21 RARE EARTH ELEMENTS (REE)

21.1 Overview

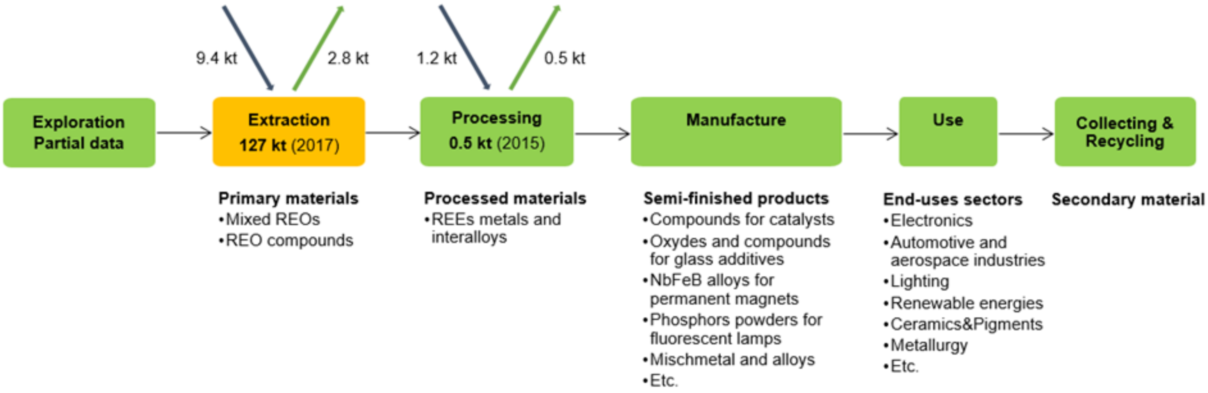


Figure 318: Simplified value chain for REE. Average 2016-2018 (WMD, 2019) (Eurostat, 2019).

The Rare Earth Elements (REE) are a group of 17 elements, comprising the elements scandium (Sc), yttrium (Y) and the 15 lanthanides (elements no. 57-71), as defined by the International Union of Pure and Applied Chemistry (IUPAC, 2005). The lanthanide group comprises: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb) and lutetium (Lu). Yttrium (Y, no. 39) and scandium (Sc, no. 21) share physical and chemical properties with the lanthanoides. However, only yttrium is to be treated together with REE, as it is found in the same ore deposits and shares a great part of REE value chain. Scandium is treated separately in the EU Critical raw materials assessment as it is mainly sourced more economically from bauxite and has specific industrial properties. Promethium which has no stable isotope in nature is not considered in this assessment. For the purpose of the assessment, the REE are split into two groups, the Light Rare Earth Elements (LREE - La, Ce, Pr, Nd, Sm) and Heavy Rare Earth Elements (HREE - Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Y), both for physico-chemical and commercial reasons.

EU CRM assessment addresses two stages of REE products. At the first stage, REE are assessed in the form of mixes of rare earth oxides (REO) or low purity single REO ores and concentrates (this roughly corresponds to mining and first stages of processing/separation) (CN codes used: 28461000, 28469010 and 28469020). The second stage considers high purity single REE in the form of metals or interalloys (this corresponds to advanced separation/refining) (CN codes used: 28053010, 28053020 and -28053030). To obtain the figures for each REE, the share of individual REE in the total EU use of REE is used.

The REE are critical for the success of the EU ambitions to become climate-neutral by 2050[219]. They are essential in the production of high-tech, low-carbon goods such as electric vehicles, wind turbines, batteries and energy efficient light bulbs. They are also indispensable in the defence sector (laser, night vision goggles, radar equipment, etc.). Currently, the structure of the EU demand of REE, 60% used in catalysts and glass making, is different from the global demand for using 79% of REE in magnets, metal alloys, catalysts and polishing.

[219] https://ec.europa.eu/clima/policies/strategies/2050_en, and the new European Green Deal.

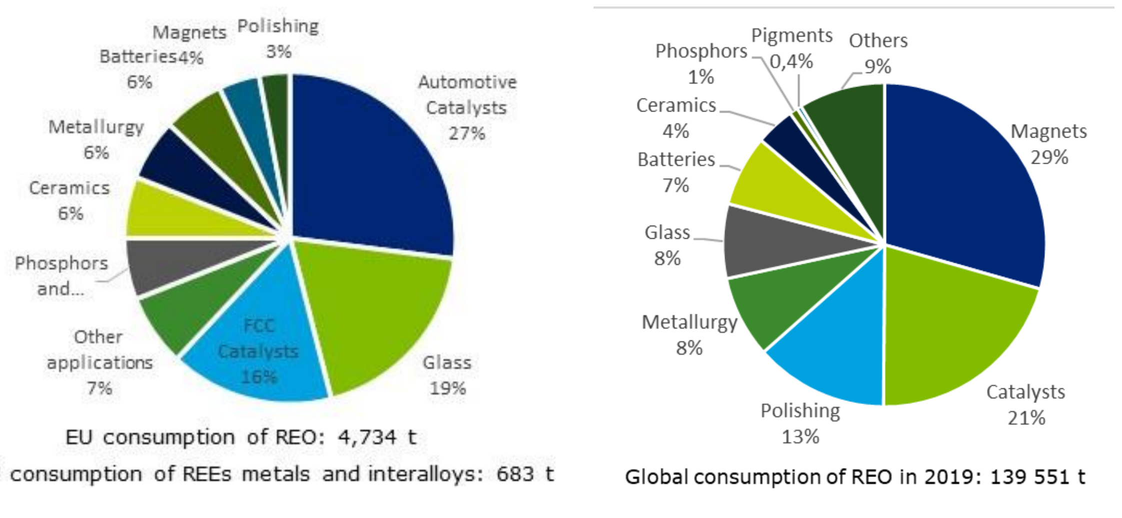


Figure 319: EU and global end-uses and consumption of REE (Eurostat, 2019; Machacek and Kalvig 2017: EURARE; Roskill 2019)

According to Roskill (2019) the global market of REE is worth 2.2 billion USD at 139,600 tonnes of rare-earth-oxide equivalent (REO[220]) in 2019 (while Zion Market Research, 2019 indicates 8,1 billion USD at 170,000 tonnes in 2018).

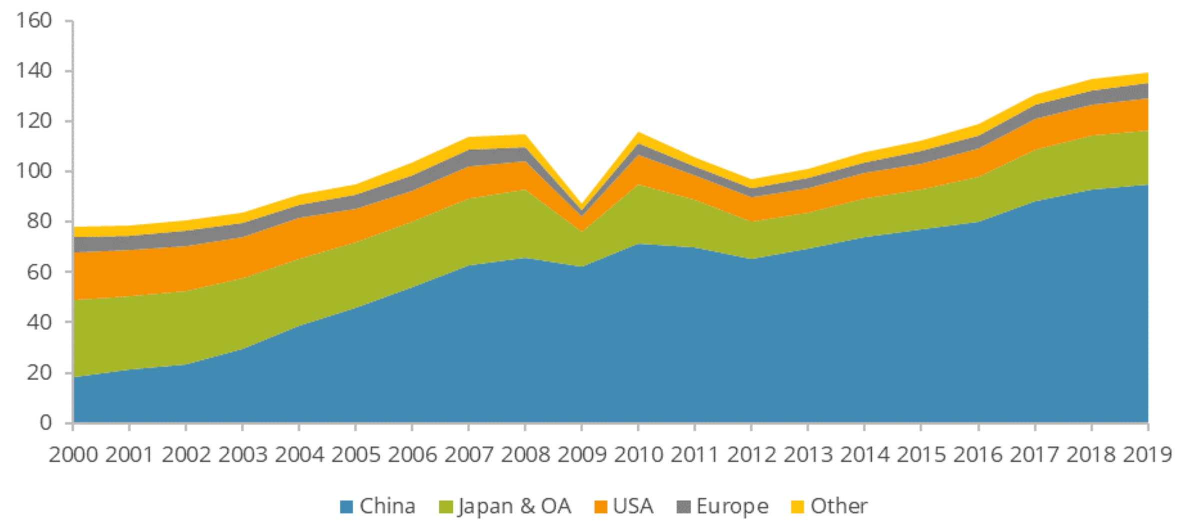


Figure 320: Global consumption of rare earths by region in 2000-2019 in tonnes REO (Roskill 2019)

However, determining the market and dynamics dominated by China is complicated by a limited understanding of the total production of REE-products in China (from mining to components) given that REE-production quota are official figures, which are not representative of the total production; the difficulty of obtaining estimates of the illegal share of production, i.e. the extent of the activities of grey miners; the volume and distribution of REE-stockpiles; high price volatility; difficulty with identification of types and quality of REE products (e.g. mixed rare earth carbonates, oxides or metals), further complicated by aggregated trade statistical codes for product groups; REE market imbalance with high demand for neodymium, praseodymium, dysprosium and terbium used in magnets, while there is excess of lanthanum and cerium products.

[220] Average conversion factor of REE metal vs. Rare Earth Oxides (REO) is estimated at 0.85 (Guyonnet et al. 2015)

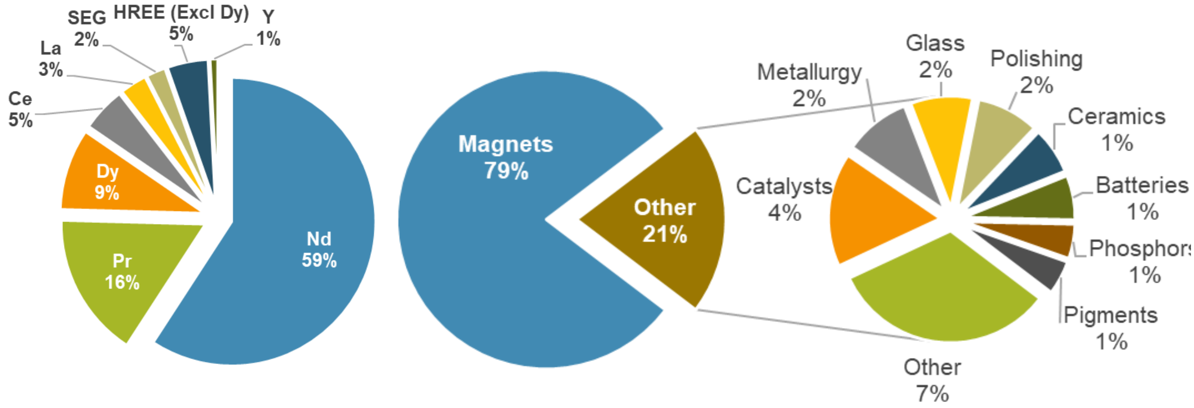


Figure 321: Estimated shares of rare earth value by element (left) and end-use (right) in 2019. Total market value: USD 2.2 billion. (Roskill, 2019)

Magnet materials neodymium and praseodymium represent 75% of the total REE value and 20% of the volume; while lanthanum and cerium account for around 70% of the volume but only 8% of the value; and other elements account for around 10% of the volume and 17% of the value.

Neodymium, praseodymium, dysprosium, samarium, gadolinium and cerium are used in permanent magnets for electricity generators and electric motors. REE permanent magnets represent 29% (41,046 tonnes of REO) of total REE global demand in 2019. NdFeB magnets have a higher energy density compared to other permanent magnets, around 5-12 times that of ferrite and 3-10 times that of AlNiCo magnets. However, they are limited to an operating temperature range of between 80°C and 120°C.

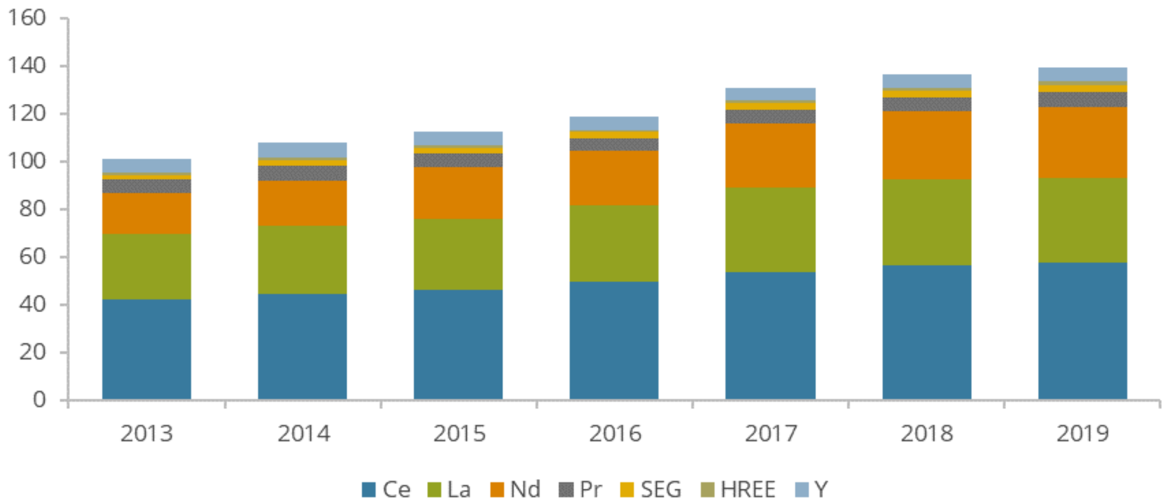


Figure 322: Global consumption of rare earths by element in 2013-2019 in tonnes REO (Roskill 2019)

Roskill (2019) forecast consumption increase by 3.3% per year over the next five years to 2024, reaching 163.9kt REO, while Kingsnorth (2018) expects 6-7% per year growths by 2025. Roskill (2019) expects slowing consumption to 2.1% per year over the following five years to 2029, reaching 181.5kt. China will continue to dominate global markets and lead growth in the consumption of REE ahead of rest of the world markets.

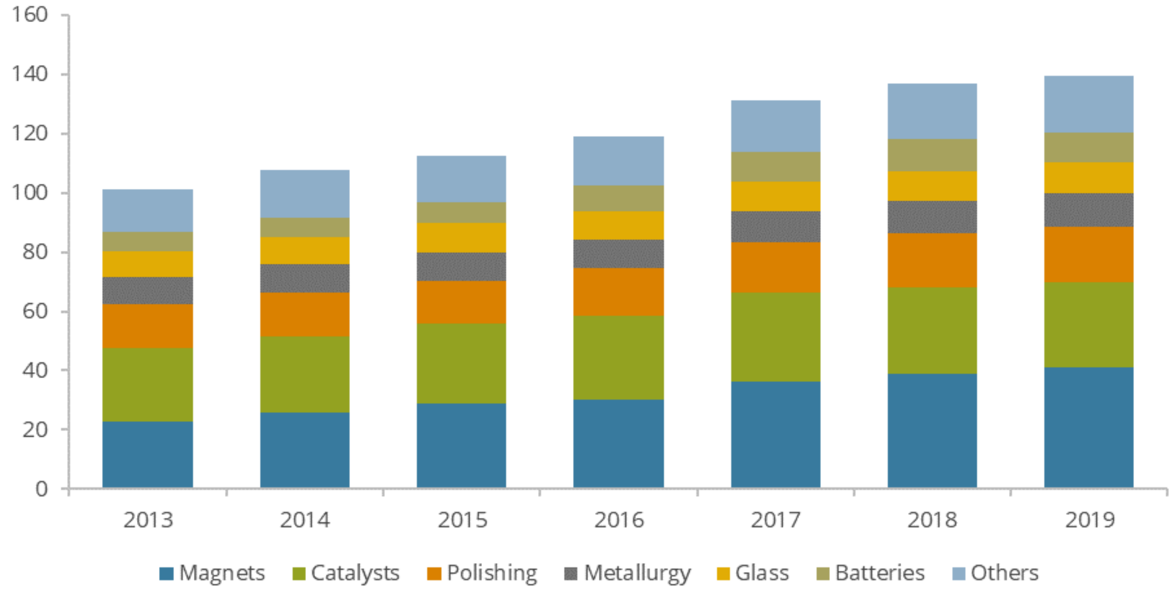


Figure 323: Global demand for rare earths by application in 2013-2019 in tonnes REO (Roskill 2019)

Magnets became globally leading application of rare earths demand in 2015. According to Adamas (2019), permanent magnet synchronous motors are up to 15% more efficient than induction motors and are the most power-dense type of traction motor commercially available (in kW/kg and kW/cm3). Global consumption of NdFeB magnets increased by 17% from 98,413 tonnes in 2015 to 118,047 tonnes in 2019 (Roskill 2019). NdFeB magnets represented around 66% of the permanent magnets market value of USD 20 billion in 2015 (Global Market Insights Inc., 2017). Binnemans (2018) states that for a 55-kW electric motor, 0.65 kg of Nd–Dy–Co–Fe–B alloy is required, which represents 200 g of neodymium (3.6 g/kW) and 30 g of dysprosium (0.55 g/kW) per motor. Direct-drive wind turbines contain 700–1200 kg of NdFeB magnets per MW, which corresponds to 175–420 kg of pure neodymium per MW.

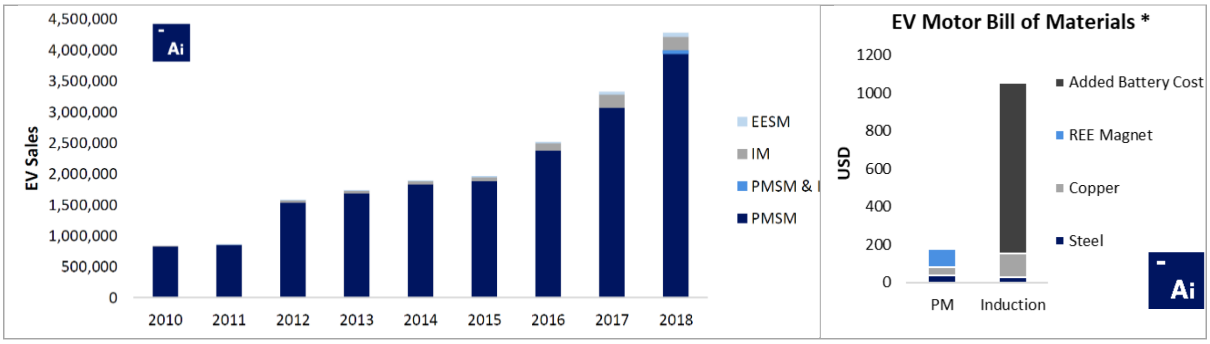


Figure 324: Left: Over 90% of all EVs produced to-date have used permanent magnet traction motors (PMSM). IM - induction motors, EESM - electrically-excited synchronous motors. Right: Added battery pack costs incurred by an automaker using less efficient motor type (Adamas Intelligence 2019)

According to Roskill (2019), China produced 160-180kt of REE permanent magnets in 2018 representing around 85% of global production, and has production capacity of 200kt to 300kt. The EU still has small magnet producers, but they are under pressure to move their production to China.

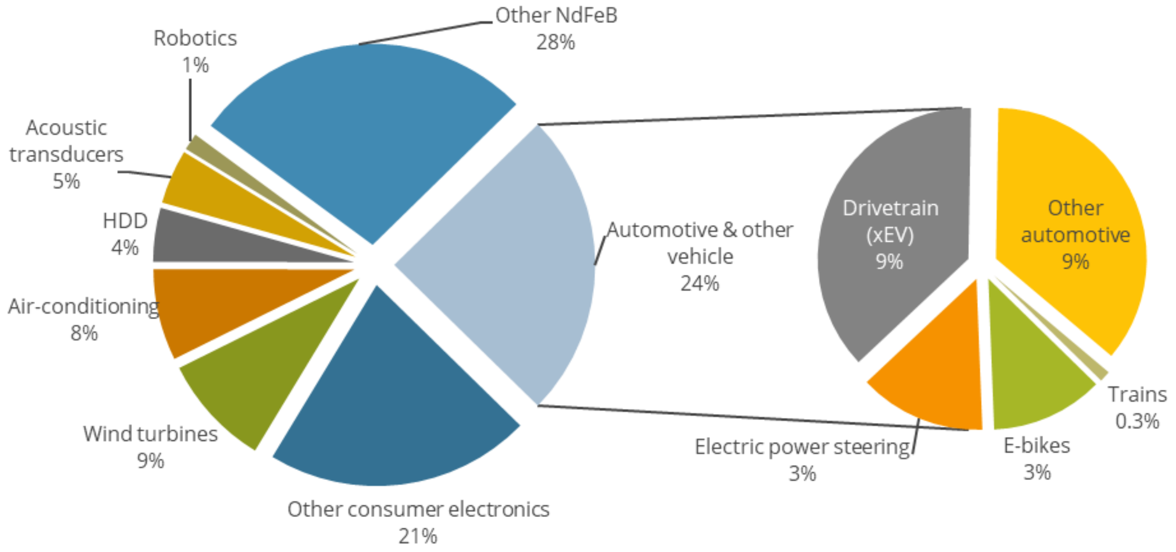


Figure 325: Global applications for NdFeB permanent magnets in 2019 (Roskill 2019)

Electric vehicles underpin the fundamental growth expected for NdFeB permanent magnets. According to Roskill (2019), drivetrains account for 9% of NdFeB demand in 2019 and is expected to increase at over 21% per year to account for 30% of demand by 2025 and 38% by 2029, with a total volume of 50kt and 77kt respectively. The longer-term future of drivetrain technology will be determined by new motor technologies capable of competing with permanent magnet motor efficiencies and the stability of the REE supply chain.

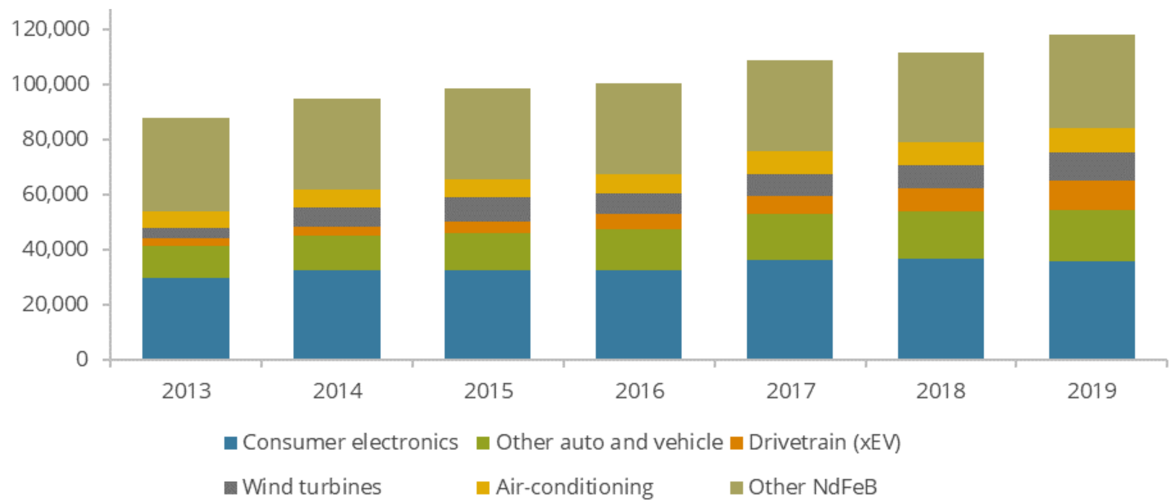
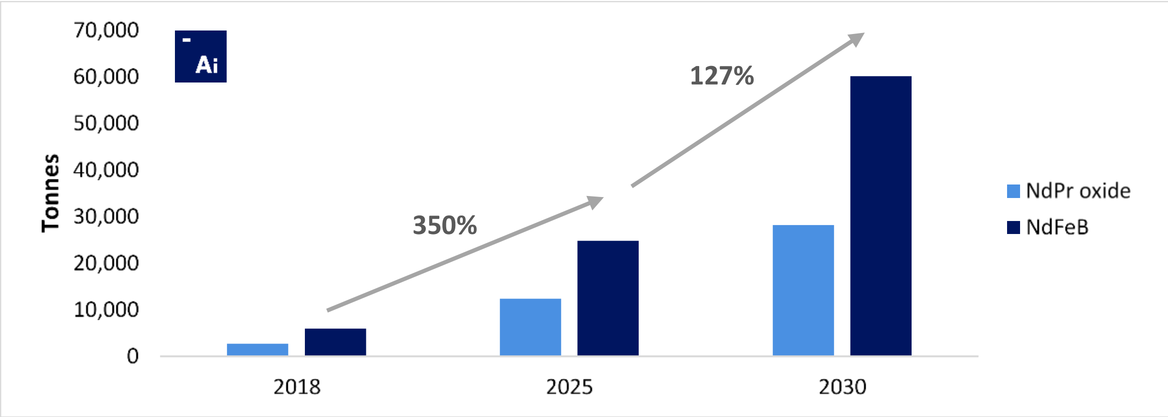


Figure 326: NdFeB magnets demand per application in tonnes in 2013-2019 (Roskill 2019)



Source: Adamas Intelligence

Figure 327: Changes in rare earths (Nd, Pr) and NdFeB magnets demand for EV traction motors to increase by 350% between 2018 and 2025 (Adamas Intelligence, 2019)

Europium, terbium, and yttrium are mainly used in lighting phosphors in LEDs. Yttrium, neodymium, erbium, ytterbium and thulium are dopants in laser crystals, used also in 5G frequencies generators.

The most abundant and cheapest REE - lanthanum and cerium are used in catalysts (both fluid catalytic cracking and car catalysts) and in glass. Glass is also the main application of erbium and holmium/lutetium/ytterbium/thulium; and ceramics of yttrium.

Most of REE applications lack material substitutes with comparable cost and technical performance. However, for economic reasons, industry focuses on reducing the amount of REE used in many different applications or on changing to REE-free technology where possible.

