation.**
   Without cutting-edge research and technical expertise, a European high-tech REE industry cannot flourish. The EC and Member States should support funding for research grants, scholarships, and training networks, and enhance European and international cooperation through coordinated calls, researcher exchanges, and joint high-level conferences.

2. **Creating the basis for informed decision-making on REEs through a European Critical Materials Observatory.**
   Mapping and monitoring of REE supply chains is necessary for informed decision-making. Expertise in Europe could be pooled in a virtual Critical Materials Observatory that provides the public with consistent and authoritative knowledge on REEs (e.g., information on advanced exploration projects, prices, key demand and supply trends, and the urban mine potential).

3. **Support promising technologies through funding industry-led pilot plants for innovative HREE processing.**
   The EC, industry and Member States should accelerate the commercialization and scaling up of key technologies through co-financing industry-led pilot plants. This should include pilots for REE recovery from heavy rare earths-rich minerals, direct-alloy recycling routes, process and sensor equipment for REE recycling, and REE recovery from industrial residues.

4. **Levelling the playing field for European HREE exploration through co-funding for prefeasibility and bankable feasibility studies.**
   Support from federal and state governments in the U.S., Australia and Canada has played a critical role in advancing project exploration. The EC and Member States should evaluate possibilities for supporting the extensive R&D necessary for pre-feasibility and bankable feasibility studies, to avoid high quality deposits in Europe simply going unexplored.

5. **Making waste management REE-friendly through eco-design, incentive schemes for collecting priority waste products, and streamlining policy and waste regulation.**
   The EC and Member States should promote recycling-friendly design to help identify and recover REE components in waste more easily. Potential incentives for stimulating REE waste collection should be evaluated and the shipment of REE wastes should be facilitated. More consistency should also be created in implementing and applying existing waste regulations.

6. **Boost supply security and de-risk strategic REE investment cases through enhanced cooperation among European end-users and other stakeholders.**
   Leading end-users should engage in strategic cooperation across industry and with governments. This could include setting up a voluntary European 'critical raw materials fund', establishing a 'European Resource Alliance' similar to the German Rohstoffallianz, and convening a high-level taskforce to examine ways in which public funding could support resilient REE supply chains for Europe.

ACKNOWLEDGEMENTS

This report is the outcome of collaborative research and discussions across the ERECON network, involving over 100 European experts from policy, academia, business and think tanks (see Annex 1 for a full list of participants).

Guided by a Steering Committee, three Working Groups conducted the research that forms the substance of the report. On the basis of a series of meetings and extensive group discussions, the chairs of the Working Groups - Günter Tiess (University of Leoben), Allan Walton (University of Birmingham), and Arnold Tukker (University of Leiden) - led the process for developing three draft chapters on primary supply, recycling, and the value chain, respectively. Oliver Gutfleisch and his team at the Fraunhofer Institute provided an additional contribution on the topic of substitution.

Working from these drafts and with substantial input from the Steering Committee, Jaakko Kooroshy (Chatham House) led the process of compiling the overall report and developing the policy recommendations. The report aims to summarize the outcomes of the discussions in the network in a balanced manner, although it may not necessarily reflect in all points the views of individual ERECON members.

The network would like to thank the following individuals:

Reinhard Bütikofer at the European Parliament and Matthias Buchert at the Öko Institute for developing the initial idea of the network and working tirelessly to realize it. Mattia Pellegrini, who chaired the Steering Committee, as well as Sebastian Zaleski, Gwenole Cozigou and their colleagues at the European Commission who helped to guide the development of the network. Marius Wulferding and his team at MOSTRA that led the ERECON Secretariat, ensured a smooth running of the network, and organized the final conference. Jaakko Kooroshy and his colleagues at Chatham House who supported the conceptual development of the network and led the production of the report. Dudley Kingsnorth at Curtin University and Gareth Hatch at Technology Metals Research who generously shared their data and insights. Paige McClanahan who provided editorial support and Giacomo Frigerio and his team at Blossoms who developed the layout and design of the report. The Politecnico di Milano for generously sharing their facilities for the final conference. And last but not least all members of the Steering Committee, the Working Groups, the chairs and external speakers who generously shared their insights, ideas, data, and drafts. Without their dedication and effort this report would not have been possible.

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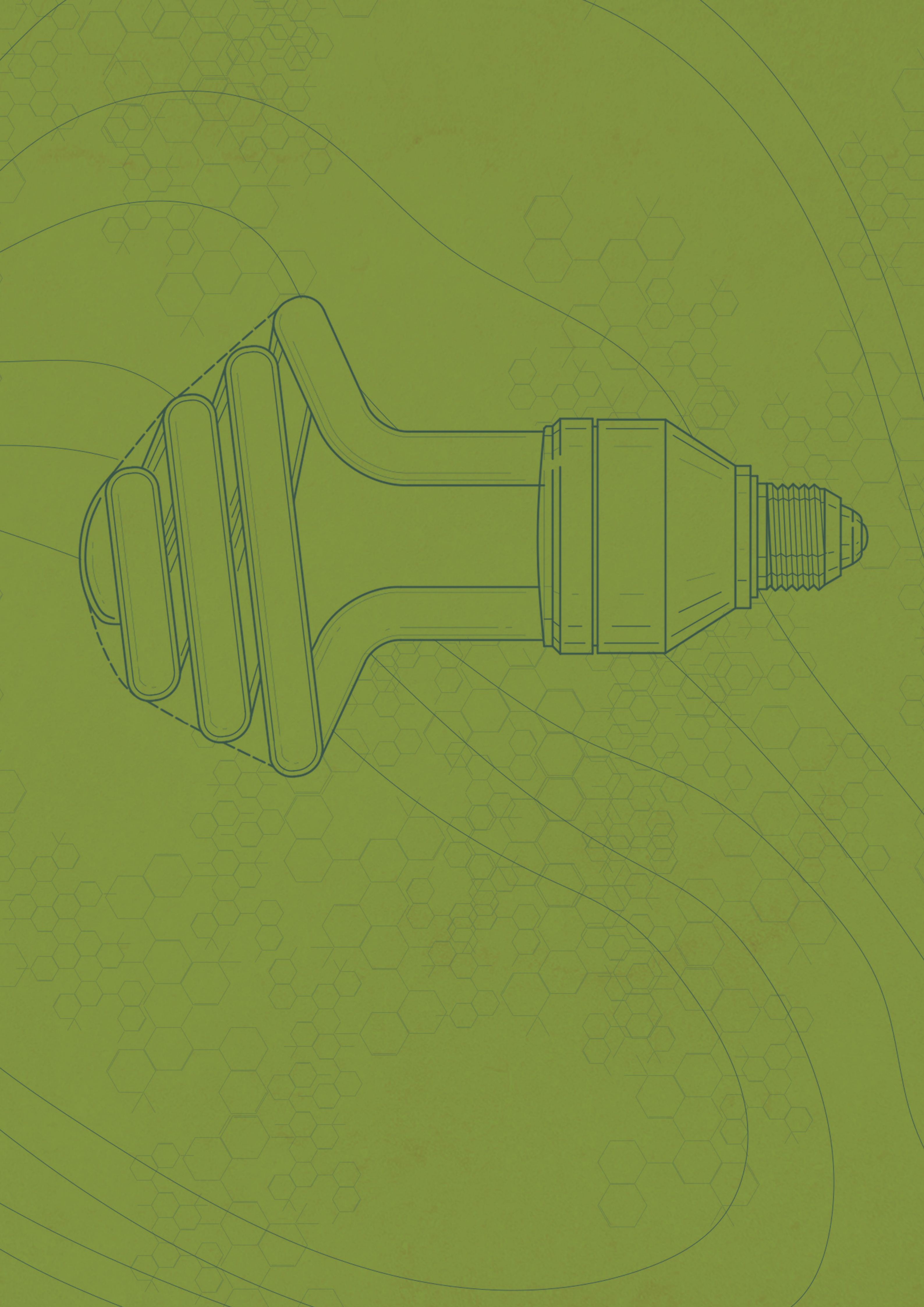
CHAPTER /01

INTRODUCTION



Rare earth elements (REEs) surround us, but they are almost always invisible. They are inside the fluorescent light bulbs in homes, offices and stores; in the hard drives of laptops; and in mobile phones, cars, washing machines, airplanes, batteries, and many other everyday products. Like salt and pepper in food, these high-tech materials are usually used in small quantities, but they are nonetheless essential ingredients in these devices (Morrison and Tang, 2012:22).

As the world moves towards a cleaner, greener future, the uses for these metals are likely to increase rapidly. Hybrid cars, wind turbines, and ultra-efficient appliances all require rare earths. New products – for example, refrigeration devices and electric vehicles – that could use large quantities of rare earths are also on the horizon.

The rare earths supply crunch in 2010/2011 served as a wake-up call to businesses and governments, highlighting the fact that future rare earths supply should not be taken for granted. Tightening export restrictions and a ban on exports to Japan by monopoly-supplier China made rare earths headline news and set off a speculative price rally. Between September 2010 (when China's export ban was imposed) and September 2011, prices for different REEs surged between four and nine times. Prices spiked inside China, but were amplified in the export market due to quotas and taxes. End-users and traders began stockpiling supplies, making it so difficult to procure rare earths that some European manufacturers were forced to fly them from one plant to another to avoid production outages. The price spike also led to a global REE exploration boom, with miners scrambling to access old mines and hundreds of new exploration projects being announced around the world, including some in Europe.

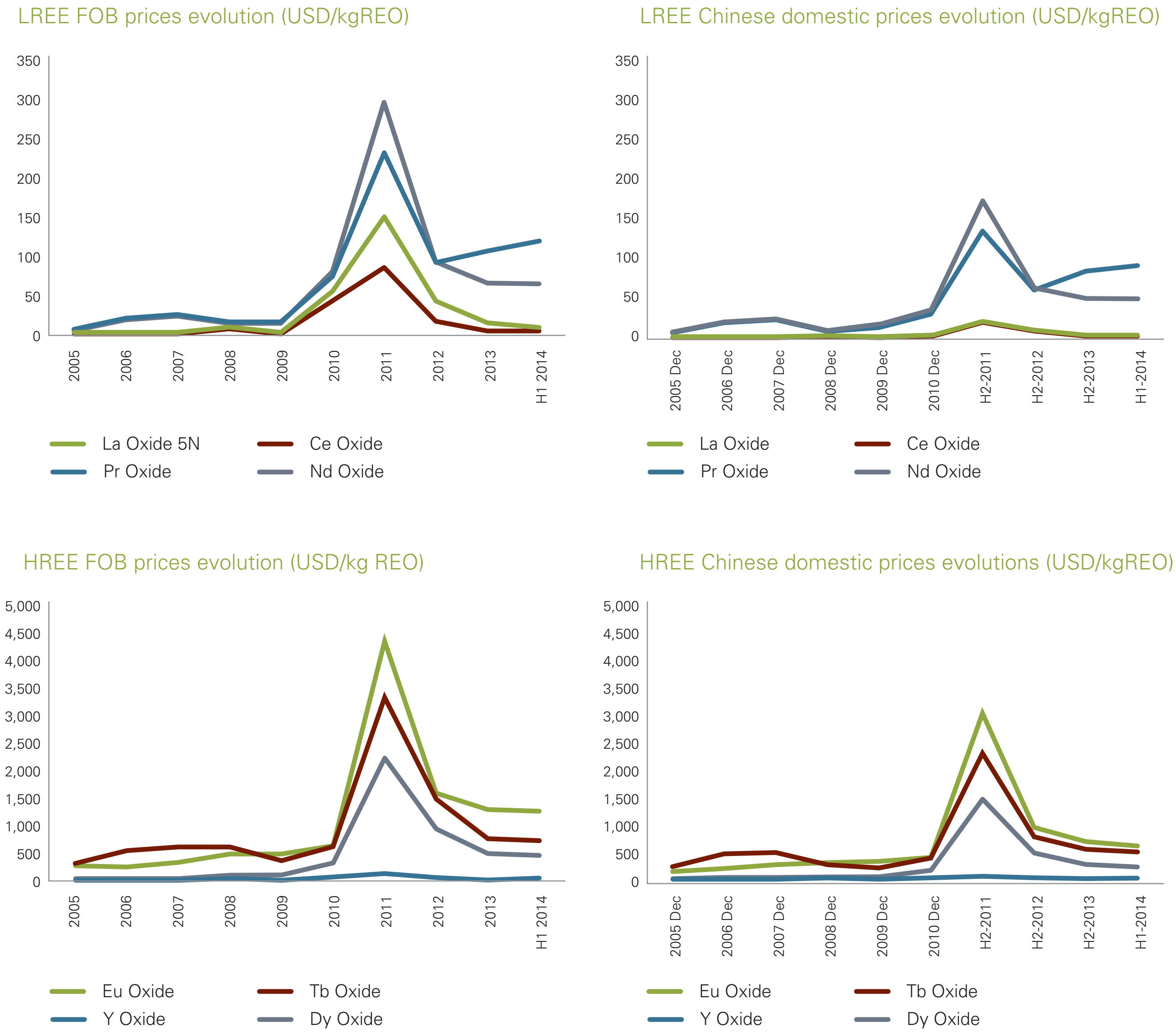
However, this speculative bubble burst in the second half of 2011, and REE markets have been suffering from an extended hangover ever since. Greater resource efficiency, substitution efforts and intensified recycling of processing wastes all contributed to a significant drop in demand. At the same time, major mining operations in Australia (Mt Weld, owned by Lynas Corp) and the U.S. (Mountain Pass, owned by Molycorp) have recommenced, expanding and diversifying the sources of supply of REEs. As result, China's share of world production has declined from over 95% in 2010 to an estimated 75% in 2014.[1] Prices—although still higher than prior to the crisis—have dropped by over 80% compared to their mid-2011 peaks.

As prices declined, the attention of investors, CEOs and policy-makers quickly faded, even though the future supply of rare earths is still far from secured. Questions remain about the extent to which the mining operations of Lynas and Molycorp are commercially sustainable, as both are struggling to become profitable at current prices and to recover the large investments that were necessary to bring them into production. If one or both of these operations were to fold, the global supply picture would look awkwardly similar to the situation prior to the supply crisis.

More importantly, China's supply monopoly remains largely intact for heavy rare earths. Both Lynas and Molycorp are producing from light rare earths deposits, with less than five per cent of the mine output from Mt Weld and Mountain Pass consisting of heavy rare earths. As exploration funding has all but dried up, many of the most promising projects that specifically target heavy rare earths have slowed their development and are fighting for financial survival. Until one of these deposits comes into production, the world will continue to depend heavily on China's supply of heavy rare earths.

Figure 1.1:

The 2010-2011 REE price spike



Source: Asian Metals. Prices shown here are spot prices for 99.9% purity metal ex-China, in US$ per kg.

Whether China will be a reliable supplier of heavy rare earths for the rest of the world remains an open question. Beijing's drive to improve the environmental record of the industry and to stamp out illegal mining may significantly affect heavy rare earths supply, as these elements are principally sourced from very low grade clay deposits in Southern China, where environmental damages and illegal mining have been rampant. Also, the long-term viability of these mining operations remains unclear; detailed reserve estimates for heavy rare earths in China have not been published for many years.

Finally, the Chinese government will continue to encourage domestic processing and value addition for what it regards as a national endowment of strategic importance. The controversial export quota regime is likely to be adjusted following the recent WTO rulings, but vertical integration or subsidies may allow China to continue to provide preferential access and pricing to domestic industries without violating existing trade rules.

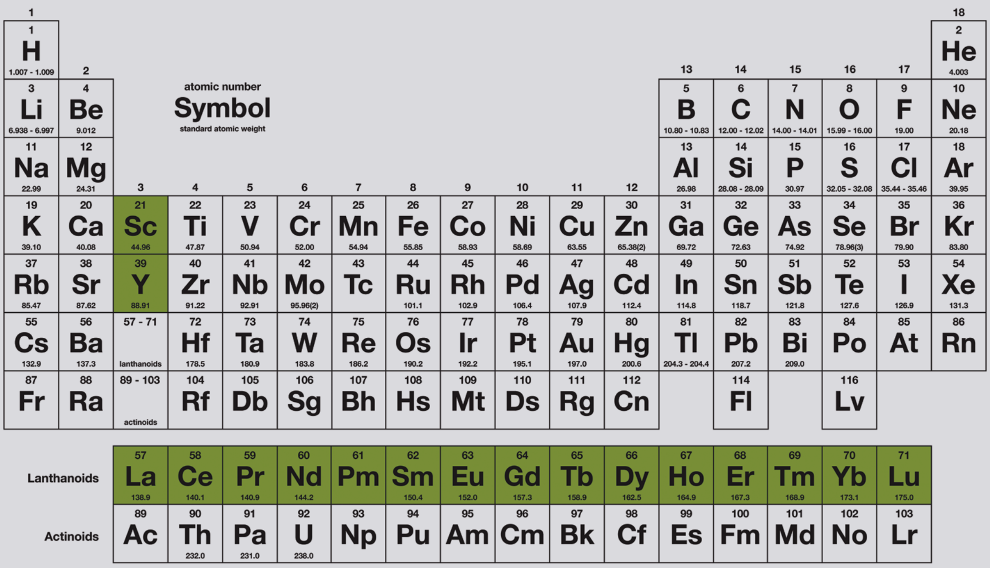
Light and heavy rare earths

Rare Earth Elements (which throughout this report are referred to as 'REEs' or simply 'rare earths') are a group of 17 metals, including the 15 lanthanides (La^{57} to Lu^{71}), $scandium^{21}$ and $yttrium^{39}$, which share many chemical and physical properties. They are commonly subdivided according to their atomic weight into light rare earths (or LREE, which include the elements La to Sm including scandium) and heavy rare earths (or HREE, the elements Eu to Lu, including yttrium). Rare earths naturally occur together in mineral deposits, although the specific distribution across the rare earths differs greatly across deposits. Typically, HREE make up a much smaller share of the total rare earths content than LREE in rare earths-bearing minerals.

REE are not physically scarce; in fact, they are more common in the earth's crust than many other metals including gold, uranium, or tin. However, mineable concentrations are less common than for most other ores. Available reserves exceed current world production by three orders of magnitude. The lion's share of the known resources is contained in the minerals bastnäsite and monazite.

Figure 1.2:

Rare Earth Elements in periodic table



1.1 THE RARE EARTHS CHALLENGE FOR EUROPE

Although public attention has shifted elsewhere, ensuring a secure future supply of rare earths remains an urgent policy challenge for European governments and industry. Rare earth markets are small: the total market value for separated REEs was between \$3 billion and \$5 billion in 2013, and annual world production would fit into one large bulk carrier. Nonetheless, REE's importance for advanced materials across a range of high-tech industries – and especially their key role in boosting energy and resource efficiency – makes them too crucial to ignore. Under a business-as-usual scenario, rare earths supply will remain precarious; and a repeat of the 2010/11 supply crisis remains a distinct possibility in the medium term. Excessive price volatility and uncertainty over future availability could slow the diffusion of best available technologies, e.g., for offshore wind turbines or electric vehicles.[2]

The centre of gravity for the global rare earths supply chain may have shifted to East Asia, but Europe still maintains world-class capabilities, technology and know-how along the rare earths value chain. This specifically includes many medium-sized high-tech companies such as Solvay Rare Earth, which has an industrial base in France, the Estonian company Silmet (controlled by the U.S. company Molycorp), the German company Vacuumschmelze and its Finnish subsidiary NeoRem, Slovenian Magneti Ljubljana, the Austrian company Treibacher Industrie, as well as the British company Less Common Metals (controlled by the Canadian company GWMG), and the UK subsidiary of the U.S. company Arnold Magnetics.

Most of these companies have many decades of experience in rare earths and many have been at the forefront of the development of REE technology. This expertise is complemented by know-how among many large European manufacturers and cutting-edge REE science in several European universities, research organizations, and geological surveys.

However, without a concerted effort to strengthen supply security and boost research, innovation and competitiveness, the European skills and knowledge base around rare earths is likely to continue to erode. Companies processing rare earths within China continue to enjoy substantial advantages in the form of a cheap and reliable raw materials supply. Moreover, many European rare earths companies have already outsourced parts of their activities to China.

1.2 ERECON AND THE PRESENT REPORT

The European Rare Earths Competency Network (ERECON) is an initiative developed by the European Commission's Directorate-General for Enterprise and Industry on the request of the European Parliament. Established in 2013, ERECON is a network of excellence comprising more than 80 European rare earths experts from industry, academia, and the policy world. It provides the appropriate organizational structures and meeting opportunities for a cross-disciplinary exchange to examine key challenges and develop recommendations for fostering a sustainable and secure rare earth supply for Europe.

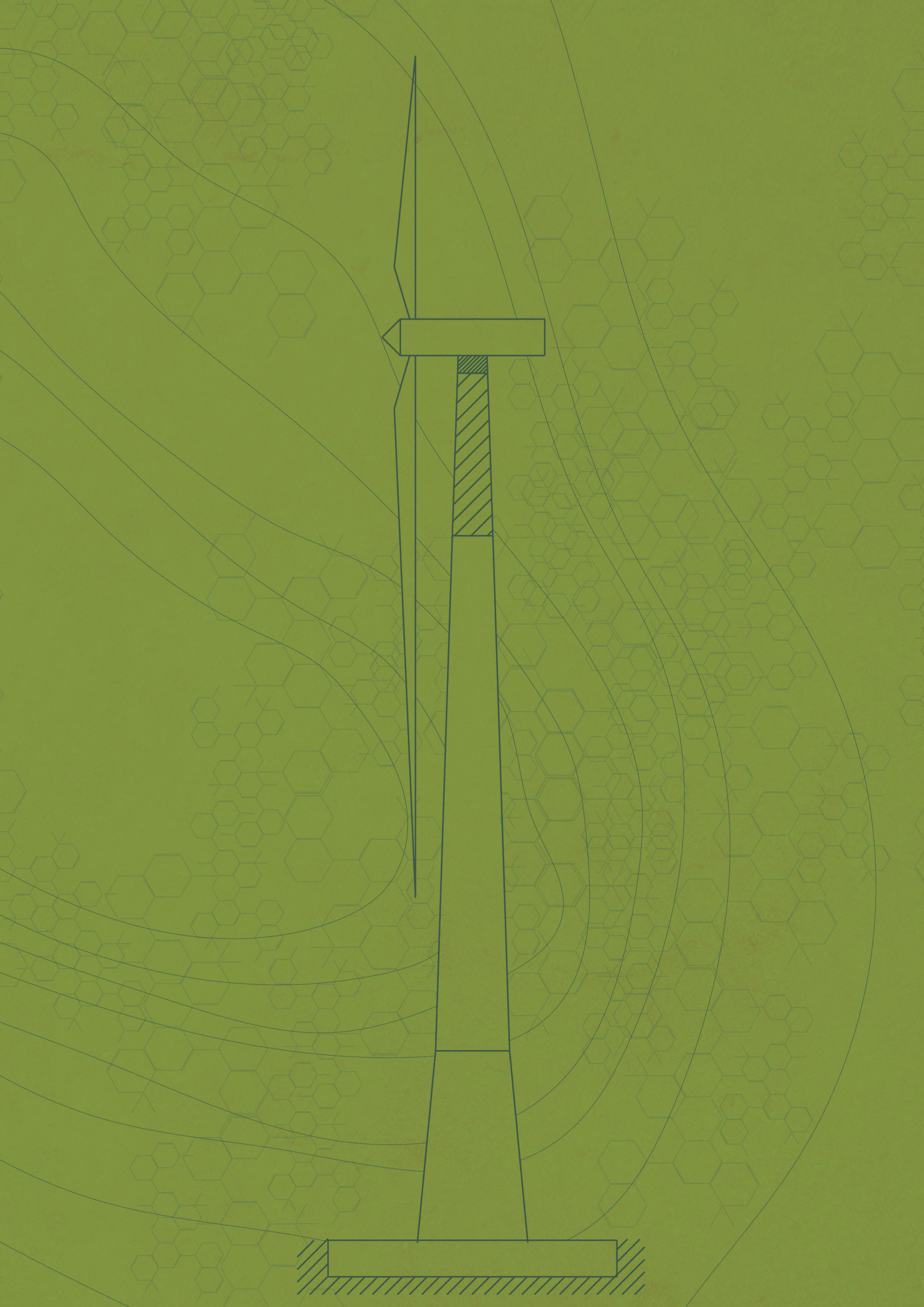
Under the guidance of a high-level Steering Committee, three working groups have examined challenges and solutions for (1) mining rare earths in Europe, (2) recycling and substituting rare earths, and (3) fostering new business models for creating a more resilient, competitive, and sustainable European rare earths supply chain.