Rare earths are mostly traded as Rare earth oxides (REO), metals or alloys. REE are not yet commodities, but customer specific chemicals, produced to precise chemical and physical specifications. Demand for REE has been steadily growing in average around 4% per year since 1975 (Kingsnorth 2018), since 2012 it has grown by 5.9% per year, recovering from suppressed demand following the 2011 price spike (Roskill 2019). Consumption of rare earths is estimated to reach 139.6kt REO in 2019. This creates a pressure on this small and highly specialised market of REE.

According to Roskill (2019), the USA was a key exporter of REE metals between 2000 and 2013, mostly related to reprocessed metals imported from China. Since 2014, exports fell below 200t and are expected to fall below 100t in 2018. Vietnam has become the second largest producer and exporter, reaching 4.000t in 2018. REE metals from Vietnam have a much higher value of close to US$40/kg, reflecting Nd-Pr and other heavy rare earth metal products (i.e. not of cerium and lanthanum). Thailand exports higher value metals (averaging over US$50/kg since 2017), while sources feeds from Malaysia, Japan, China and Estonia. Philippines exports are low, likely representing scrap products exported to Japan. Japan exports small volumes of metal, but typically of much higher value, with annual average unit values between US$80-105/kg since 2016. Exports from Netherlands, Spain, Austria, USA and Belgium reflect re-exported trade.

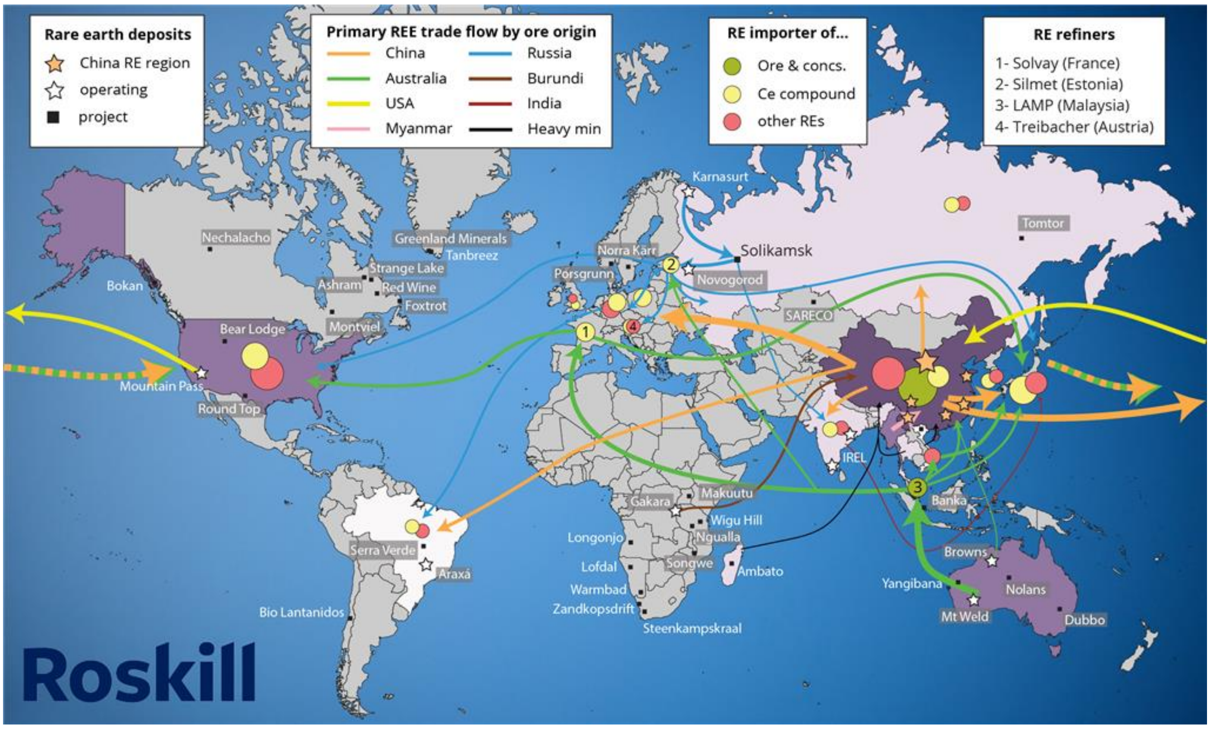


Figure 328: World map of rare earth deposits, production and trade flow, 2019. (Roskill 2019)

According to Roskill (2019), Norway, India, USA, Thailand, Germany and France are consistent importers of rare earth metals. The unit value for Japanese and Thai imports are the highest unit value importers at US$29/kg and US$36/kg, respectively, and probably reflect imports from magnet manufacturing facilities. USA and Germany import rare earth metals with an average unit value of around US$10-12/kg.

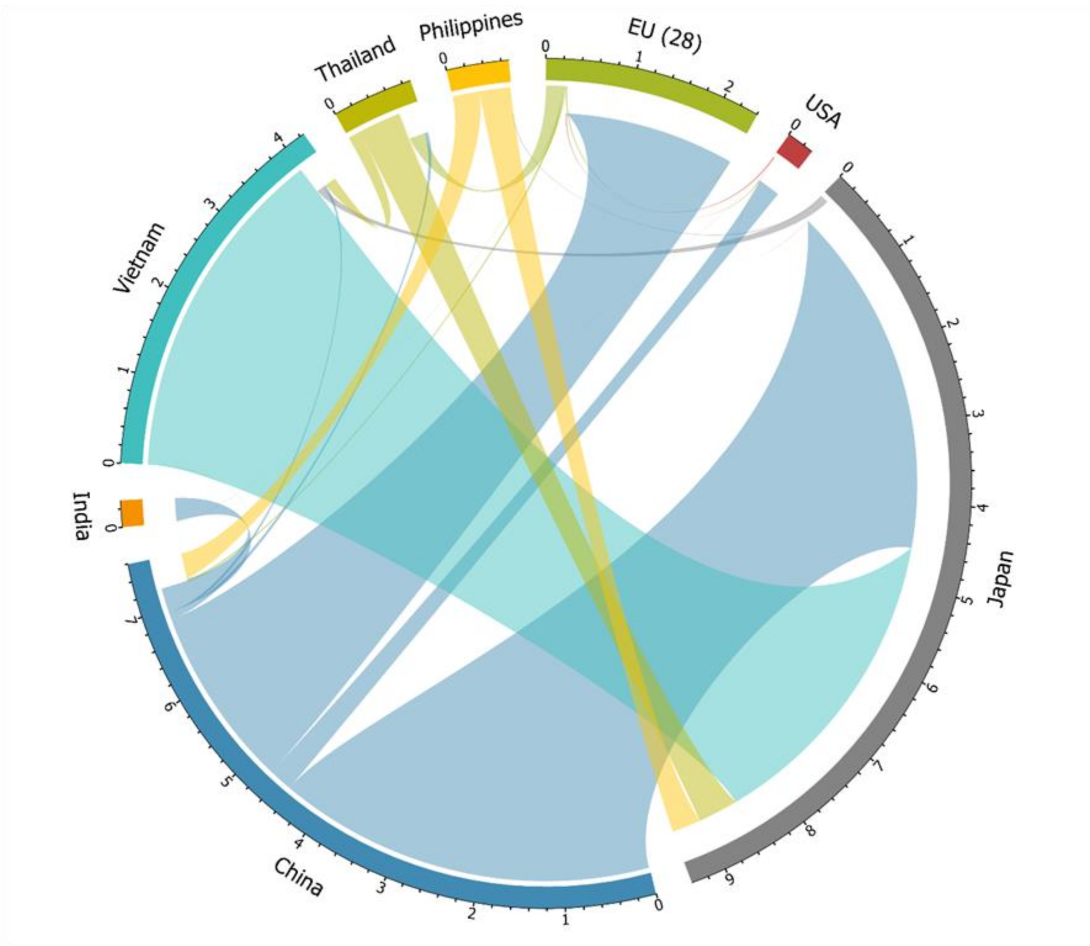


Figure 329: Rare Earths metal trade flows in 2018 in gross kt. (Roskill 2019)

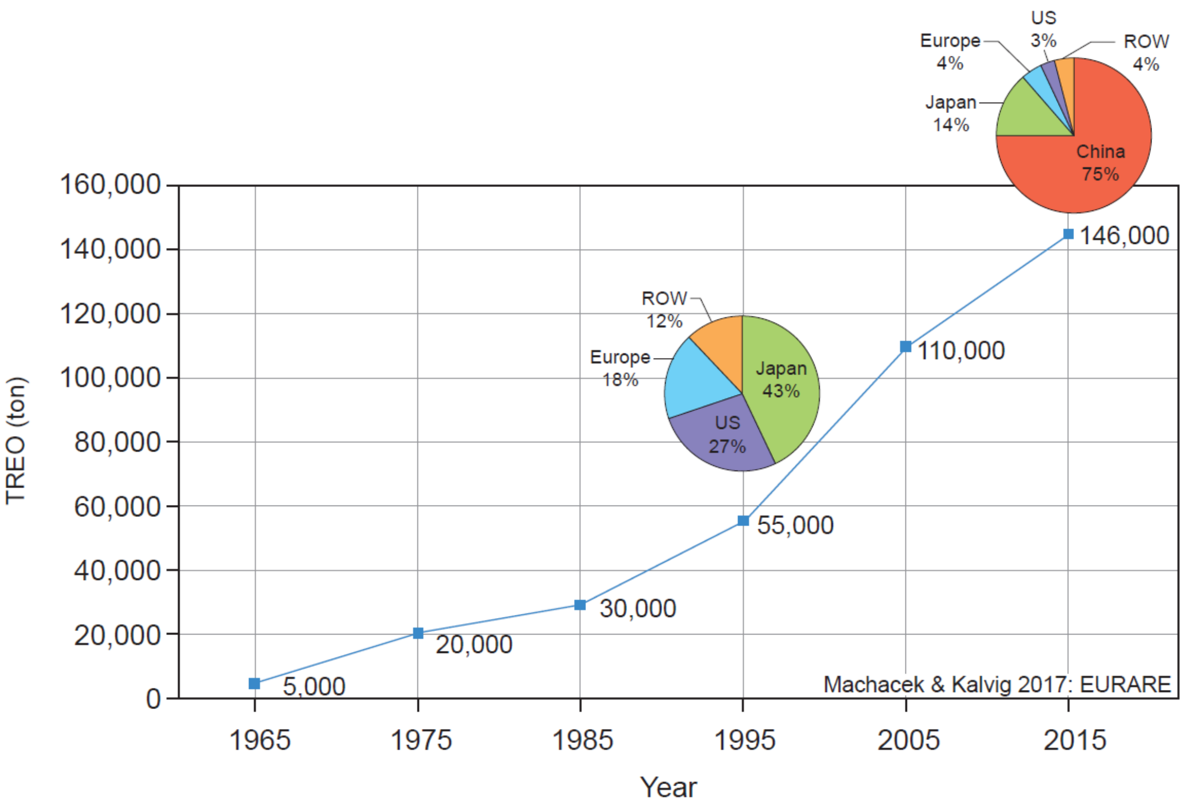


Figure 330: Long-term evolution of REE consumption REE (Machacek and Kalvig, 2017: EURARE)

The EU is entirely dependent on imports of REE for its consumption. The average EU imports during the 2016-2018 period were 9,438 tonnes of REE compounds, 1,162 tonnes of REE metals and interalloys, while the EU exports were 5,464 tonnes of REE compounds and 601 tonnes of REE metals and alloys.

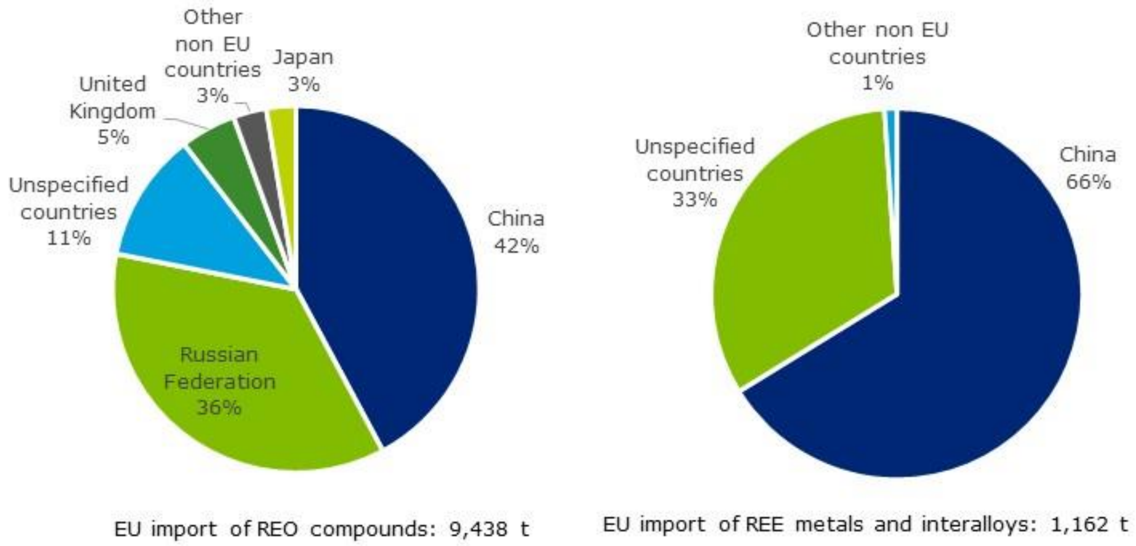


Figure 331: EU imports of REE compounds (CN8 2846-1000, -9010 and -9020) and REE metals and interalloys (CN8 2805-3010, -3020, -3030) (Eurostat Comext, 2019).

The EU imports 9,438 tonnes of REO compounds mainly from China (42%) and Russian Federation (36%). However, the significant share of Russian Federation is due to the import of Cerium compounds (64% of the total import of Ce oxide in EU). The EU imports HREE mainly from China, but also from Japan (18%), UK (6%) and Russian Federation (5%). EU import of 1,162 tonnes of REE metals and interalloys come from China (66%) and a not negligible share (33%) is reported under the label "Unspecified countries" and probably related to the Chinese market.

Prices of REE experienced great variations in the last decade, as shown on an example of neodymium (Figure 332). In 2010-2011 a 12-fold increase was observed, mainly triggered by a strong reduction of Chinese export quotas and geopolitical tension in a period of high demand for permanent magnets, driven by the expected growth of the renewable energy and electric vehicles markets. The highest price changes were observed for europium, most expensive REE for 15 years, but now taken over by terbium. Europium price increased from 785 USD/kg in 2002-2003 to an all-time high of USD 6,800 per kg in July 2011, then continuously decreasing to USD 35 USD/kg in 2019 (DERA 2019). From early 2012, prices were already down from half and went down almost continuously until 2019. An important exception is dysprosium, which price slightly increased in the last two years.

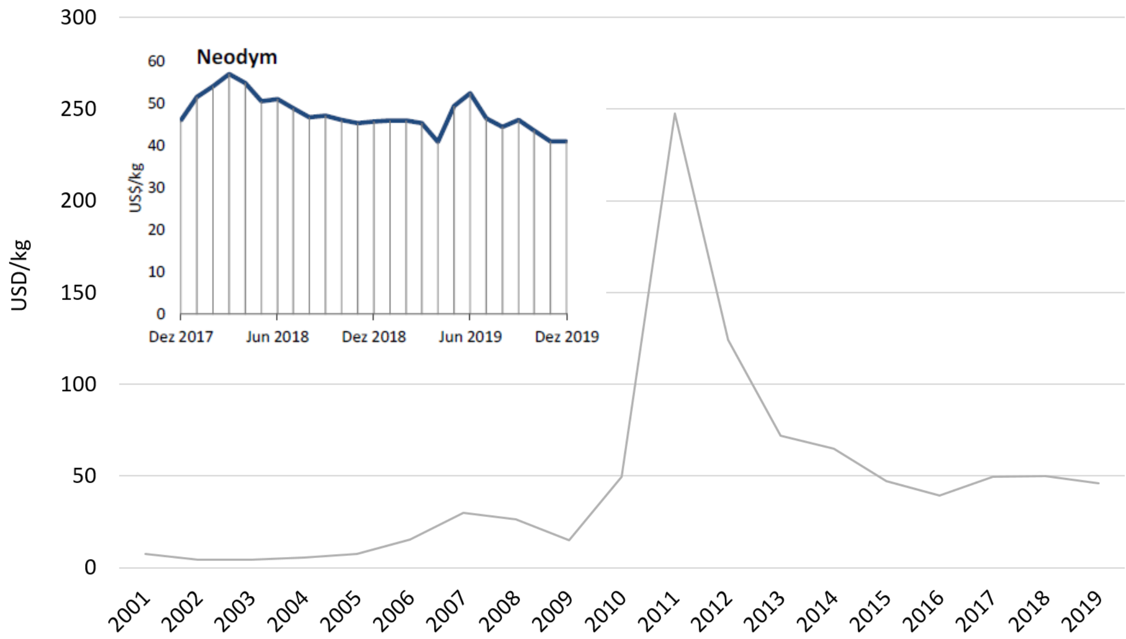


Figure 332: Annual average prices of 99% neodymium oxide in USD/kg from 2001 to 2019 (FOB China, DERA 2019, 2020)

The feasibility of REE production depends on the geology, tonnage and grade of REE resources, available processing technologies, production costs and commodity prices.

Reserves of REE estimated by the USGS 2019 were around 120 million tonnes REO. BRGM (2015) estimates are more conservative and amount to 80 million tonnes REO. Largest resources are identified in China, Brazil, Vietnam, Russia, India, Australia, USA, Tanzania, Canada, South Africa, Malaysia and Greenland. Projects on REE are at different stages in the world, with the majority still developed in China, followed by India, Australia, US, Russia. A few projects at construction level in RSA and Kazakhstan, feasibility studies in other countries, including Canada.

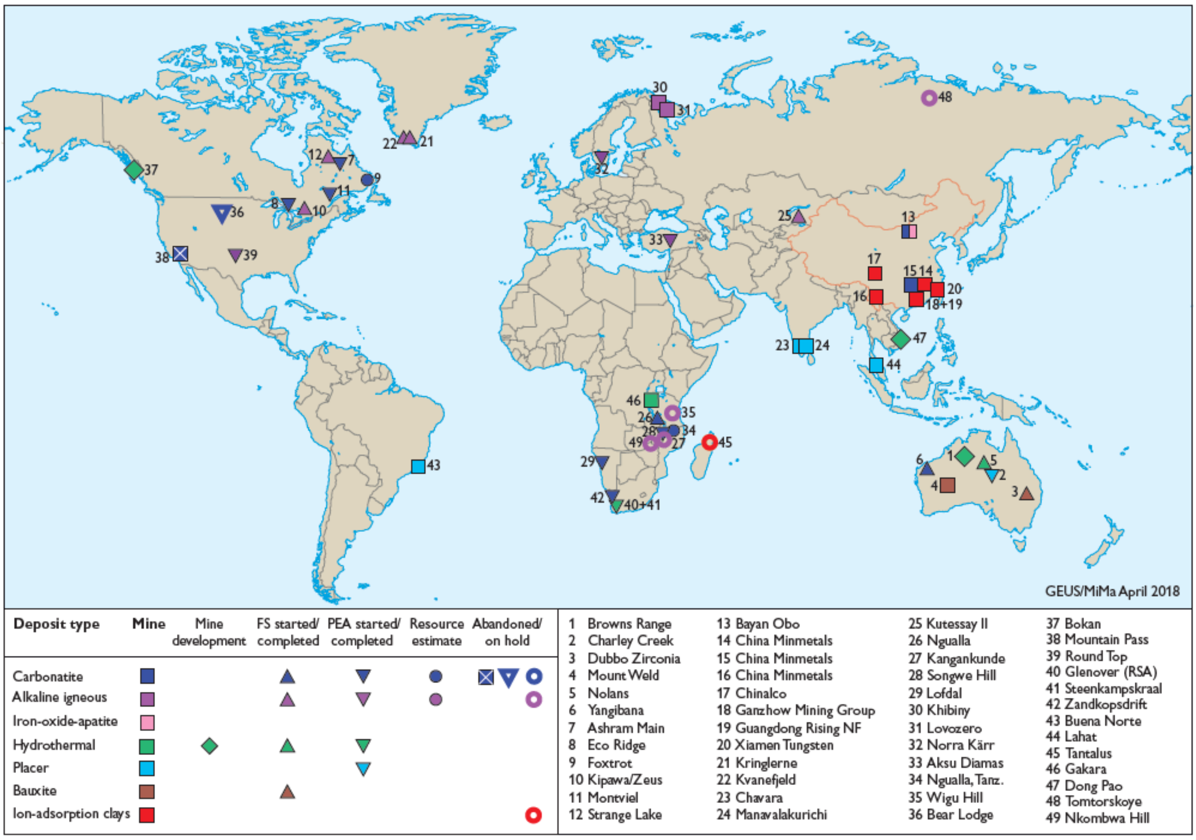


Figure 333: Major REE mining and advanced REE-exploration projects. (GEUS/MiMa, 2018)(Machacek and Kalvig, 2017: EURARE)

In the EU, there are several potentially commercial projects classified under UNFC (E2; F2; G1,2,3) in Sweden (333,000 tonnes REO); Spain (36,000 tonnes REO) and Germany (10,000 tonnes REO).

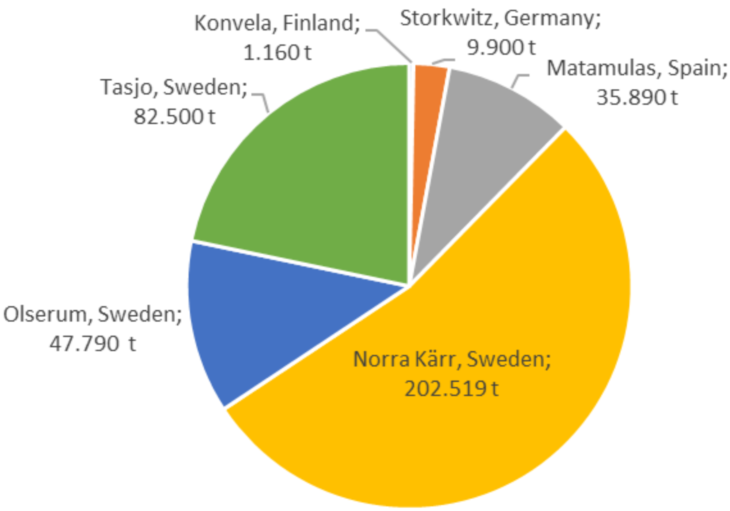


Figure 334: Potentially commercial projects of rare earths in the EU with estimated quantities in tonnes of REO content classified according to UNFC - E2; F2; G1,2,3[221]. (EU Member States survey 2019)

[221] see United Nations Framework Classification (ECE ENERGY SERIES No. 42): https://www.unece.org/energywelcome/areas-of-work/unfc-and-sustainable-resource-management/publications/unfc-and-resource-classification/2013/united-nations-framework-classification-ece-energy-series-no-42/docs.html)

Europe has several potentially economic and other deposits (Norra Kärr, Grängesberg, Olserum and Tasjoin Sweden; Matamulas and Gemas, Tesorillo in Spain, Kvanefjeld and Kringlerne in Greenland; Fen, Kodal and Misværdalen in Norway; and Kontioaho, Korsnas and Konvela in Finland; andVale de Cavalos in Portugal), but there is no REE mining operation in the EU.

Global mine production of REO equivalent in 2019 reached 210,000 tonnes according to USGS (2020). There are several active mines globally, but the information and statistics vary significantly.

In recent years, China's share of global rare earth mine production has fallen slightly. However, China's share of downstream value-adding capacity to convert rare earth mine outputs in oxides, metals, alloys and magnets has continuously expanded. (Adamas Intelligence, 2019)

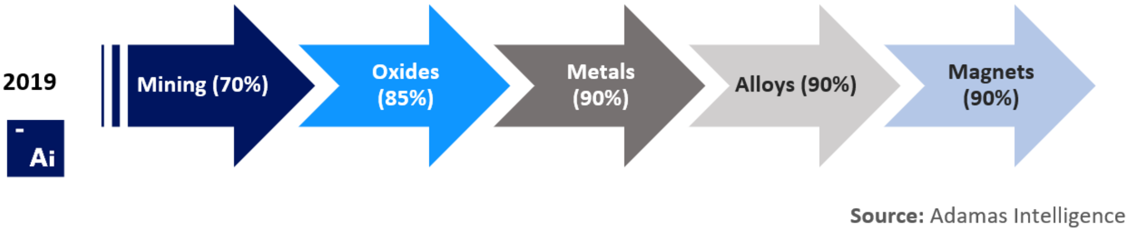


Figure 335: Share of Chinese production in rare earths value chain (Adamas Intelligence, 2019)

China, producing around 70-90% of the world REE production, controls the world market through production controls, export restrictions (e.g. quotas, tariffs), mine closings and company consolidation. All these factors contributed to unstable supply, significant price increases and volatility on the world market. China's official production quota increased to 132,000 tonnes in 2019 from 120,000 tonnes in 2018, 105,000 tonnes in 2014-17, while undocumented annual production over last years was estimated at 60,000-80,000 tonnes (Kingsnorth, 2018). According to ACREI (2019), the production capacity of the six Chinese rare earth producers was 227.000 tonnes in 2018, while the capacity of the whole industry including comprehensive recycling of rare earth resources was estimated to be about 300,000 tonnes.

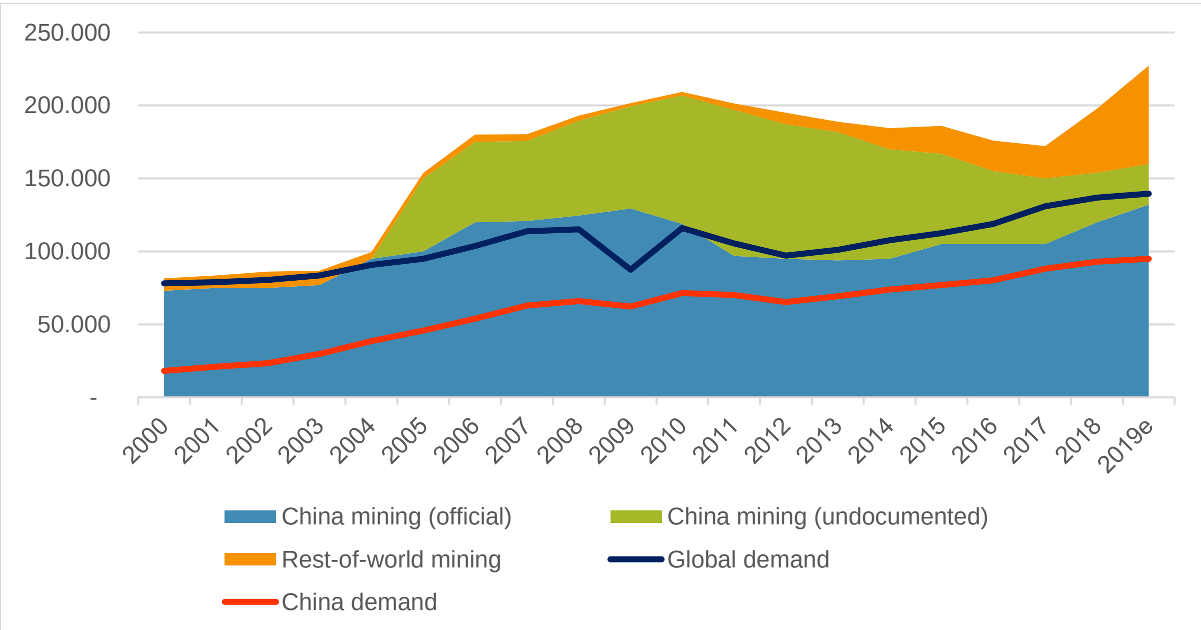


Figure 336: Rare earths mine supply and demand 2000-2019 (WMD 2020, Roskill 2019)

After a break in 2015-2017, US restarted mining in Mountain Pass reaching 18,000 tons in 2018, and 26,000 t in 2019 (USGS, 2020). But their ores and concentrates are shipped to China for refining, from where it sources 80% refined rare earths. In 2019, Australia mined 21,000 tonnes of REO, Myanmar 22000 tonnes, India 3000 tonnes, Russia 2,700 tonnes and Madagascar 2,000 tonnes and Thailand 1,800 tonnes. Brazil, Burundi, Malaysia, Vietnam and other countries produced 1000 tonnes or less (USGS, 2020).

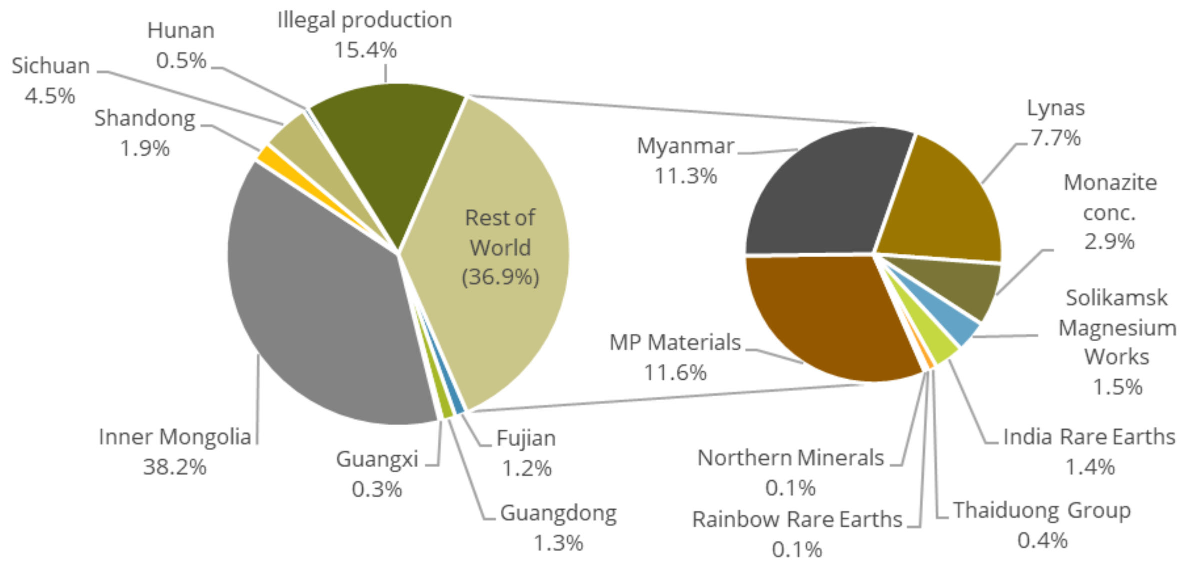


Figure 337: World mine production of rare earths by company/Chinese province in 2019 (Roskill 2019)

Over the last decade the EU substantially decreased the REE processing and refining capacity, but still has several companies producing different REE product, including NPM-Silmet operation in Estonia and Solvay REE operation in La Rochelle, FR Nevertheless, LKAB in Sweden develops a process to start a small REE production from the iron ore mining waste. Yara in Norway, currently develop processes to start a small rare earths production from their phosphate mining wastes. Potential exists also in coal and aluminium ore mining wastes.

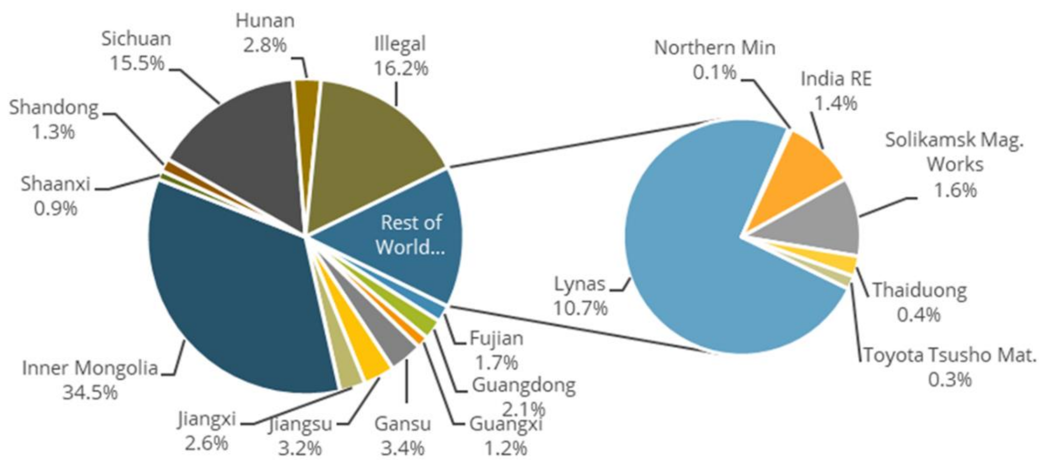


Figure 338: World refined production of rare earths by company/Chinese province in 2019 (Roskill 2019)

Global mine production of REE is forecast by Roskill (2019) to increase by 3.3%py between 2019 and 2029, reaching a high of 252.0kt REO by the end of the forecast period. In the short term, additional Chinese official mine supply is expected to counteract the continued fall in illegal Chinese mine production. Illegal mine production is forecast to fall from 28.0kt REO in 2019 to 10.6kt REO in 2029, as the government crackdown and consolidation of the Chinese REE industry continues, although it should be noted that any forecast for illegal production is open to a range of unquantifiable variables.

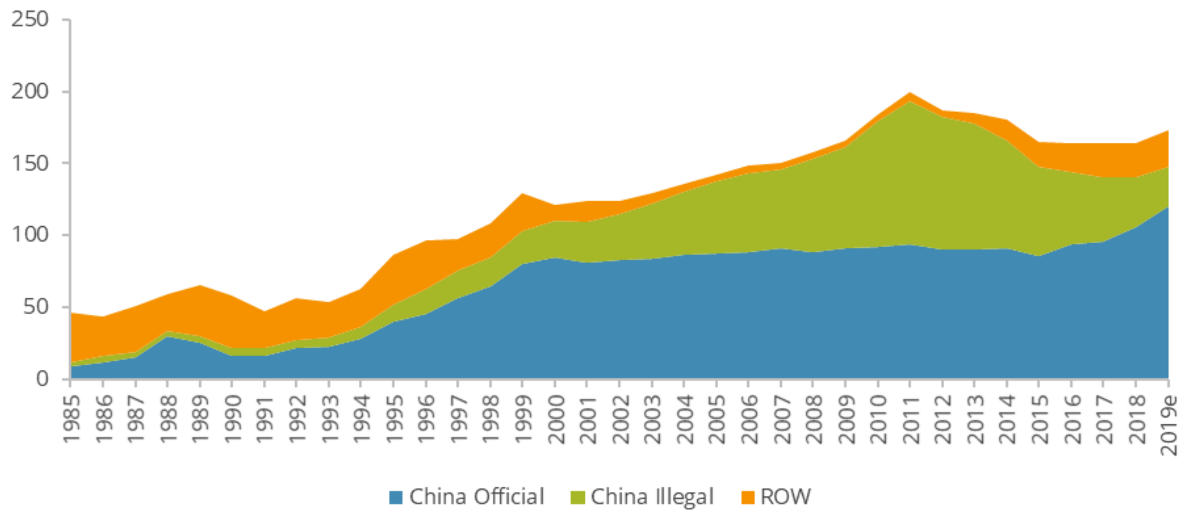


Figure 339: Global supply of refined rare earths during 1985-2019 in kt REO (Roskill 2019)

The recycling input rates of REE are very limited, usually less than 1%. Even if technologies exist for reuse or recycling of individual REE, e.g. from magnets, industrial production is hampered in the EU. Main reasons are lack of efficient collecting systems and prohibitive costs of building REE recycling capacities, technology issues, products life time and changing chemistry or commercial viability. The processes required are energy intensive and complex. Higher recycling input rates for europium, yttrium and terbium are reported only thanks to recycling of fluorescent lamps, which are phasing out.

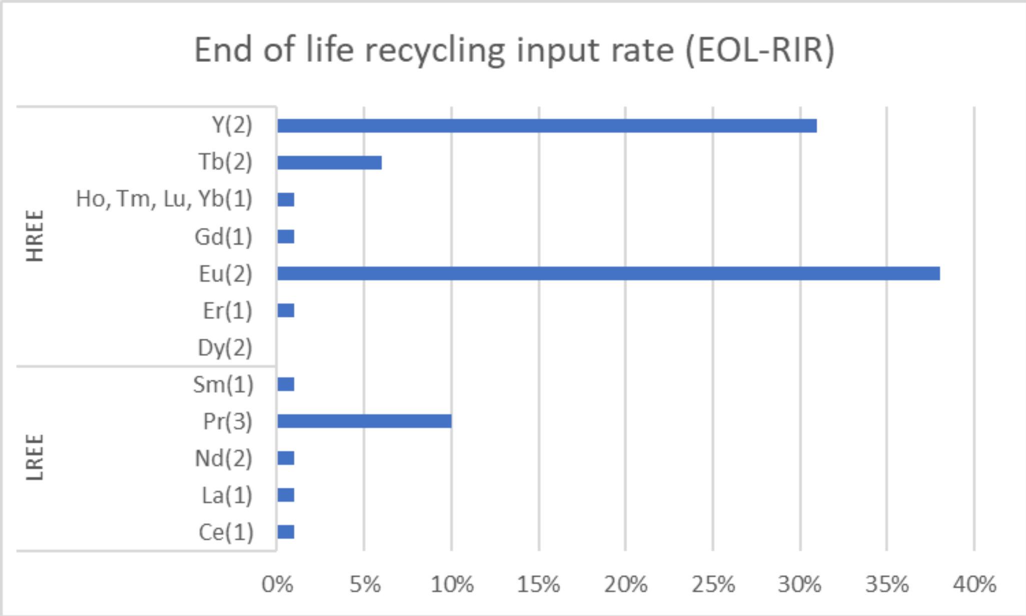


Figure 340: End of life Recycling Input Rates of individual REE (1-UNEP, 2013; 2-Bio Intelligence Service, 2015; 3-BRGM, 2015)

China is also a technology leader in REE refining, separation and recycling. China also host the ISO technical committee TC 298 [222] on REE formed under the International Organization for Standardization in 2015. 11 ISO standards are under development in the fields of REE mining, concentration, extraction, separation and conversion to REE compounds (including oxides, salts, metals, master alloys, etc.), recycling, packaging, labelling, and REE traceability in the supply chain.

REE extraction and processing faces environmental and health and safety challenges, including handling of radioactive elements usually present in small quantities in the REE ores. At present, however, information regarding the environmental aspects of REE mining is limited. Toxicological data about the effects of REE on aquatic, animal, or human health are also limited (USGS 2017b). Recent studies (Werker et al., 2019) raise socio economic issues of social responsibility, fair competition and corruption connected with extraction of REE and magnets.

21.1.1Individual rare earths

Rare Earth Elements (REE) are a group of 17 elements, comprising the elements scandium (Sc), yttrium (Y) and the 15 lanthanides (elements no. 57-71), as defined by the International Union of Pure and Applied Chemistry (IUPAC). For the purpose of the EU criticality assessment, radioactive promethium is not included and scandium is considered separately.

The term REE dates back to the discovery of the first unknown REE-minerals in Sweden in 1794; it took more than 150 years to identify all 17 elements. At the beginning of this period, the word "earth" referred to a metal oxide and not to soil. "Rare" at that time simply meant something strange or extraordinary. REE are relatively abundant in the upper part of Earth's crust, although with significant variations. The upper crust is assumed to contain 63 ppm of Ce and 33 ppm of La, which are the most abundant of the REE, to

[222] https://www.iso.org/committee/5902483.html

somewhat less than 0.3 ppm for Tm and Lu, the rarest of the REE (Weng et al. 2015). La and Ce are both more abundant than the average crustal concentrations of Cu (28 ppm) and Pb (17 ppm) (Rudnick and Gao, 2003). whilst the rarer HREE are still more abundant than gold, silver and platinum group elements (Rudnick and Gao, 2003). (Machacek and Kalvig 2017: EURARE)

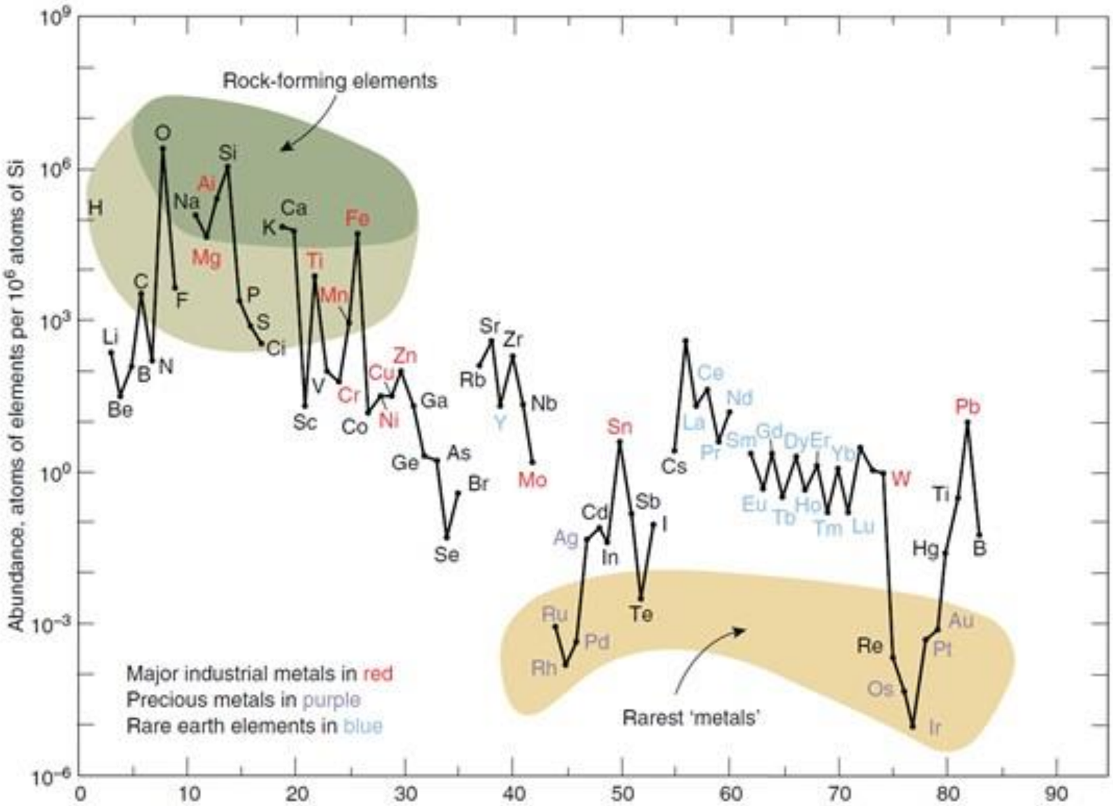


Figure 341: Abundance of chemical elements in the Earth's upper continental crust. (Haxel et al., 2002) (Machacek and Kalvig 2017: EURARE)

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

Physically, the REE have a number of unique properties that make them useful for a wide range of applications. For example, REE such as Gd, Dy, Er, Nd and Sm have ideal characteristics for magnet manufacturing; and Y and Tb provide sharply defined energy states which can be efficiently used in lighting and laser applications. The REE are frequently grouped, according to their atomic weight and properties into the two groups: the light REE (LREE) and the heavy REE (HREE). The definition of these two groups is varying among scientific disciplines." (Machacek and Kalvig 2017: EURARE)

Some of the classifications are illustrated in Figure 342.

<table>
<tr><th rowspan="2">Element</th><th rowspan="2">Symbol</th><th rowspan="2">EURARE</th><th rowspan="2">IUPAC</th><th colspan="2">China MLR</th><th rowspan="2">China State Council White Paper</th></tr>
<tr><th>I</th><th>II</th></tr>
<tr><td>Lanthanum</td><td>La</td><td rowspan="5">LREE</td><td rowspan="6">Unpaired electrons in 4f shells</td><td rowspan="4">LREE</td><td rowspan="4">LREE</td><td rowspan="4">LREE</td></tr>
<tr><td>Cerium</td><td>Ce</td></tr>
<tr><td>Praseodymium</td><td>Pr</td></tr>
<tr><td>Neodymium</td><td>Nd</td></tr>
<tr><td>Samarium</td><td>Sm</td><td rowspan="3">MREE</td><td rowspan="6">MREE</td><td rowspan="12">HREE</td></tr>
<tr><td>Europium</td><td>Eu</td><td rowspan="10">HREE</td></tr>
<tr><td>Gadolinium</td><td>Gd</td><td rowspan="10">Paired electrons in 4f shells</td></tr>
<tr><td>Terbium</td><td>Tb</td><td rowspan="7">HREE</td></tr>
<tr><td>Dysprosium</td><td>Dy</td></tr>
<tr><td>Holmium</td><td>Ho</td></tr>
<tr><td>Erbium</td><td>Er</td><td rowspan="4">HREE</td></tr>
<tr><td>Thulium</td><td>Tm</td></tr>
<tr><td>Ytterbium</td><td>Yb</td></tr>
<tr><td>Lutetium</td><td>Lu</td></tr>
<tr><td>Yttrium</td><td>Y</td><td></td></tr>
<tr><td>Scandium</td><td>Sc</td><td></td><td></td><td></td></tr>
</table>

Figure 342: Classifications of REE elements in light REE (LREE) and heavy REE (HREE) (Machacek and Kalvig 2017: EURARE)

21.1.1.1 Cerium

Cerium (chemical symbol Ce) is considered as a light REE. Its upper crust abundance is 63 ppm (Rudnick, 2003). It is a silvery metal which tarnishes in air in a few days. It does not occur naturally as a metallic element and is found (for commercial exploitation) mainly in the minerals bastnäsite, loparite and monazite. Because of its chemical and optical properties and relative abundance it is found in many applications such as autocatalysts, glass and ceramics, polishing powders, fluid cracking catalysts (FCC), metallurgical alloys (mischmetal) and NiMH batteries (mischmetal).

21.1.1.2 Dysprosium

Dysprosium (chemical symbol Dy) is considered as a heavy REE. Dysprosium's upper crust abundance is 3.9 ppm (Rudnick, 2003). It does not occur naturally as a metallic element and is found (for commercial exploitation) almost exclusively in the minerals xenotime and ion-adsorption clays (in Southern China). Dysprosium is a silvery very hard metal which slowly oxidizes in air (a few years). Its main and almost exclusive use is in permanent magnets NdFeB, where it improves resistance to demagnetization and high working temperature performance up to 200°C.

21.1.1.3 Erbium

Erbium (chemical symbol Er) is considered as a heavy REE. Erbium’s upper crust abundance is 2.3 ppm (Rudnick, 2003). It is a silvery hard metal, which slowly oxidizes in air (a few years). It is used mainly used in optical fibres, for glass colourising, dopant in lasers (also for 5G) and phosphors.

21.1.1.4 Europium

Europium (chemical symbol Eu) is considered as a light REE. Its upper crust abundance is 1 ppm (Rudnick, 2003). It does not occur naturally as a metallic element and is found in minerals such as bastnäsite and monazite. It is a moderately hard, silvery metal which readily oxidizes in air and water. The main use of europium is in lighting and exploits the phosphorescence of europium compounds.

21.1.1.5 Gadolinium

Gadolinium (chemical symbol Gd) is considered as a heavy REE. Gadolinium's upper crust abundance is 4 ppm (Rudnick, 2003). It does not occur naturally as a metallic element and is found in minerals such as bastnäsite and monazite. Gadolinium is a silvery-white, malleable and ductile rare earth metal. Gadolinium metal possesses unusual metallurgic properties, to the extent that as little as 1% gadolinium can significantly improve the workability and resistance to high temperature oxidation of iron, chromium, and related alloys. Its main applications are permanent magnets, lighting and metallurgy. Gadolinium as a metal or salt has exceptionally high absorption of neutrons and therefore is used for shielding in neutron radiography and in nuclear reactors.

21.1.1.6 Holmium, Lutetium, Ytterbium, Thulium

Holmium (chemical symbol Ho), thulium (chemical symbol Tm), ytterbium (chemical symbol Yb) and lutetium (chemical symbol Lu) are all heavy rare earth elements. They are at the end of the lanthanide series, with a very low natural abundance and only few niche applications mostly related to their optical properties (Laser dopants, radiography, etc.).

21.1.1.7 Lanthanum

Lanthanum (chemical symbol La) is considered as a light REE. Its upper crust abundance is 31 ppm (Rudnick, 2003). Although it is classified as a rare earth element, lanthanum is the 28th most abundant element in the Earth's crust, almost three times as abundant as lead. It is the second most common of the lanthanides after cerium. In minerals such as monazite and bastnäsite, lanthanum composes about a quarter of the REE content. It is a silvery white metallic element. It tarnishes rapidly when exposed to air and is soft enough to be cut with a knife. Lanthanum compounds have numerous applications as fluid cracking catalysts, additives in glass and ceramics, as well as in mischmetal for batteries.

21.1.1.8 Neodymium

Neodymium (chemical symbol Nd) is considered as a light REE. Neodymium's upper crust abundance is 27 ppm which is more than cobalt (17.3 ppm) (Rudnick, 2003). It is one of the most abundant REE, together with lanthanum and cerium. It does not occur naturally as a metallic element and is mainly found (for commercial exploitation) in the minerals bastnäsite, monazite, and ion-adsorption clays. It is a soft silvery metal that tarnishes in air in a few days. Its most important use is in permanent magnets NdFeB. It is also valued for its chemical and optical properties in other applications such as metallurgical alloys, ceramics, or as a laser dopant (BRGM, 2015).

21.1.1.9 Praseodymium

Praseodymium (chemical symbol Pr) is considered as a light REE. Praseodymium's upper crust abundance is 7.1 ppm (Rudnick, 2003). It does not occur naturally as a metallic element and is found in minerals such as bastnäsite and monazite. It is a soft, silvery, malleable and ductile metal. It is valued for its magnetic, electrical, chemical, and optical properties. Its main uses are in permanent magnets NdFeB, batteries, ceramics, metallurgy, catalysts, polishing powders and glass.

21.1.1.10 Samarium

Samarium (chemical symbol Sm) is considered as a heavy REE. Its upper crust abundance is 4.7 ppm. Although classified as a rare earth element, samarium is the 40th most abundant element in the Earth's crust and is more common than such metals as tin. Samarium does not occur naturally as a metallic element, and is found in several minerals including cerite, gadolinite, samarskite, monazite and bastnäsite, the last two being the most common commercial sources of the element. Samarium is a moderately hard silvery metal that readily oxidizes in air. Its main and almost exclusive use is in permanent magnets SmCo, and also niche applications mostly related to its optical properties (Laser dopant, radiography, etc.).