This report summarizes the key findings and recommendations that have resulted from discussions in this network. Chapter 2 provides an overview of the drivers of rare earths demand, including materials efficiency, disruptive technological change and substitution efforts. It also discusses key global supply trends. Chapter 3 surveys the geological potential to mine rare earths in Europe and existing advanced stage exploration projects; it also analyses the key challenges to bringing European mines into production. Chapter 4 examines the potential to recover rare earths from end-of-life waste and the barriers to such recycling, particularly for REE magnets and phosphors. Chapter 5 analyses supply security from an end-user and production chain perspective. It identifies a series of market failures that are contributing to supply chain insecurity and examines the challenges that could face potential market interventions. Chapter 6 concludes the report and offers policy recommendations to European industry, European governments and the European Commission.

CHAPTER /02

RARE EARTHS AFTER THE HYPE:

Global rare earths markets four years after the supply crunch



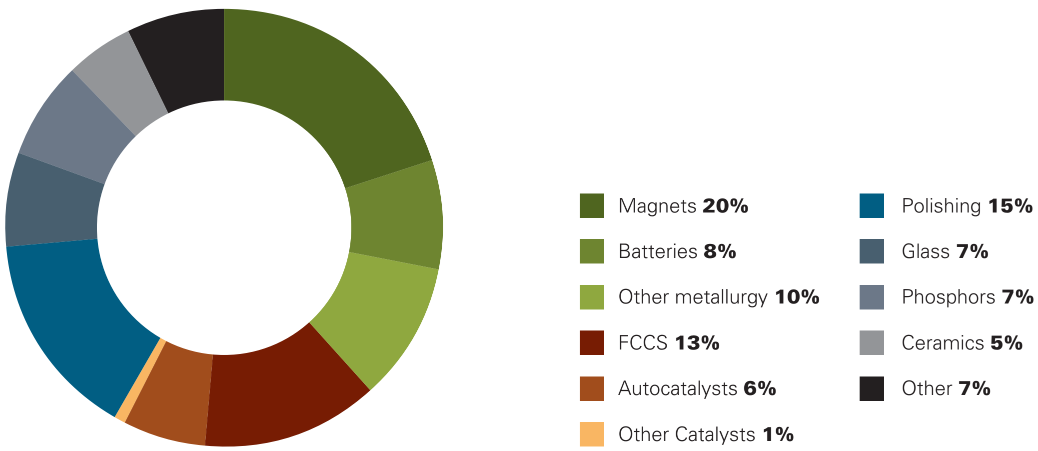
2.1 DRIVERS OF RARE EARTHS DEMAND

2.1.1 Applications of rare earths

The end uses of rare earth elements can be grouped into two broad categories.[3] In the first category, rare earths act as 'process enablers', i.e. they are used in the production process but they are not actually contained in the end product. For instance, light rare earths are used in polishing powders in the glass, electronics, and optics industries; they also serve as fluid-cracking catalysts in refining and other chemical processes.

In the second category, REEs act as 'product enablers' that give advanced materials unique properties that play a key role in the performance of high-tech products. REE-based permanent magnets, pioneered in the 1980s, are currently perhaps the most important of these product-enabling applications. The addition of rare earths can boost the force of permanent magnets by an order of magnitude; this discovery has revolutionized magnet-based technologies such as electric motors and turbines (see box). REE phosphors for lighting and displays are another key application, enabling technologies such as compact fluorescent lamps and LCD screens. Other important uses are in batteries; in the coating of autocatalysts used to clean exhaust; and as additives in high-tech alloys, glass, and ceramics, e.g. to improve their workability or for colouring (see Figure 2.1).

Figure 2.1:
Breakdown of estimated rare earth consumption by sector, 2012



Source: report on Critical Raw Materials for the EU. Critical Raw Materials Profiles, 2014, page 153, based on data by Roskill Information Services and IMCOA. Total REE consumption for 2012 is estimated at 113,250 tonnes of rare earth oxides.

These applications rely on individual rare earths to different extents, creating a unique demand profile for each of the elements. Among the light rare earths, lanthanum is for example mainly used in batteries and fluid-cracking catalysts, while neodymium is mostly used for magnet-making. Among the heavy rare earths, dysprosium is also used in magnets while europium is used almost exclusively for REE-based phosphor applications.

Table 2.1:
Breakdown of estimated European rare earth consumption by sector, 2010

Auto Catalyst	2200 t REO	27%
FC Catalyst	1300 t Reo	16%
Glass	1500 t REO	19%
Polishing	250 t REO	3%
Metal Alloy	1000 t REO	12%
Magnet	300 t REO	4%
Phosphor	500 t REO	6%
Ceramics	500 t REO	6%
Others	500 t REO	6%
Total	**8050 t REO**	**100%**

Source: Based on consolidated ERECON estimates.

Rare earth-based permanent magnets

Permanent magnets play a key role in many applications, including in energy devices such as generators (e.g., off-shore wind turbines) and electric motors (cars), as well as in magnetic resonance imaging, hard disc drives, and speakers, among other products. In terms of value, two-thirds of the permanent magnets on the market today contain rare earths.

Mass-produced REE permanent magnets are based on either neodymium-iron-boron (NdFeB) or samarium cobalt (SmCo) alloys. In this report, the focus will be on the NdFeB market, given that (1) the SmCo magnet market is relatively small and (2) there is less concern about the supply of samarium.[4]

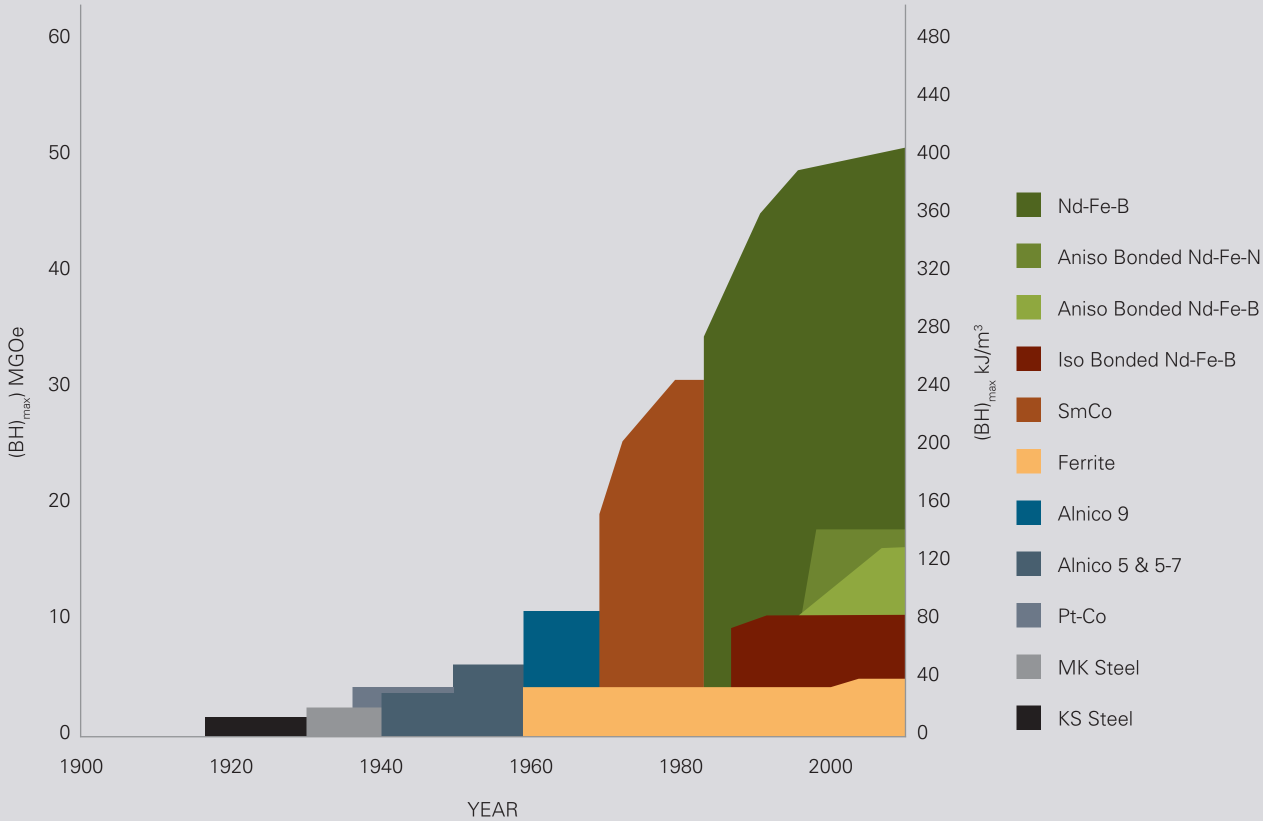
Smaller amounts of heavy rare earths and other metals are sometime added to NdFeB magnets to fine-tune their characteristics. The most important additive is dysprosium, which improves the resistance to demagnetization (coercivity) and hence allows the magnet to be used at higher temperatures. Up to 11wt% dysprosium is added to NdFeB magnets in high temperature applications such as electric engines or turbines. Because of the high price of dysprosium, the value of the magnet in these devices could be twice that of magnets in lower-grade applications.

No magnet-making material with superior qualities to NdFeB has been discovered so far (see Figure 2.2). The magnetic strength of NdFeB magnets, measured in terms of their energy product, can be as high as 470 kJ/m^3, close to the theoretical maximum of 512 kJ m^3/ 512 kJ/m^3.

REE-based magnets compete with the other major class of permanent magnets, so-called hard ferrites. Discovered in 1946, the latter still represent the greatest share by mass of magnets produced each year (Gutfleisch et al. 2011, 827; Coey 2012, 525). Hard ferrites can easily be mass-produced at comparably low cost. They resist corrosion and are widely used in lower-performance motor applications, sensors, and other larger electronic devices. However, they are much weaker magnets, making them unsuitable for high-performance applications, where REE-based magnets dominate.

Figure 2.2:

The development of magnet making materials, 1900 – 2000



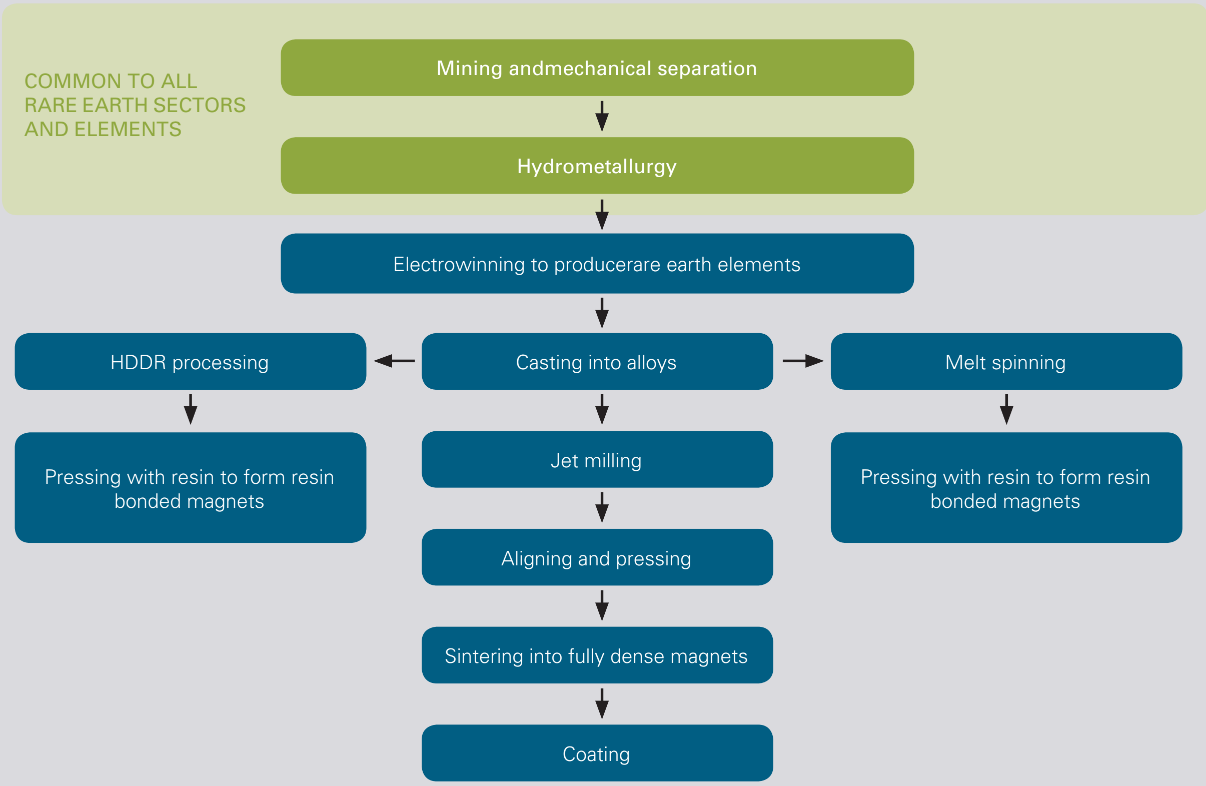
Source: Constantinides, S. (2014) 'The technology and market issues of magnetic materials'. Slide 34, presentation at the IEEE Energy Conversion Congress and Expo, Pittsburgh, USA, September 14.

There are three primary ways to produce NdFeB permanent magnets: (1) by sintering microcrystalline powders; (2) by resin-bonding magnets using nanocrystalline powders; and (3) by hot deformation using nanocrystalline powders. By mass, the market share across these three routes is approximately 70 kt sintered, 10 kt of resin bonded, and 1kt of hot pressed magnets (Chengzhi, Yang, & Wei). Figure 2.3 shows production routes (i) and (ii) for the main NdFeB magnets.

Like in other high-tech industries, intellectual property is key to the control of rare earths supply chains. In the case of NdFeB permanent magnets, the Japanese company Hitachi Metals Ltd. holds the main patent (US patent 5 645 651). This patent expired in July, and in August 2014 an alliance of several Chinese companies launched a lawsuit in the U.S. against Hitachi, which is seeking to obtain an extension of this key patent. Magnet producers around the world license the patent from Hitachi, including EU-based producers of NdFeB permanent magnets, such as Vacuumschmelze, Morgan Crucible Company, and Neorem, Magnetfabik Schrambach.

Many of the technologies that would depend on high-performance permanent magnets are only just beginning to reach mass markets. This includes the already mentioned wind turbines and electric vehicles as well as future technologies such as magnetic cooling, which has big potential in domestic as well as industrial refrigeration and air conditioning (e.g., automotive and building). Compared to existing cooling technologies, magnetic cooling produces fewer environmentally hazardous gases, is more energy efficient, and generates less noise during operation.

Figure 2.3:
Principal processing routes for sintered and bonded NdFeB magnets



Source: Allan Walton, University of Birmingham.

2.1.2 Demand trends for rare earths

Both the financial crisis in 2008 and the rare earths supply crisis of 2010 adversely affected demand for rare earths. The financial crisis weakened demand fundamentals and slowed the growth of markets for REE-intensive high-tech products; meanwhile, export restrictions put upward pressure on REE prices, further curtailing demand. Consumption fell sharply in 2009 and, after an initial recovery, dipped again 2011 following the tightening of Chinese export restrictions. It wasn't until 2014 that demand recovered to its pre-2008 peak of approximately 124 kt of rare earth oxides (see Figure 2.4).

Since the supply crunch, the more efficient use of rare earths – which was driven by higher prices and supply concerns – has contributed to weakened demand for virgin material. Breakthroughs have been achieved particularly in the use of processing wastes during manufacturing. This includes techniques that allow REE polishing powders to be re-used several times; such methods were pioneered by Japanese companies in the aftermath of the supply crisis.

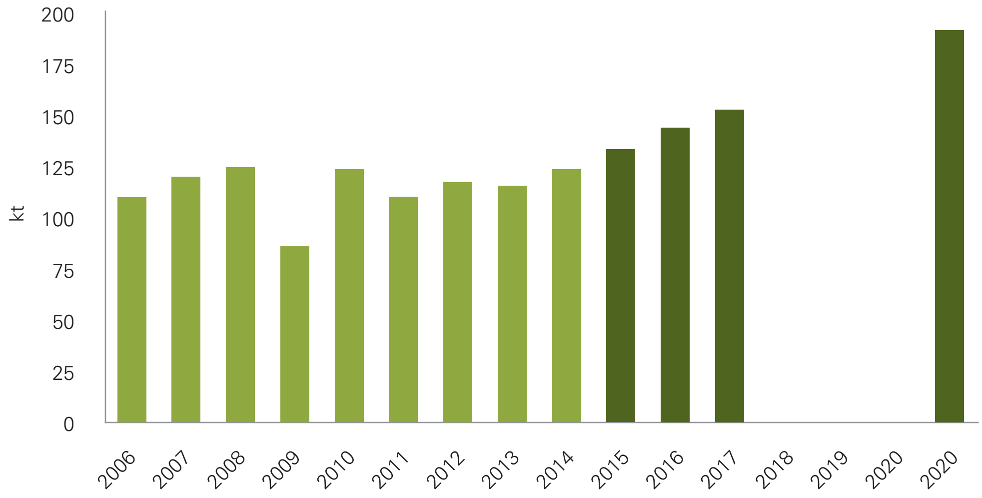
More recently, Chinese companies have developed methods to successfully recover rare earths from magnet filings, also known as swarf. Currently most NdFeB magnets are produced in the shape of simple blocks that have to be cut and ground to achieve their final shapes, creating large quantities of magnet swarf in the process. So-called 'near net-shape' processes like hot deformation are still too costly in mass production and are currently only used to manufacture niche products. As result, magnet manufacturers produce large amounts of swarf each year and stockpiles have been accumulating in China. Novel techniques have allowed Nd, Pr, and Dy to be recovered in a cost effective manner. It has been estimated that between 30kt and 50kt of the rare earths that are used in magnet making – which is equivalent to between one and two years' worth of supply – can be recovered from these stockpiles.

In addition to the recycling of processing wastes, more frugal use of rare earths in final products has also reduced demand for mined material. In the case of magnets, large reductions in the use of dysprosium have been achieved through pioneering so-called grain boundary diffusion processes. These enable magnet manufacturers to place the costly and scarce heavy rare earth in particular areas within the NdFeB microstructure, that is, at the grain boundaries, where their hard magnetic properties are mostly needed. This makes it possible to use much less dysprosium than before without significant performance loss (Park et al. 2000; Komuro et al. 2010).

Throughout the REE crisis, such resource efficiency measures have played a key role in managing supply constraints. But they also have had a lasting effect on demand, as lower quantities of REEs are needed to fulfil their process- and product-enabling roles. Such efficiency-linked demand destruction is a common phenomenon in resource markets that have been affected by supply crises: concerted efforts to boost energy efficiency in the aftermath of the oil shocks of the 1970s, for example, led to lasting demand destruction in crude oil markets.

Looking forward, however, REE demand is projected to increase considerably in the coming years. Greater market penetration for many maturing REE-intensive products such as hybrids and electric vehicles, lower REE prices, and a recovering world economy are all contributing to higher REE demand. Magnet applications in particular could see double-digit growth rates in the coming years. At the same time, the low-hanging fruit in terms of boosting material efficiency appears to have been picked. While further efficiency gains are undoubtedly possible, they will require intensified R&D efforts and are unlikely to lead to breakthroughs that could significantly slow demand growth in the near term. According to estimates by Curtin University and IMCOA, REE demand is projected to increase by more than 20% compared to 2014 levels by 2017, and could be over 50% higher than 2014 levels by 2020 (see Figure 2.4).

Figure 2.4:
Historical and forecasted rare earth consumption, 2006-2020



Source: Curtin University, IMCOA, 2014. REE production and consumption statistics are subject to considerable margins of error and difficult to verify due to the existence of a REE black market fuelled by illegal exports from China.

2.1.3 The impact of disruptive technological change on future REE demand

While it is clear that rare earths demand is likely to grow in the coming years, demand projections such as those made in Figure 2.4 are subject to large margins of uncertainty, especially looking ahead to 2020 and beyond. Design changes can have a significant impact on the material profile of individual products. Engines and batteries for electric vehicles (EVs), for example, currently come in several versions; some contain large quantities of rare earths, but others contain none or only negligible amounts. What type of batteries and engines will come to dominate the EV market depends on a combination of factors, including regulatory pressures and company considerations about safety, performance, cost, consumer preferences, and intellectual property. Concerns about the supply security of the required materials typically play a secondary role in the decision-making process.

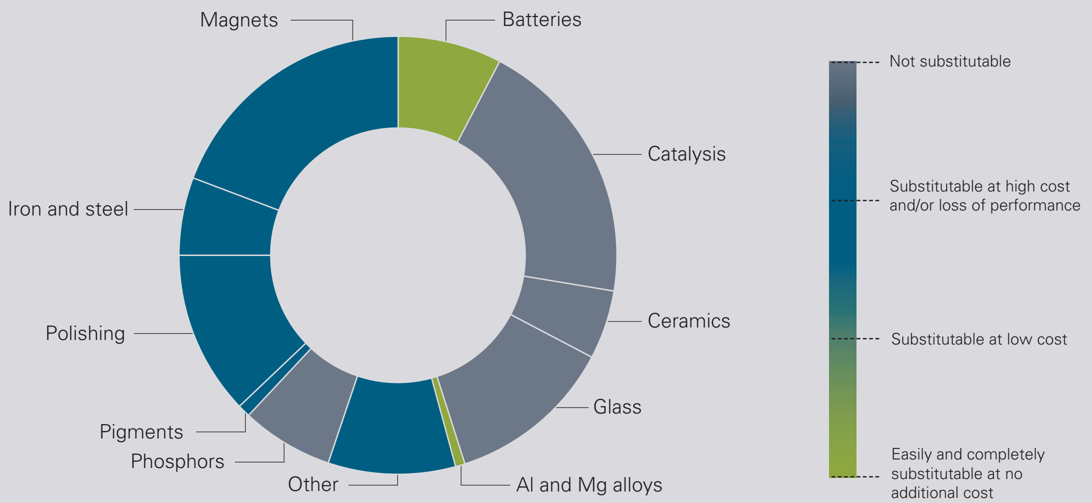
In combination with questions about the speed and extent to which EVs will gain market share, this creates significant uncertainty about future REE demand from electric vehicles. If EVs replace conventional vehicles rapidly and REE-based technologies dominate the market, this could trigger exponential demand growth for REEs towards 2020 and beyond. If, however, the transition to EVs turns out to be a slow process or REE-based battery and engine designs play a minor role in the market, the impact of EVs could be fairly small. Similar uncertainties exist for many other REE-based high-tech applications, making forecasts for future REE demand liable to unusually large margins of error.

Trends around the use of lighting phosphors illustrate the dramatic impact that such technology trends can have in a niche market such as rare earths (see box).

Can rare earths be substituted in key applications?

Today, research and development into the substitution of critical metals is happening at many levels: elemental, material, product, process, and system. The substitutability of individual rare earth elements varies greatly across applications (Figure 2.5). This box focuses on presenting current developments in the strategically important fields of permanent magnetism and lighting.

Figure 2.5:
Current substitutability of rare earths by application



Source: CRM_Innonet.

Substitution strategies for rare earth elements in permanent magnets

In recent years, a number of promising research initiatives have begun to look for new ways to substitute or at least radically reduce the amount of REEs needed in magnet applications. This research and development could have short- and long-term impacts on permanent magnet markets, with knock-on effects on REE demand.

In the short and medium term, NdFeB magnets used in motors may in some cases be replaced by lower-performance ferrites. Manufacturers are working to determine more precisely where high-performance permanent magnets are really needed and where they overdo their job. Where possible, producers are already re-designing machines to make them compatible with ferrite magnets (examples include servo motors in cars and motors in industrial applications).