21.1.1.11 Terbium

Terbium (chemical symbol Tb) is considered as a heavy REE. Its upper crust abundance is 0.7 ppm (Rudnick, 2003). It does not occur naturally as a metallic element and is found mainly in the minerals xenotime, monazite and ion-adsorption clays (for commercial exploitation). It is a silvery very hard metal which slowly oxidizes in air (a few years). Most of the world's terbium supply is used in green phosphors. It is also important in permanent magnets, as a substitute for dysprosium

21.1.1.12 Yttrium

Yttrium (chemical symbol Y) is considered a heavy REE. Its upper crust abundance is 21 ppm which is more than cobalt (17.3 ppm) (Rudnick, 2003). It does not occur naturally as a metallic element and is mainly found (for commercial exploitation) in the minerals xenotime and ion-adsorption clays (in Southern China).Yttrium is a silvery metal with high thermodynamic affinity for oxygen. It is mainly used in various phosphors, for display screens and energy efficient lighting. It also has applications in ceramics and glass, metallurgical alloys, and various medical applications and tracing.

21.2 Market analysis, trade and prices

21.2.1 Global market analysis

REE are not yet commodities, but customer specific chemicals, produced to precise chemical and physical specifications. The REE market is a specialty market, characterized by business to business trade rather than exchanges on metal markets.

The global mine production and market of REE is estimated at 170,000t of rare-earth-oxide equivalent (REO[223]) in 2018, and 8.10 billion USD in 2018 (Zion Markey Research 2019). While Kingsnorth, 2018 estimates the world global market of rare earths in 2017 at about 170.000t of REO worth 3-5 billion USD. According to China’s Ministry of Commerce, production of REO in China was estimated to be at least 180,000 tonnes based on magnet material production. China dominates the market with around 80-90% of the world production, including the official production quota of 120,000 tonnes for 2018 and undocumented production.

Roskill (2019) estimates REE annual demand growth of over 5% between 2014-2019, driven by the increased use of rare earth permanent magnets in automotive and renewable energy applications, supported by underlying demand growth in catalysts, ceramics and polishing powders.

Production of lanthanum and cerium oxides accounts for about 70%, praseodymium and neodymium oxides for around 20%, and other elements account for around 10%.

Issues with determining the market size and dynamics is limited by:

- the difficulty of obtaining estimates of the illegal share of production, i.e. the extent of the activities of grey miners;
- a limited understanding of the total production of REE-products in China (from mining to components) given that REE-production quota are official figures which are not representative of the total production;
- high price volatility;
- the volume and distribution of REE-stockpiles;
- difficulty with identification of types and quality of REE products (e.g. mixed rare earth carbonates, oxides or metals), further complicated by aggregated trade statistical codes for product groups;
- REE market imbalance, demand for neodymium, praseodymium, dysprosium and terbium used in magnets is high, while there is excess of lanthanum and cerium products.

According to the available data for 2012-2016 the average global consumption of REE was only 115.000 tonnes of REO. For comparison, the annual REO production is similar to cobalt - about 130,000 tonnes, while the annual production of the iron ore was around 1,5 billion tonnes (WMD 2019).

[223] Average conversion factor of REE metal vs. Rare Earth Oxides (REO) is estimated at 0.85 (Guyonnet, et al. 2015).

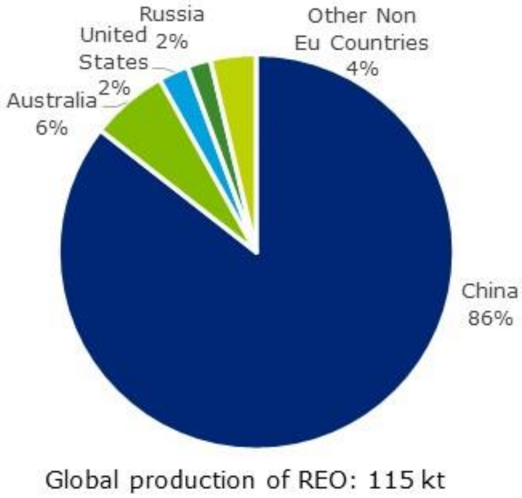


Figure 343: Global production of REO, average 2012-2016 (WMD, 2019)

REE are mostly traded as rare earth oxides (REO), metals or alloys. Demand for REE has been steadily growing in average around 4% per year since 1975, slightly increasing in the last years (Kingsnorth 2018). This creates a pressure on this small and highly specialised market of REE.

Error! Reference source not found. illustrates the changes in the total rare earth demand from 1965 to 2015 per decade: In 1965, global demand amounted to about 5,000 tonnes REO, while in 2015 it was estimated at approximately 145,000-150,000 tonnes REO. Importantly, **Error! Reference source not found.** shows the significant shift in regional demand patterns: In 1995, Japan accounted for about 43% of global demand, the USA for about 27%, Europe for 18% and the ROW for 12%. (Machacek and Kalvig 2017: EURARE)

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

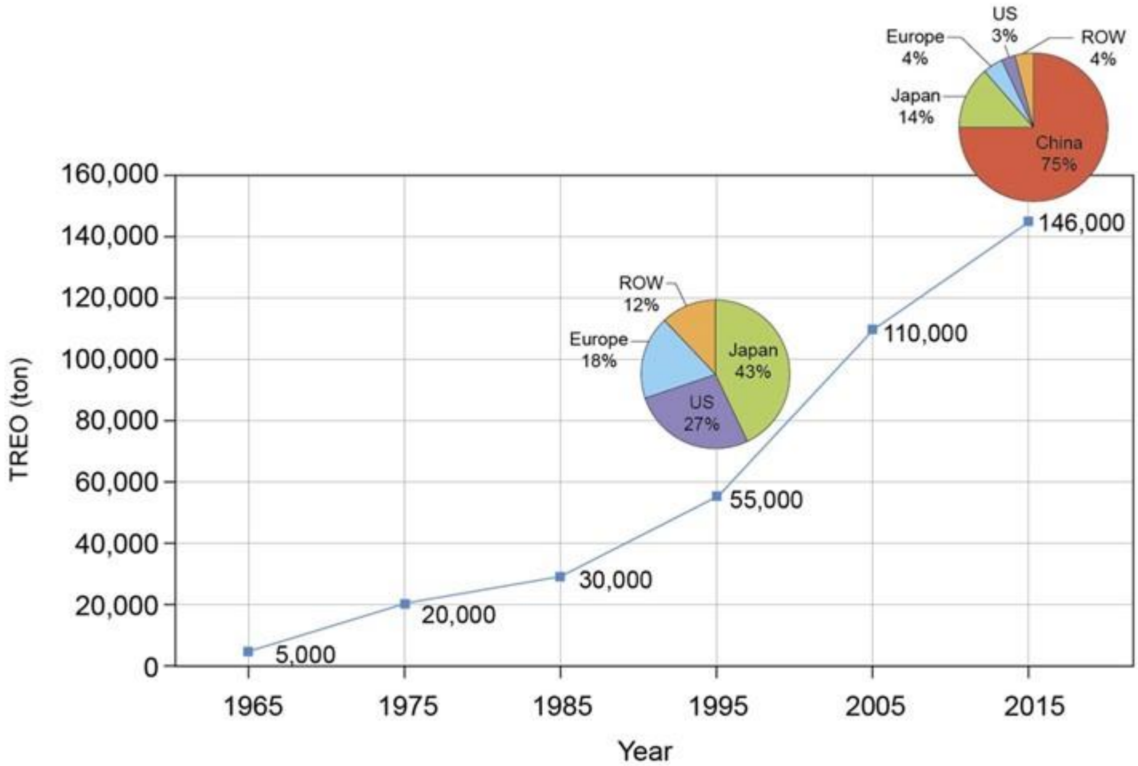


Figure 344: Changes in total rare earth demand during 1965-2015 (t REO). (Machacek and Kalvig 2017: EURARE)

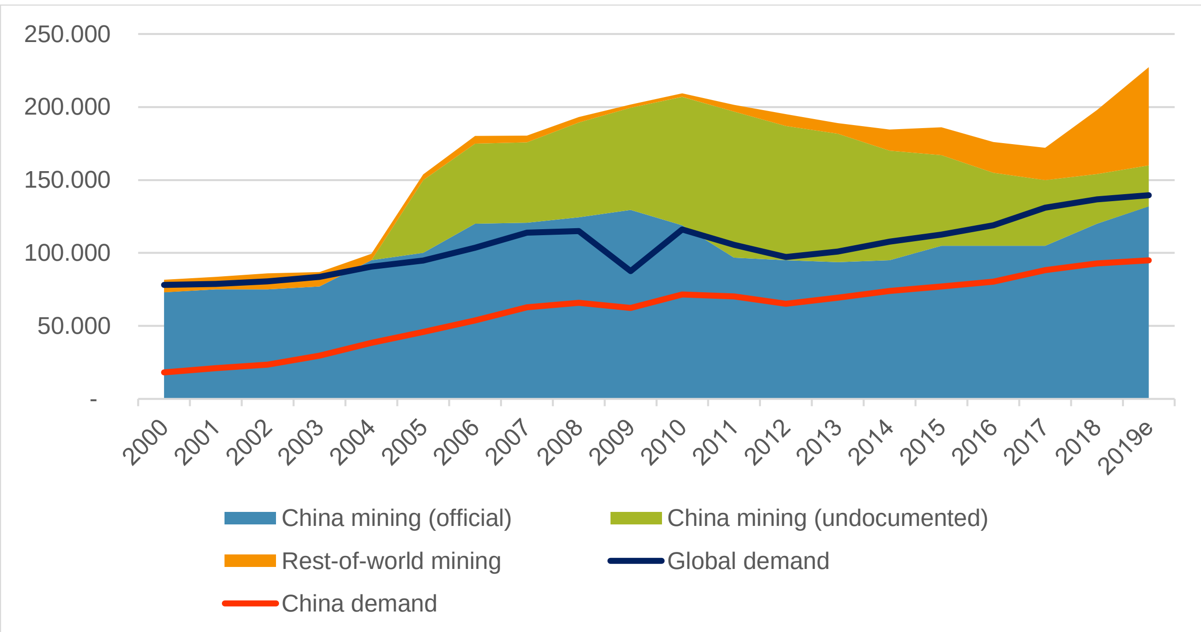


Figure 345: Rare earths mine supply and demand 2000-2019 (WMD 2020, Roskill 2019)

For comparison, slightly different picture with more moderate estimate of undocumented mining is shown for the period 2010-2020 by Kingsnorth (2018).

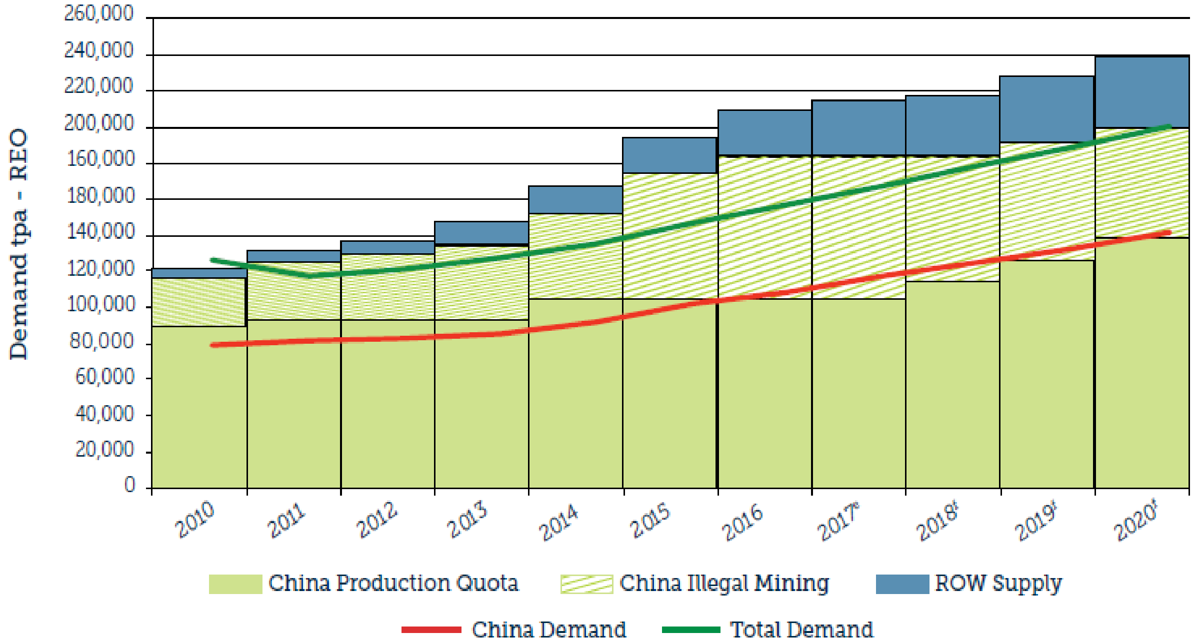


Figure 346: Rare Earths mining supply and demand 2010-2020. (Kingsnorth, 2018)

China's position as a reliable low-cost supplier of raw materials for manufacturing deteriorated as its market share and domestic consumption grew and a combination of production controls, export restrictions (e.g. quotas, tariffs), mine closings, and company consolidation contributed to significant price increases and volatility on the world market.

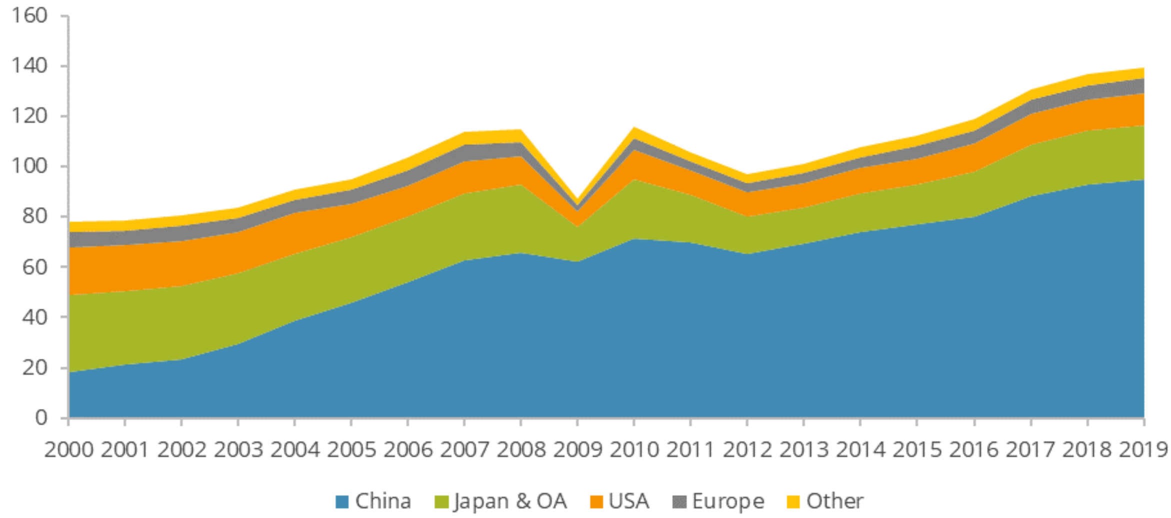


Figure 347: Global consumption of rare earths by region in 2000-2019 in tonnes REO (Roskill 2019)

The negative effects on competitiveness of non-Chinese manufacturers led China's trading partners to bring a series of complaints before the World Trade Organization (WTO)[224], beginning in 2009 and culminating in May 2015 with China's removal of export restrictions on rare earths, tungsten, and molybdenum.

[224] WTO, *China—Measures Related to the Exportation of Various Raw Materials*, Dispute Settlement DS394, January 28, 2013; WTO, *China—Measures Related to the Exportation of Rare Earths, Tungsten and Molybdenum*, Dispute Settlement DS431, DS432, DS433, May 20, 2015.

In 2009, the United States and the European Union (EU) brought a complaint against China's trade restrictions on various forms of bauxite, coke, fluorspar, magnesium, manganese, silicon carbide, silicon metal, yellow phosphorus, and zinc. When the WTO ruled in favour of the United States and the EU, China appealed and lost, then took full advantage of the "reasonable period of time" allowed under WTO rules before finally removing export duties on these materials on 1 January 2013, the very day the time for compliance expired.

In the meantime, between 2010 and 2013 prices of some rare earth metals spiked by thousands of percent and exploration activities boomed all over the world. However, even though many deposits were identified, almost none of those projects reached the production stage.

In 2012, just after the peak of prices in 2011, the United States, EU, and Japan brought an additional complaint against China's trade restrictions on rare earths, tungsten, and molybdenum. This dispute was also settled in favor of the United States, EU, and Japan. China appealed again and lost, and finally removed export duties and export quotas, as well as restrictions on trading rights of enterprises exporting rare earths and molybdenum. China again acted on the last day, in this case, 2 May 2015.

However, price volatility and instability of market have halted several perspective projects worldwide and contributed to the collapse of Molycorp - the major US producer in 2015.

A policy document on rare earths released in October 2016 by Chinese ministry of industry and information technolgy summarizes what China plans to do with the industry in coming years. The document advocates more state intervention to tackle internal problems such as illegal rare earth production, illegal transaction and processing, lack of innovation, overcapacity problems in upstream sectors and poor legal and regulatory systems to address environmental pollution (MIIT, 2016).

The Chinese government's objectives on REE development is summarized in the table below.

Table 144: The development of the rare earth industry main target during the "13th Five-Year Plan"

Indicators	Actual in 2015	Targets by 2020	Cumulative percentage change during "13th five-year"
1. ,Economic Indicators			
Average annual growth rate of industrial added value（%）	12.5	16.5	—
Industry profit margins（%）	5.8	12	[6.2]
R & D expenditure of key enterprises accounted for the proportion of the main income（%）	3	5	[2]
2. Production Indicators			
Smelting separation capacity (Million tons)	30	20	[-10]
Production of rare earth smelting and separation products (Million tons)	10	< 14	[<4]
Recovery rate of mineral processing of light rare earth ore（%）	75	80	[5]
Comprehensive recovery rate of recovery of ion type rare earth ore (%)	75	85	[10]
Light rare earth smelting separation recovery rate（%）	90	92	[2]

Indicators	Actual in 2015	Targets by 2020	Cumulative percentage change during "13th five-year"
Ion type rare earth smelting separation recovery rate（%）	94	96	[2]
The integration of the two standards of Enterprise Accounting (%)	30	90	[60]
3. Green Development Indicators			
Reduction of major pollutants emission intensity in the whole industry (Containing sulphur dioxide, ammonia nitrogen, waste water, etc., %）	—	—	[20]
Proportion of enterprise achieving energy consumption standard (%)	40	90	[50]
4. Application Industry Development Indicators			
Market share of high-end rare earth functional materials and devices（%）	25	50	[25]
Proportion of primary raw materials on export products（%）	57	30	[-27]

Inside the brackets [ ] are cumulative numbers for five years. Source: MIIT 2016, Rare Earth Industry Development Plan (2016-2020) (translated from Chinese).

21.2.2Future market for REE

COVID-19 crisis has impacted global economy, the rare earths products market is expected to decrease in 2020, but should increase again in 2021. Fast growing electric vehicles production, from couple of million cars today to 30 million in 2030, should stay a dominant application of REE, though the proportion of REE permanent magnets technology should decrease from 90% to 70-80% in 2030.

Adamas predicts 11% decrease in 2020 and then growth of 8% per year until 2030 reaching 150% more demand than today. Kingsnorth (2018) expects the REE demand to grow 6-7% per year by 2025. Roskill (2019) forecasts only 3.3% annual growth by 2024 and slowing to 2.1% annually between 2024 and 2029. Roskill expects that permanent magnet growth slows and battery demand declines by 6.8% per year, while lanthanum NiMH batteries will continue to lose market share to lithium-ion batteries.

By 2025, rare earth magnets are forecast to exceed a third of total demand, changing the focus of rare earth producers and processors. The changing emphasis towards rare earth magnet raw materials is expected to impact rare earth pricing mechanisms, with operations becoming increasingly dependent economically on a small number of individual rare earths.[225]

[225] https://roskill.com/market-report/rare-earths/. Accessed on 14 February 2020

21.2.2.1 Cerium

The overall demand for cerium is expected to increase by around 6% per year (Rare Earth Investment News, 2016). However, as for lanthanum, supply is expected to more than keep up, moving the market into an increasing surplus. Roskill (2019) expects more than doubling surplus by the mid-2020s and, by 2029, reaching a surplus of 31.0kt of cerium oxide.

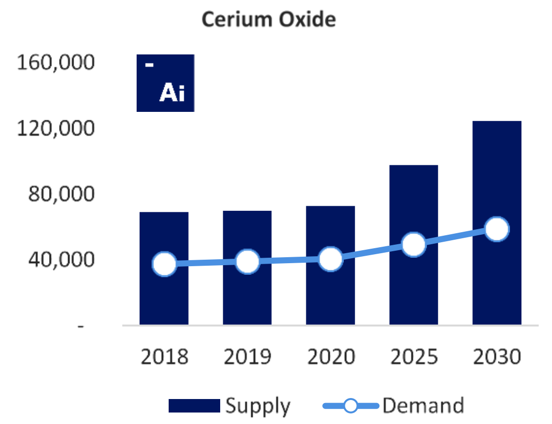


Figure 348: Global annual supply of cerium is expected to continue exceeding global annual demand by 2030 (Adamas Intelligence,2019b)

21.2.2.2 Dysprosium

The future evolution of dysprosium demand is driven by two forces:

- The anticipated growth of the permanent magnet market for the manufacture of wind turbines and electric vehicles. Those applications are supported by green energy and green transportation initiatives which are likely to incentivise a growth of their production (Rare Earth Investing News, 2016). Globally, the rapid increase of the demand for air conditioning by Indian and other South-East Asian customers could also play in the expected growth of the permanent magnets market (Powder Metallurgy Review, 2016). As a result of those factors, the demand of Dy-containing magnets is expected to increase;
- Efforts to reduce the content of dysprosium in NdFeB magnets: Adamas expects the content of dysprosium in magnets to drop from 2.3% in 2014 to 1.9% in 2020 (Guyonnet et al., 2015).

Adamas Intelligence (2019) forecasts that global annual demand for dysprosium oxide (or oxide equivalent) will increasingly exceed global annual production between 2020-2030, resulting in the depletion of historically-accumulated inventories and, ultimately, shortages of dysprosium if global production is not increased beyond what is currently forecasted.

Specifically, by 2030, Adamas Intelligence forecasts that global demand for dysprosium oxide (or oxide equivalent) will exceed global annual production by upwards of 300 tonnes – equal to the amount of material needed for production of approximately 3.0 million electric vehicles traction motors.

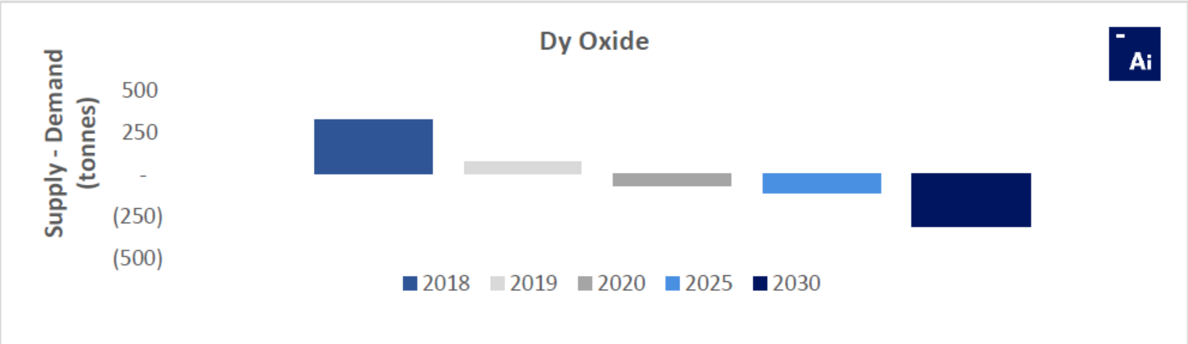


Figure 349: Global annual demand of dysprosium to exceed global annual production by 300 tonnes in 2030 (Adamas Intelligence 2019)

21.2.2.3 Erbium

The overall demand for erbium is expected to increase by around 6% per year until 2020 (EC, 2014).

21.2.2.4 Europium

The demand of europium is likely to drop considerably in the future (Guyonnet et al., 2015). The future decrease of europium demand is directly linked to the significant reduction (at least 65%) of rare earth needs for the lighting industry between 2015 and 2030 (Guyonnet et al., 2015).

This evolution is due to the changes in the lighting market structure and is driven by two forces:

- The anticipated decrease of the fluorescent lamps market face to the growing new technology LEDs (Mc Kinsey, 2012): in the lighting market as a whole, LED lighting penetration is projected to be around 40% in 2016 and over 60% in 2020 (Mc Kinsey, 2012).
- The content of rare earths (including Eu) in LEDs is much lower than in fluorescent lamps (1,000 times lower) (Guyonnet et al., 2015).
- As the lifetime of LED is 40,000-50,000 hours, compared to 10,000-25,000 hours for fluorescent lamps, the decrease in rare earth need for the lighting sector will amplify in the coming years (Guyonnet et al., 2015).

21.2.2.5 Gadolinium

The overall demand for gadolinium is expected to increase by around 9% per year until 2020 relating to uses in magnets (linked to a possible growth in magnetic refrigeration) and in medical imagery (EC, 2014).

21.2.2.6 Holmium, Lutetium, Ytterbium, Thulium

The overall supply and demand for Ho-Tm-Yb-Lu supply is expected to increase by around 8% per year until 2020 (EC, 2014).

21.2.2.7 Lanthanum

The supply of lanthanum is expected to more than keep up, moving the market into an increasing surplus. Roskill (2019) expects more than doubling surplus by the mid-2020s and, by 2029, reaching a surplus of 25.3kt of lanthanum oxide.

21.2.2.8 Neodymium and Praseodymium

The future evolution of neodymium and praseodymium demand is driven by two forces:

- Efforts engaged by many companies to eliminate REE in general and neodymium in particular from their supply chain following the Chinese export restriction era. It included avoiding REE permanents magnets technologies where possible, and proved successful in some specific functions, notably in the automotive, aerospace, and renewable energies sectors. However, REE performances remain superior in many applications and are likely to be used if prices and availability are favourable;
- The present context of anticipated growth for green energy and green transportation initiatives. These sectors, as well as increasing demand for air conditioning by Indian and other South-East Asian customers remain potential important markets for REE-based permanent magnets (Rare Earth Investment News, 2016; Powder Metallurgy review, 2016)

From 2018 through 2030, Adamas Intelligence (2019) forecasts that global annual production of neodymium oxide and praseodymium oxide (or oxide equivalents) will increase at a slower rate than global demand, resulting in the draw-down of producer inventories and, ultimately, shortages of these materials if supply is not increased beyond what is currently anticipated.

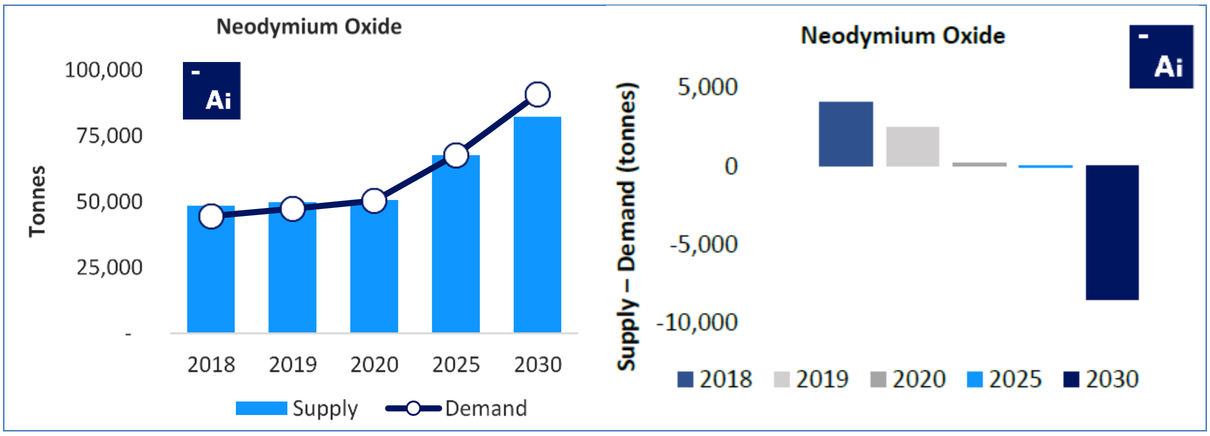


Figure 350: Global annual demand of neodymium oxide to exceed global annual production in 2030 (Adamas Intelligence, 2019b)

Even with substantial production increases in China in the years ahead, and the development of 40,000 tonnes-per-annum of new rare earth oxide production capacity outside China, Adamas Intelligence forecasts that global annual demand for neodymium oxide and praseodymium oxide (combined) will exceed global annual production by upwards of 7,500 tonnes in 2030 – equal to the amount of material needed for production of approximately 6.7 million EV traction motors. While Roskill (2019) forecasts the supply-demand balance of neodymium within 1,500 tonnes of supply-demand equilibrium by 2029.

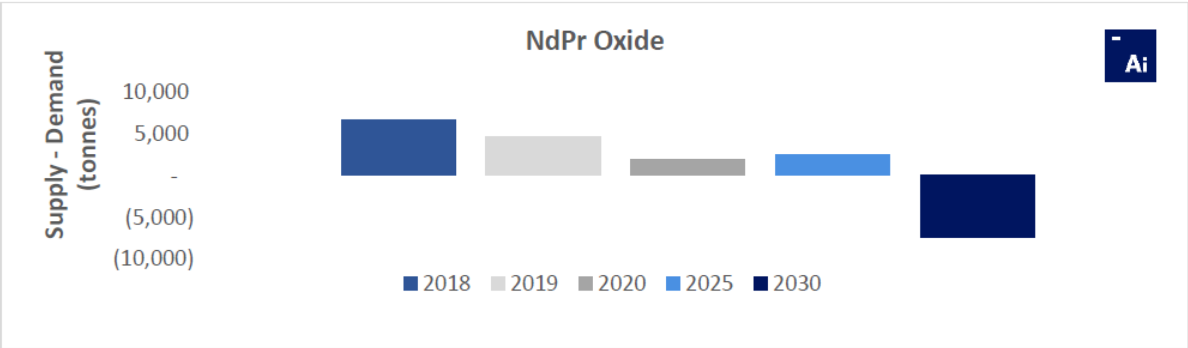


Figure 351: Global annual demand of neodymium-praseodymium oxide to exceed global annual production by 7,500 tonnes in 2030 (Adamas Intelligence, 2019)

Adamas Intelligence (2019) forecasts that around 80% of EVs produced in the future will opt to use permanent magnet synchronous motors (PMSM), and with an average peak motor power of 131 kW by 2025 and 152 kW by 2030, will create demand for approximately 25,000 tonnes of NdFeB annually by 2025 and 60,000 tonnes by 2030.

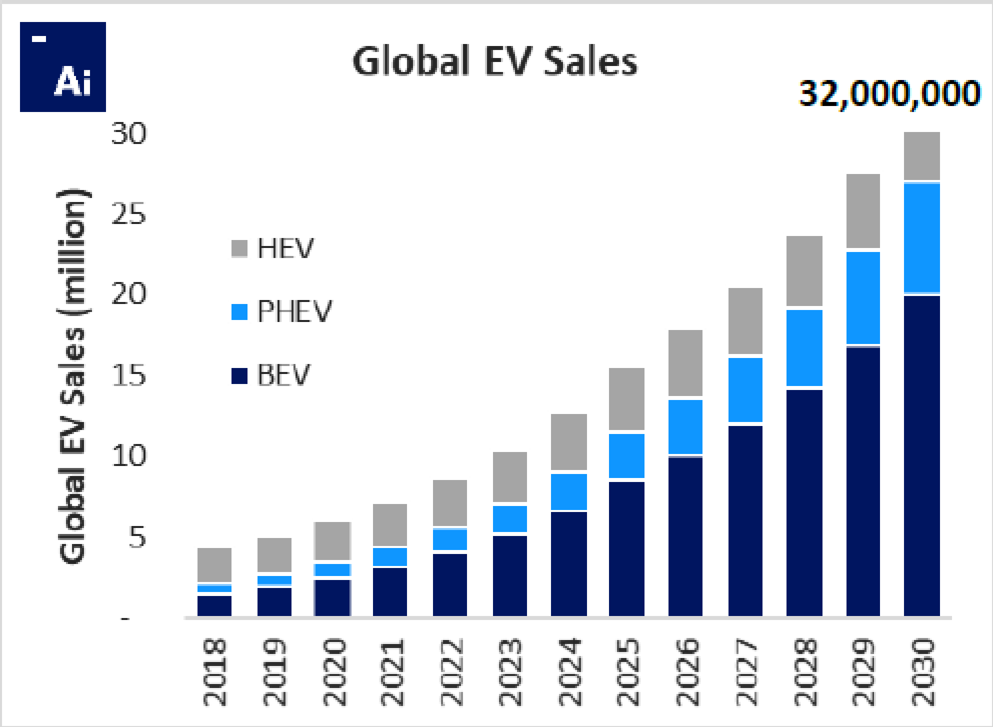


Figure 352: Global EV sales forecasted to reach 32 million per annum by 2030 (hybrid electric vehicles (HEVs), plug-in hybrids (PHEVs), and battery electric vehicles (BEV)) (Adamas Intelligence, 2019)

Taking into account the yields and losses incurred during metal, alloy and magnet production, we forecast that demand for NdPr oxide for EV traction motors will increase from approximately 3,000 tonnes in 2018 to 13,000 tonnes in 2025 and 28,000 tonnes in 2030 – equal to approximately 20% of total global demand in 2030.

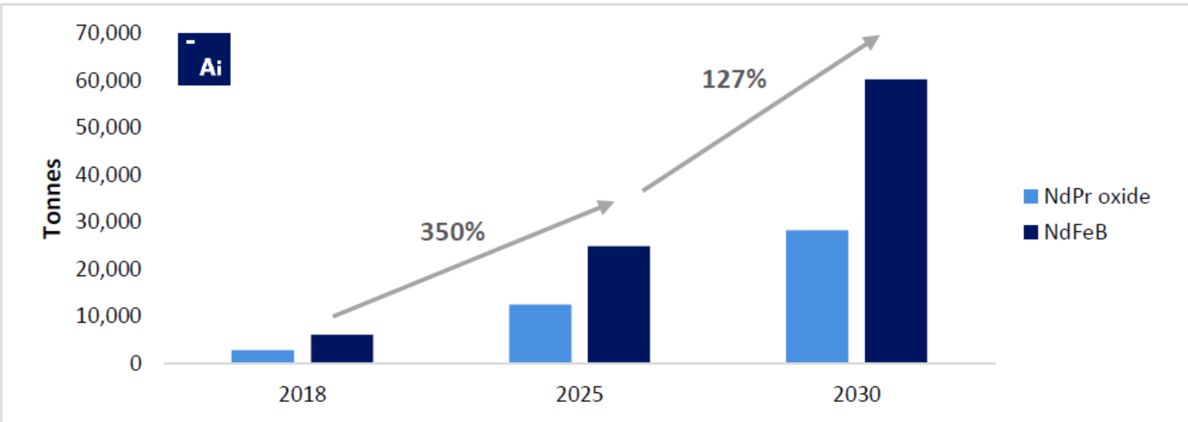


Figure 353: Changes in total rare earth demand for EV traction motors to increase by 350% between 2018 and 2025 (Adamas Intelligence, 2019)

Adamas Intelligence estimates that, on average, a PMSM for an EV contains approximately 1.2 kg of NdFeB magnets per 100 kW of peak motor power yielded. During production of this 1.2 kg of NdFeB magnets, Adamas estimates that an additional 0.4 kg of NdFeB alloy is diverted to waste streams during casting, crushing, milling, sintering, cutting, grinding, coating and inspection of the final magnets, and as such, a total of 1.6 kg of NdFeB alloy is consumed per 100 kW of peak motor power.

In 2018, Adamas Intelligence indicates that globally, the sales-weighted-average EV's 93 kW traction motor, almost double what it was in 2011. Looking forward to 2025, Adamas forecasts that as BEV sales growth continues to outpace PHEV and HEV sales growth globally, the sales-weighted-average motor power will increase to 131 kW in 2025, creating demand for 1.0 kilogram of NdPr oxide (and minor Dy/Tb) for every new EV equipped with a PMSM.

Table 145: Current and future use of in a permanent magnet traction motor (Adamas Intelligence, 2019)

	Material Intensity (Per 100 kW) *	Avg. EV Motor in 2018 (93 kW)	Avg. EV Motor in 2025 (131 kW)
NdFeB	1.6 kg	1.5 kg	2.0 kg
NdPr metal	0.6 kg	0.5 kg	0.8 kg
NdPr oxide	0.7 kg	0.7 kg	1.0 kg

* Magnet, metal and oxide mass estimates account for material losses from oxide to metal to alloy to finished NdFeB

21.2.2.9 Samarium

The overall demand for samarium is expected to increase by around 10% per year until 2020 (EC, 2014). The future evolution of samarium demand is driven by the anticipated growth of the permanent magnet market.

21.2.2.10 Terbium

The demand of terbium is likely to drop in the future because of the reduction of rare earth needs for the lighting industry (this industry is currently representing 68% of terbium applications). This reduction is expected to amount to at least 65% between 2015 and 2030 (Guyonnet et al., 2015). This evolution is due to the changes in the lighting market structure and is driven by two forces:

- The anticipated decrease of the fluorescent lamps market face to the growing new technology LEDs: in the lighting market as a whole, LED lighting penetration is projected to be around 40% in 2016 and over 60% in 2020 (Mc Kinsey, 2012).
- The content of rare earths (including Tb) in LEDs is much lower than in fluorescent lamps (1,000 times lower) (Guyonnet et al., 2015).
- As the lifetime of LED is 40,000-50,000 hours, compared to 10,000-25,000 hours for fluorescent lamps, the decrease in rare earth need for the lighting sector will amplify in the coming years (Guyonnet et al., 2015).

21.2.2.11 Yttrium

The demand of yttrium is likely to drop in the future because of the reduction of rare earth needs for the lighting industry (this industry is currently representing 46% of yttrium applications). This reduction is expected to amount to at least 65% between 2015 and 2030 (Guyonnet et al., 2015). This evolution is due to the changes in the lighting market structure and is driven by two forces:

The content of rare earths (including Y) in LEDs is much lower than in fluorescent lamps (1,000 times lower) (Guyonnet et al., 2015).

As the lifetime of LED is 40,000-50,000 hours, compared to 10,000-25,000 hours for fluorescent lamps, the decrease in rare earth need for the lighting sector will amplify in the coming years (Guyonnet et al., 2015).

21.2.3EU trade

Import reliance on REOs compounds and REE metals and interalloys is 100%.

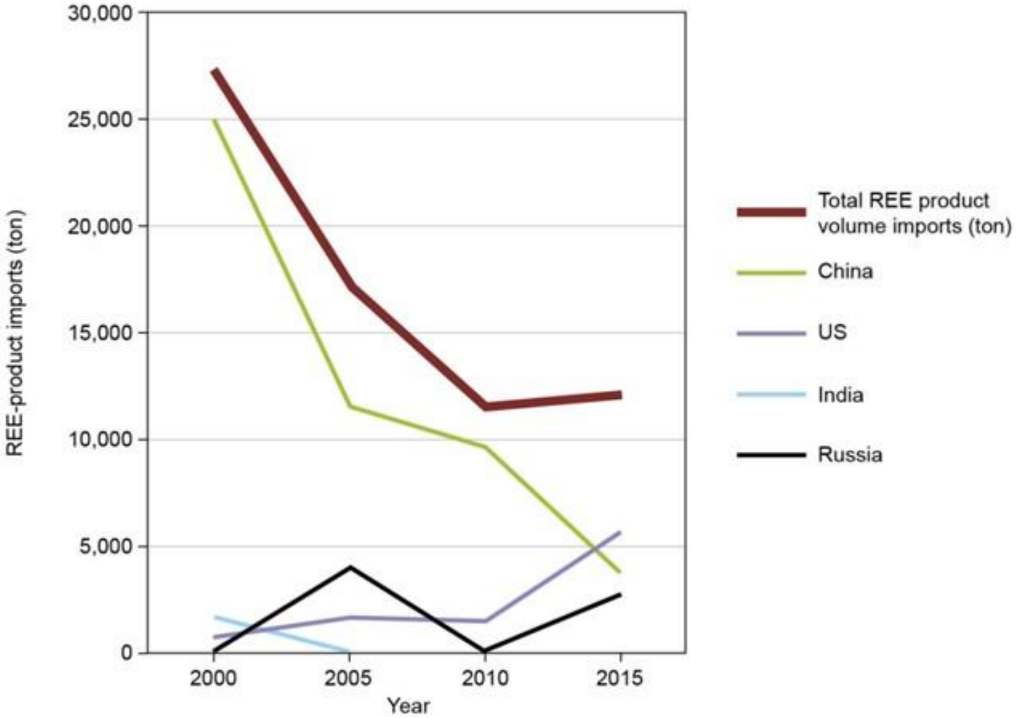
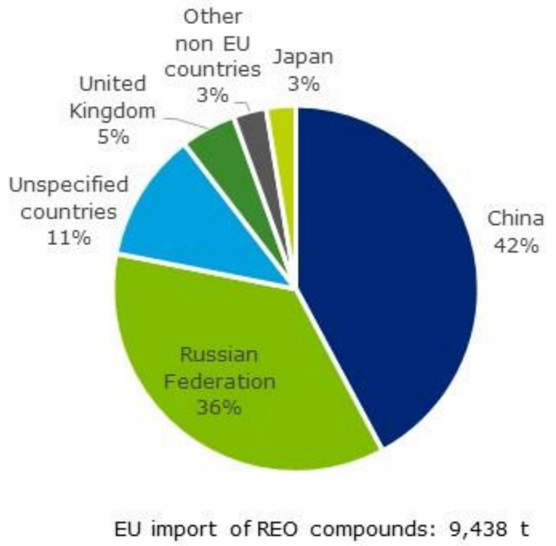


Figure 354: Total EU-import of REE-metals and -compounds, 2000 – 2015. (MiMa-GEUS with data retrieved from Eurostat, 2016. Note: REE-metal and –alloy imports are summarized from four HS product codes (28053010, 28053090, 28461000 and 28469000) for which data is available for the time period, and by importing country (Machacek and Kalvig (edit) 2017).

The EU is entirely dependent on imports of REE for its consumption. The average EU imports during the 2016-2018 period were 9,438 tonnes of REE compounds, 1,162 tonnes of REE metals and interalloys, while the EU exports were 5,464 tonnes of REE compounds and 601 tonnes of REE metals and inter-alloys.



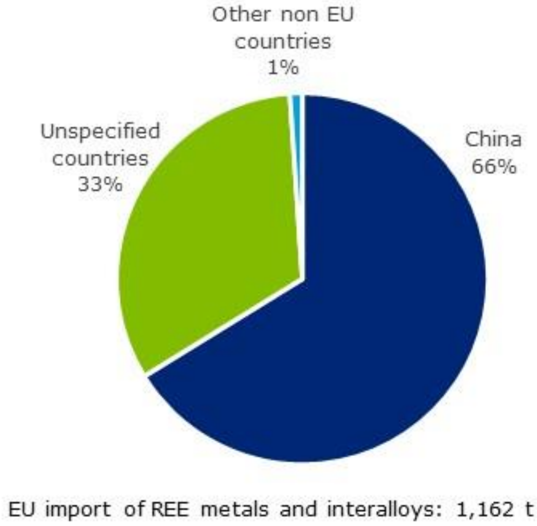


Figure 355: EU imports of REE compounds (CN8 2846-1000, -9010 and -9020) and REE metals and interalloys (CN8 2805-3010, -3020, -3030) (Eurostat Comext, 2019).

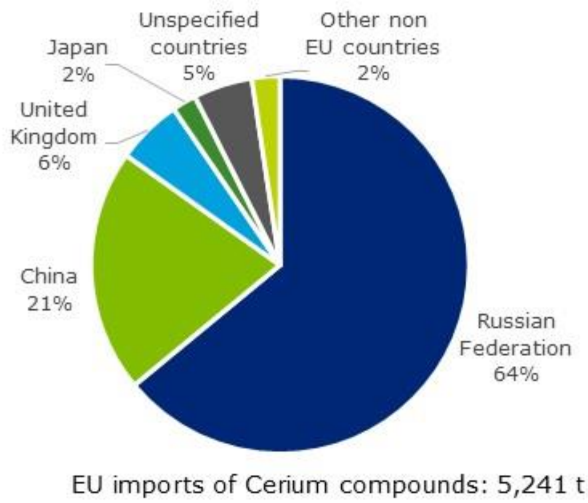


Figure 356: EU imports of cerium (CN 2846 1000), average 2016-2018(Eurostat, 2019).

According to EUROSTAT data (CN code 2846 9010) (see Figure 357), the main supplier of the EU is China (77%), followed by United Kingdom (3%) for L-REE (excl. Cerium) compounds (La, Nd, Pr, Sm) expressed in oxide content. As for H-REE compounds (Dy, Er, Eu, Gd, Ho, Tm, Lu, Yb) EUROSTAT data (CN code 28469020). The main supplier of the EU is China (33%), followed by Japan (18%).

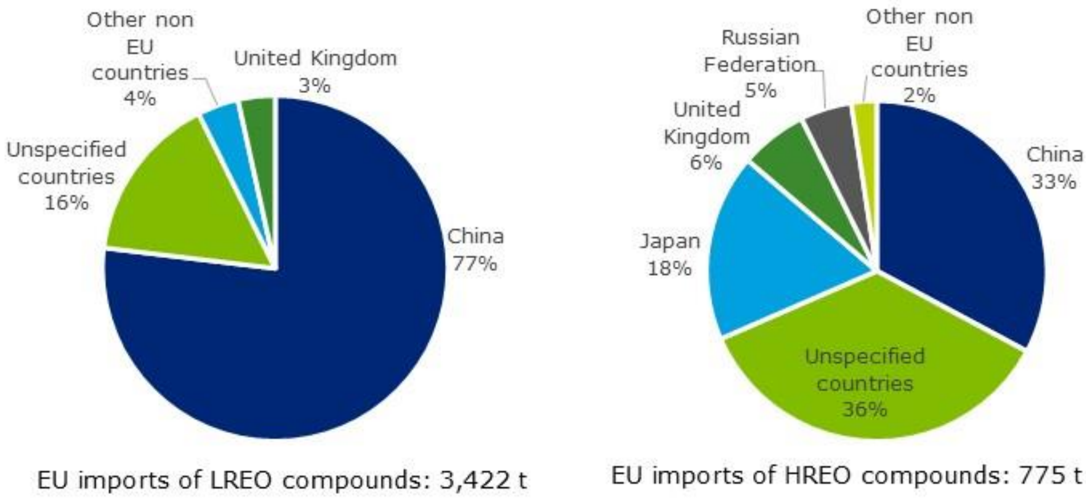


Figure 357: Extra-EU imports of mixed La, Nd, Pr, Sm compounds (LREE except Ce) expressed in oxide content. Extra-EU imports of mixed Dy, Er, Eu, Gd, Ho, Tm, Lu, Yb, Tb and Y compounds (HREE) expressed in oxide content. Average 2016-2018. Data from Eurostat Comext (Eurostat, 2019)

According to Eurostat Comext, EU imports REE metals and interalloys from China (98-99%). The separation of REE is primarily a technical issue for the global REE-industry, with competency still centred mostly in China.

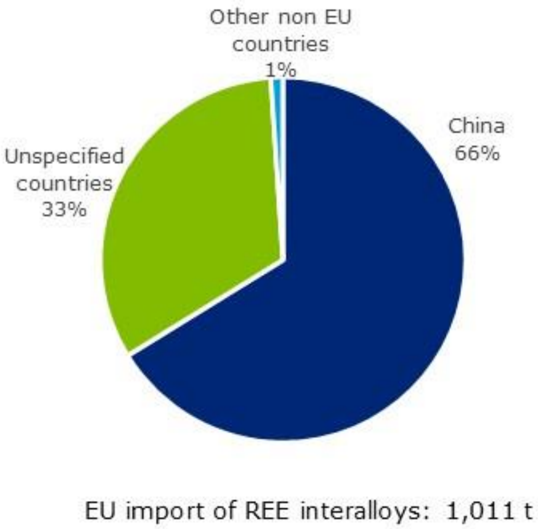


Figure 358: Extra-EU imports of intermixtures or interalloys of REE. Average 2016-2018. Data from Eurostat Comext (Eurostat, 2019)

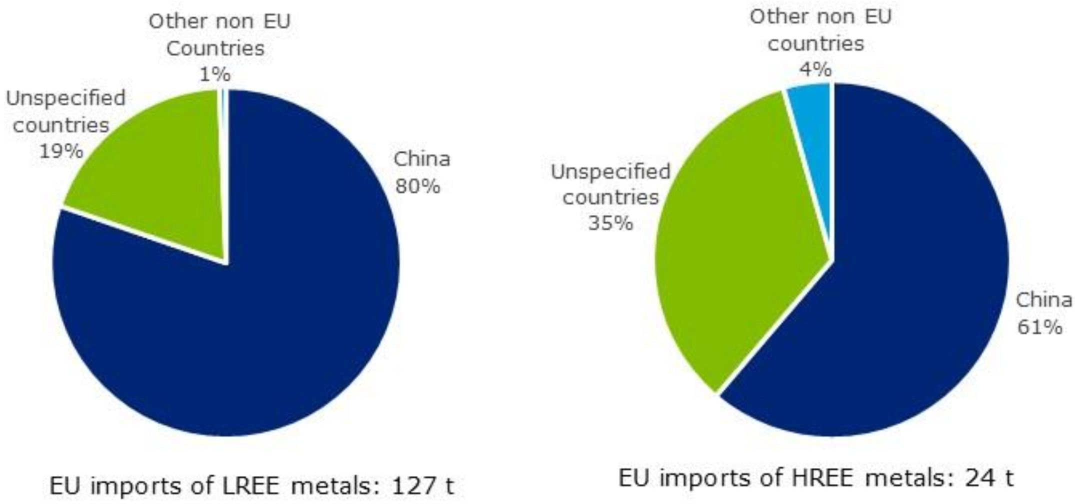


Figure 359: Extra-EU imports of LREE (left) and HREE (right) metals. Average 2016-2018. Data from Eurostat Comext (Eurostat, 2019)

21.2.3.1 Trade restrictions

Table 146: China production and export quota in 2010-2019 in kt (Kingsnorth, 2018)

year	China production quota	China export quota
2010	89,2	30,3
2011	93,8	30,2

2012	93,8	31
2013	93,8	31
2014	105	30,6
2015	105	-
2016	105	-
2017	105	-
2018	120	-
2019	132	-

Estimated quota for individual REE for the period 2012-2016 are displayed in Table 147. In May 2015, China ended its rare-earth export quotas, removed export tariffs, and began to impose resource taxes on rare earths based on sales value instead of production quantity (Metal Pages, 2015).

Export quotas are provided by OECD (2019) and the relative production of individual REO relative concentration in deposits is used to calculate quota. Imports and quotas are shown in Table 147.