In the long term, research in physics and fundamental material science is likely to lead to the discovery of new hard magnetic materials. In the ideal case, such materials would have the same energy density as NdFeB – or perhaps even higher – and would show equivalent or even better properties at high temperatures.

More realistically, it would still be a breakthrough success to find a permanent magnet material that shows significantly better properties than existing ferrites and that can be mass-produced inexpensively. There is a huge potential market opportunity for such a new material, which could fill the gap between NdFeB and ferrite magnets. In high-end applications (e.g., small and energy-efficient devices, such as disc drives, fast-moving servo motors (robots), and consumer electronics) where high energy densities are required, the substitution of NdFeB will remain undesirable. But in lower-value applications, permanent magnets that are cheap but surpass the performance of ferrites could ease pressure on REE-based magnet materials.

The physics of magnetism means that the hunt for such a material needs to focus on transition metal-based compounds to develop a ferromagnetic material. Finding such a new material is not straightforward and will take time, but it is certainly not impossible[5]. In the early 1980s, the research groups that discovered the NdFeB permanent magnet were motivated by the cobalt crisis, which had put the production of SmCo-based magnets at risk.

On a system level, substitution research currently focuses on finding or improving systems that do not require permanent magnets, like induction motors. However, it is important to note that the electric engines that do not contain REE-based permanent magnets are currently less energy efficient.

Rare earth elements in luminescent materials: Substitution strategies

REEs can emit light in the visible range due to their special chemical and physical properties; as such, they currently play a key role in the global lighting industry, REE-doped phosphors provide particularly energy-efficient lighting sources. Substituting rare earths in lighting applications can take several forms:

- Material substitution: substituting the dopant, sensitizer, host material or the complete phosphor.
- Component substitution: substituting core components like the electronics, phosphors, or mercury (in the case of fluorescent lamps) or semiconductor material (in the case of LEDs).
- System substitution: replacing the entire lighting system. The best example of this is the current displacement of fluorescent lamps by LED-based illuminants.

Currently, the lighting industry is heavily affected by systems substitution. Lighting industries in advanced economies have been under sustained policy pressure to improve energy efficiency. This helped to accelerate the transition from filament bulbs to fluorescent lamps, and it is now increasingly driving the switch from fluorescent lamps to LED illuminants.

The transition towards fluorescent lamps has been an important source of demand growth for the heavy rare earths that are contained in the lighting phosphors, but the switch to LEDs reduces REE demand significantly. LEDs have a longer lifetime and contain only about 1% of the phosphors that would be needed in a fluorescent lamp with an equivalent lighting efficiency.

LEDs have penetrated the lighting market much more quickly and extensively than industry experts had predicted just a few years ago. The consequence of this is much lower consumption of REE-based lighting phosphors. As LEDs come to dominate lighting markets over the next five to ten years, the markets for europium, terbium and yttrium will experience a significant drop in demand. The development of new applications (in specialty ceramics for yttrium and in magnets, where terbium could help to substitute dysprosium), could partly offset the drop in demand for REEs in lighting applications. But the market for europium is almost 100% based on lighting applications, which means this element could be in oversupply in the coming years.

On a materials level, current research on the substitution of phosphors is also driven by energy efficiency concerns. New alternative compounds are still likely to contain REE-dopants, since currently these appear to be the most energy efficient ones (such as REE-doped borate-glasses[6] and REE-doped nitride[7]). Only a few kinds of luminescent materials have been investigated so far, however, and an even smaller fraction has been put forward to industrial production and application. There is therefore considerable potential to discover energy- and resource-efficient phosphors that do not contain critical REEs.

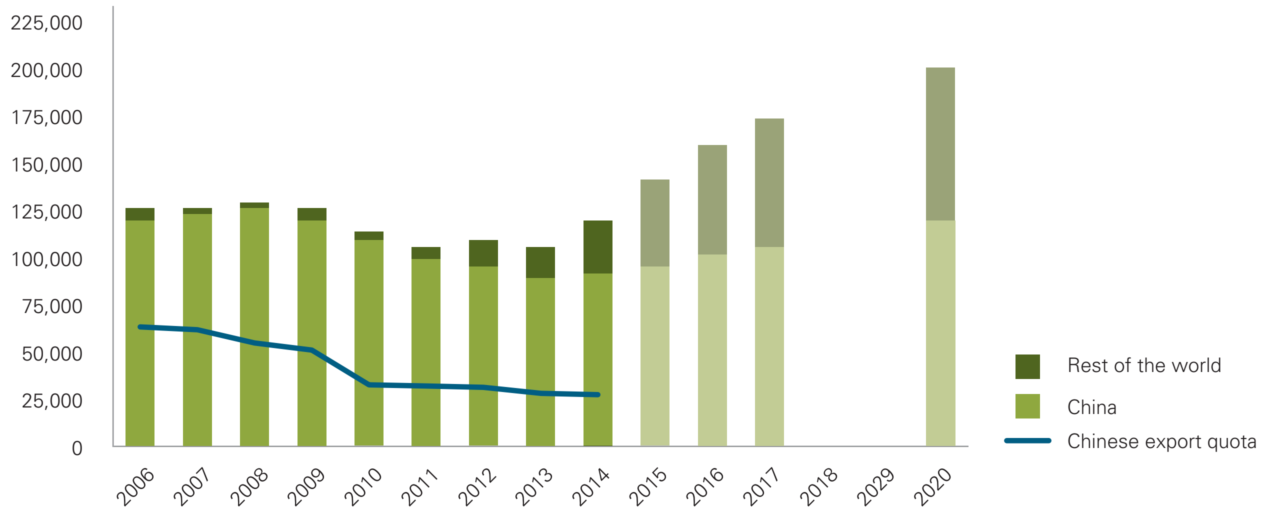
2.2 Enduring challenges for supply towards 2020

From 2008 onwards, cuts in Chinese production and exports reduced global REE supply significantly (Figure 2.6). From 2008 onwards, efforts to phase out illegal and inefficient production in China, in combination with a gradual tightening of export quotas, caused Chinese rare earths production to plummet by over a quarter between 2008 and 2013. Since last year, China's production has stabilized, but it is projected to increase only gradually over the coming years as the sector undergoes further consolidation.

Efforts to bring new mines into production have contributed to a substantial supply expansion outside of China. Assuming appropriate funding can be secured, this is likely to continue towards 2020. The lion's share of supply growth will come from two operations: the Mountain Pass mine in California and the Mount Weld mine in Australia. Mountain Pass is a historical mine that used to be the world's premier source of REE supply, before it was shut down in 2002 amid low prices, over-supply, and permitting challenges. The Mount Weld deposit was discovered in the late 1980s and has been developed into a full-fledged mining operation over the past decade.

At target capacity, these two mines (in combination with smaller mining operations in other countries) will likely be able to meet non-Chinese demand for light rare earths in the coming years. Both operations have begun production and are currently working to optimize process flow sheets and reduce costs. The companies have a combined initial target capacity of about 40kt of REE oxides. Molycorp and Lynas, the companies operating the mines, have also invested heavily in state-of-the-art separation facilities that allow ore concentrates to be separated into individual rare earth oxides.

Figure 2.6:
Historical and forecasted rare earth supply, 2006-2020



Source: ERECON based on data from Curtin University, IMCOA, 2014. REE production and consumption statistics are subject to considerable margins of error and difficult to verify due to the existence of a REE black market fuelled by illegal exports from China.

However, the composition of the ore that is being mined at Mountain Pass (19 ktpa initial target capacity; Nd/Pr: ~15%; <2% HREE) and Mount Weld (11 ktpa initial target capacity; Nd/Pr: ~25%; <5% HREE) implies that these operations will be unable to meet the demand for heavy rare earths outside of China. Until additional mining operations commence, Chinese suppliers will therefore continue to dominate heavy rare earths supply.

China's trade policy with regards to rare earths: Past, present and future

China's export policy will remain a key factor in shaping the future supply of rare earths. The Chinese government appears to be pursuing a mix of goals, including combatting illegal production and exports, consolidating the industry, improving efficiency and environmental practices, increasing rare earths prices, and boosting the domestic processing industries. After phasing out its earlier policies to promote REE exports, the Chinese government introduced a system of export quotas, duties and licenses in 2006. Export restrictions were gradually tightened in subsequent years, with overall quotas being reduced and duties being increased. Quotas have also become increasingly specific (targeting light and heavy rare earths separately), while the number of companies licenced to export rare earths has been reduced. At the same time, the government has established stockpiles and pricing platforms (see Table 2.2).

Doubts about the further evolution of China's export policies have created considerable uncertainty over future REE supply outside of China. The successful WTO challenge to China's controversial rare earths export regime – which was brought by the EU, the U.S., and Japan – has thrown this system into limbo. While the Chinese government is likely to overhaul its system in the aftermath of the WTO rulings, it is unclear to what extent this will entail an adjustment of the country's policy priorities. By adopting other policy measures – such as converting quotas into royalties and domestic subsidies or vertically integrating major miners with key downstream processors – China could allow its domestic industries to maintain preferential access to rare earths while still complying with the WTO ruling.

Table 2.2:
China's REE export policy, 2005 to present.

2005	Export rebates abolished
2006	System of export licences and quotes introduced (53 companies)
2006-09	Export quota reduced by average 6.5%pa
2007	10% export duty introduced
2009	Goverment-funded LREE stockpiles established in Baotou
2010	Export quota reduced by nearly 40% Export taxes increased to 15% or 25% China temporarily suspended shipment of rare earths to Japan
2011	Export restrictions extended to more downstream products Export licensed issued to just 37 companies
2012	Introduction of separate export quotas for LREEs and HREEs Introduction of Baotou Rare Earths Trading Platform (launch October 2013) goverment-funded HREE stockpiles established in South China
2013	Concerted effort to accelerate industry consolidation and vertical integration

A small portion of the exploration industry is now focused on developing the next generation of rare earth mines. While more than 50 advanced-stage rare earth exploration projects are under development in 16 countries around the world, fewer than 10 projects have been adequately funded to achieve further technical milestones. However, given the size of the global REE market, there is only scope for a handful of HREE-rich deposits to develop into actual mines by 2020. To become mines, prospective projects have to overcome a number of hurdles including securing financing, developing a viable business model for separating rare earths, and obtaining the relevant permits, especially with regards to the management of potentially radioactive tailings. Falling REE and share prices have made it increasingly difficult for projects to access funding, creating uncertainty about the timelines for future mines. This topic is discussed in greater detail in the next chapter.

CHAPTER /03

MINING RARE EARTHS IN EUROPE:

Pipe dream or overlooked potential?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Europe currently has no mine supply of rare earths. In the past, however, the elements have been mined on an industrial scale as by-products in Finland, and potentially mineable deposits have been reported in a number of European countries.[8] REE-bearing apatite concentrate was also mined as a by-product in the Korsnäs lead mine from 1963-1970.[9]

Until recently, the geological and economic potential to mine such rare earths deposits in Europe had not been comprehensively assessed. However, since the 2010/2011 spike in REE prices, concerns about the security of Europe's rare earths supply have led European geological surveys to intensify their data collation efforts, and spurred companies, from both Europe and abroad, to do more exploring.

Translating European exploration projects into actual rare earth mines requires making a strong case for their economic viability. This remains challenging against the backdrop of an uncertain outlook for global demand, supply, and prices for rare earths. Moreover, scalable metallurgical processes need to be developed for cost-effective processing of individual ores.

The question of how to separate rare earths is of particular importance for the development of supply. Separating mixed concentrates into individual rare earths is costly and technically challenging, and it has a significant environmental footprint. Whether rare earths mining projects develop their own separation plants or cooperate with existing facilities is therefore a particularly salient question. Advanced separation facilities currently exist in France and Estonia, which currently rely on the supply of concentrates from China and other producers such as the U.S. and Russia.

3.1 GEOLOGICAL POTENTIAL FOR RARE EARTHS IN EUROPE

Europe has a diverse range of bedrock and consequently has a strong potential for the presence of REE deposits. The oldest bedrock is known from the Nordic countries and Greenland, where the most significant REE discoveries have thus far been made.

Only in recent years – or in special geological contexts – have the databases from European Geological Surveys and other institutions or companies included relevant geochemical information on REEs. Most of these institutions have ample information on exploration for a multitude of minerals and metals, but as REEs were of limited commercial interest in the 20th century, they have consequently received little exploration funding or attention.[10]

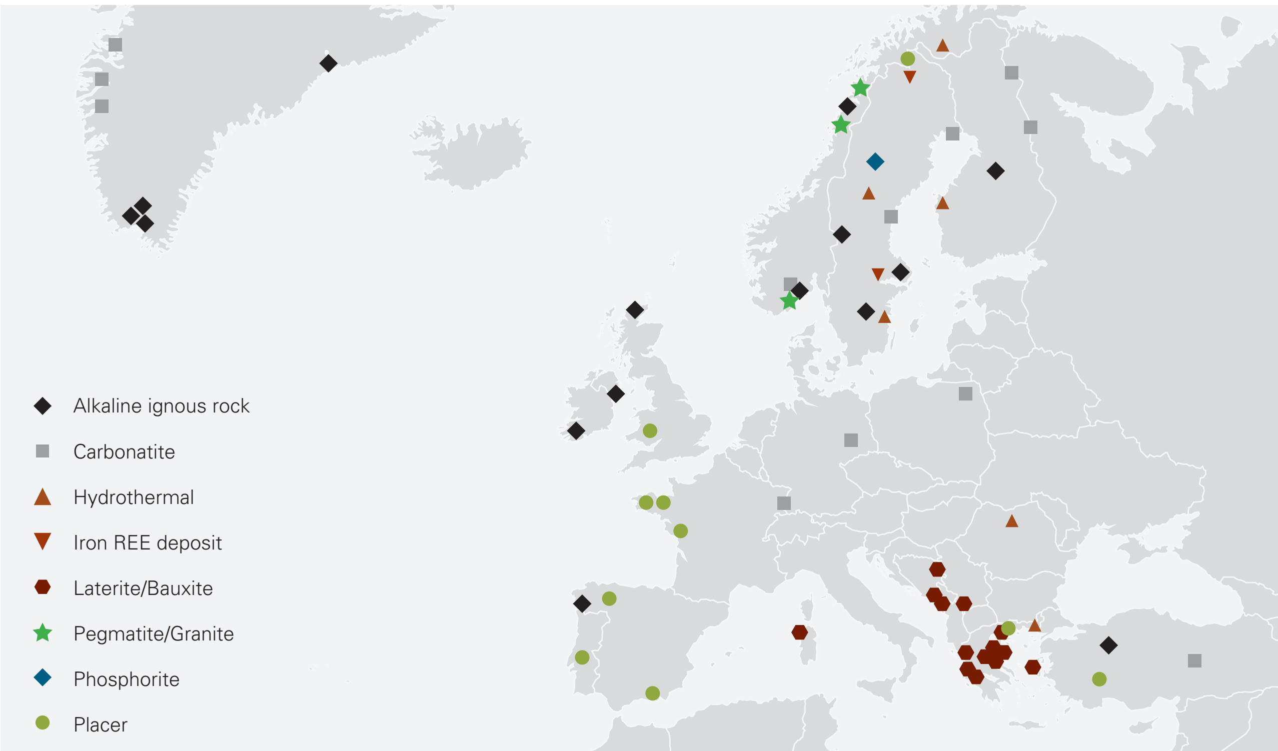
At present, no standard for quoting mineral resources exists across Europe. Quotation of mineral resources for REE deposits in Europe therefore should follow internationally well-known definitions, standards and codes, such those of the Canadian Institute of Mining, Metallurgy and Petroleum (CIM) or Australian Joint Ore Reserves Committee (JORC). Adherence to such standards allows like-with-like comparison of mineral resources, gives investors confidence in the quality of the estimates, and requires an extensive and well-verified database from which conclusions can be drawn on tonnage and grade.

The EU-funded project EURARE is currently conducting an in-depth assessment of exploitable REE resources in Europe, as well as carrying out research to improve the flow sheets for some of the key deposits. The resulting data will be collated into a publicly available Information & Knowledge Management System, which will be released via an internet portal. The project, which is scheduled to report in December 2016, aims to boost the development of the European REE industry.[11] An earlier assessment, which was conducted as part of the ProMine project, provided a database of REE occurrences in Europe but did not differentiate the occurrences based on their economic potential.[12]

Numerous discoveries of significant HREE-enriched and LREE–enriched deposits have been made in Greenland and the Nordic countries. Geological information and assessments of some of the most important European deposits have been gained through projects licensed to commercial exploration groups, of which a few have reached advanced exploration stages, with detailed geological information now publicly available. Figure 3.1 provides an overview of major REE mineralization types in Europe and Greenland.

Less significant LREE-enriched deposits have also been found in coastal areas of north-western France, Greece and the west Balkans, including Turkey. A number of small REE occurrences have been identified in a wide range of other European countries, including the UK, Spain, Portugal, Italy, and Germany. Many of these geological occurrences will still require a proper evaluation, which can help to build a sufficient understanding of Europe's REE potential over the medium and long term.

Figure 3.1:
Overview of major REE mineralisation types in Europe and Greenland



Source: EURARE, 2014

3.1.1 Existing advanced-stage exploration projects in Europe

Several advanced stage REE projects are currently being explored in Europe.[13] The best known of these are in Sweden (Norra Kärr), and Greenland (Kvanefjeld). Given their size and grade, these projects could potentially secure European REE supply for decades to come. These projects have been owned and explored by Canadian and Australian companies, respectively.

Extensive drilling (hundreds of drill holes) has been completed on both deposits, with resources calculated by independent experts under the JORC and NI43-101/CIM systems. Furthermore, extensive physical and hydrometallurgical processing research has been completed to explore potential beneficiation strategies and economics for these projects. With adequate funding and assuming that permitting issues can be resolved, either of these projects could begin to mine REE concentrates before the end of the decade.

Norra Kärr is a large heavy REE deposit that lies in south-central Sweden, close to existing infrastructure and a skilled workforce in the local area. Drilling for rare earths began in 2009 under the current owner, Tasman Metals Ltd. Tasman Metals currently plans to start production in 2017; however, as with all projects, this timeline will be driven by environmental permitting and the company's ability to finance further development. The Preliminary Economic Assessment (PEA) of the project published in May 2012 indicates a resource of 59 Mt, with a planned mine output of 1.5 Mt per year and an 80% total REE recovery rate. For some of the most critical rare earths this would equate to ca. 2300 tpa of Y, 280 tpa Dy, and 40 tpa Tb. Norra Kärr is unusually low in radioactive elements, not significantly elevated above surrounding granite rocks.

The Kvanefjeld deposit lies in southern Greenland, and is a very large and well-known Zn-U-REE deposit; it is currently being explored by Greenland Minerals and Energy ltd. A PFS published in May 2012 outlines a production of 40,200 tpa TREO (of which 5600 t HREO) by a mine throughput of 7.2 Mt/year. The Kvanefjeld study outlines an initial development scenario (with an annual mine through put of 7.2 Mt,) to generate REE, uranium and zinc products as well as a high-grade zinc sulphide concentrate. The study envisaged Heavy Rare Earth Hydroxide – 4,200 tpa TREO; Mixed Rare Earth Carbonate – 10,400 tpa TREO; and Light Rare Earth Carbonate – 26,200 tpa TREO. Recently the company has announced scaled-back plans to approximately 23,000 tpa TREO.

The project has an initial mine life of over 33 years, based on the indicated mineral resources established near surface of the larger Kvanefjeld deposit.[14] The latest plans for start of production are currently targeting 2018-2019.[15] Environmental issues related to radioactive waste, yellowcake production and transport will probably be the largest hurdles. Refinery, some preparation of REE, as well as the yellowcake production is currently planned in Greenland. The separation of critical REEs is currently planned to take place in China, with products marketed jointly as part of a joint venture with the Chinese company NFC.

There are a number of other less developed advanced-stage exploration projects in Greenland, of which the Kringlerne project owned by Tanbreez Mining Greenland A/S is perhaps the most interesting (other advanced stage projects in Europe are Sarfartoq in Greenland, Olserum in Sweden and Storkwitz in Germany). The mining license for the Kringlerne project is currently under application. The business model and detailed geological data have not been disclosed, but initial drilling results indicate that the deposit could be among the biggest in the world, with significant HREE concentrations. Similar to the Nora Karr project, the deposit would be mined for an eudialyte concentrate, which contains no elevated U and Th levels.

Table 3.1:

Most advanced REE exploration projects in Europe compared to advanced projects in other regions

Project Title (Deposit)	Region	Country	Developer / Operator	Mineral resource (Mt)	Grade (TREO wt%)	Basket price (USD/kg)
Kvanefjeld	Europe	Greenland	Greenland Minerals and Energy Ltd.	619	1.06	23
Norra Kärr	Europe	Sweden	Tasman Metals Ltd.	58.1	0.59	39
Ngualla	Africa	Tanzania	Peak Resources Ltd	41.7	4.19	23
Songwe Hill	Africa	Malawi	MkangoResources	31.8	0.16	28
Steenkampskraal	Africa	South Africa	Great Western Minerals Group Ltd	0.7	14	27
Bear Lodge	North America	United States	Rare Element Resources Ltd	52.1	2.71	28
Kipawa	North America	Canada	Matamec Explorations Inc.	27.1	0.4	37
Nechalacho	North America	Canada	Avalon Rare Metals Inc	125.7	1.43	37
Strange Lake	North America	Canada	Quest Rare Minerals Ltd	20	1.44	37
Browns Range	Oceania	Australia	Northern Minerals Limited	6.5	0.74	53
Hastings	Oceania	Australia	Hastings Rare Metals Limited	36.2	0.21	51
Nolans Bore	Oceania	Australia	Arafura Resources Ltd	47.2	2.62	28

Source: ERECON based on data from TMR. The table shows the two most extensively explored projects in Europe, comparing them to the most extensively explored projects in the rest of the world.

3.1.2 Existing early-stage exploration projects in Europee

There are a number of known REE occurrences in Europe that have been less well explored; such areas hold potential for long-term exploration and future discoveries. However, falling REE prices over the last two years have discouraged early stage/high risk investments in REE exploration. Most early stage projects around the world are therefore struggling to obtain adequate funding for active exploration. These projects are unlikely to make a meaningful contribution to rare earths supply before the end of this decade.

One example of an existing early-stage REE project is the placer deposits in the continental shelf of the Northern Aegean Sea, which are rich in heavy minerals that contain promising concentrations of REE elements. This project has just begun, and no detailed information has yet been made available.

The Fen deposit comprises a large body of carbonatite in southern Norway that is readily accessible for bulk mining. The site is well known for its high thorium grades. Two exploration groups, REE Minerals and Thor Resources, are working on different sites at the Fen deposit. To date, 15 drill holes have been completed within REE Minerals's exploitation license, delineating an inferred resource of 84 Mt with an average grade of 1.08% TREO. Preliminary metallurgical test work completed in 2013 has outlined a processing route that uses low-cost optical sorting and gravity methodology.

Monazite sands in the Matamulas (Ciudad Real) in Spain are also a potential source of rare earths. The Quantum Minería (QM) company has provided the first assessment of the value of an ore deposit of monazite sands valued in Europe.[16] The Matamulas deposit could contain 20,000t of rare earth oxides. Additionally, Portugal together with France, Belgium, Luxemburg and Germany are known to have occurrences of REE-bearing monazite.

REE exploration activities are also being conducted in Finland. Northland Resources has the mine concession for the *Hannukainen iron-copper-gold deposit* in western Lapland. The company has investigated the REE potential of the deposit's country rocks, but has not yet published any data.