Table 147: Imports and quotas (Eurostat, 2019; OECD, 2019) [226]

REE		EU imports[1]	Imports evolution over 2010-14[1]	Chinese quotas[2]	Additional export tax[3]
		tonnes		tonnes REO/y	
LREE	Ce	5,763	-	13,743	no
	Nd	532	↑	4,892	15%
	La	3,408	↑↑	7,608	15%
	Pr	216	↑	1,454	15%
	Sm	33	↑	671	25%
HREE	Eu	36	↑	113	25%
	Tb	36	↑	55	25%
	Gd	18	↑	429	25%
	Er	13	↑	130	25%
	Dy	18	↑	273	25%
	Y	778	↑	1,454	25%
	Ho, Tm, Lu, Yb	13	-	177	15%

Legend: ↑↑ increased steadily
↑ slight increase

21.2.3.2 Relevant trade codes

From 2016 on the Eurostat (2019) product codes provide more detail on the individual REE imported (see Table 148**Error! Reference source not found.**). Therefore, the results are shown by averaging data from 2016 to 2018. Cerium, LREE (excluding Ce) and HREE have specific code in Eurostat Comext database, split in rare earth metals and compounds. The use of term "compound" opens for various interpretations, such as to whether it refers to different types of compounds (metals, alloys, oxides, salts), and thus, REE that encompasses all types of compounds, or whether it refers to rare earth metals, as metals of individual elements in form of alloys.

At the extraction stage, REE are assessed as mixes of REO or low purity single REE ores and concentrates (this roughly corresponds to mining + first stages of processing / separation). CN8 codes used for this stage are: 28461000 "Cerium compounds", 28469010 "Compounds of lanthanum, praseodymium, neodymium or samarium, inorganic or organic" and 28469020 "Compounds of europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium or yttrium, inorganic or organic". Eurostat data have been reported as REO content by using the conversion factors (see Table 182**Error! Reference source not found.**).

At the processing stage, high purity single REE (this correspond to advanced separation / refining) are assessed. The trade codes used for EU trade are CN8: 28053010 "Intermixtures or interalloys of rare-earth metals, scandium and yttrium", 28053020 "Cerium, lanthanum, praseodymium, neodymium and samarium, of a purity by weight of >=95% (excl. intermixtures and interalloys)", 28053030 "Europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium and yttrium, of a purity by weight of >=95% (excl. intermixtures and interalloys)". Eurostat reports some trade data under the label "Countries and territories not specified for commercial or military reasons in the framework of trade with third countries". For the purpose of the assessment and to calculate the supply risk, this share of import has been combined with China, because of its leading position within the REE market. However, charts in this factsheet report the shares of this trade flow as "Unspecified countries".

Table 148: List of CN codes on REE available on Comext Eurostat (2019)

CN codes	Label
28053010	Intermixtures or interalloys of rare-earth metals, scandium and yttrium
28053020	Cerium, lanthanum, praseodymium, neodymium and samarium, of a purity by weight of >=95% (excl. intermixtures and interalloys)
28053030	Europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium and yttrium, of a purity by weight of >=95% (excl. intermixtures and interalloys)
28053080	Rare-earth metals, scandium and yttrium, of a purity by weight of <95% (excl. intermixtures and interalloys)
28053090	Rare-earth metals, scandium and yttrium (excl. intermixtures or interalloys)
28461000	Cerium compounds
28469000	Compounds, inorganic or organic, of rare-earth metals, of yttrium or of scandium or of mixtures of these metals (excl. cerium)
28469010	Compounds of lanthanum, praseodymium, neodymium or samarium, inorganic or organic
28469020	Compounds of europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium or yttrium, inorganic or organic
28469090	Compounds of mixtures of rare-earth metals, yttrium and scandium, inorganic or organic

21.2.4 Prices and price volatility

Prices of REE experienced great variations in the last decade, as shown in Figure 360. In 2010-2011 a 12-fold increase was observed, mainly triggered by a strong reduction of Chinese export quotas and geopolitical tension in a period of high demand for permanent magnets, driven by the expected growth of the renewable energy and electric vehicles markets. From early 2012, prices were already down by half and went down almost continuously until 2019, showing short-term volatility.

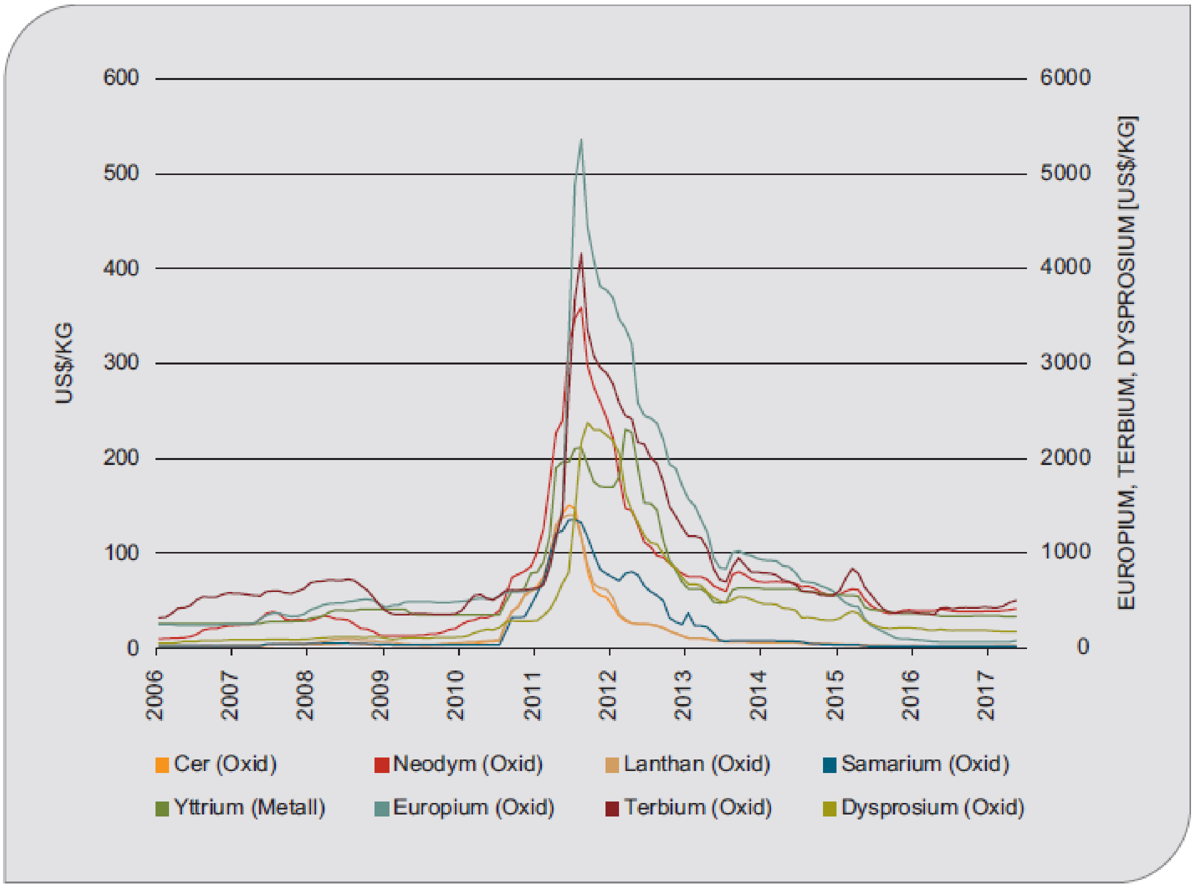


Figure 360: Rare-earths oxide prices 2006-2017. 99% FOB China USD/kg. (Asian Metal from DERA, 2018)

Table 149: Significant historical events that have affected rare earth prices (Roskill, 2019)

1983	NdFeB magnet introduced
1985	Environmental regulations limit lead in gasoline
Late 1980s	China develops its ion adsorption ore deposits
1993	Regulations mandating the use of auto catalysts
1994	Rhodia switches to Chinese feedstock
1994	Chinese producers form a cartel to stop price cutting
1997-99	Asian economic crisis; Chinese cartel collapses
2000	Shortage in supply of Chinese rare earth ores, number of Chinese producers falls to less than 80
2000	Rapid increase in demand by telecommunications and computing industries; prices rise and large number of Chinese producers recommence operations to meet the demands of a rapidly expanding domestic electronics industry
2001-02	Collapse in demand by telecommunications and computing industries; prices fall by 40%
2003	Chinese government attempts to force an industry restructure into two major groups; one centred in Baotou and the other in Southern China, which was unsuccessful. In an effort to stabilise and strengthen prices China announced that it would be introducing rare earth export quotas in 2004.

2004	Start of present recovery of rare earth prices due to steady increase in demand. Chinese exports of low value concentrates banned and the VAT rebate eliminated.
2005	Neodymium demand matches supply; leading to a run-down in stocks.
2006	China places quotas on rare earth mineral production and reduces rare earth export quotas. China implements 10% tax on rare earth exports (initially just oxides). In addition, the distribution of mining licences, production quotas and export quotas are used as a means of consolidating the rare earths industry, to enable more government control, resulting in fewer recipients of licences and quotas. The major beneficiaries of this policy have been the major state-owned enterprises such as Baotou Rare Earth and China Minmetals.
2007	Chinese export taxes were increased to 15% or 25%
2008-09	Global economic downturn from the second half of 2008 leads to lower demand for rare earths from North America and Europe and slower growth in China
2010	Chinese rare earth export quota reduced by 40% to encourage downstream production and secure reserves of raw material. Continued limitation on Chinese exports leads to a shortage and sharp increases in the fob price of traditionally low-value rare earths such as lanthanum and cerium, as exporters chose to use their quota for higher value products.
2011	Distorting effect of export quotas on export prices continues. Chinese taxes kept at 15-25% on rare earth metals and oxides in early 2011 but extended to include some alloys. Total export quota remained flat, but inclusion of quota for ferrous alloys (containing >10% rare earths by weight) effectively resulted in a decline in the quota for oxides and metals. From April/May 2011, speculative buying within China boosted prices still further. Sharp fall in purchases from the ROW forced prices downward from August. In November, a resources tax of RMB60/t for LREEs and RMB30/t for HREEs was imposed on rare earth mining companies in China
2012	Destocking following the large inventory build in 2010-11 which followed the Chinese export quota reduction. Thrifting in some application
2013	Continued thrifting in certain applications. Technological innovation in lighting as LEDs began to replace CFLs and led to lower demand and prices for phosphor rare earths
2014	Attempts to drive prices up by stockpiling failed Global oil price fell from U$100/bbl in mid-2014 to less than US$60/bbl by the start of 2015, resulting in lower demand for La and Ce in FCC catalysts
2015	Chinese export taxes removed from 2 May 2015 following WTO ruling China's economy grew at a slowing rate - GDP grew by 8.3% and consumer prices by 1.4% in 2015 Chinese output of crude steel declined for the first time that year EV and wind turbine production ramped up worldwide. New incentives resulted in strong growth of EVs in China
2016	Strengthening magnet demand driving global prices for permanent magnet materials, mainly Nd/Pr Withdrawal and reintroduction of Chinese EV incentives because of widespread corruption – EV demand lower than expected this year

	The Chinese economy continued to slow - China's GDP increased by 8% in 2016. Consumer prices, however, strengthened, growing at 1.8%py in 2016.
2017	Price rise as bottomed out and neodymium market tightens In China as producers refused to accept low prices any longer Plant closures following environmental regulation caused some tightness of supply Traders holding stocks on speculation of further price rises; stocks began to be released in the second half of the year Further strengthening of magnet demand from the growing Chinese EV market – pressure building on Nd/Pr supply
2018	USA-China trade war and tariff lists add uncertainty to Chinese dominant commodities
2019	President Xi Jinping visits JL Mag and RE processing facilities in China Chinese officials threaten 'cut-off' of REE exports to USA

21.2.4.1 Prices forecasts

Adamas Intelligence (2019b) forecasts that prices of high-demand elements, like neodymium, praseodymium, dysprosium and terbium will rise to pay for losses that producers are incurring by necessarily over-producing cerium, lanthanum, and other unsaleable, surplus rare earths; unless new end-uses and applications are developed for them in the near-term. The industries that will feel these price increases the most in the coming decade are those reliant on use of high-strength rare earth permanent magnets, such as the automotive industry, the wind power sector, the consumer electronics industry, the defence industry, and many others.

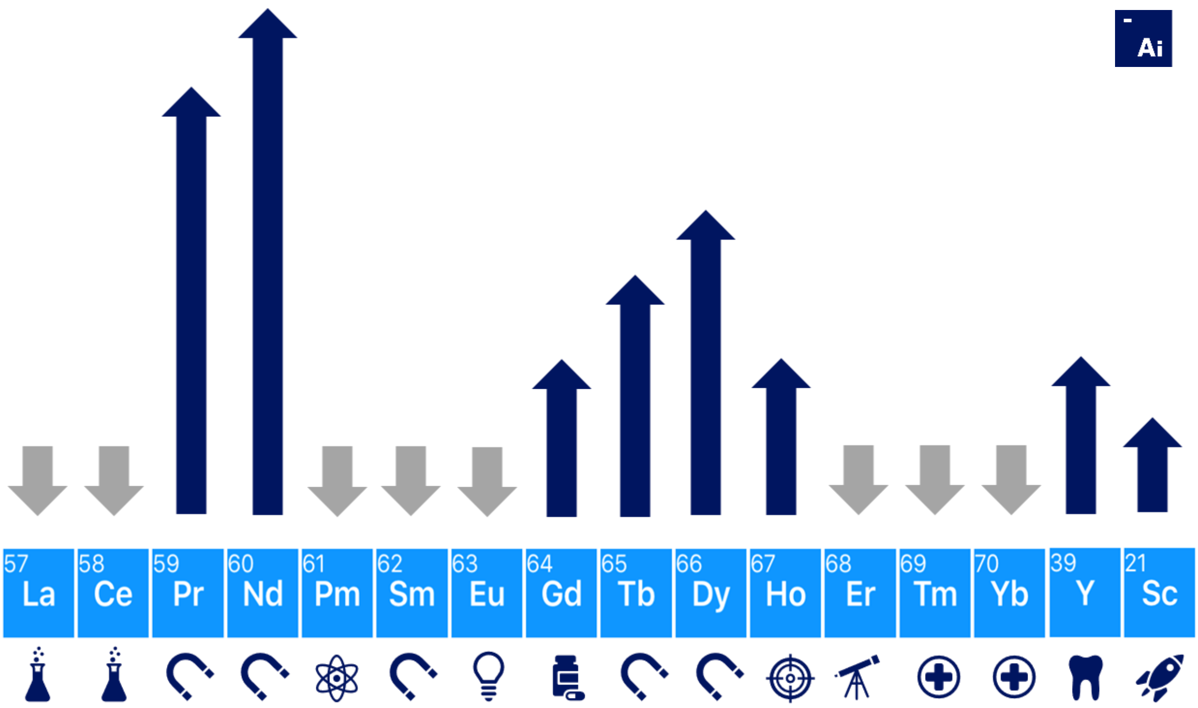


Figure 361: Prices of some rare earths are expected rise to compensate for losses incurred on other surplus rare earths (Adamas Intelligence, 2019b).

21.2.4.2 Cerium prices

Prices of cerium metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from USD 3 per kg in 2002-2003 to an all-time high of USD 170 per kg in July 2011, prices of Ce metal went down to reach a relatively stable value of around USD 6 per kg in 2015 and 2016 (DERA, 2019). The skyrocketing of prices in 2010 – 2011 was triggered by the strong reduction of Chinese quotas.

High prices in 2011 reinforced the role of China as the worldwide larger producer of Ce polishing powders, also considering its dominance in manufacturing of glass products and electrical components. Research activities are being carried out in China to improve the quality of polishing powders based on CeO2, in particular by applying the CMP (i.e. Chemical Mechanical Planarisation) method to obtain higher grades powders for the polishing of electronic components (Roskill, 2016).

The price spike in 2011 boosted the industrial research both for improved technical solutions enabling the reduction of Ce use, as well as for alternative materials such as zirconia (especially for lower quality products). However, as price decreased again, these efforts to find substitutes were put on hold and the traditional use of CeO2 were maintained.

According to Roskill (2019), nominal prices for cerium are forecast to remain mostly flat over the forecast period to 2028, remaining below US$2/kg. Relatively low prices will be ensured by continued oversupply as the drive to produce larger quantities of magnet materials will also result in large quantities of cerium production, effectively as waste.

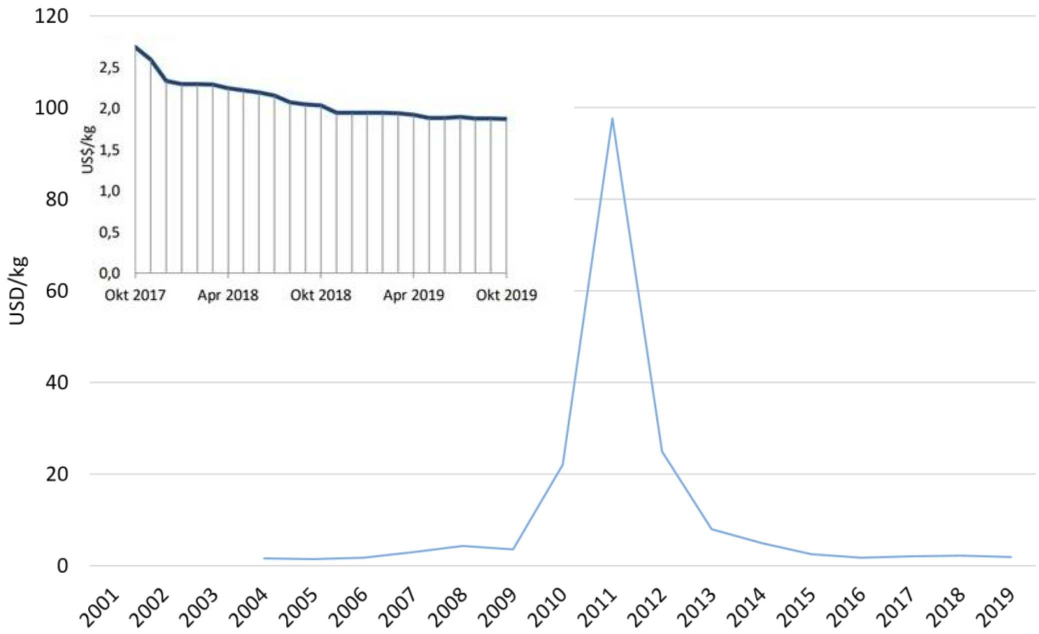


Figure 362: Annual average prices of 99% cerium oxide in USD/kg from 2004 to 2019 (FOB China, DERA 2019)

21.2.4.3 Dysprosium prices

Prices of dysprosium metal and oxide experienced great variations from 2010 to 2016. Dy oxide prices (99% FOB China) went from USD 30 per kg in 2002-2003 to an all-time high of USD 3,400 $per g in July 2011. Since then, they have continuously decreased to around USD 600 per kg in 2014, to USD 320 per kg in 2015, USD , and USD 190 per kg in 2017, and increased to USD 310 per kg in 2019 (DERA, 2019).

According to Roskill (2019), dysprosium prices are forecast to continue their decline in 2020, after being inflated for much of 2019. The supply of dysprosium should tighten following growing demand for NdFeB magnets from EVs and move into deficit by 2023. As supply of HREEs is more restricted compared to neodymium and other LREEs, the price is likely to see more volatility. Much like neodymium, dysprosium is forecast to see a widening supply gap from the end of the 2020s, which will require additional supply to maintain balance and price stability.

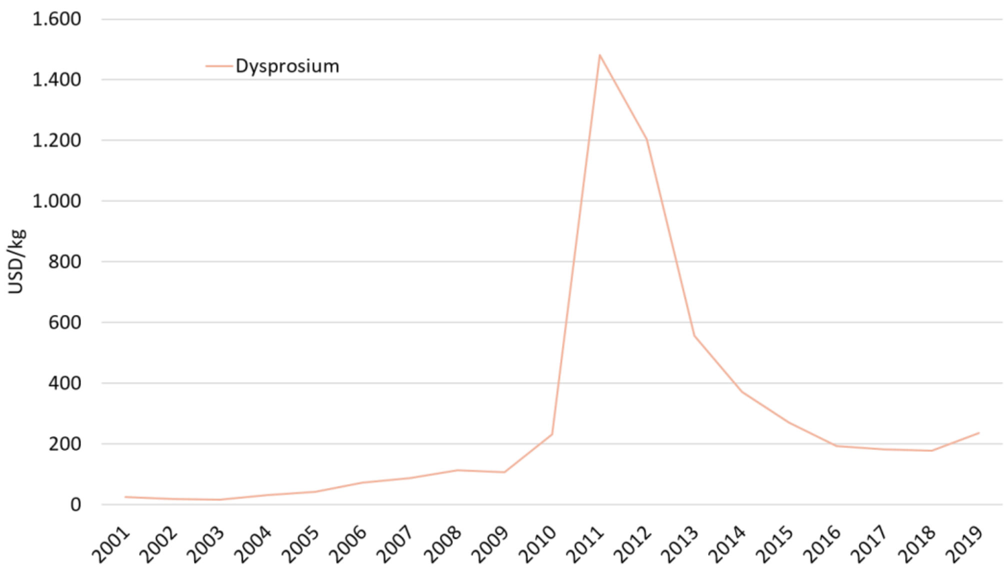


Figure 363: Annual average prices of 99% dysprosium oxide in USD/kg from 2001 to 2019 (FOB China, DERA 2019)

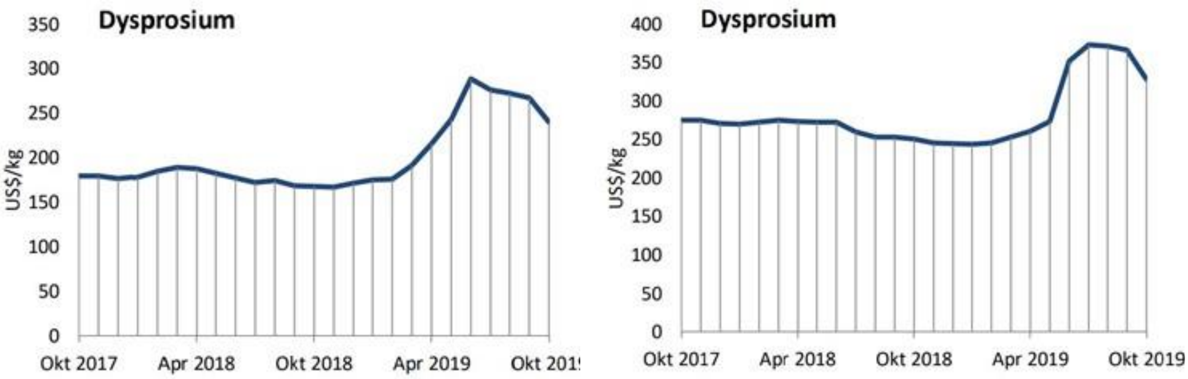


Figure 364: Prices of 99% dysprosium oxide (left) and dysprosium metal (right) price in USD/kg from 2017 to 2019 (FOB China, DERA 2019)

21.2.4.4 Erbium prices

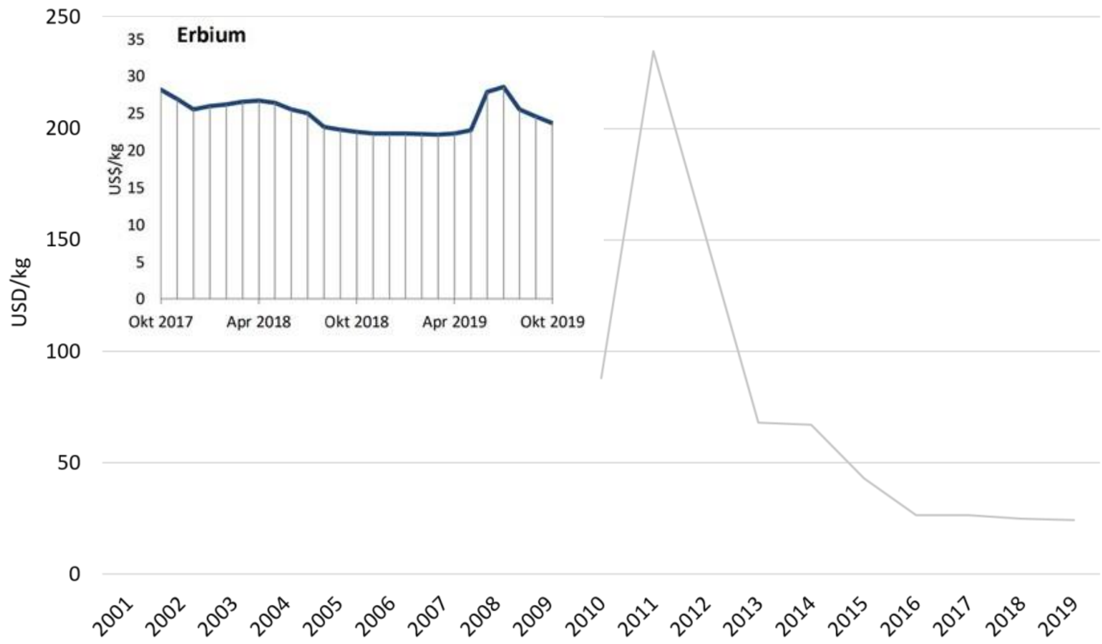


Figure 365: Annual average prices of 99% erbium oxide in USD/kg from 2010 to 2019 (FOB China, DERA 2019)

21.2.4.5 Europium prices

Prices of europium metal and oxide experienced great variations from 2010 to 2016. Eu oxide prices (99% FOB China) went from USD 785 per kg in 2002-2003 to an all-time high of USD 6,800 per kg in July 2011 (one of the highest growth ever for metal prices). Since then, they have continuously decreased, to USD 445 per kg in 2015, USD 70 per kg in 2017 and USD 35 per kg in 2019 (DERA 2019). Despite europium was for more than 15 years the most expensive of all the REE, its uses and value have decreased and terbium took the lead in 2014-2015.