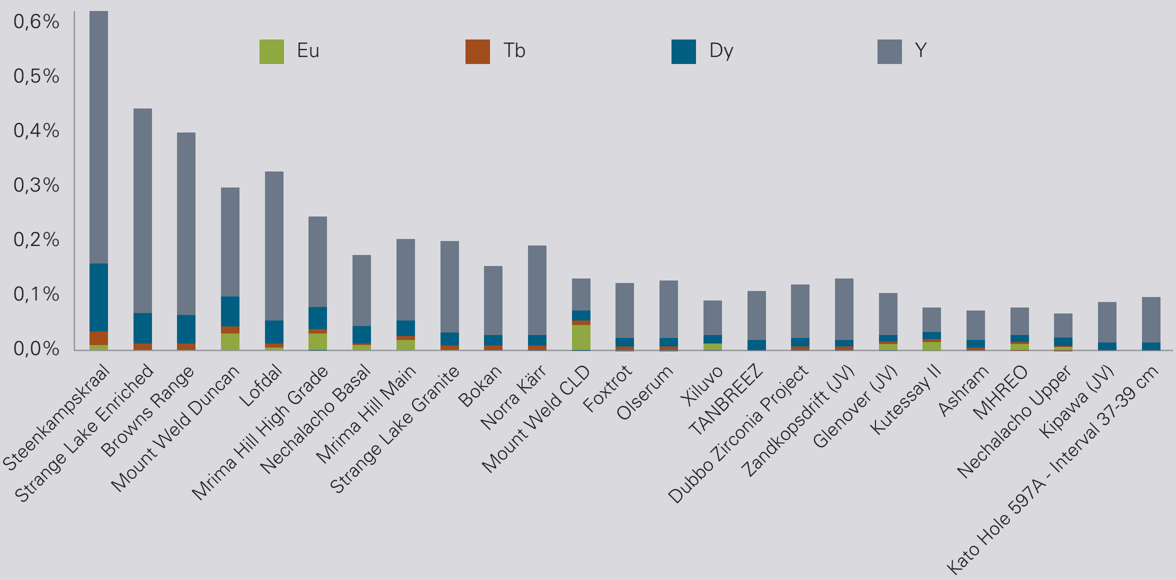
REE type of mineralization associated with the deep sea

In line with the growing interest in deep-sea mining, the potential for mining rare earths in the sea has received considerable interest. An article published in Nature in July 2011 by Kato et al. attracted considerable interest. The authors stated: "We show that deep-sea mud contains high concentrations of rare-earth elements (...) at numerous sites throughout the eastern South and central North Pacific. We estimate that an area of just one square kilometre, surrounding one of the sampling sites, could provide one-fifth of the current annual world consumption of these elements."

The commercial viability and environmental challenges associated with the potential exploitation of such REE deposits have so far not been systematically explored, but appear questionable. Even the most promising results from the study (hole 597-A) show considerably lower REE concentrations than most advanced terrestrial REE exploration projects (see Figure 3.2).

REE have also been reported from manganese nodules and cobalt crusts, two important types of deep-sea mineralizations. But on the basis of average values published by Hein et al. (2013), the concentrations appear much too low to be of possible significance as a primary REE source. If these nodules were mined for their manganese and cobalt content rare earths could be a potential by-product, but even then the low grades may prove insufficient to justify their recovery.

Figure 3.2:
Comparison of best Pacific mud-intersection from Kato et al with terrestrial REE deposits for Dy, Eu, Tb, Y



Source: Patrice Christmann (BGRM) based on Kato et al. 2011 and company reports.

3.1.3 Mineable tailings/by-product potential in Europe

Mining wastes, including various waste streams across the minerals value chain, such as weakly mineralized waste rocks, processing tailings and metallurgical residues, could turn out to be potential resources for recovering exploitable grades of REE (in the literature these have been variously described as *anthropogenic, urban, and technospheric resources*).

In contrast to recycling of rare earths from end-of-life (EOL) products, much less attention has been devoted to previously landfilled stocks and freshly produced flows of rare–earth-containing industrial process residues. Generally, these secondary resources contain much lower concentrations of rare earths than EOL consumer goods. Nevertheless, the volumes of these residues are often very large; thus, the amounts of rare earths locked in these residues can be considerable. The most important resources in this regard include industrial process residues from metal production – such as phosphogypsum, bauxite residue, mine tailings, metallurgical slags – and industrial process residues from thermal treatment facilities (coal ash, incinerator ash). Likewise, scientists are investigating whether wastewater streams could be a source of rare earths as well.

The abandoned historical mine waste dumps in the Bastnäs district in Sweden are an example of such resources. If one considers mines that are currently in production, the Kiruna-Malmberget iron ore mines run by the Swedish state-owned company LKAB (and the stockpiled apatite leftovers) could also be considered a potential source of REEs. The tailings at the Kiruna mine are estimated to contain 5.6 Mt of apatite, carrying about 0.5% TREO of which approximately 20-25% are HREE.[17] Titaniferous mines are also potential secondary resources of REEs.[18] The Salamanca region in Spain has remained an active mining site for tin mineral (cassiterite) processing, in which the REE minerals make up to 5wt% of the concentrates.

Norwegian fertilizer company Yara operates an apatite mine (and fertilizer plant) in Siilinjärvi, with potential for REE-mining as a by-product. The apatite deposit is in a carbonatite-syenite formation. In addition, Yara owns a mine concession of the phosphorus-niobium deposit in the alkaline massive of Sokli, in north-eastern Finnish Lapland. Yara has investigated the REE potential of both gypsum waste heaps in Siilinjärvi and the apatite-niobium deposit of Sokli, but has not yet published data or plans for REE exploitation.

Bauxite residues (BR), sometimes referred to as ‘red mud’, are a red slurry consisting of the un-dissolved portion of the bauxite ore. On a dry basis, these are produced at an almost 1:1 mass ratio with alumina, globally amounting to a total of 100 Mt to 120 Mt BR per year. BR consists for the most part of Fe and Al oxides, with lesser or trace amount of Si, Ca, Na, Ti, V and REE oxides. At present, BR are not being exploited but rather stored in artificial ponds and landfills. Stockpiled BR (e.g., red mud residues derived from alumina extraction in Greece and elsewhere in Europe) may be considered an important low-grade resource for extracting REEs. The technical feasibility and commercial viability of beneficiating REEs in red mud are currently being studied by the EURARE project and will be separately investigated by the recently approved MSCA ETN REDMUD.

3.2 CHALLENGES TO THE DEVELOPING RARE EARTH MINES IN EUROPE

REE exploration projects, in Europe and elsewhere, face a number of complex challenges that need to be overcome before actual mining of rare earths can commence. These are principally related to project economics, metallurgical challenges, sound management of environmental impacts, permitting, access to finance, and the establishment of a marketing channel for the product of the mine. Viable answers to all of these challenges need to be found before investors will commit to a project and the decision to mine can be taken. This section examines issues related to project economics and permitting, including managing environmental and radioactivity issues. Questions about the processing and marketing of mine products will be discussed in Chapter 5.

3.2.1 Project economics

Aspiring mining projects need to demonstrate that mining the deposit presents an attractive business opportunity. In the first instance, this relates to the **quality of the deposit**, in terms of the *size of the deposit* and the average concentration of rare earths in the mineable ore (also known as ore grade). Very low grades will make mining prohibitively expensive, and small deposits have short lifetimes that won't justify the required capital expenditures.

Perhaps even more important than the overall concentration of REEs in the deposit is the specific *mix of rare earths* in the ore. Deposits with a relatively high share of low-value REEs such as cerium and lanthanum are economically much less attractive than deposits that are unusually enriched in high-value rare earths such as dysprosium. Deposits are often compared according to the 'basket price', i.e. the USD value of an average kilogram of rare earths that would be produced from that deposit.

Evaluating project economics for rare earths becomes more complex if the planned mining operation includes the production of *by-products* (such as zirconium or uranium) that can add to the value of the ore. The cost of recovering, beneficiating, and marketing such by-products need to be carefully evaluated, but, depending on the deposit, they can be a significant benefit to the REE project economics. The advanced stage exploration projects in Europe discussed above (as well as many projects around the world) mostly include plans for the beneficiation of by-products.

Even high-value deposits can be economically unattractive if the ***operating costs*** are very high. These costs relate to a variety of factors. Firstly, the cost of *beneficiating* the ore can vary widely, depending on the geology of the deposit and the technology used to liberate the rare earths component from the ore into a concentrate. Exploration companies spend considerable time and resources on R&D to optimize these processes, first on the bench-scale and then in pilot plants, with the goal of enhancing recovery rates and reducing costs. The required amount of energy and acids to treat the ore are often critical to these operating costs and vary considerably across projects.

Location is also a significant factor for operating costs. Remote projects often struggle with high operating costs, as energy needs to be generated at the site, the workforce needs to be flown in and housed at the project site, and transport of materials to and from the mine site is difficult and costly. Where projects can benefit from pre-existing infrastructure, grid electricity, short transport routes and access to a skilled workforce, operating costs tend to be much lower.

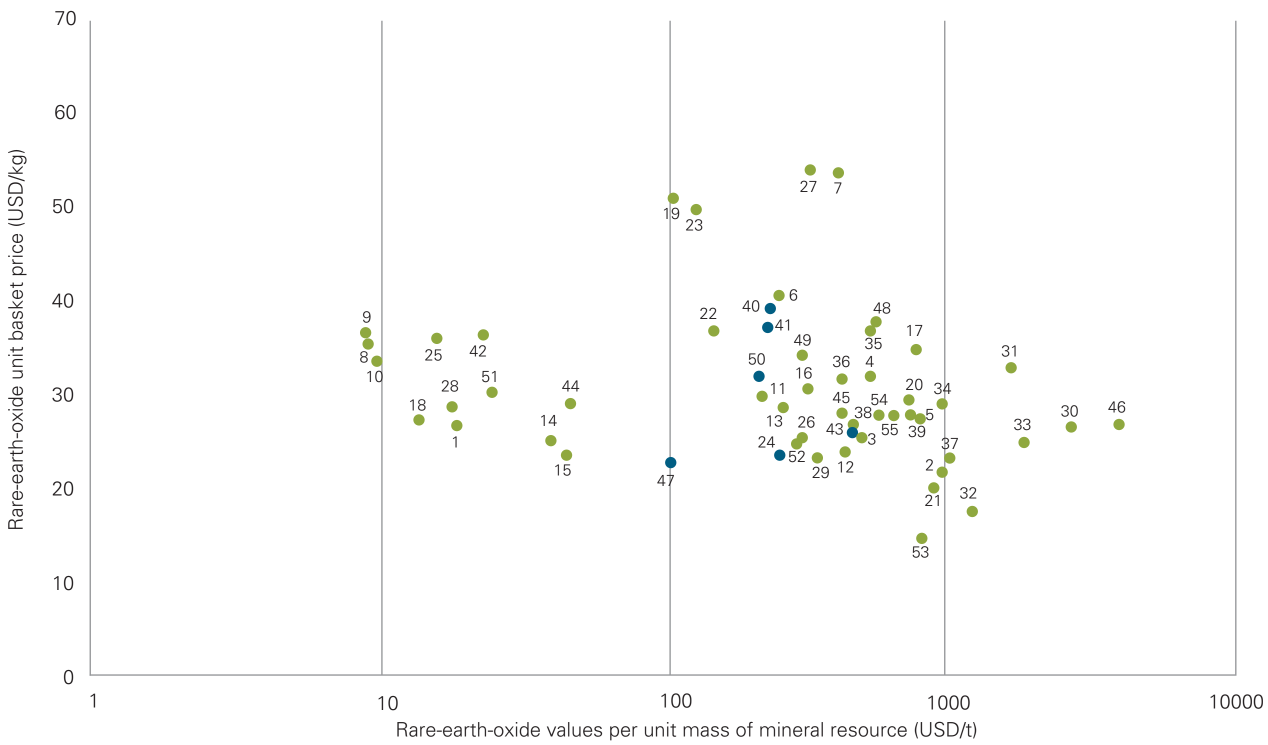
The initial **capital expenditure** required to start the mining operations is also a key factor for evaluating mining operations. High overheads do not only weigh on the potential revenues from a mine, they also create high risks for investors, who may be reluctant to spend hundreds of millions of dollars up-front to start a risky mining venture.

Like for operating costs, *location* is again a key factor for determining the capital expenditure needed to develop a project. Remote operations often require the construction of costly dedicated infrastructure (such as power plants, housing, roads, railway lines or ports) that can increase up-front capital needs. The *geology of the deposit* and the *design of the mine* can also affect capital requirements: Deposits at greater depth, for example, require more stripping of overburden (for open-pit operations) or deeper mine shafts (for underground mines), creating higher costs before actual mining can begin.

Figure 3.3:

Value metrics for advanced rare earths projects, September 2014

1 Aksu Diamas
2 Araxá
3 Ashram Main
4 Ashram MHREO
5 Bear Lodge
6 Bokan
7 Browns Range
8 Buckton
9 Buckton South
10 Charley Creek
11 Clay-Howells
12 Cummins Range
13 Dubbo Zirconia Project
14 Eco Ridge
15 Elliot Lake Teasdale
16 Foxtrot
17 Glenover
18 Grande-Vallée
19 Hastings
20 Hoidas Lake
21 Kangankunde
22 Kipawa
23 Kutessay II
24 Kvanefjeld
25 La Paz
26 Lavergne-Springer
27 Lofdal
28 Milo
29 Montviel
30 Mount Weld CLD
31 Mount Weld Duncan
32 Mountain Pass
33 Mrima Hill High Grade
34 Mrima Hill Main
35 Nechalacho Basal
36 Nechalacho Upper
37 Ngualla
38 Niobec
39 Nolans
40 Norra Kärr
41 Olserum
42 Round Top
43 Sarfartoq
44 Serra Verde
45 Songwe Hill
46 Steenkampskraal
47 Storkwitz
48 Strange Lake Enriched
49 Strange Lake Granite
50 TANBREEZ
51 Tantalus
52 Two Tom
53 Wigu Hill Twiga
54 Xiluvo
55 Zandkopsdrift



Source: Gareth Hatch, Technology Metals Research, prices are calculated based on Metal Pages prices on an FOB China basis.

Given their complexity, the economics of individual REE exploration projects are subject to much controversy among miners, investors and the expert community. Meaningful comparisons are often possible only for advanced stage exploration projects, where the deposit, mine design, potential metallurgy and logistics have been studied extensively and information has been made publicly available in pre-feasibility studies and economic assessments. Although like-for-like comparisons among mining projects remain difficult, existing assessments regularly rank some of the advanced stage REE exploration projects in Europe among the top-tier projects in the world in terms of their economic attractiveness (see e.g. Figure 3.3).

3.2.2 Environmental management, radioactivity and permitting

Potential rare earths mines tend to have a significant environmental footprint. Where rigorously applied, state-of-the-art environmental technology and management practices can effectively reduce such impacts to a near-zero level. If such impacts are not carefully mitigated, monitored and managed, REE mining and beneficiation can become a source of damage to the environment and human health. The adverse consequences of poor environmental management practices in REE mining and processing in China – where decades of malpractice in the sector have taken a heavy toll on humans and the environment – serve as a powerful warning in this regard.[19]

There are a number of environmental problems associated with REE mining in China:

- No or insufficient filtering of acidic off-gas (hydroflouric acid, sulfuric acid, dust, etc.);
- Only basic operational waste management, which creates large quantities of hazardous tailings (with impacts on groundwater, impoundment failure risks, no post-closure management);
- No control over liquid discharges (with respect to acids, salts, toxic and in situ radioactive constituents);
- Misuse of tailings material, e.g. for bricks used in construction, leading to significantly elevated doses in houses and offices;[20] and
- No post-operational clean-up of production sites, leaving behind unconsolidated and unreclaimed hazardous waste piles and ponds.[21]

In Europe, strict regulations and industry standards (e.g., for the treatment of the off-gas, dust emissions, liquid effluents, and tailings) govern any potential mining operations and are part of licensing requirements across the continent. Technologies to achieve a high environmental performance are readily available and can easily be tailored to the needs of any potential European mining project.

Obtaining the necessary environmental permits is a major hurdle for all potential deposits, and cumbersome European licensing processes are often regarded as particularly challenging in industry circles. Concerns focus not only on the safeguards that are required, but also on the duration of the permitting process. Even where permits can be secured, subsequent appeals can often postpone the start-up of a mine or processing plant.

While such strict environmental policies can contribute to higher capital and operating costs, they are unlikely to be a decisive factor in the competitiveness of European REE projects. Operations such as Mountain Pass in the U.S. have demonstrated that stronger environmental standards can go hand-in-hand with efficiency gains and cost reductions.

At the same time, public pressure to improve the environmental performance of REE industries across the globe is likely to continue to increase. Given the frequent use of REEs in green products, sources of REEs that are not considered environmentally sound or state of the art are likely to come under growing public scrutiny. In China, for example, the government is systematically tightening environmental regulations and guidelines for the REE industry. The growing pressure on manufacturers to account for environmental impacts across the entire product life-cycle will also increase the need to search for alternative suppliers that have a strong environmental record.

Managing radioactivity

Managing radioactivity poses a particular challenge for REE mining operations. REE ores are commonly enriched in thorium and uranium, together with their respective decay chains. Radioactivity concerns from rare earth production must be taken into account from mining to mineral processing. There are no such concerns in the downstream steps of the value chain (REE separation, formulations and final applications) since all of the radioactivity has been removed during the mining and mineral processing steps.

This creates additional challenges for REE mining projects that need to comply with strict regulations and demonstrate viable plans to manage such radioactivity issues throughout mining, processing, and transport. Uranium and thorium content is therefore an important factor for evaluating the attractiveness of REE deposits, as management of highly radioactive ores can add to costs and is a key challenge for the permitting of a project. For deposits producing a Th-rich concentrate, permitting of disposal of Th in Europe in particular could be the largest hurdle.

There are large differences in radioactivity across the different REE deposits that are currently being explored. However, the key criterion to assess the projects from the radioactivity point of view is the ratio between Th and U and REE. As shown in Table 3.2, uranium and thorium concentrations in REE ores can differ by up to two orders of magnitude among major REE deposits, from deposits where radioactivity is similar to background levels, to deposits where concentrations are so high that they could justify uranium mining operations.

With regard to ore treatment, two concerns have to be considered:

- Radioprotection: Mining and processing companies must ensure that they comply with international and local regulations for their own employees and the surrounding population. Two criteria have to be considered: ingestion/inhalation (dust) and exposure (radiation).

- Waste management: Mining and processing companies must follow the international and local regulations regarding specifications, handling and storage of their radioactive wastes.

During the mining and physical concentration (milling, magnetic separation and flotation) steps, the ^{232}Th, ^{238}U and ^{235}U radioactive families remain stable in their original mineral. So there is no risk of disseminating radioactive daughters; the main risks to take into account are dust – from a radioprotection point of view – and waste storage conditions.

During the hydrometallurgical steps (cracking and leaching) the minerals are cracked and all the radioelements are liberated. At this step each member of the radioactive families will have its own chemical behaviour. Due to the extremely different types of chemical radioelements that are present in the ore, each of them must be followed carefully – in particular during the chemical steps, where some of them can be solubilized and/or concentrated. Therefore at each process step, the two criteria mentioned above (radioprotection and waste management) must be applied.

While these challenges must not be trivialized, the safety and health standards in the radiation field in Europe are state of the art and allow for responsible management of radioactivity during REE mining. The key question that remains, however, is public acceptance. In this regard, it is important that the treatment, management and storage of all radioactive materials are conducted in the country where the deposit exists.

Table 3.2:
Uranium and thorium content in the ores of a selection of major REE deposits

Site	Deposit	Company	U (ppm)	Th (ppm)	REO	Th/REO
Greenland	Kringlerne	Tanbreez	30	88	0,65%	0,14%
Sweden	Norra Kärr	Tasman Metals	14	7	0,59%	0,01%
Canada	Nechalacho	Avalon	29	160	1,43%	0,11%
USA	Mountain Pass	Molycorp	20	292	6,57%	0,04%
RSA	Zandakopsdrift	Frontier	47	178	2,23%	0,08%
Greenland	Kvanefjeld	Greenland Minerals	257	700	1,06%	0,66%
Canada	Strange Lake	Quest		280	1,44%	0,19%
China	Bayan Obo	Baogang		320	5,0%	0,06%
Australia	Mount Weld	Lynas	11	630	9,80%	0,06%
Canada	Kipawa	Matamec		72	0,42%	0,17%

Source: Consolidation of data from Erecon team.

Relevant EU regulations for the mining of REE in Europe

Three different EU regulations apply to mining and milling waste and other aspects of REE mining and processing.

- **EIA directive /EU 1452/**[22] concerns regulatory processes in cases where environmental effects are not negligible. It requires member states to set up licensing procedures that explore projects' potential environmental impacts, evaluate those impacts, and describe ways to reduce those impacts to certain levels. Given the considerable environmental impacts of REE mining, this directive is applicable to REE mining projects. The process laid out in the directive, if properly followed, guarantees that those impacts are reduced to acceptable levels.

- **Directive /EU 0621/**[23] regulates mining wastes, which requires Member States to "prohibit the abandonment, dumping or uncontrolled depositing of extractive waste obligate mining operators" to comply with high environmental standards and "to ensure that extractive waste is managed without endangering human health and without using processes or methods which could harm the environment" (Article 4). The Directive also requires a "waste management plan for the minimization, treatment, recovery and disposal of extractive waste" (Article 5), with particular attention to water pollution issues (Article 13). The directive is backed by a 557-page document that describe the state-of-the-art and best-available technologies in Europe.[24] This describes in detail the latest ways to manage the life-cycle of mines, including how to manage acid run-off, seepage, emissions to water, noise, dam design and construction, raising of dams, dam operation, closure and aftercare.

- **Directive /EU 1359/** regulates radiation protection issues in the EU member states. It contains provisions for the re-use and disposal of wastes from naturally occurring radioactive materials (NORMs) and sets protection limits for exposures to limit health damages. It is applicable to REE mining wastes, as these are considered a typical NORM waste in the directive. The directive sets exposure limits, but, unlike the mining waste directive, it does not include guidance on how to achieve those goals and has no specific requirements for large-mass wastes such as tailings from uranium plants and REE production facilities.[25]

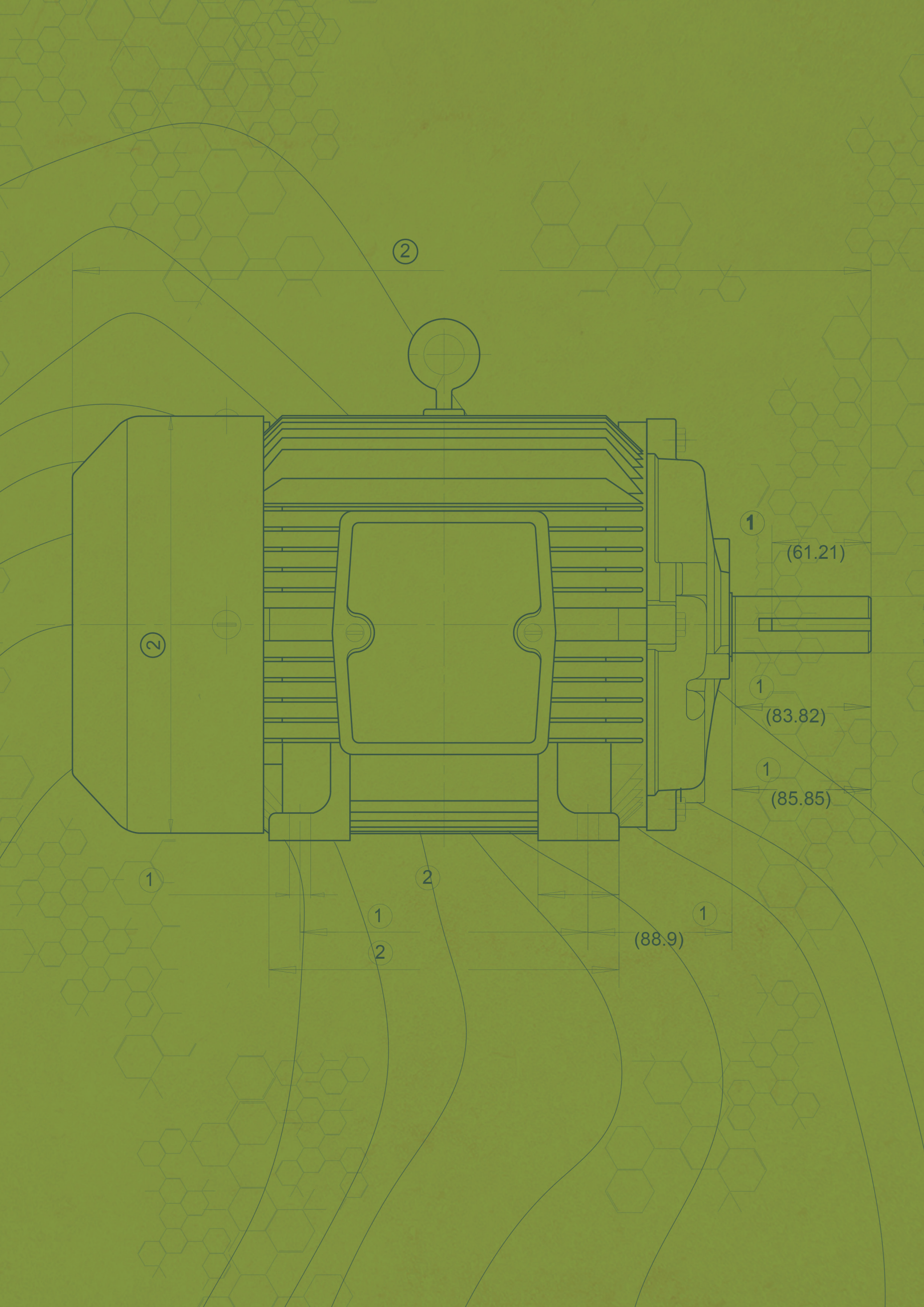
REE mill tailings – including both radioactive as well as non-radioactive hazardous constituents – are covered and well addressed by directives that limit environmental consequences to the extent possible and practical. Additional regulations specific to rare earths do not currently appear to be necessary.

However, two factors could complicate practical regulatory processes in Europe: (1) The separate regulation of radioactive and toxic constituents of mining and milling wastes in the EU regulation framework and (2) the lack of additional guidance below the level of the directive on radiation protection. Such factors could lead to unnecessarily long discussions between licensees and the radiation protection regulators, as the permitting of REE mining and processing facilities could become single-case decisions. More specific requirements for the long-term enclosure of large-volume NORM wastes in above-ground disposal facilities for mill tailings could increase transparency and help to speed up the regulatory process.

CHAPTER /04

CLOSING THE LOOP:

Re-use and recycling rare earths in Europe


2
2
1
(61.21)
1
(83.82)
1
(85.85)
1
2
1
2
1
(88.9)

4.1 INTRODUCTION

Waste is generated at different steps of the REE value chain. This includes the mining and refining stage (e.g., as tailings and slags), during processing (so-called 'new scrap', such as swarfs from magnet manufacturing), and when products reach their end-of-life (so-called 'old scrap'), which is eventually disposed of (e.g., into landfills).

This chapter focuses on the recovery of REEs from end-of-life (EOL) products that are still flowing through the economy. The potential to mine tailings or other mine-stage residues has been discussed in the previous chapter; the existing efforts for 'new scrap' recycling have already made a significant impact on boosting materials efficiency for rare earths, as was discussed in Section 2.12. Identifying and recovering REEs after they have already been disposed of (for example, in landfills) would involve great technical and economic difficulties, and is not further examined in this report.

EOL electrical products could provide a valuable, secure and long-term additional source of REE material for European industries. Europe is one of the world's largest producers and consumers of automotive, electrical and electronic goods that contain rare earths.[26] As a result, the bloc produces large quantities of high-tech wastes each year and some of the world's most advanced waste management systems can offer a sound basis for REE recycling efforts. Unsurprisingly, this has been an active field of research. Indeed, a recent study from the World Intellectual Property Organisation (WIPO) reported a rapid growth in patents related to REE recycling, particularly outside of China.[27]

A mature recycling route for rare earths could offer a number of potential advantages over primary production. These include, for example, a smaller environmental footprint, shorter lead times and a cheaper source of material compared to primary production. Moreover, recycling leaves no radioactive elements to dispose of, and recycling products that contain the most sought-after rare earths could help alleviate the balance problem in primary supply (see section 5.3.2).[28]

However, while it is in prinicple technically feasible today to recycle rare earths from many applications, the recycling rates for REEs from end-of-life products across the world are still reported to be very low (<1%). Only REEs contained in phosphors and batteries have started very recently to be recycled at their end of life (EOL) at an industrial scale.[29] As is the case for primary supply, the drop in REE prices since the supply crisis of 2010/2011 has challenged the economics of recycling schemes.

There still remains considerable uncertainty about the size of the potential market for recycled REE materials. This is due to lack of research to comprehensively quantify the urban mine and to determine what fraction of the waste can be processed economically. Detailed studies taking into account historical and predicted future sales are available only for some REE applications such as for hard drives.[30] Such detailed numbers are however necessary to estimate the size of waste flows of REE-containing products and the average amounts of individual REEs that are contained in them. This could then provide the foundation for estimating what share of these REE-containing products can be economically collected, and what share of the REEs contained in them can be economically recovered.

It is also important to note that a recycled source of rare earth material will never meet the primary demand in a growing market. The faster demand grows and the longer the lifetimes of products are, the smaller the potential contribution of recycling to primary supply. To illustrate, in a market that grows at 10% per year with an average seven-year lifespan for products, the theoretical maximum contribution of recycling is about half of supply. Imperfect product collection rates and recycling yields will reduce this further: If half of the end-of-life products were collected and three quarters of the raw materials were recovered, the recycling contribution would be around 20%. Nonetheless, even limited recycling of rare earth magnets in Europe would probably yield enough material to meet the requirements of the remaining magnet-making industries in the EU. Therefore this material could be used to secure these industries in the short term whilst longer term primary mined sources are developed.

In the short to medium term, commercially viable recycling efforts are likely to concentrate on recovering rare earths from products with high concentrations of valuable rare earths and that allow for considerable economies of scale. Given the relatively small quantity of rare earths in many applications it is likely that key products such as HDDs and end-of-life automomobiles have the biggest potential to be processed on a large scale (HDDs, for example, account for approximately 10% of the world market for sintered NdFeB magnets annually).[31] In the future, applications such as offshore wind turbines and electric vehicles are likely to be particularly valuable targets for recycling efforts due to the large quantities of REEs they potentially contain. Currently, however, they offer limited potential as these products have long lifetimes and their market penetration is still low.

In the absence of detailed data, this chapter provides an analysis of priority products that are likely to be most amenable to economically viable recycling efforts. It surveys existing efforts and identifies key barriers to recycling. It also examines the technologies currently available to recycle key products.

4.2 PRIORITY AREAS FOR END-OF-LIFE (EOL) RECYCLING

Recycling of rare earths from EOL life streams requires a series of steps. The approach taken at each of these steps can have significant implications for the overall economics of recycling rare earths and therefore needs to be examined in detail:

- **Identification** of products that contain rare earths in waste streams based on detailed market analysis
- **Collection** of the identified products in sufficient quantities to make recycling viable on a commercial scale
- **Detection** of the rare earth-containing component/material in the scrap (e.g., the magnet, tube, or battery)

- **Separation** of the components from the rest of the waste stream through manual or mechanical dismantling, sorting, or any other process designed to isolate the smallest fraction containing most of the rare earths

- **Extraction** of the rare earth-containing material from the components (this could be in the form of an alloy, oxide or salt)

- **Refining** of the separated rare earth fraction to an alloy, compound or element

- **Re-processing** of the purified elements or alloys into a new form of material (e.g., a finished magnet or phosphor)

Based on the main applications of rare earths (see Chapter 2.1), priority sectors can be identified in which recycling could have a significant impact on the most critical elements. The main rare earths contained in these products are listed alongside the sectors. The priority list is as follows:

1. **Permanent magnets** (Nd, Pr, Dy, Tb, Sm)
2. **Phosphors** (Eu, Tb, Y, Ce, Gd, La)
3. **Batteries** (La, Ce, Nd, Pr)
4. **Polishing compounds** (Ce)
5. **Catalysts** (La, Ce, Pr, Nd, Y)

This priority list takes into account the criticality of the rare earths used in those sectors, as well as the potential value of the waste stream, the future demand, the concentration of rare earths, the size of the sector, the difficulty in finding substitutes, and whether there are any remaining technical challenges to recycling.

Efforts to recycle rare earths should be concentrated on the first two sectors on this priority list, namely magnets and phosphors. This is because commercial industrial-scale recycling technologies already exist for the recycling of rare earth batteries;[32] the rare earths used in polishing compounds and catalysts are less critical; and the refractory character of the materials concerned makes their recovery particularly difficult and uneconomical at current rare earth prices.[33] However, many of the technologies used in recycling of the latter three sectors are common to all. These will be covered jointly in this report.

4.3 RECYCLING REE PERMANENT MAGNETS

The range of products and applications that use NdFeB magnets has expanded dramatically in recent years, particularly with regard to clean energy technologies. There are a number of applications that were identified by the ERECON network for which recycling may present a significant opportunity. The priority list is as follows:

1. Hard disk drives, DVD and CD players
2. Automotive applications
3. Motors in industrial applications (e.g. servo motors from robotics)
4. Loudspeakers
5. Air conditioning compressors
6. Magnetic separators
7. Mixed electronics
8. Electric bicycles
9. Wind turbines

The ranking of the list took into account the following factors:

- Availability of the scrap
- Ease of identifying the products
- Collection rates
- Amount of material in the application
- Rare earth fraction in the material
- Ease of removing rare earth from the application
- The extent to which particularly scarce REEs such as dysprosium are used

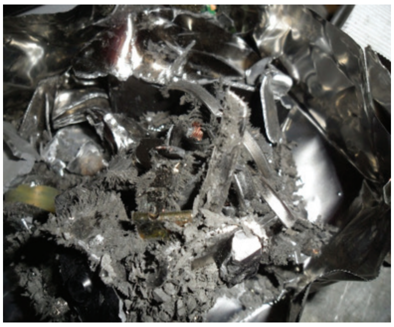
There is only very limited data on the rare earth magnet content for many of the applications listed above; further work is required to demonstrate the scrap potential over time (both future and historical) for each application. The barriers to recycling the rare earth fraction vary considerably depending on the application and often bring unique technological challenges, as is demonstrated by the examples of mixed electronics and automotive industries.

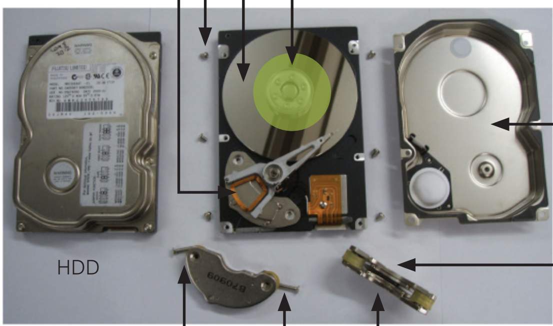
The magnets contained in **mixed electronics** (e.g., mobile phones, electric toothbrushes, shavers, drills, etc.) are often very small (up to 0.5g in a smartphone and considerably less in smaller mobiles)[34] and come in the form of sintered or resin-bonded magnets. The sintered magnets are typically coated with nickel or a multilayer of Ni-Cu-Ni and then glued into position. The component itself forms part of a complicated architecture and is often in different positions within the product.[35] All of these factors make mixed electronics less attractive as a recycling source. The bonded magnets present a particular challenge as they are made up of a rare earth alloy powder intimately mixed with a resin binder.

When they reach their end-of-life, many electronic goods are shredded in order to break the products into pieces that can be separated using standard recycling processes, such as magnetic and electrostatic separation. However, sintered REE magnets are very brittle and break apart when the product is shredded. The powder is still magnetic and tends to stick to the ferromagnetic components in the waste and to the shredder itself (see Figure 4.1). Recovering the powder at this point becomes very difficult; moreover, the powder will be heavily oxidized, which will limit the downstream re-processing routes. Therefore, it is advantageous to remove the REE-containing components prior to crushing, if they are to be recycled. This often would require manual labour, which poses both technical and economic challenges.

Figure 4.1:

Shredded electronic products showing NdFeB powder and a hard disk drive with NdFeB components highlighted





Source: provided by Allan Walton (University of Birmingham).

Several applications in the electronics sector represent significant opportunities for REE recycling. Computer hard disk drives (HDDs) are one such application (see Figure 4.1). Hard drives are collected in large numbers for secure destruction, which means that there is a well-defined waste stream that can be easily accessed. The content of NdFeB in HDDs is relatively high (1g-30g) and the magnets are nearly always in the same position in the device.[36] Moreover, HDDs have a relatively short lifespan and they are already pre-separated in many instances from the rest of the computer.

There are hundreds of applications for permanent magnets in the automotive sector. However, many of the magnets are very small, which creates problems similar to those for recycling electronic goods. However, there are some applications in the automotive sector that use considerable quantities of REE material, for example in drive motors for HEV/EV (1kg-1.5kg), in electric power steering (50g-100g), generators (-0.5 kg) and stop/start technology (50g-100g).[37] The magnets contained in these applications tend to be rich in Dy, as the devices run hot. Therefore, the potential value of this waste will be higher than that of waste from the electronics sector.

These large assemblies may present a significant opportunity for recycling as the components can be separated before the car reaches the shredding stage. However, although the magnets do not tend to be coated they are often embedded in the motor using epoxy resins, which creates challenges for separation. There is often little interaction between material scientists and the motor engineers who design the systems. This disconnect can lead to non-efficient use of the magnetic materials and difficulties for potential recycling. The use of rare earth magnets in the automotive sector is a relatively new development and the magnets are likely to be in service for in excess of 15 years. Therefore it will take time before considerable quantities of NdFeB become available from this sector. For wind turbines, which have a lifespan of 20 years or more, the wait could be even longer.

The following sections discuss the individual stages for recycling permanent magnets, and the challenges they pose.

Identification, collection and detection of magnets for recycling

It is often difficult to identify products that contain rare earth magnets. For example, large amounts of NdFeB magnets are used in loudspeakers. However, the majority of loudspeakers use ferrite magnets and it is not clear whether the NdFeB magnets are only used in certain types.[38] Again, this points to the need for more detailed market analysis from both a top-down approach (tracking the electronics market) and a bottom-up approach (taking apart scrap products to identify magnets). Once a clearer picture has been established for the market, it will be easier to put in place incentives for the collection of those products. The French-German research project "Innovative Re-use and Recycling Value Chain for High-Power Magnets (RECVAL-HPM)" is working to produce a Material Flow Analysis of high performance magnets from WEEE (waste from electrical and electronic equipment) as well as a substance flow analysis of rare earths.

For mixed electronics in particular, it will be crucial to detect the magnets in a moving waste stream. Most current detection techniques such as XRF rely on analysis of the surface of a material and could detect REE magnets only after they have been exposed by shredding. Novel detection systems could help to identify REE components prior to shredding. The EU project Remanence,[39] for example, is investigating such novel sensors.

Separating and extracting detected magnets

Once the products containing the REE magnet have been identified, the magnetic material needs to be separated from the rest of the waste stream and from the coatings on the surface of the magnets. In many ways, the extraction step is the biggest hurdle to the recycling of NdFeB, but it is often overlooked. If the material cannot be extracted from the electronics in a manner that is economically viable, then the downstream processes for re-manufacture are irrelevant; the process will already be too expensive.

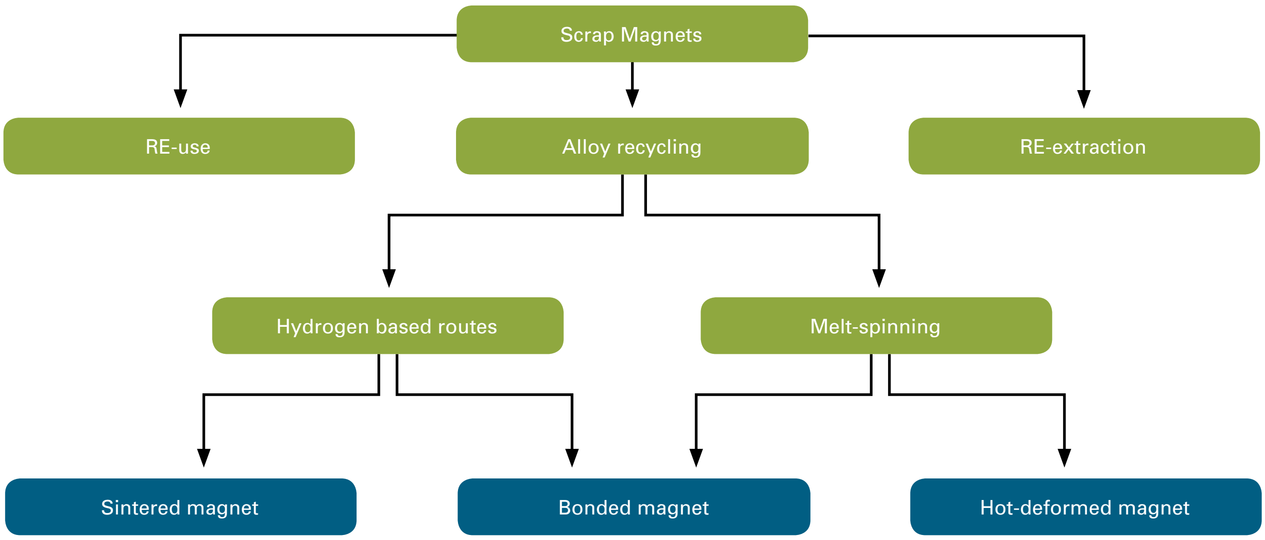
At present, two techniques have been presented in the literature. The Japanese company Hitachi has developed a mechanical-based technique to separate voice coil assemblies from hard disk drives and motors from air conditioning units. Alternatively, researchers at the University of Birmingham, the Fraunhofer IWKS/TU Darmstadt and University of Leuven are developing various alternative processes. One is a hydrogen-based process that reduces magnets to a demagnetized powder within the electronics; the powder can then be extracted mechanically (the Remanence project is also examining such a process for the case of HDDs.)[40] A third approach consists of melting the waste scrap and separating the rare earths in the slag phase (pyrometallurgical technique). This technique is already being applied to batteries.

The separation of magnets is difficult in part because of the complicated architecture of the devices in which they are used. However, if the devices were designed to be recycled, then recycling could become more viable on a commercial scale. At Fraunhofer IWKS, a pilot-scale separation plant is currently being developed for the treatment of complex waste streams, including WEEE.

Re-processing of extracted magnets

Once the magnetic material has been separated, there are several ways to re-process it into new products (see Figure 4.2). These are described in the following sections.

Figure 4.2:
Schematic overview of possible options for recycling of NdFeB magnets



Source: Roland Gauß, Oliver Diehl, Oliver Gutfleisch, Fraunhofer Project Group IWKS

The most energy- and material-efficient way to recycle is to detach and simply re-use or refurbish the existing magnet. The major advantage of this approach is the cost savings in terms of labour and energy in comparison to employing more complex rare earth extraction and separation processes.

Overall, the major challenges to using such a 'short-loop' process derive from the quality of the scrap materials that is recycled. Newly designed machines and technologies usually require magnets with specific kinds of material properties (e.g. magnetic properties, corrosion resistance, and size) and scrap magnets may not always fulfil these requirements. In addition, one would have to define whether the scrap magnet material had undergone some kind of degradation due to corrosion prior to its reuse.

Another approach is to **re-manufacture the magnets in alloy form**. This can be achieved in a number of ways. Firstly scrap magnets can be melted down to a master alloy that can go back into the primary supply chain (pyrometallurgical technique).[41] The advantage of this approach is that the magnet's oxygen content can be reduced during the processing. Alternatively, the separated magnets can be processed using hydrogen-based routes to form sintered magnets or material suitable for bonded magnets (more detailed descriptions of these routes can be found in the Annex.)

In all of the above cases, the success of the direct alloy routes very much depends on the compositional control of the input material as well as oxygen control during processing. The recycler will have to identify the chemical heterogeneity of the scrap magnet material, since the process of each individual synthesis route as well as the value of the recycled magnet very much depend on the quality and amount of additives found in the alloy. Indeed, there can be a large spread in the chemical composition of NdFeB scrap magnets, depending on the degree and quality of the sorting and separation steps that precede the metallurgical processes. If a sufficiently good magnet can be produced from these processes, this approach will have a good chance of being economically successful in the short term[42].

Many of these routes have been demonstrated on a lab-scale using controlled compositions. However, further research is required to take these processes to a commercial scale. Specifically, they need to be taken to pilot-scale facilities where researchers can determine how large batches of material with compositional variations (as with real scrap) affect the quality of the final magnets.[43] Detailed life-cycle assessments and economic analysis will also be needed to show the benefits of these approaches.

In order to synthesize new magnets of very specific compositions, it will be necessary to extract **individual rare earth elements from the waste materials**. It should be noted that the cost and environmental footprint of extracting individual rare earths is considerably higher than reprocessing the existing alloy (which in turn is much higher than re-using the existing magnet). However, the magnetic properties of the resulting magnets will have a narrower range and can be controlled much more precisely. If the quality of the input material is very low (for example, if it has a high oxygen concentration or other impurities) then direct re-manufacture from the alloy will not be possible and extraction of the elements will be the only way forward.

There are several methods that can be used to extract the individual elements from scrap magnets; these are explored in greater detail in the annex. The common hydrometallurgical technique involves the dissolution of the magnet in acids to extract the REE elements into solution. That is followed by complex purification processes involving solvent extraction and selective precipitation of individual REEs, or the separation of LREEs and HREEs. This hydrometallurgical route can process REE concentrates from different sources and is common for primary and secondary fields. If the hydrometallurgical purification processes could be simplified, then the cost of rare earth separations could drop significantly.

Researchers have also developed electrochemical methods to create alloys directly from magnet powders. At present, however, quite large quantities of reagents and energy are required to process rare earths in this way.

More research is required to validate and upscale new processing methods including electrochemical methods and alternative chemistries for REE separation (for example, using ionic liquids in extraction). These various processes, reagents and equipment have to be re-engineered to reach sufficient standards of robustness, yield, safety and cost efficiency for secondary materials, with respect to both magnets and other REE-containing streams. Further research into leaching, precipitation, solvent extraction and electrochemistry could give the EU a competitive advantage in this area.

The recovery of rare earths from NdFeB magnets is currently the topic of extensive research efforts, including the EU "European Rare Earth (Magnet) Recycling Network" (EREAN) and the nationally funded RECVAL-HPM project.[44]

4.4 RECYCLING REE-BASED PHOSPHORS

The initial steps to producing the rare earth elements are common to all rare earths based products, beyond the mining and separation stages, however, the processing differs significantly between phosphors and magnets. For example, the rare earths contained in phosphors are in the form of oxide powders, whereas the magnet materials are in the form of solid metallic alloys in which the oxygen content has to be kept to very low levels.

REE phosphors are used to coat the insides of glass bulbs, tubes, and visualization screens; these products are all rich sources of the heavy rare earth elements europium, terbium, and yttrium.[45] Phosphors can also contain the less critical elements lanthanum, cerium and gadolinium. Their role is to convert non-visible radiation (UV light or an electron beam) into the three visible components of red, green and blue, from which any colour (including white for lighting applications) can be generated.

REE phosphors are currently used in a number of applications:

- **Cathode Ray Tube (CRT) screens.** No new screens are currently being produced, but considerable stocks exist, either as screens still in use, or as phosphors that have been retrieved from television recycling processes.
- **Plasma screens.** Rare earth phosphors are the key component for colour rendering in plasma screens. This application is declining, but some stocks still exist.
- LCD backlighting. **Used in flatscreens in competition with LED flat panels, LCD** backlights are long and very thin tubes (a few millimeters wide) that are coated with rare earth phosphors and that have an internal metallic electrode. LED flatscreens have now become the dominant technology (they contain a much lower quantity of rare earths), and will soon be displaced by organic LEDs (OLED), which contain no rare earths.
- **Fluorescent lamps.** In the form of tubes or bulbs, fluorescent lamps have replaced the traditional tungsten bulbs because they last longer and require five to seven

times less energy. They are currently being replaced by LED lighting (see Chapter 2), but LED is still too expensive or not suitable for some applications. A considerable number of fluorescent lamps have been installed that will need to be recycled. Not all of the fluorescent lamps contain rare earth elements, however; the first generation of tubes was based on other types of phosphors. All of the last generation contains rare earth because they offer the best colour rendering and energetic yield.