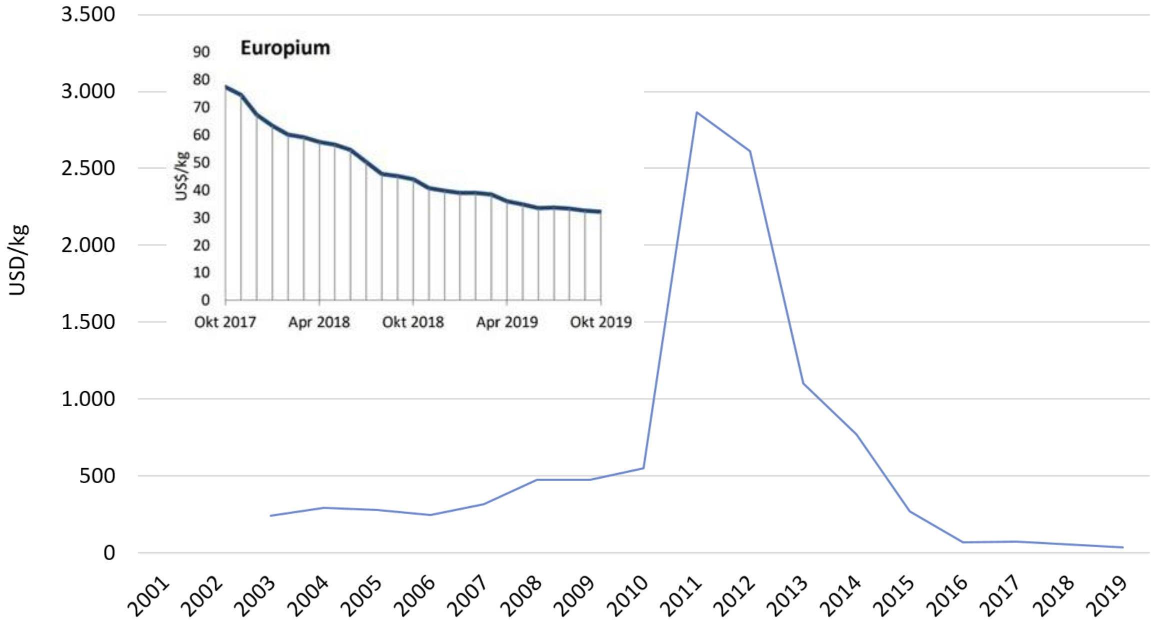


Figure 366: Annual average prices of 99% europium oxide in USD/kg from 2003 to 2019 (FOB China, DERA 2019)

21.2.4.6 Gadolinium prices

Prices of gadolinium metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from USD 30 per kg in 2008 to an all-time high of USD 226 per kg in July 2011, prices of Tb metal went down to reach a relatively stable value of around USD 61 per kg in 2015 (BRGM, 2015).

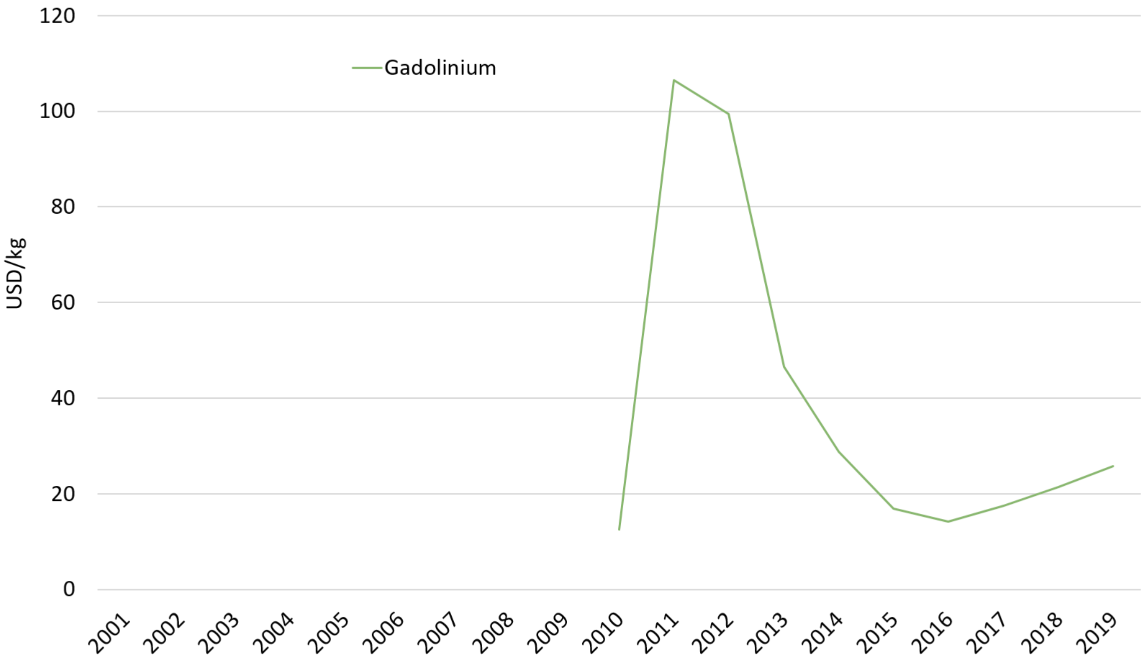


Figure 367: Annual average prices of 99% gadolinium oxide in USD/kg from 2010 to 2019 (FOB China, DERA 2019)

21.2.4.7 Holmium, Lutetium, Ytterbium, Thulium prices

No data for thulium prices is available.

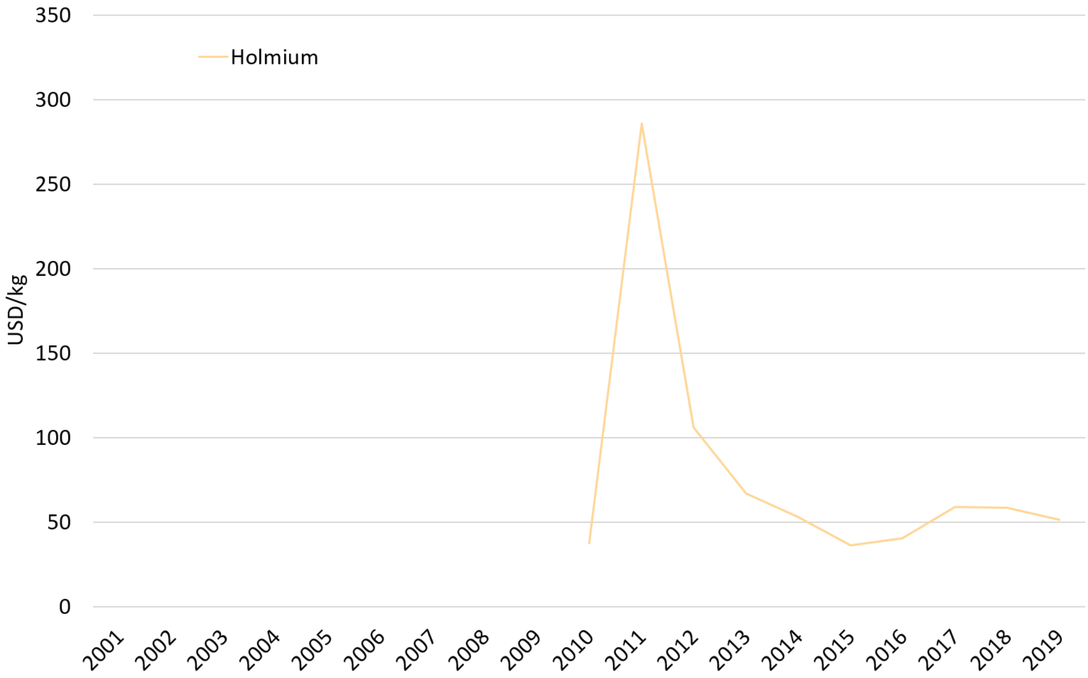


Figure 368: Annual average prices of 99% holmium oxide in USD/kg from 2010 to 2019 (FOB China, DERA 2019)

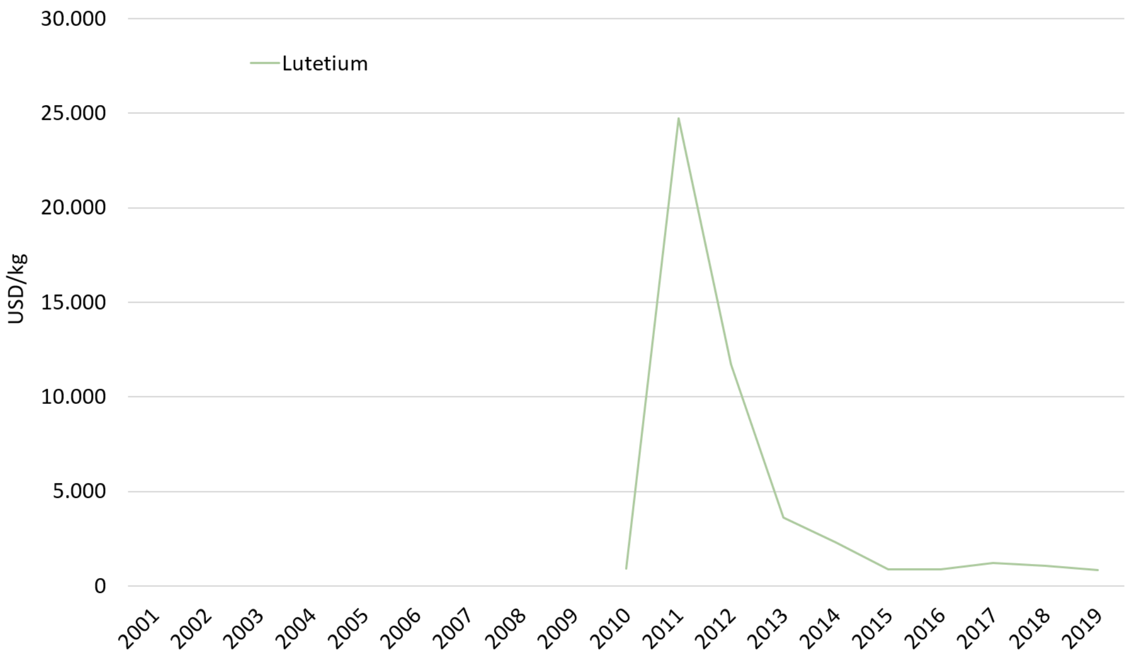


Figure 369: Annual average prices of 99% lutetium oxide in USD/kg from 2010 to 2019 (FOB China, DERA 2019)

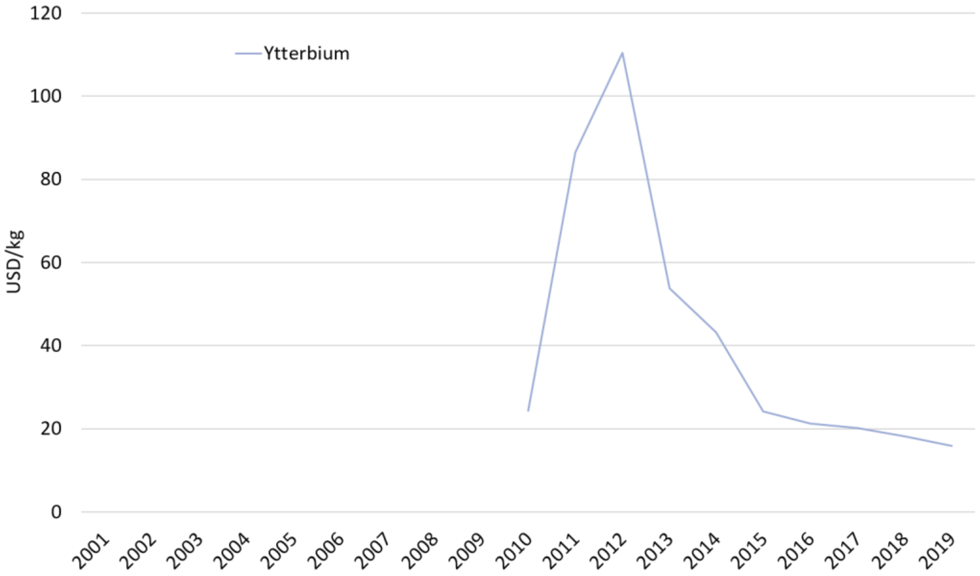


Figure 370: Annual average prices of 99% gadolinium oxide in USD/kg from 2010 to 2019 (FOB China, DERA 2019)

21.2.4.8 Lanthanum prices

Prices of lanthanum metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from USD 3 per kg in 2002-2003 to an all-time high of USD 166 per kg in July 2011, prices of La metal went down to reach a value of around USD 6 per kg in 2015 (BRGM, 2015) and USD 4 per kg in 2019 (DERA 2019).

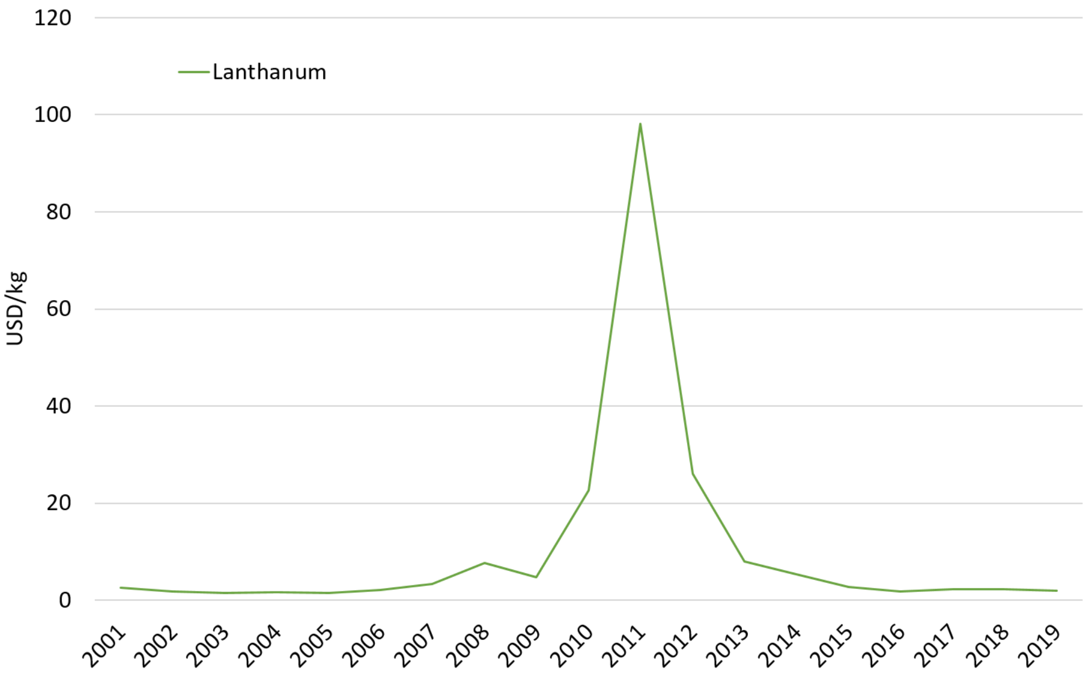


Figure 371: Annual average prices of 99% lanthanum oxide in USD/kg from 2001 to 2019 (FOB China, DERA 2019)

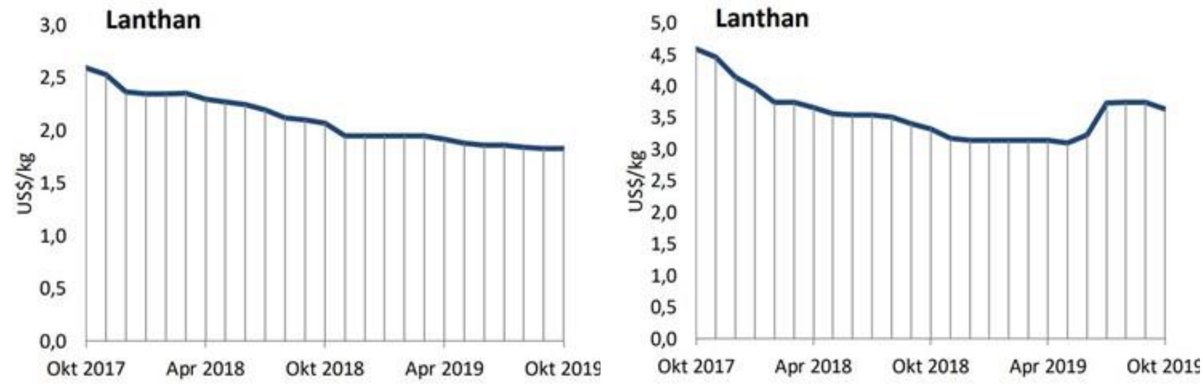


Figure 372: Prices of 99% lanthanum oxide (left) and 99.999% lanthanum oxide (right) in USD/kg (FOB China, DERA 2019)

21.2.4.9 Neodymium prices

Prices of neodymium metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from USD 7 per kg in 2002-2003 to an all-time high of USD 467 per kg in July 2011, prices of Nd metal went down to reach a relatively stable value of around USD 60per kg in 2015-2019 (DERA, 2019).

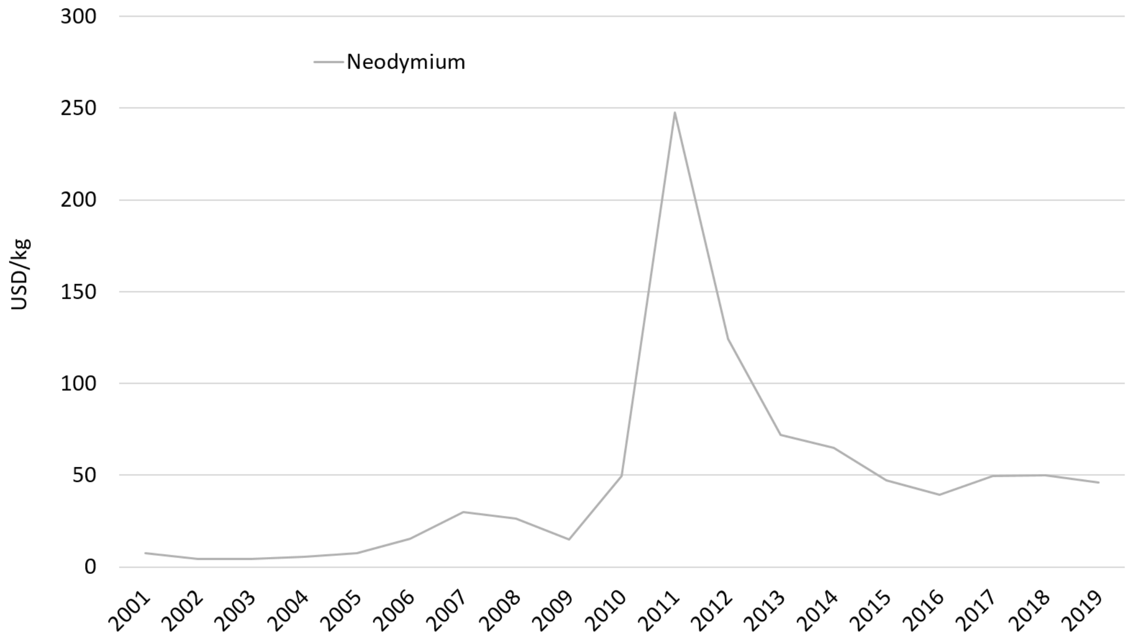
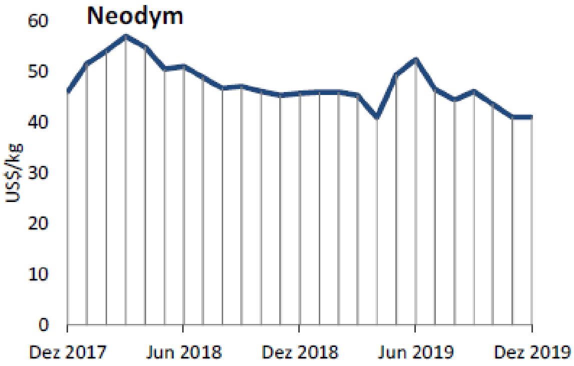


Figure 373: Annual average prices of 99% neodymium oxide in USD/kg from 2001 to 2019 (FOB China, DERA 2019)



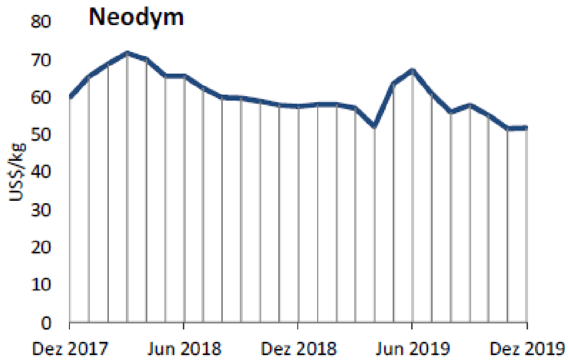


Figure 374: Prices of 99% neodymium oxide (left) and neodymium metal (right) price in USD/kg (FOB China, DERA 2019)

21.2.4.10 Praseodymium prices

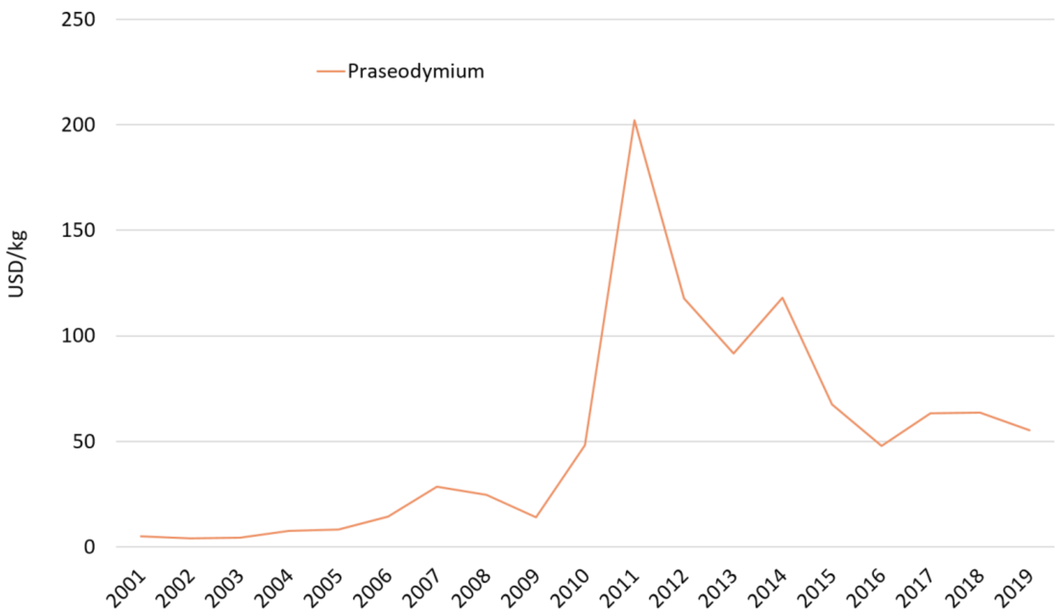


Figure 375: Annual average prices of 99% praseodymium oxide in USD/kg from 2001 to 2019 (FOB China, DERA 2019)

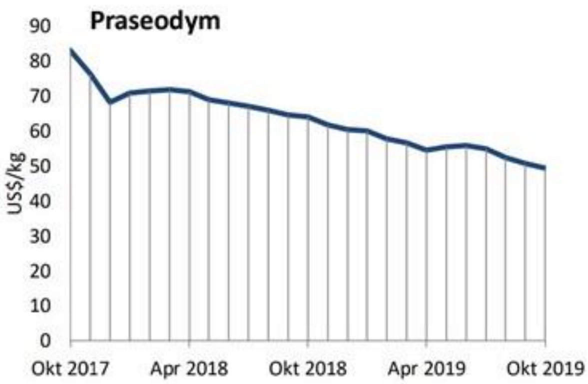


Figure 376: Pr oxide price; 99% Europe. DERA 2019 China USD/kg

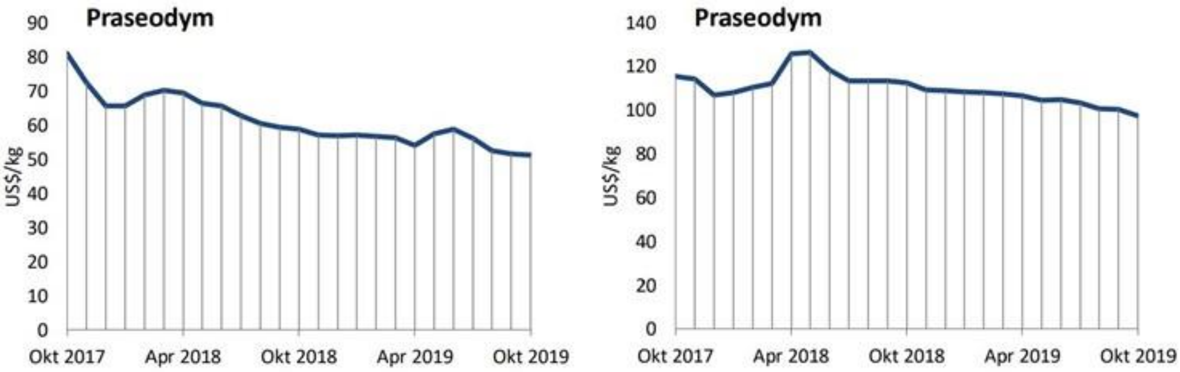


Figure 377: Pr oxide 99% (left) and Pr metal (right) price. Data from DERA 2019 99% FOB China USD/kg

21.2.4.11 Samarium prices

Prices of samarium metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from USD 13 per kg in 2002-2003 to an all-time high of USD 190 per kg in July 2011, prices of Sm metal went down to reach a relatively stable value of around USD per kg in 2019 (DERA 2019).