- White LEDs. These contain rare earth elements, but in very small amounts compared to other lighting technologies. Quantities of LEDs on the market are still low and far from end of life.

4.4.1 Priority list

The group has sorted the different sources of recycled REEs by decreasing order of interest:

1. Fluorescent Lamps (Eu, Tb, Y, Ce, Gd, La)
2. LCD Backlights (Eu, Tb, Y, Ce, Gd, La)
3. Plasma Screens (Eu, Tb, Y, Ce, Gd, La)
4. CRTs (Eu, Y, Sm)
5. LEDs (Lu, Ce, Y)

The reasons for this ranking are as follows:

- Fluorescent lamps offer the largest potential in terms of mass of the waste fraction. They are already collected for their other components and they are not mixed with other non-lamp applications. A market is already in place for collecting and physically sorting the metal, glass and mercury components of the lamps. Only the phosphor powder (contaminated by glass) was until recently landfilled and not recycled. The main challenge to extracting REEs from recycled fluorescent lamps is how to manage the contaminants, particularly with regard to older generation phosphors (non-rare earth), glass contamination, and mercury management in waste streams. Rare earth-containing phosphors contain significant amounts of more critical HREEs (Eu, Td and Gd). Moreover, the selling price can compensate for the cost of the recycling processes. The industrial and economic feasibility of recovering the rare earth components in phosphors have been demonstrated, although improvements are still desirable with regard to collecting and physical sorting.

- LCD backlighting is an appreciable market, although phosphors have been used only in the latest generation of these products. The challenges are very similar to those for lamps, but sorting phosphors from the glass and electrodes is technically more difficult and can prevent further processing. LCD backlighting tubes are not systematically collected and separated from the screen, which limits the available resource.

- Plasma screens suffer from the small market size, with very few sales today and no systematic collection or dismantling specifically for the phosphor powder. Otherwise, the phosphor powder fraction composition is similar to that of LCD backlighting and lamps, so rare earth recovery should be possible if sufficient quantities can be retrieved.

- **Cathode Ray Tube screens** contain lower quantities of critical materials than the other applications (only Y and Eu). In addition, they contain large quantities of zinc and sulphur, making the process more delicate. Finally, the market for CRTs disappeared some years ago and the waste streams will soon decrease drastically.

- **LEDs** contain Y, Ce and Lu in very small quantities, embedded in resins and associated with electronic components. The market is growing rapidly, but due to the exceptional longevity of these products, it will be many years before appreciable amounts of end-of-life LED lamps begin to be recovered.

For end-of-life LED illuminants, it is much more difficult to separate the phosphors and extract the raw materials for later use. Experts doubt that there is an economic method for LED recycling.[46] However, due to the rapidly growing market for LED illuminants, it is only a matter of time before large quantities of end-of-life LEDs will become available, creating the need for viable recycling methods.

4.4.2 Overview of principal options for recycling REE based phosphors

Compared to magnets, the recycling loop for phosphors contains fewer steps, as the material remains as an oxide and there is a more straightforward path to a recycled product.[47] If we take the example of lamp phosphors recycling, three options can be considered:

- **Direct re-use** of the recycled phosphor in new applications. It is very challenging to selectively recover the individual phosphors without damaging their properties because they are mixed in a cured coating and bound with other components, which impairs their performance. Moreover, each manufacturer uses specific phosphors that have different compositions and different morphologies. In the scrap, all phosphors from the various origins are mixed, so it is impossible to retrieve the particular phosphor/morphology best suited for a particular manufacturing process. Only low-performance materials can be retrieved in this manner; however, it is doubtful that these would find a market. Direct recycling of lamp phosphors is recommended only for the special case when the lamp producers can recycle the phosphors from their own EOL fluorescent lamps. The Belgian waste-processing company Indaver, in close collaboration with Philips Lighting, has developed a process to recycle the phosphors from the company's linear fluorescent tube lamps in this way.[48]

- **Recycling individual phosphor components** by physical and chemical separation methods, followed by reprocessing for re-use in new lamps. This is quite similar to the direct re-use, but involves some re-processing to eliminate impurities and restore some properties to improve the final performance. Differences in the morphology of the phosphors could, however, prevent the lamp manufacturer from forming a suitable coating on the new lamp, making the quality of the resulting lamps an issue.

- **Chemical attack of the phosphors to recover their REE content.** This hydrometallurgical route involves dissolving the phosphors in acids and recovering individual rare earths components (see annex). Solvay is currently running this process at an industrial scale (see box). Other projects, such as the HydroWEE initiative in association with Relight, have also studied this technique.

Detection and extraction in REE phosphor recycling.

Prior to chemical separation, the lamps must be pre-processed and their rare earth fraction must be assessed to determine the phosphor's type and quality. Then crushing, shredding and sieving via wet or dry processes are used to separate glass particles from the lamps. At this point, however, the material can still contain up to 50% glass and it is often difficult to collect phosphors with sufficiently low glass content. As the phosphors can be extracted from the lamps, standard analytical techniques such as ICP and XRF can be used to determine the composition of the extracted powders.

Figure 4.3:
Schematic overview of possible options for recycling of NdFeB magnets

4.5 BARRIERS TO EOL RECYCLING

Many of the recycling technologies outlined in this report are common to magnets and phosphors as well as to batteries, polishing compounds and catalysts. However the challenges and the range of possible recycling technologies are significantly greater for magnets due to the fact that this material is in the form of a magnetic alloy rather than an oxide.

It is clear that it is technically feasible to recycle both rare earth magnets and phosphors from some key applications. Within the current policy framework, however, it will be challenging to create recycling flow sheets for magnets and phopshors that can compete - in terms of both price and quality – with rare earth materials produced from primary sources in China.

This is where further R&D and pilot plant development can have a big impact. They can help to increase the cost-efficiency and competitiveness of dismantling, sorting, separating and re-processing of end-of-life products that contain rare earths and improve the yield and costs of the various REE recovery routes. Research funding and pilot plant development should be put in place to accelerate these developments. Incentive schemes for collecting key rare earth-containing wastes could also potentially have a dramatic impact on recycling rates.

For recycling of rare earth materials to become a reality on a large scale, several common challenges have to be overcome. Specific barriers may arise depending upon the type of waste and the recycling techniques used:

Insufficient and often non-selective collection rates. Scrap is currently not collected for its REE content, with the exception of manufacturing companies that collect their internal production residues and surplus or rejected products. An overall recycling target by weight or by number does not allow for the selective collection of REE-containing materials, as they normally constitute only a small fraction of the object. Often metals such as copper, gold or silver are more valuable than small quantities of REE in the waste stream. The pre-treatment methods and processing are therefore not optimized for the recovery of minor elements.

Lack of information about the quantity of REE materials available for recycling. Consumer products containing rare earth materials have been produced and imported into Europe for many years. Unlike Japan, the EU has not surveyed the end use and accumulated resource of REEs that this represents. Therefore, the potentially accessible resource is largely unknown.

Dissipative use. The quantity of rare earths per component or device is often very small. This can make it uneconomical to separate the rare earth fraction; it can also make it difficult to detect the rare earth material in mixed waste streams.

Presence of contaminants. Even when highly efficient separation processes are applied to liberate and purify the rare earth materials, the end product will often contain contaminants. This can cause problems, in particular for short-loop recycling processes. Further investigation is required to understand their effects.

Price volatility for scrap and products such as magnets or phosphors. The volatility of rare earth prices makes the future value of scrap difficult to assess, which increases the financial risk of recycling initiatives.

Shipping of waste. More consistency throughout the EU in defining, implementing and applying existing waste regulations is needed. The preparation of the required paperwork for transboundary waste shipments within and from outside the EU is currently very time consuming and can hinder and delay shipment of waste. Continuous efforts should also be made to achieve better coordination between the EU waste shipment regulation and the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal in order to facilitate the shipment of waste internationally, without compromising environmental, health, and safety standards.

Technical recommendations for tackling the challenges that face REE recycling are outlined in the annex.

CHAPTER /05

POLICY OPTIONS TO IMPROVE EUROPEAN RARE EARTHS SUPPLY SECURITY:

A value-chain perspective

5.1 INTRODUCTION

Understanding the challenges facing rare earths supply today requires consideration not only of the sources of rare earths (whether from mines or waste streams), but of the functioning of markets along the entire production chain, which includes processing industries and downstream manufacturers. This chapter adopts such a systemic production-chain perspective to examine options available to policy makers to improve the functioning of global rare earths markets and enhance European supply security for rare earths.

At the core of this chapter are two basic arguments. The first is that the rare earths markets suffer from persistent market failures, which contributed to the 2010/11 supply crisis and have since hampered an effective response by industry. The second is that any interventions to fix this problem – by the Commission, Member States and the private sector – need to be carefully crafted and precisely targeted to be effective and, indeed, to avoid causing more problems than benefits.

5.2 AN UNNECESSARY REE CRISIS?

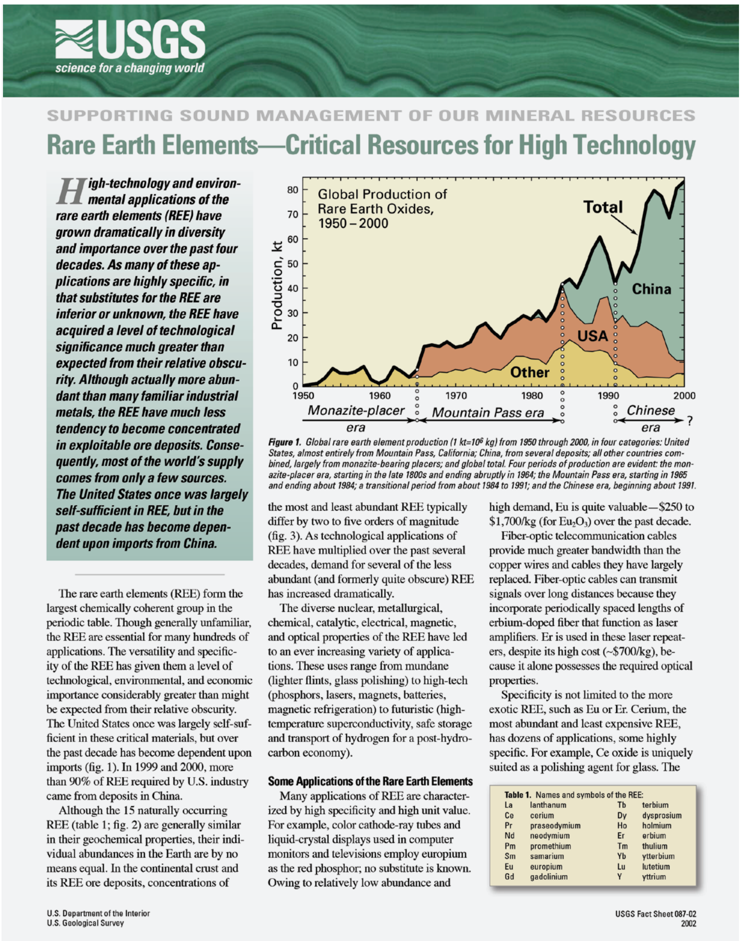
The Chinese government announced a large reduction in REE export quotas[48] on July 8, 2010. Two months later China imposed an informal export ban on Japan following a maritime incident in the East China Sea.[49] These events drove prices for REE to very high levels in the second half of 2010 and in 2011, and supply to non-Chinese companies was in danger.

However, the crisis that was triggered by these events could have been predicted. Since the closure of the Mountain Pass mine in 2002, China had become the effective REE monopoly supplier to the world. Already that year the USGS warned that the Chinese monopoly would erode REE related technical capabilities and innovation potential in the US and in Europe, and created a precarious situation where the "[a]*vailability of Chinese REE* […] *depends on continued stability in China's internal politics* […] *and its relations to other countries*" (USGS 2002, p. 4).

The export restrictions announced in the summer of 2010 presented a reinforcement and acceleration of a pre-existing policy trajectory. After 20 years of promoting exports, the Chinese government begun to discourage exports in 2006. A series of licensing requirements, quotas and taxes were introduced[50] seeking to (1) consolidate a chaotic, inefficient industry with a poor environmental record, (2) cut oversupply and bolster export prices, and (3)provide supply for its own, carefully developed high-tech industry that required growing quantities of rare earths (Morrison and Tang, 2012). The gradual ratcheting up of these restrictions in tandem with growing REE demand led to sharp increase in prices from 2006 onwards. With the world depending entirely on Chinese supply, ever tighter export restrictions eventually had to trigger supply crisis outside of the country.

Figure 5.1:

USGS brochure from 2002 warning for US dependence on REE imports from China



USGS
science for a changing world

SUPPORTING SOUND MANAGEMENT OF OUR MINERAL RESOURCES

Rare Earth Elements—Critical Resources for High Technology

High-technology and environmental applications of the rare earth elements (REE) have grown dramatically in diversity and importance over the past four decades. As many of these applications are highly specific, in that substitutes for the REE are inferior or unknown, the REE have acquired a level of technological significance much greater than expected from their relative obscurity. Although actually more abundant than many familiar industrial metals, the REE have much less tendency to become concentrated in exploitable ore deposits. Consequently, most of the world's supply comes from only a few sources. The United States once was largely self-sufficient in REE, but in the past decade has become dependent upon imports from China.

Figure 1. Global rare earth element production (1 kt=10⁶ kg) from 1950 through 2000, in four categories: United States, almost entirely from Mountain Pass, California; China, from several deposits; all other countries combined, largely from monazite-bearing placers; and global total. Four periods of production are evident: the monazite-placer era, starting in the late 1800s and ending abruptly in 1964; the Mountain Pass era, starting in 1965 and ending about 1984; a transitional period from about 1984 to 1991; and the Chinese era, beginning about 1991.

The rare earth elements (REE) form the largest chemically coherent group in the periodic table. Though generally unfamiliar, the REE are essential for many hundreds of applications. The versatility and specificity of the REE has given them a level of technological, environmental, and economic importance considerably greater than might be expected from their relative obscurity. The United States once was largely self-sufficient in these critical materials, but over the past decade has become dependent upon imports (fig. 1). In 1999 and 2000, more than 90% of REE required by U.S. industry came from deposits in China.

Although the 15 naturally occurring REE (table 1; fig. 2) are generally similar in their geochemical properties, their individual abundances in the Earth are by no means equal. In the continental crust and its REE ore deposits, concentrations of the most and least abundant REE typically differ by two to five orders of magnitude (fig. 3). As technological applications of REE have multiplied over the past several decades, demand for several of the less abundant (and formerly quite obscure) REE has increased dramatically.

The diverse nuclear, metallurgical, chemical, catalytic, electrical, magnetic, and optical properties of the REE have led to an ever increasing variety of applications. These uses range from mundane (lighter flints, glass polishing) to high-tech (phosphors, lasers, magnets, batteries, magnetic refrigeration) to futuristic (high-temperature superconductivity, safe storage and transport of hydrogen for a post-hydrocarbon economy).

Some Applications of the Rare Earth Elements

Many applications of REE are characterized by high specificity and high unit value. For example, color cathode-ray tubes and liquid-crystal displays used in computer monitors and televisions employ europium as the red phosphor; no substitute is known. Owing to relatively low abundance and high demand, Eu is quite valuable—$250 to $1,700/kg (for Eu_2O_3) over the past decade.

Fiber-optic telecommunication cables provide much greater bandwidth than the copper wires and cables they have largely replaced. Fiber-optic cables can transmit signals over long distances because they incorporate periodically spaced lengths of erbium-doped fiber that function as laser amplifiers. Er is used in these laser repeaters, despite its high cost (~$700/kg), because it alone possesses the required optical properties.

Specificity is not limited to the more exotic REE, such as Eu or Er. Cerium, the most abundant and least expensive REE, has dozens of applications, some highly specific. For example, Ce oxide is uniquely suited as a polishing agent for glass. The

Table 1. Names and symbols of the REE:

La	lanthanum	Tb	terbium
Ce	cerium	Dy	dysprosium
Pr	praseodymium	Ho	holmium
Nd	neodymium	Er	erbium
Pm	promethium	Tm	thulium
Sm	samarium	Yb	ytterbium
Eu	europium	Lu	lutetium
Gd	gadolinium	Y	yttrium

U.S. Department of the Interior
U.S. Geological Survey

USGS Fact Sheet 087-02
2002

Source: USGS, 2002.

The crisis was not only predictable, it was also preventable. The USGS estimates proven, reserves of REEs at 800 times current demand. The technologies for mining, beneficiation and separation of REE are available outside China. With an adequate, one-off investment, REE supply could have been diversified and supply security been guaranteed. A single REE mine is likely meet all of Europe's current rare earth requirements, and a handful of mines could meet the world's demand outside of China. Estimates of the required investment costs vary, but some indicative figures can be given based on available preliminary economic assessment and feasibility studies of major exploration projects today (see Figure 5.1). Opening a state-of-the-art rare earths 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).[51]

Table 5.1:
Estimated investment costs in REE mining and beneficiation

	Resource (t REO)	Planned capacity (tpa)	Investment costs (US$ per kg)	Operational costs (US$ per kg)
Min	70,912	4,008	19,961	2,90
Max	5,5331,400	40,800	295,510	68,06
Mean	773,705	13,130	85,402	28,95

Source: Pothen, 2013: data provided on the basis of a review of feasibility studies of some 17 Rare Earth mining projects outside China.

For comparison this is the value of a handful of Airbus 330s[52], one or two large, state-of-the art hospitals, a few dozen kilometres 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.[53]

Governments in the West relied purely on markets to guarantee supply of REE, and did not see a role for them to intervene. China in contrast, as a guided economy carefully developed its REE supply system and related high tech industries with various forms of support and state intervention. Over many years, China supported technology development for mining, beneficiation and separation of REE, implying that at this point China may have both a technological and cost advantage. (e.g. Lei, 1998; Hurst, 2010). In contrast, a general trend in the OECD countries was to off-shore basic production like mining to low-cost countries, leading to an erosion of the innovation system of such activities (Fifarek et al, 2008; Humphries, 2012).

5.3 MARKET FAILURES AND RARE EARTHS SUPPLY SECURITY

Given the critical role of REEs in sustaining innovation in high-tech industries, boosting resource efficiency, and strategic energy technologies such modest investment would appear worthwhile. A Dutch study based on detailed trade data estimates global trade in REE containing products in 2010 at -1.5 trillion, or some 13% of global trade, and finds that 10% of the value Europe's exports consists of products containing REEs (HCSS and TNO, 2011). More recent work of the EU-funded CRM INNONET suggests that this may be still a conservative estimate.[54] Several studies (JRC, 2011; DOE, 2011; BP 2014) have pointed to the critical role that rare earth supply will have to pay in green energy technologies, which in turn are key to decarbonizing economies and combatting climate change.[55] Why has it been so difficult to move a relatively small fraction of this added value to investment in mining, beneficiation and refining, to ensure REE supply security?

This points to potential market failures, defined in Bator's 1958 classic as 'the failure of (…) price-market institutions to sustain "desirable" activities'[56]; in this case ensuring the reliable production of sufficient quantities of REEs. Several characteristics of rare earths markets can be identified that create excessive risks and limit benefits for potential miners, hindering an supply expansion and undermining supply security.

5.3.1 Missing markets and high barriers to entry

Rare earths mining projects outside of China are being developed by relatively small companies, with a market capitalisation of 200 to 300 million US dollars at most (during the height of the crisis, these were up to ten times as high). These companies lack the capital and struggle to attract the financing to develop REE mines (Bade, 2010; US DoE, 2011).

For aspiring miners, this creates high barriers to entry as they either have to attempt to enter downstream separation to produce marketable rare earths products, or enter partnerships with the small number of companies that have REE separation capabilities.

This problem of attracting market capital is Is compounded by the fact that markets in the conventional sense do not exist for rare earths concentrates that mines produce and there are currently no exchanges on which standardised rare earths products can be traded. Instead, producers, global traders, and consuming companies trade separated oxides and metals bilaterally. These so-called over-the-counter (OTC) markets are subject to weak regulatory frameworks, relatively illiquid and lack transparency on trade volumes and prices (publicly available prices are compiled by industry publications such as Metal Pages, which survey traders to collect price information).

Particularly in comparison to their small size, this creates for aspiring miners high barriers to entry as they either have to attempt to enter downstream separation to produce marketable rare earths products, or enter partnerships with the small number of companies that have REE separation capabilities.

Both Molycorp and Lynas are developing LREE processing facilities (Molycorp has additionally acquired the Estonian separation plant Silmet) – but it is not clear that the next generation of HREE mines will invest into similar dedicated processing facilities. The slump in REE prices makes it more difficult for full-scale hydrometallurgical separation facilities, which can easily double the required upfront capital expenditure of a mining project, to be a commercially viable option. Further, the difficulties and delays Lynas and Molycorp are facing in developing their separation operations are a reminder of the technical and permitting challenges involved in opening such a facility. Many exploration projects with initial plans to develop such facilities have now abandoned these plans, as they are trying cutting costs and capital outlays.

Instead, most exploration projects are now focusing their efforts on forging long-term agreements with existing downstream processors. Companies are exploring various business models, such as long-term supply contracts, joint-ventures, or various forms of toll-processing models. However, forging such long-term agreements creates its own set of challenges for miners and entails significant transaction costs. The few existing potential downstream partners wield considerable negotiation power and can be reluctant to make long-term commitments given the uncertain outlook for demand and prices. Existing separators with limited capacity may also be willing to only separate specific rare earths from concentrates, or offer off-take or toll-refining at prices that are not attractive for prospective miners.

Several exploration companies have made announcements for such cooperation agreements, but it is unclear whether these arrangements are sufficient to convince potential investors.[57] The Kvanefjeld project in Greenland for example announced earlier this year that it had signed an MoU with Chinese company NFC to jointly develop the mine with plans to separate the concentrates produced at a facility in China. Canadian exploration company Avalon claimed around the same time that it had struck an agreement with Belgian company Solvay that it would separate the concentrates Avalon plans to produce at its mine on a toll-refining basis.

5.3.2 Bundling and unstable demand

REE-bearing minerals always contain a mix of individual rare earths that typically does not match the mix of required by markets, which is determined by the demand for different REE containing products. As miners can only decide on the overall quantity of concentrate they mine, the supply of overrepresented REEs (compared to demand) is implicitly subsidised at the expense of the underrepresented ones.

This natural 'bundling' leads to excess supply and depressed prices for REEs such as lanthanum and cerium, whose share in the REE mix in most deposits exceeds their share in global REE demand. At the same time this leads to inflated prices and suboptimal supply of the underrepresented rare earths, such as dysprosium (see Table 5.1).

An additional complication is that in some cases REEs are mined as by product of a major metal. This has considerable price advantages – extraction is already paid for – but implies that the output of REE is determined by the demand for the major metal. This situation exists with the Bayan Obo mine in China, one of the main (and cheapest) REE mines globally, which produces iron ore with REEs as by-product.

Table 5.1:
HREE and LREE supply balance forecast for 2020

Rare Earth Oxide Group	Demand: tonnes REO		Production: tonnes REO	
	Global	Rest of the World excl. China	Global	Rest of the World excl. China
Lanthanum & Cerium	95,000t	40,000t	122,500t	52,500t
Selected Magnet Rare Earths (Pr, Nd, Tb, Dy)	45,00t	9,000t	36,000t (excludes recycled swarf)	12,500t
Selected Phosphor & Ceramic Rare Earths (Eu, Tb, Er & Y)	10,500t	3,000T	8,000	1,000t

Source: Dudley Kingsnorth, 2014.
Note: This forecast expects that the total REE supply will be higher as REE demand in 2016, but that shortages will remain for Eu, TB, Dy and Y.

For exploration companies that want to bring new deposits into production, this means that it will be difficult to find customers for the most abundant rare earths for which plenty of supply is available – and project economics need to be sustained on the basis of a limited set of products. While explorers focus their efforts on HREE-rich deposits for this reason, even these typically contain significant amounts of lanthanum and cerium.

This problem is exaggerated by the combination of quickly changing demand for REEs in a very innovative high-tech industry, in combination with a supply system that is inherently inflexible. In the decade-long process to start production, the demand for rare earths can change considerably (as discussed in Chapter 2). The switch from REE based technologies in data storage (solid state drives instead of HDDs) and lighting (from fluorescent lamps to LED technologies) shows how quickly demand can disappear. At the same time studies such as Kleijn (2012) and Alonso et al. (2012) calculated that if society bets massively on renewable energy systems, and will grow the use of electric vehicle technology significantly, unprecedented amounts of REE will be needed. This adds significantly to the risk for investors, who need to make long-term bets on supply while facing uncertain demand.

5.3.3 Threat of market intervention

Irrespective of further supply development outside of China, the country will remain both the most important source for and user of rare earths for considerable time to come. China's own demand, next to its export and pricing policy therefore will remain, for better or for worse, a key factor in shaping REE market dynamics. Given that rare earths are a long-standing policy priority for the Chinese government, it would be naïve to rule out the possibility of restrictive Chinese policy interventions in future, similar to the export restrictions of the past.

In light of the recent WTO rulings and ongoing reforms of the REE sector in China, there is significant uncertainty about the future course of Beijing's REE policy. A decision to reduce restrictions and boost supply could lead to a period of oversupply and a further depression of prices, while a renewed tightening of export restrictions and a determined crackdown on environmental offenders and illegal exports could curtail output, reignite supply security concerns, and lead to another price spike. Potential action from other countries seeking to secure their supplies (such as the US for example) exacerbates this policy uncertainty in REE markets.

With the threat of policy intervention hanging over global REE markets, companies face additional uncertainty and risks that reduce the willingness of private investors to enter these markets.

5.3.4 Externalities, public goods, and collective action problems

Apart from the sound reasons why China may have a cost advantage in producing REE (i.e. deposits allowing for co-mining, a long history of technological research), externalities may also contribute to market failures. A first set of negative externalities relate to the fact that a significant share of REE mining in China takes place as part of illegal operations, with low environmental standards, contributing to the lower costs. and discouraging the emergence of supply outside of China. Ongoing Chinese efforts to end smuggling and raise environmental standards may gradually reduce the size of these externalities, but until then will continue to contribute to market distortions.

Second, and perhaps more importantly, there are positive externalities associated with diversifying supplies, which do not appear to be adequately priced by markets. Sustainably sourced rare earths from outside of China would contribute to more diversified supplier base and significantly enhance supply security. From a European perspective this could contribute to positive knock-on effects, most importantly in terms accelerated innovation and diffusion of green-tech applications based rare earths, and in terms of maintaining the innovation potential and competitiveness underpinning European manufacturing industries. Such benefits have public goods character (it is difficult to exclude companies from the benefit of greater supply security across REE markets and all companies can benefit from supply security at the same time), but are not mirrored in current prices, which simply reflect the supply demand balance in markets.

This also points to information failures and collective action problems. Manufacturers of end use products may have had limited awareness of the strategic risks REE supply disruptions could pose to their organisation, as the amounts and value of REE used are small and supply chains are long. For example such risks were not identified by traditional supply chain risk methodologies applied by end-users (e.g., Chopra and Sodhi, 2004; cf Sheffi, 2005; Tang and Tomlin, 2008). Even where individual companies recognize the risks confronting them and would be willing to invest in more sustainable and secure supply, for individual actors the amounts are unlikely to be sufficient to induce a significant supply diversification.

5.4 TOWARDS A DIVERSIFIED AND STABLE REE SUPPLY CHAIN FOR EUROPE

Textbook economics suggests that the expectation of growing demand for rare earths driven by expanding high-tech applications should result in upward pressure on prices, which in turn entices miners to invest in expanding supply. With long lead times for opening new mines decisions should have been taken to invest in mining outside China in the 2000s.

However, this did not happen due to ample availability of Chinese supply and the market failures analysed in the previous section. As shown by the aforementioned warning of USGS, it probably could have been foreseen in this period that somewhere in future Chinese supply would not be sufficient anymore for the global demand.

With the introduction of Chinese export restrictions from 2006 onwards prices began to climb and interest in REE exploration began to grow. Lynas was able to secure $250 million in funding from financial markets in 2007 and in 2008, Molycorp was formed as a private entity taking over the Mountain Pass mine and processing facility from Chevron. Soon afterwards, the financial crisis and the temporary collapse of REE demand brought the industry again to a halt.

It took the REE supply crisis and price spike in 2010 to revive investor interest, triggering a very large but short-lived cash infusion to the industry. It was this money that allowed to Lynas and Molycorp to proceed to the production stage and funded the global exploration push (see Figure 5.2) that laid the foundation for a new generation of advanced HREE exploration projects. But the financial and technical difficulties facing Lynas and Molycorp – and the small number of projects that have serious prospects to follow in their footsteps – are a stark reminder that market failures have not gone away.

After the demand destruction in the wake of the crisis, rare earth demand has now resumed its growth path – but, if left to their own devices, markets may well experience another supply crisis. Barriers to entry, externalities, disruptive technological change, the lack of well-developed markets, and the ever-present threat of state intervention all create important risk for long-term investment into future supply. This may scare away potential investors, unless some form of guarantee for demand and price levels can be given for a reasonable period of time, reducing the investment risk, The inconvenient question Europe needs to pose itself is whether it can afford this boom/bust growth scenario for the future of the rare earths industry. Unnecessarily expensive, volatile and insecure rare earth supply could hobble innovation and diffusion for key technologies, particularly electric vehicles. At the same time, the strategically important and commercially attractive downstream industries will continue to move to where supply currently continues to be cheapest and most secure: China.

Policy-makers in Beijing have recognized the strategic importance of rare earths a long time ago, and, to their credit, have nurtured the sector in good times and bad times. Expecting Beijing not to try to capitalise on the opportunities this offers in terms of gaining a foothold in key high-tech industries would be politically naive.

Figure 5.2:

REE mining projects in different stages of development in June 2013, some of which have seems become dorment

Development stage (Sep 2014)

- ▲ Resource Defined
- ▼ Preliminary Economic Assessment
- ■ Pre-Feasibility Study
- ◆ Demonstration Plant/Feasibility Study
- ★ Engineering/Construction
- ⬢ In Production

Resource/reserve type (Sep 2014)

- Inferred Resource
- Inferred + Indicated Resource
- Inferred + Indicated + Measured Resource
- Probable/Proven Reserve
- Historical Resource/Reserve

Source: Technology Metals Research Note: only REE projects having achieved before June 2013 a certification of the resources/reserves contained in their deposit are indicated on this map. It is however known to ERECON that other REE projects are currently being developed by European companies (e.g. the Maboumine project in Gabon, conducted by Eramet) although their resources are not certified yet.

Rather than pointing fingers at China, the more salient question is what European industry leaders, Member States and the European Commission are prepared to do to support the development of a more sustainable and resilient REE supply chain. The challenge for the European end users is that they require a sustainable, reliable and affordable source of material. Today such a resilient and competitive supply chain does not exist, and in the current market environment it may not emerge. This raises the difficult and politically sensitive question of market intervention. Should, and if so how should Member States or the Commission intervene in rare earths markets? Or is there a model that can be developed where market players and Member States and the Commission embark a public-private partnership?

5.4.1 Intervening in REE markets: Some pertinent points to consider

The often advanced argument that securing rare earths supply is a task for industry rather than governments, and that policy-makers hands are tied on this issue is a rhetorical red herring. European governments and the European Commission intervene frequently and extensively in markets for a variety of reasons. Whether in agriculture, waste, banking, defense, infrastructure, energy, pensions, or healthcare – where they see public interests threatened governments and regulators in Europe and elsewhere regularly intervene. Given the niche character of rare earth markets, the scale and scope of potential interventions would be significantly lower than in the above cases.

At the same time, however, market interventions can end up being costly, politically difficult to sustain, and not in all cases managed to achieve their goals. An US program on stockpiling strategic materials provide a good example: they were maintained for decades at great cost, disbanded when prices hit historic lows in the 1990s, and ultimately never used.[58]

Any suggestions for interventions need to consider the capabilities and incentives of key actors. Most European end-users and governments have no interest in running mines, separation plants, or stockpiling schemes; the political and commercial risks and the financial and managerial burden would be prohibitive. However, end-users may be willing to cooperate with other companies and provide long-term off-take agreements for separated products that provide market stability for potential suppliers. Policy-makers also may be willing to make substantial public funds available to support the development of a REE supply chain, as long as those funds are allocated through a transparent process that does not require bureaucrats to make pricing or volume decisions and politicians are not seen to be 'picking winners'.

Second, any potential interventions need to be considered in the context of a globalized REE industry (see Figure 5.3). Rare earths travel across continents as they move from mineral deposits into products and eventually into waste streams. At the same time, most of the companies involved – whether they are exploration companies, processors, component manufacturers or end-users – are global players in one form or another, with activities and financial ties across many countries.

If policy-makers were for example to support European mining operations, the concentrates produced could well be processed in China or elsewhere, unless controversial restrictions were placed on them in terms of the markets into which they could sell their products. Global companies would also carefully evaluate an offer to participate in any type of European supply security scheme in terms of the impact on their activities in other jurisdictions, e.g. in North America or Asia. It also raises difficult questions about how to define European supply security and competitiveness – should an arrangement where European separation companies source concentrates from North American mines and sell to component manufacturers in South Korea and Japan, which in turn supply European manufacturers, be regarded as satisfactory? Or would it be enough that in each step of the supply chain significant non-Chinese capacity is available to ensure competitiveness without bothering to try to build a separate the non-Chinese supply chain?

Table 5.3:

The global supply chain of REE used in magnets

Mining of ore	RE Carbonate	Seperated RE Products	RE Metal/ magnetic alloys	NdFeB magnets
China • Bayan Obo (bastnäsite/ monazite) • South China (ionic clays) • Sichuan (bastnäsite) • Other provinces **USA** • Molycorp **Australia** • Lynas Corporation **India** • Indian Rare Earth **Russia** • Solikamsk (loparite)	**China** • Boatou rare earth • Mianning Fanxing • Mianning Beida • Large number of small provinces **USA** • Molycorp **Europe** • Molycorp **Australia** • Lynas Corporation **India** • Indian Rare Earth	**China** • Baotou rare earth • Molycorp • Liyang Rhodia • Mianning Founder • China RE Holdings • >100 other small companies **USA** • Molycorp **Europe** • Silmet • Rhodia • Treibacher **Japan** • Shin Etsu • Mitsui Mining and Smelting • A few small companies	**China** • Baotou rare earth • Molycorp (Neo) • Jingxi Magnetism • Ningbo Yunsheng • Shanghai Roco • Ganzhou Qiandong • Grirem Advanced Material • 50-100 other small companies **Europe** • Less Common Metals • Vacuumschmelze **Japan** • Shin Etsu • Santoku • Showa Denko • Hitachi Metals • Chuden Rare Earth **Vietnam** • Santoku • Shin Etsu	**China** • Beijing Zhongke San Huan • AdvancedTechnology and Materials • Ningbo Yunsheng • Jingxi Magnetism • Shanghai Roco Magnetism • Shanxi Huiqiang Magnets • Hengdian Group Magnetics • Ningbo Zhao Bao • Molycorp (Neo) • At least 50 other small companies **Japan** • Shin Etsu Chemical • TDK Hitachi Metal JV • Santoku • Hitachi Metal • Daido Electronics **Thailand** • Molycorp (Neo) **USA** • Arnold Magnetic Tech. **Europe** • Vacuumsschmelze

Source: Based on Roskill/IMCOA 2012.

This also points to a third key question. At what level in the supply chain would potential policy interventions be most effective? Smart interventions at a particular stage in the supply chain can be used to leverage change across the supply chain. Separators, which act form one of the natural bottlenecks in REE supply chains may be an interesting starting point. Policy interventions that seek to leverage existing actors and capabilities in Europe are clearly more likely to yield success than those that seek to create new activities. For example, there are promising advanced stage REE exploration projects in Europe today, as well as sophisticated separation capabilities and a strong end-use sector. In contrast, there are presently no active mines only small-scale recycling, and limited alloy and magnet making activities – which reflects the fact that Europe only represents 10% of the REE use(see box).

Existing separation and downstream processing capabilities in Europe

The Silmet refinery plant in Estonia is owned by Molycorp and provides a capacity of 3,000-4,000 Mt/pa of LREEs. The plant is separating bastnäsite concentrate from Mountain Pass and has in the past received REE concentrates from Russia. Silmet is also a significant producer of Nb and Ta.[59] Silmet began producing rare earth metals in Soviet times in 1970 and now has the capacity to produce up to 3,000 metric tons per year (tpa) of (LREE) rare-earth products. The company has produced cerium, lanthanum, neodymium, praseodymium, and samarium-europium-gadolinium products (as well as niobium and tantalum metal chips, ingots, metallic hydrides, and powders).[60]

The **La Rochelle separation plant in France**, which is owned by Solvay (formerly Rhodia), is the world's longest-running solvent extraction plant dedicated exclusively to separating and purifying rare earths; it has run for 44 years. It is capable of separating both LREEs and HREEs and today perhaps the most advanced REE separation facility in the world. Total output capacity of individual rare earths at the plant is estimated between 5000 tpa and 10000 tpa depending on REE distribution of the feed. The plant can separate and purify all of the rare earths as well as scandium and yttrium. La Rochelle is estimated to be operating at only a small part of its total capacity, so potentially has the capacity to process several thousand additional tonnes per year.[61] Solvay La Rochelle is not only a producer of separated rare earths; it also produces advanced formulations for downstream rare earth-dependent businesses, in particular cerium based catalyst supports for automotive industry, HREE based phosphors for lighting applications and cerium based polishing powders for optical applications.

In the UK, **Less Common Metals** has been producing metals and alloys of rare earths for the last 30 years. LCM relies on the supply of rare-earth oxides from South Africa (part of the Great Western Mineral Group Ltd), where the minerals are currently mined and beneficiated. LCM is part of a supply chain, producing rare earth magnet alloys for the automotive sector.[62] LCM produces Nd-Fe-B magnetic alloys, pure metals, Sm-Co alloys, magneto-optic and magnetostrictive materials, hydrogen storage systems and master alloys.

The Austrian company **Treibacher AG** – which has branches in Germany, Slovenia, Canada China, and Japan – is currently using separated rare earth compounds to add value to downstream manufacturing. Treibacher is producing polishing powders, compounds for catalysts and ceramics, rare earth master alloys, flints, and several special products for niche markets. However, the company does not produce alloys for magnets. Treibacher AG has the basic know-how for separation and has separated rare earths in the past, but it does not have a separation plant.[63]

Finally, there is also a question about how sustainable policy interventions would be. Efforts to subsidise certain steps in the value chain could e.g. easily end up creating inefficient operations that are artificially shielded from international competition. More smartly designed interventions instead could effectively nurture innovation and leverage investment, boosting the long-term competitiveness of key value chains.

This chapter has examined the set of market failures that continue to challenge the functioning of rare earths markets and undermine supply security. But any potential market interventions would need to be carefully designed and framed, and consider a range of potential pitfalls.

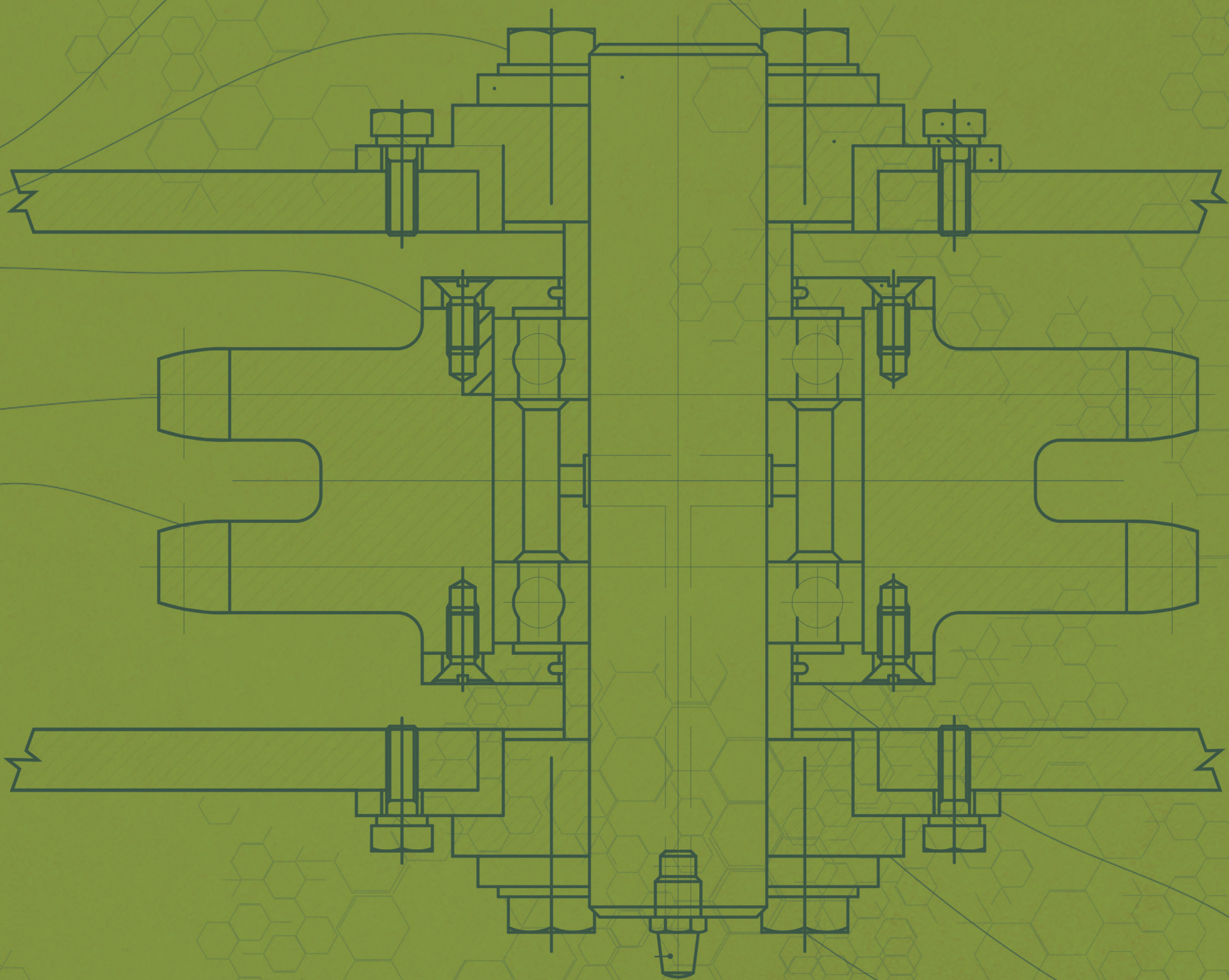
To inform the debate on potential interventions more rigorous analysis is necessary. There is an urgent need to draw lessons from other markets with high uncertainties, inelastic supply, and oligopoly characteristics as to how market-based mechanisms may be capable countering the specific problems in REE markets. Also concrete and realistic proposals for market interventions need to be developed and evaluated - ideally following models that have proven their effectiveness in other, similar markets as REE.

The recommendations offer some suggestions in this direction, but developing concrete proposals for intervening in REE markets is beyond the scope of this report and would require further in-depth research and discussion. Given the scale of the challenge and the stakes involved, however, Europe may well require unorthodox solutions. Further, given the relatively small size of the European use of REE, it is likely that a collaborative solution with other REE users outside China is needed.

CHAPTER /06

STRENGTHENING EUROPE'S RARE EARTHS SUPPLY CHAIN:

An agenda for action



6.1 MAINTAINING AND STRENGTHENING THE EUROPEAN SKILLS AND KNOWLEDGE BASE THROUGH RESEARCH FUNDING, S&T EDUCATION AND INTERNATIONAL COOPERATION

The European rare-earth industry is small but of great importance, and maintaining the necessary skills and knowledge base along the entire REE value chain in Europe is critical to long-term supply security. Without generously funded, cutting-edge research capabilities and the availability of skilled scientists and technical experts, a rare-earths high-tech industry cannot flourish in Europe

The Commission and Member States should support pre-competitive research in exploration, mining, separation, recycling and substitution of rare earths. Breakthroughs in these areas can lead to greater resource efficiencies and cost reductions and help to increase the competitiveness of rare earth-dependent industries in Europe. Science and technology education is critical to maintaining Europe's skills and knowledge base. This could be supported through research grants, scholarships, and training networks, as well as by pooling the best European capacities and enhancing international cooperation (for example with the U.S., South Korea and Japan) by means of coordinated calls, researcher exchanges, and joint high-level conferences.

Knowledge and skills especially need to be maintained and strengthened in the following areas:

- Better understanding of the **geology of rare earth elements (REE)**. This is important to ensure successful exploration in the long-term. In particular the understanding of the formation of deposits rich in heavy rare earth elements (HREE) with low radioactivity should be improved to support targeted exploration.

- **REE-specific metallurgical processes** and know-how for both primary and secondary feedstocks. Research on improved pyro- hydro- and solvo-metallurgical processes is required to improve yields and selectivities, simplify processes, bring down costs, and reduce environmental footprints.

- **Thermochemical and thermophysical properties of the RE-oxide systems** in order to optimize high temperature treatments.

- Modern and environmental friendly **electrolytic processes for RE metal production**, for which knowledge in Europe is currently limited.

- **Permanent magnet technologies.** This should include more efficient use of rare earths-based permanent magnets in higher-temperature applications and systematic research to identify new permanent magnetic materials that can fill the gap between Nd-Fe-B and ferrite magnets. Also technical research in the areas of HDDR processing, melt spinning and strip casting of scrap magnets should be supported.

- Research into new **high volume applications for less critical rare earths**, such as lanthanum and cerium. New applications for these elements, which are currently in oversupply, could help to improve the match between the balance of REEs in the demand and supply portfolio, and help to improve the economics of primary REE production.

6.2 CREATING THE BASIS FOR INFORMED DECISION-MAKING THROUGH AN EU CRITICAL MATERIALS OBSERVATORY

Despite recent research efforts, we still have only a rudimentary understanding of how REE materials flow through both the European and global economies. Detailed mapping and monitoring of complex and changing REE supply chains – from mines to separation plants to end-users and end-of-life disposal – is necessary to support informed decision-making. This could include monitoring of advanced exploration projects (production schedules, timelines, funding, beneficial ownership), prices along the supply chain, key demand and supply trends, and mapping the urban mine potential.

Such research is to some extent already being undertaken by national geological surveys and other national and EU institutions, in various EU and national research projects (such as EURARE, CRM-Innonet, ASTER, CRM study, MSA study, WEEE 2020). However, this type of research remains piecemeal and intermittent rather than offering comprehensive and continuous monitoring of rare earths markets and supply chains. Leading expertise in Europe could be pooled in a virtual critical materials observatory that could provide the public with consistent, authoritative, and high-profile knowledge. These efforts should also be clearly linked to the Raw Materials Initiative, the European Innovation Partnership on Raw Materials, and the European Union Raw Materials Knowledge Base.

Previous efforts to pool such knowledge emphasize the need for sufficient political backing and resources; a halfway solution is worth very little. In its most extensive form, an institution responsible for monitoring raw materials in the EU be set up with a similar information role as the USGS in the U.S., or possibly the IAEA at the international level. This could be anchored in already existing European networks that are being developed within and outside of the European Commission.

6.3 SUPPORT PROMISING TECHNOLOGIES THROUGH FUNDING INDUSTRY-LED PILOT PLANTS FOR INNOVATIVE HREE PROCESSING.

The European Commission, industry and Member States should support and accelerate the scaling up and commercialization of key technologies through co-financing industry-led pilot plants for rare earth production and processing. This could include life-cycle analysis and technological and economical assessments that analyze the commercial potential and environmental footprints of processes. Such pilots should aim to bring together a wide range of experts and stakeholders.

For example, pilot plants should be supported in the following fields:

- **Process development for optimal REE recovery from HREE-rich minerals, such as eudialyte and xenotime**, which are important for the next generation of REE mines and for which currently no established industry-scale extraction processes exist;
- **Process development for direct alloy reprocessing routes for recycling of REE magnets**, including re-melting separated materials melt spinning and re-sintering.
- **Process, sensor and equipment development** for the detection, collection, characterization, pre-processing and separation of REEs from discarded REE-rich products.
- **Process development for the recovery of REE from industrial residues** such as bauxite residue (red mud), phosphogypsum, mine tailings and metallurgical slags.

6.4 LEVELLING THE PLAYING FIELD FOR EUROPEAN HREE EXPLORATION THROUGH CO-FUNDING FOR PRE-FEASIBILITY AND BANKABLE FEASIBILITY STUDIES

In the aftermath of the rare earths crisis, REE exploration efforts have identified a dozen or so promising HREE deposits (mostly in OECD countries), which have been extensively explored and which have the potential to go into production before 2020. Some of the existing advanced exploration projects in Europe are among the serious contenders for this next generation of rare earths mines.

Given the size of the rare earths markets, only a few of these exploration projects will actually become mines over the next decade. Which ones ultimately go into production is difficult to predict, but it will depend on investors, who will have to provide the several hundred million in funding required to develop exploration projects into actual mines. The 'decision to mine' is based on the geological potential and economic attractiveness of individual exploration projects, as assessed by a bankable feasibility study that is conducted according to strict rules.

Some of the HREE projects that have made the most progress towards exploitation in recent years have done so with support from federal and state governments. There are many examples of such support schemes, including direct equity investment (e.g., through the Japanese agency JOGMEC, or the state government in Quebec), public loans (such as the $145 million credit line opened by the Alaskan State government in support an REE project), and R&D tax credits (such as in Australia, where 45% of R&D expenditure by REE exploration companies is covered by public funds).

The European Commission and Member States should evaluate the possibility of providing similar financial support for the extensive R&D that is necessary to produce pre-feasibility and bankable feasibility studies. Whether HREE mines in Europe or elsewhere eventually go ahead will depend on the decisions that commercial investors make based on the outcome of such studies. Without adequate support, Europe's high-quality deposits may simply be left unexplored.

Ensuring sufficient land access for the exploration and exploitation of key deposits is also important and will require strong political backing. Like other mines, REE projects sometimes face unbalanced competition on land use issues. The notion of 'deposits of public interest' – which is being discussed in Horizon2020 research– could provide a framework for balancing the various demands on competitive land uses.

6.5 MAKING WASTE MANAGEMENT REE FRIENDLY THROUGH ECO-DESIGN, INCENTIVE SCHEMES FOR COLLECTING PRIORITY EOL PRODUCTS, AND STREAMLINING EU RECYCLING POLICY AND WASTE REGULATION

Industry, the European Commission and Member States should promote more recycling-friendly design, so that REE components can be more easily identified and recovered in products that contain high volumes of REEs. Dialogue could be encouraged between product designers (e.g., in the automotive and electronics industries) and recyclers. Where relevant, encouragement to highlight rare earths content and other critical materials may be added into relevant legislation (e.g. WEEE, ROHs, ELV). The potential to develop a databank containing this type information could also be evaluated.

Different types of collection schemes (such as take-back/buy-back schemes) should be evaluated for their potential to stimulate collection rates of high-priority products (such as HDDs, automotive products, and fluorescent lamps). This could create incentives for consumers to return their end-of-life products. This would however need to be designed in a manner that enables competition and spreads the burdens amongst the actors in the value chain. Any possible fee should reflect the actual costs of that product group or type of product.

The European Commission and the EU Member States should aim to create more consistency throughout the EU in defining, implementing and applying existing waste regulations. The quantity of paperwork required can make transboundary (hazardous) waste shipments, within and from outside of the EU, prohibitively time consuming. Currently, this administrative burden has to be borne by recycling companies that legally ship waste material for the recovery of rare earths.

Recycling policy should move from a material-centric to a more product-centric approach. A large proportion of REEs are used in devices for which specific end-of-life-rules are already in place, however they are now formulated in a "weight-based" manner, which does not stimulate the recycling of low-volume materials such as REEs. Regulations could be fine-tuned to emphasize the importance of REE recycling, where applicable and financially and environmentally sound processes exist, similar to existing requirements for hazardous components.

While the current regulations for handling radioactive wastes provide adequate protections in the EU, detailed guidelines for Naturally Occurring Radioactive Materials (NORM) mining wastes do not exist. The lack of regulations here could potentially slow down permitting processes for REE projects. Formulating such clear guidelines (as currently exist for the Mining Waste Directive, for example) could provide useful guidance to miners and regulators and increase the efficiency of the permitting process.

6.6 BOOST SUPPLY SECURITY AND DE-RISK STRATEGIC INVESTMENT CASES THROUGH ENHANCED COOPERATION AMONG END-USERS AND OTHER STAKEHOLDERS.

Europe's automotive, chemical, and electronics industries are heavily dependent on a secure supply security of rare earths. While many end-user companies are aware of the importance of REEs for their products and have evaluated the risks they are facing, so far only few companies have taken active steps to support long-term supply security and the diversification of REE supply, as they have struggled with opaque markets and high capital risks.

The currently low prices of REEs do not reflect long-term supply security in the volatile REE markets, which continue to depend on a small number of sources of supply and remain vulnerable to government intervention. To support the diversification of the rare earths supply chain and increase supply security, leading end-users could strengthen their efforts to engage in strategic cooperation across industry, along the entire value chain, and with governments and other stakeholders with the goal to de-risk strategic investment cases. In particular, such efforts should focus on strengthening and developing existing REE-related businesses and know-how centres, in Europe as well as with international partners.

The owners of REE separation technologies and equipment play an especially critical role in maintaining supply security, as they typically source selected REE concentrates from mining and processing operations and make them available as separated, pure REE compound products. The REE compounds are then used by high-tech alloy-, magnet- and phosphor-making industries and will eventually end up in the products of the European end-user industries.

There is an urgent need to systematically explore smartly designed, collaborative ways to provide cost effective, long-term competitive supply security. Potential approaches could include:

a) Setting up a voluntary European 'critical raw materials fund' that invests upstream to de-risk projects and support the development of diversified supply chains for critical materials. The fund would rely on private sources backed by governmental support, such as public guarantees.

b) Setting up a 'European resource alliance' following the example of the German Rohstoffallianz (which could be private, or a public-private partnership). Functions of such an alliance could focus on bundling of REE demand and user interests, and ensuring 'stable supply at a predictable price' via long-term off-take guarantees or supply-contracts with upstream players, such as separators.

c) Setting up a small, high-level taskforce to examine realistic options for publicly funded support to ensure the resilience of the European REE supply chain. This taskforce could also explore how policy-makers could stimulate the development of more transparent global market structures for REEs that could help market participants to hedge against sudden price changes.

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3. This grouping builds on Innovation Metals Corp. (IMC). See http://www.innovationmetals.com/end-uses-of-rare-earth/.

4. In fact, Sm is much less abundant than Nd, yet it is currently much less critical in terms of supply than Nd. This is due to the fact that by far the largest amount of mass produced applications that require high-performance permanent magnets use NdFeB. If all these applications shifted to the use of SmCo-based magnets, samarium would rapidly turn into a critical raw material.

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8. Rare-earth elements were first mined in the world in the late 1800's in the Bastnäs Mines in the Bergslagen district in Sweden; type-locality for the important REE mineral "bastnäsite". Bastnäs is also the source of the material from which the elements cerium (in 1804 by Hisinger & Berzelius) and lanthanum (in 1839 by Mosander) first were discovered.

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11. The project also plans to develop an Integrated Knowledge Management System for EU REE resources which will provide information on REE and build up the knowledge to be developed within the frame of the project.10 EU-countries covered (20 partners). See *EuRare* (http://www.eurare.eu).

12. See the website of the project at promine.gtk.fi.

13. The classification of exploration projects as 'advanced stage project' follows the 'Advanced Rare-Earth Projects Index' by the consultancy Technology Metals Research (TMR), http://www.techmetalsresearch.com/.

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TECHNICAL ANNEX RECOVERY METHODS FOR REE RECYCLING

This annex reviews some of the technical detail of the principal options available to recycle REEs that have been discussed in Chapter 4.

Techniques for direct alloy reprocessing

Two principal options are available. A pyrometallurgical technique can be used to melt down the scrap magnets to obtain a master alloy. This has the advantage that the oxygen content of the alloys can be reduced by separating the slag layer from the melt.[1] Once the composition of the batch has been determined, the material can be fed into any conventional magnet synthesis route. Another pyrometallurgical technique can be applied to the scrap magnets by using a melt-spinning process. This is a particular way to re-cast the material: the scrap magnets are melted down in an induction furnace and then a stream of molten alloy is ejected under pressure onto a water-cooled copper wheel, where it is rapidly quenched to form flakes with a nanocrystalline microstructure.[2] These can be used to produce isotropic-bonded or anisotropic hot deformed magnets.

Alternatively, hydrogen-based routes (hydrogen decrepitation (HD) or hydrogenation disproportionation desorption and recombination (HDDR)) can be used to regain anisotropic NdFeB powders from scrap magnets.[3] The HD route can be used to extract a clean source of hydrogenated NdFeB powder which can be pressed and re-sintered to form new fully dense anisotropic magnets with properties close to the starting material.[4] The HDDR process can also be applied (high temperature hydrogen process); this produces material that can be used to make isotropic- or anisotropic-bonded magnets. The re-sintering and re-melting routes have been demonstrated on a labscale and further pilot plant development is required. The HDDR and melt spinning routes require further R&D to optimise the processes for mixed composition feedstocks.

Selective recovery of REE from recycled sources

Pyrometallurgical route

Pyrometallurgical techniques can also be used to extract the REEs from transition metals in the metallic state, a process called liquid metal extraction. Rare earth metals (REMs) are in fact very chemically active; that is, they have a high affinity with the non-metallic elements such as carbon, nitrogen, oxygen, sulfur and phosphorus, among others. In a mixed waste stream, the REM-oxides are usually mixed with other metals and their oxides. Melting the waste scraps in a reducing atmosphere will reduce metals like iron and nickel, while REM-oxides will go completely to the oxide phase, together with other elements that have a high affinity with oxygen, like calcium and aluminium.

The oxides of rare earths will then be concentrated in the slag (oxide) phase of the melt. The slag usually has a lower density than the metallic phase of the melt and can therefore easily be separated. It can then be processed using hydrometallurgical techniques until a rare earth concentrate is obtained, containing 95% of RE or more. REMs may also convert to carbides at high temperatures. The RE carbides may be separated from the rest of scraps by magnetic separation followed by hydrolyzing of the carbides to hydroxides.

Similar pyrometallurgical treatments have been devised for rare earth batteries; these have shown that the process has great potential for industrial applications.[5]

Hydrometallurgical route

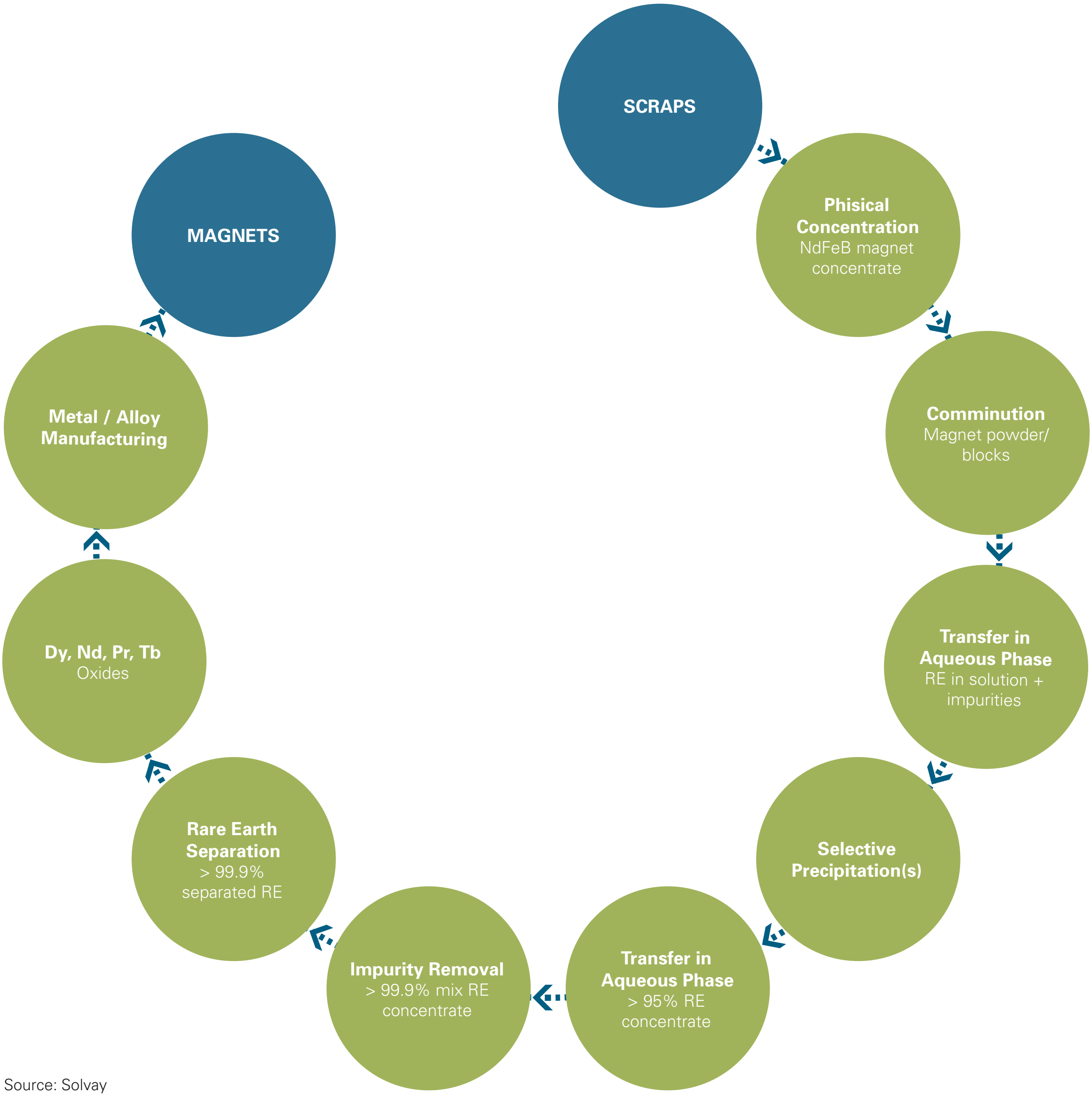
Hydrometallurgy refers to the use of a solvent (most often water) in combination with reactants (acids or bases, plus other reagents) to extract, purify and finally obtain pure RE concentrates (>99.99% purity) suitable for use in further applications, including magnet manufacturing processes.[6]

In the case of magnet-containing scraps, pre-processing is necessary in order for hydrometallurgical routes to work effectively. The magnets have to be de-magnetized, either by exposure to medium temperature to take them above the Curie temperature (~320°C) or by exposure to hydrogen (as discussed earlier). Most of the impurity materials (steel plates, cases, glues, etc.) need to be removed prior to treatment to optimize cost and avoid the interference of impurities with the purification process.[7] It is preferable to reduce the size of the rare earth-containing material in order to increase the reaction rates during hydrometallurgical processes; therefore, grinding or fracturing is often considered.[8]

Schematically, the process consists of an initial dissolution of the magnet in acid, which converts the rare earth elements into soluble species, mixed together with other impurities. From this initial state, several successive precipitation or dissolution steps can be carried out in order to obtain a solution that contains a high concentration of rare earths, with purity higher than 95%. At this point, the most efficient route is to use liquid/liquid extraction techniques to remove the remaining impurities and obtain a solution that contains several rare earths with impurities of ≤0.01%. In the last step, liquid/liquid extraction techniques are used to obtain several solutions that contain only one rare earth element, with a purity of 99.9% or more, depending on material specification. The solutions are individually converted into oxides, which are then converted into metals using electrolytic extraction.

Table A:

Processing route to separate rare earth elements from NdFeB magnet scrap



Source: Solvay

All of these steps rely on techniques that are used on an industrial scale for other materials. Thus, the various processes, reagents and equipment will have to be re-engineered in order to reach sufficient standards of robustness, yield, safety and cost efficiency for secondary materials and with respect to magnets. At present, quite large quantities of reagents are required in order to dissolve and precipitate the rare earth concentrates; this means that the process entails high costs and leaves a large environmental footprint.[9] Therefore, research is required into ways to improve the efficiency and yield of dissolution/ precipitation processes. The purification stages of dissolution, selective precipitation, and solvent extraction are relevant for all hydrometallurgical processing of REEs (in both primary and secondary streams).

The recovery of rare earths from NdFeB magnets is the topic of the EU FP7 Marie Curie Initial Training Network "European Rare Earth (Magnet) Recycling Network".[10]

Ionic liquids as an alternative to conventional organic phase solvent extraction

One possible alternative to conventional solvent extraction is to use ionic liquids (ILs) to replace the conventional organic phase.[11] Ionic liquids are solvents that consist entirely of cations and anions. They are non-volatile and non-flammable, so that they can be safer alternatives for molecular organic solvents in extraction processes. However, ionic liquids can provide new chemistries for the separation of metals from aqueous solutions. Some ionic liquids with functional groups in the cation and/or anion can act both as extractant and diluent. In this way, very selective extracting phases can be designed.

The main challenges to deal with when designing ionic-liquid-based solvent extraction processes are: (1) the high viscosity of ionic liquid phases; (2) the tendency of the ionic liquid to extract via an ion exchange mechanism, resulting in losses of ionic liquid components to the aqueous phase; (3) hydrolytic instability of some fluorinated anions such as hexafluorophosphate; (4) recyclability of the ionic liquids; (5) (cyto)toxicity; (6) high costs of most types of ionic liquid.[12] Due to their relatively high cost the large scale industrial use of ionic liquids in bulk processes is unlikely in the near future.

So far, most extraction studies with ionic liquids have been carried out on a small lab scale.[13] However in time larger scale processes may be developed into semi-industrial scale plants. There exist very few extraction studies of ionic liquids on a larger scale, so proof-of-principle for their use in industrial solvent extraction processes is largely lacking. New solvent extraction equipment dedicated to the use of viscous ionic liquid phases has to be designed. By developing ground-breaking new technologies for better recovery and separation of rare earths based on ionic liquids, a competitive advantage could be gained over the older Chinese separation processes.

Electrolytic reduction of rare earth oxides to metals

Currently, the two main industrial routes for the production of RE metals from oxides (resulting from the hydrometallurgical processes) are metallothermic (calciothermic and lanthanothermic) and electrolytic reduction. The advantages of the electrolytic over the metallothermic process (the former is easy, low cost and continuous) makes it the natural choice in the case of the production REMs with low melting points. These include Nd, Pr, Ce, La, misch-metal, didymium (Nd-Pr alloys), as well as alloys of these REEs with transition elements (Fe, Cr, Co, Ni or Cu).

Today's electrolytic production of RE metals is primarily carried out in China. The metals are then combined with iron, boron and other metal additions to form alloy precursors for the magnet industry. Further work is required on novel feedstocks to the electrolysis process, for example NdFeB carbides and oxycarbides, which are likely to be the result of pyrometallurgical separation. Most of the electrochemical treatment methods for recycling REE are usually refining steps. Both molten chlorides and molten fluorides, as well as mixtures of chlorides and fluorides melts have been used, although the proposed methods have been tested only in a laboratory scale.

Previous studies on rare earth metals have been mostly devoted to the electrochemical purification of yttrium and gadolinium, as well as cerium.[14] In more recent years, and due to the increased use of NdFeB permanent magnets, and the large amounts of waste scrap generated during their manufacture, some innovative research has been carried out dealing with direct electrolytic extraction of RE metals from Nd-based magnetic scrap.[15] This approach allows the conversion of RE-containing waste which is difficult to recycle (as magnetic dust) to RE magnetic alloys that can be used for manufacturing new permanent magnets.

At present there is little knowledge in the EU regarding electrolysis of rare earths, as this is now almost exclusively performed in China on an industrial scale. The development of modern and environmentally friendly electrolytic processes for RE metal production is necessary in order to avoid dependency on Chinese sources. The same electrolytic process, with modifications, can be used in the production of RE metals and alloys from both primary and secondary (waste) raw materials.

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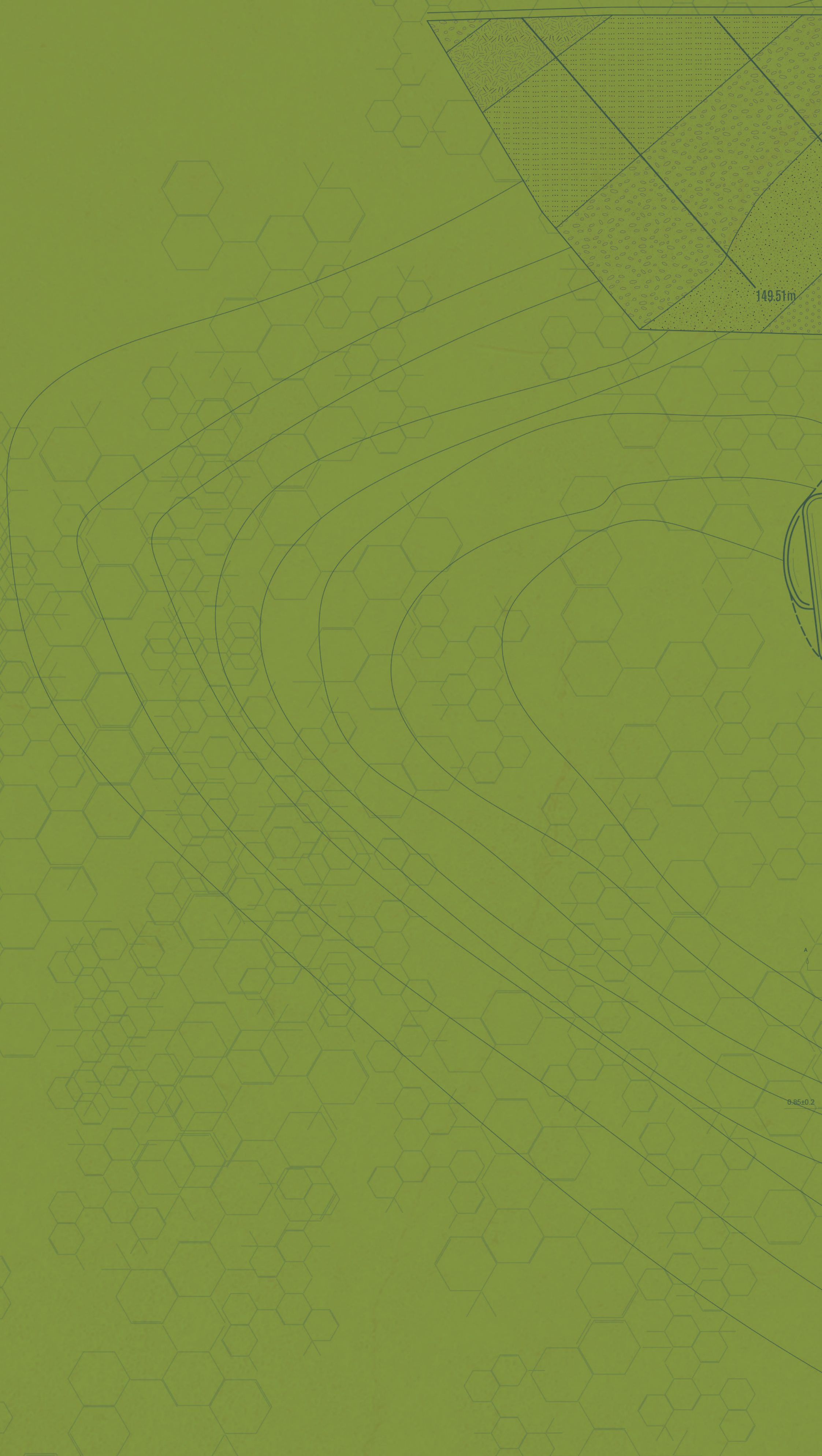
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