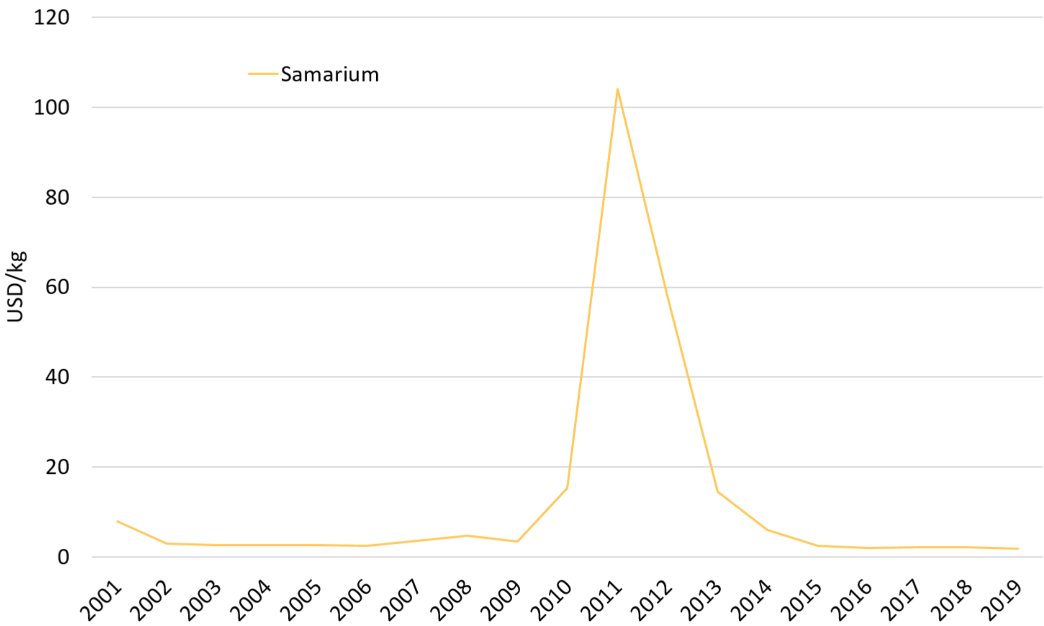


Figure 378: Annual average prices of 99% samarium oxide in USD/kg from 2001 to 2019 (FOB China, DERA 2019)

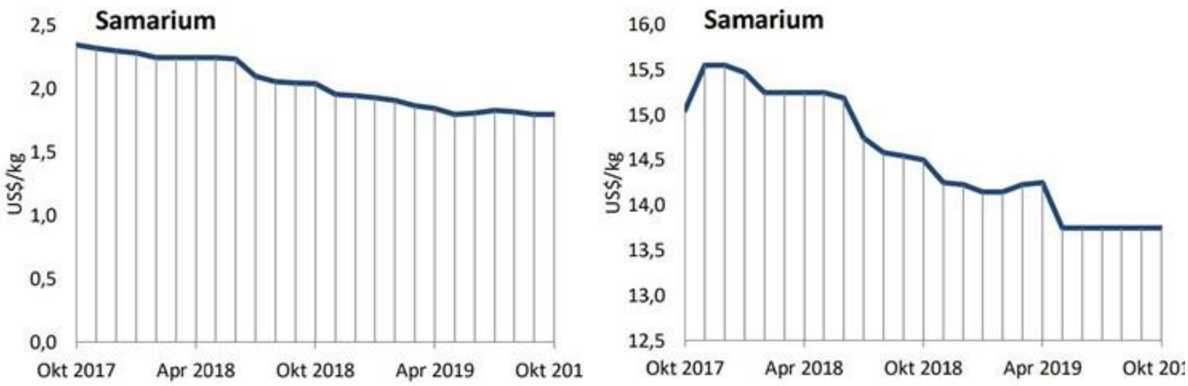


Figure 379: Sm oxide 99% (left) and Sm metal (right) price. Data from DERA 2019 99% FOB China USD/kg

21.2.4.12 Terbium prices

Prices of terbium metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from USD 200 per kg in 2002-2003 to an all-time high of USD 5,100 per kg in July 2011, prices of Tb metal went down to USD 700 per kg in 2015-2019 (DERA, 2019).

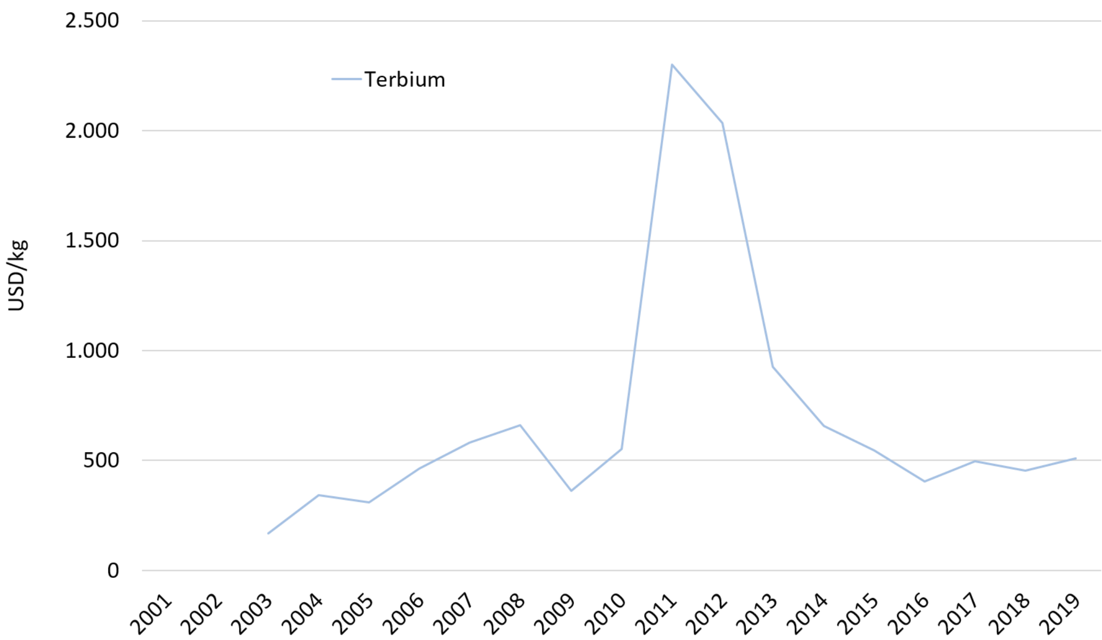
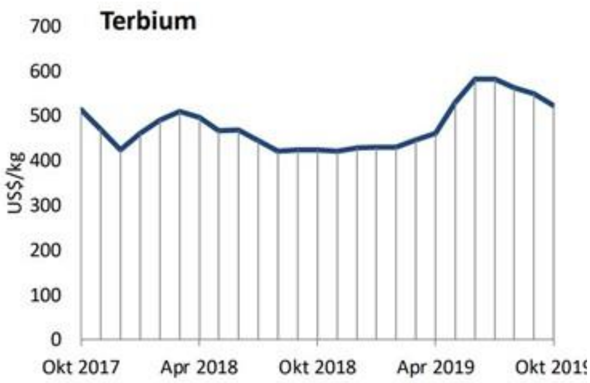


Figure 380: Annual average prices of 99% terbium oxide in USD/kg from 2003 to 2019 (FOB China, DERA 2019)



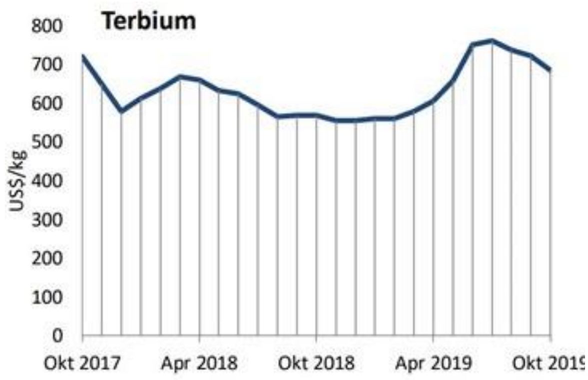


Figure 381: Terbium oxide 99% (left) and metal (right) price. Data from DERA 2019 99% FOB China USD/kg

21.2.4.13 Yttrium prices

Prices of yttrium metal and oxide experienced great variations from 2010 to 2014. After a sharp increase from 2010 to 2011, from USD 10 per kg in 2008-2009 to an all-time high of USD 180 per kg in July 2011, prices of Y metal went down to reach a relatively stable value of around USD 30 per kg in 2019 (BRGM, 2015).

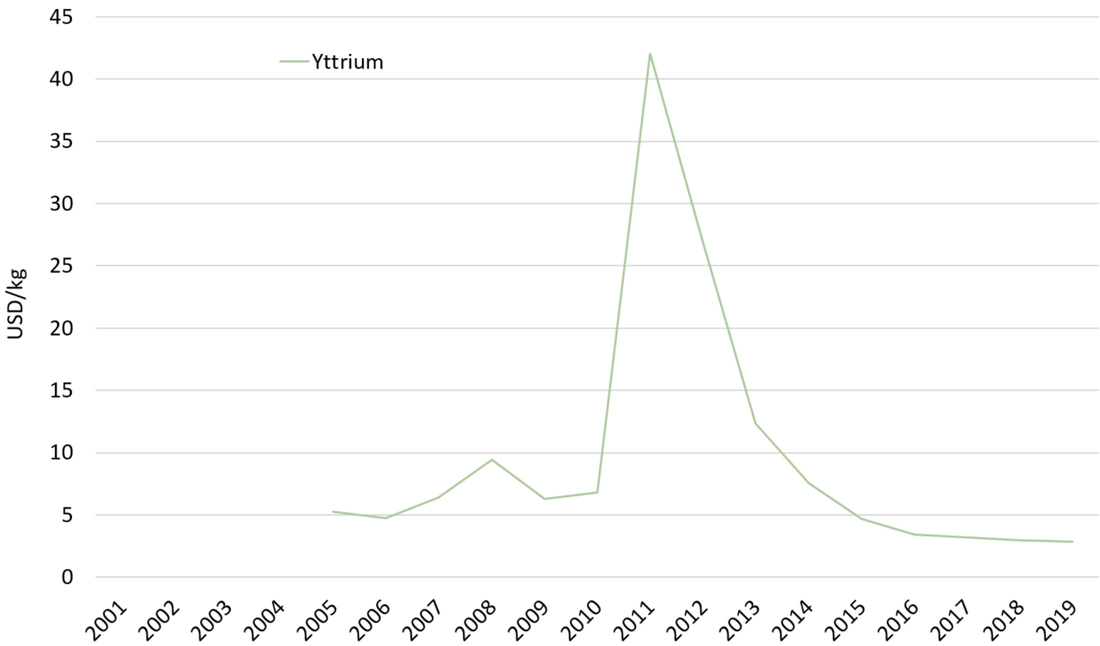


Figure 382: Annual average prices of 99% yttrium oxide in USD/kg from 2005 to 2019 (FOB China, DERA 2019)

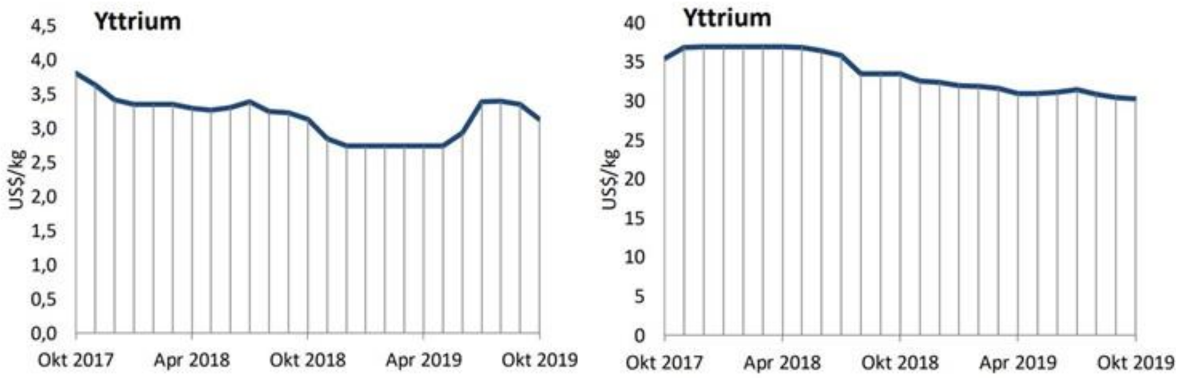


Figure 383: Y oxide 99% (left) and metal (right) price. Data from DERA 2019 99% FOB China USD/kg

21.3 EU demand

21.3.1 EU demand and consumption

The EU consumption of REE is 4,734 t/y of compounds (expressed in REO content) and 683 t/y of REE metals and interalloys during the 2016-2018 period and is entirely based on imports, which amount to 9,438 t/y for the REO compounds and 1,162 t/y of REE metals and interalloys[227]. Consumption of individual REE is presented in Table 150.

Table 150: EU consumption of individual REE (Eurostat, 2019; Guyonnet et al., 2015; Bio Intelligence Service, 2015).

REE consumed by the EU		Compounds [t]	Metals and Interalloys [t]
LREE	Ce	3,722	305
	Nd	61	39
	La	394	251
	Pr	25	16
	Sm	4	2
	tot LREE	4,206	613
HREE	Eu	21	3
	Tb	21	3
	Gd	10	1
	Er	8	1
	Dy	12	2
	Y	450	59
	Ho, Tm, Lu, Yb	8	1
	tot HREE	529	70
	Total	**4,734**	**683**

[227] UNCOM data shows EU-28 imported – 12,508 tons of RE compounds and oxides and 882 tons of metals and alloys

"*The REE-consuming sectors demand specific type and quality of the REE-products to fit to their needs; e.g. some sectors will need REO or REE carbonate, whilst other sectors demand high purity of REE metal. Thus a wide range of REE-products are produced, tailored to each of the sectors and sub-sectors; the vast majority of these products are manufactured in China*" (Machacek and Kalvig 2017: EURARE).

"*Purity is the main quality parameter applied for measuring the REE-products. The purity refers to the relative, thus proportional, maximization of some elements in the final REE-products as compared to the others. In other words, the product CeO_2, for example, could have a purity of 99.9% (see for instance Panadyne Abrasives, 2012-2016), or in industry jargon 'three N' or '3N'. This explains that the cerium oxide contains 99.9% cerium, yet traces of the other REE are still present which jointly account for 0.1%*" (Machacek and Kalvig 2017: EURARE).

"*The configuration of the REE chemical separation plant is engineered to match specific purity levels defined by the industrial user, and the processes occurring during the chemical separation are therefore tightly controlled. Commonly, the client will test the REE-product in a qualification process that can take from a few weeks up to a year (Mintek, 2013; Lynas Annual Report, 2013). As a general rule, high-N products are orders of magnitude more expensive as opposed to low-N products. Consumers therefore try to find the adequate balance between price and quality*" (Machacek and Kalvig 2017: EURARE).

"*The aim of maximizing purity of REOs is to reach the specifications set out by the intermediate industrial users of these separated REE, e.g. purity levels in the range of 99 to 99.9999%, depending on intermediate industry requirements (Leveque, 2014). For instance, firms which produce fluorescent lamp bulbs and use REE-phosphor-based powders to coat the bulbs demand purities of up to 99.9999%, as the purity of the specific REE (Eu, Tb, Y) affects whether the bulb will be able to meet the light spectra it should be showing"* (Machacek and Kalvig 2017: EURARE).

"*The downstream segments of the filament of REE-based permanent magnets require several processing steps to obtain the material magnet producers require as input. The first segment in this REE-permanent magnet manufacturing process sequence is metal making. The individual REO are fed into the process which can involve amongst others molten salt electrolysis and electrolysis of REE-bearing ionic liquids, producing high purity REM, such as Nd metal, or alloys of REE, such as mischmetal (La-Ce; La-Ce-Pr; or La-Ce-Pr-Nd) used in the iron and steel industry and in the production of La-rich battery alloys (Kingsnorth, 2014), lighter flints or ferro-alloys (GWMG, 2012 and Roskill, 2011)*" (Machacek and Kalvig 2017: EURARE).

"*Didymium, a mixture of the elements praseodymium and neodymium, can be a further output of the metal making process which is supplied to magnet alloy producers. Residues such as SEG (Sm-Eu-Gd) and the heavier fractions are sold on for further separation (Roskill, 2011). High purity REE-metals and other metals are then used to produce specialist alloys, or so-called "super alloys" of aluminium or permanent magnet alloys such as NdFeB or SmCo (Roskill, 2011)*" (Machacek and Kalvig 2017: EURARE).

21.3.2 Uses and end-uses in the EU

Figure 384 illustrates a general REE value chain from mineral raw materials, REE- salts, -compounds and -metal alloys up to final goods and services deployed on the market, including the production of REE salts and compounds and the manufacture of intermediate engineered products (catalysts, magnets, glass and ceramics, metallurgy and batteries, lighting, electric and other light vehicles, appliances and consumer electronics, communication devices, defence technologies, chemicals, oil refining, electric power, health care products and other final goods and services).

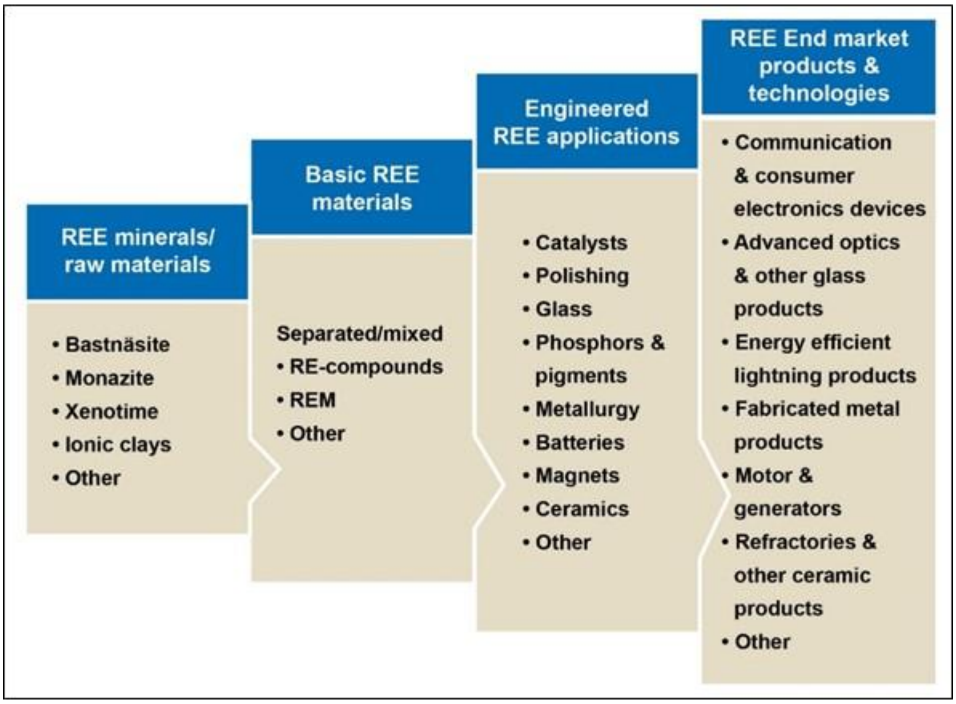


Figure 384: Simplified REE value chain from mineral raw materials up to end-products and technologies (Machacek and Kalvig 2017: EURARE).

The major applications vary according to individual Rare Earth Elements, but also regionally. Overall, the EU global consumption of REE by end-use is the presented in Figure 385 (expressed in tonne). The repartition of end-uses is different in the EU compared to the global situation (see Figure 386), with a higher use of REE in catalysts in the EU, whereas REE are by far less used in magnets.

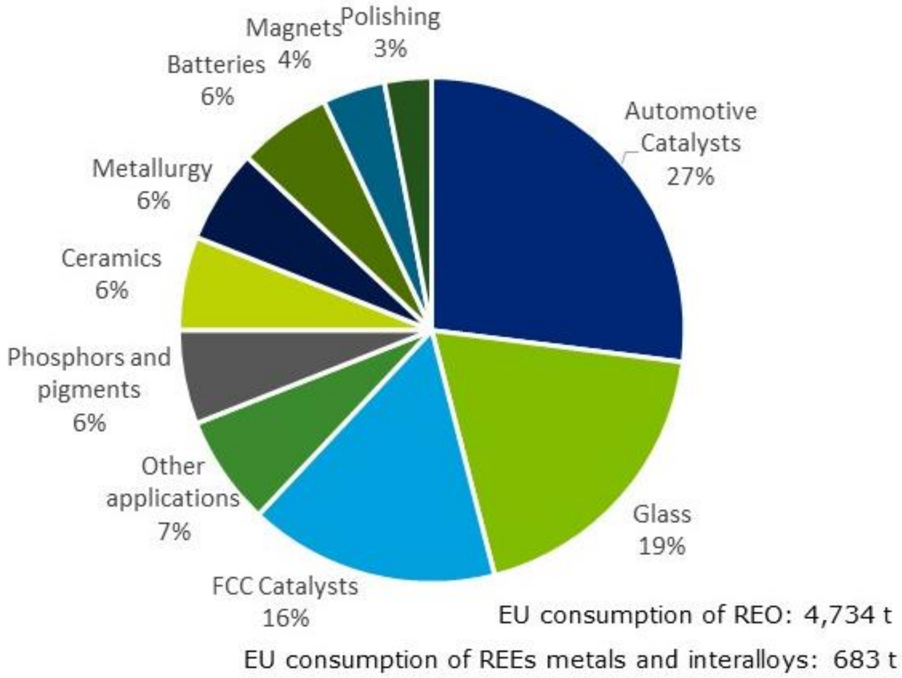
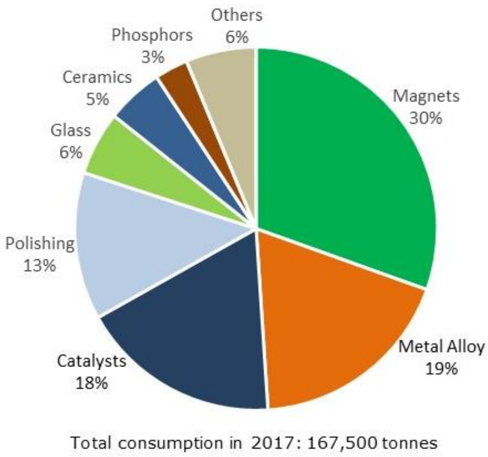


Figure 385: EU end uses of REEs and EU consumption, average 2016-2018 (EURARE, 2017; Eurostat Comext, 2019)



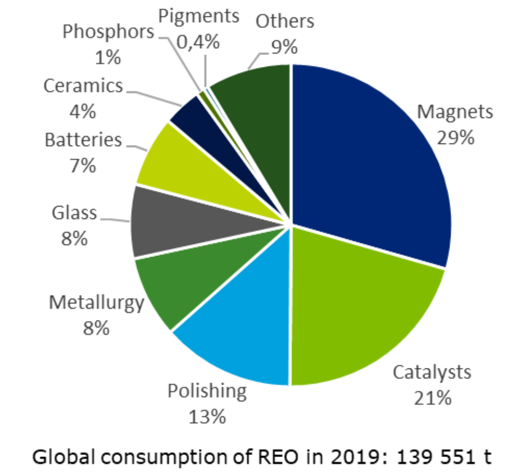


Figure 386: Global end uses and consumption (Left in 2017: Kingsnorth, 2018. Right in 2019: Eurostat, 2019; Machacek and Kalvig 2017: EURARE; Roskill 2019))

Globally, the main markets for most abundant rare earths - lanthanum and cerium are in catalysts (both fluid catalytic cracking and car catalysts) and in glass. The main markets for praseodymium, neodymium dysprosium, samarium and gadolinium are in magnets. Europium, terbium, and yttrium are mainly used in lighting phosphors. Glass is the main application of erbium and holmium/lutetium/ytterbium/thulium; and ceramics of yttrium.

Table 151: Applications of the REE (Data from the ASTER project – Guyonnet et al., 2015, and Average figures for 2016-2018 Eurostat, 2019)

Applications	Heavy REE	Light REE

	Eu	Tb	Gd	Er	Dy	Y	Ho, Tm, Lu, Yb	Ce	Nd	La	Pr	Sm
Magnets	-	32%	**97%**	-	**100%**	-	-	-	**37%**	-	**24%**	**97%**
Metal	-	-	-	-	-	-	-	6%	12%	3%	11%	-
Batteries	-	-	-	-	-	7%	-	6%	13%	10%	12%	-
FC Cracking	-	-	-	-	-	-	-	8%	-	**67%**	-	-
Car catalysts	-	-	-	-	-	-	-	**35%**	6%	-	10%	-
Polishing	-	-	-	-	-	-	-	11%	-	5%	10%	-
Glass	-	-	-	**74%**	-	4%	**100%**	**31%**	8%	10 %	8%	-
Phosphors	**96%**	**68%**	-	26%	-	**46%**	-	1%	-	2%	-	-
Ceramics	-	-	-	-	-	**35%**	-	2%	11%	2%	15%	-
Others	4%	-	3%	-	-	8%	-	-	10%	-	10%	3%
Total use in EU (t)	**23**	**23**	**12**	**9**	**14**	**509**	**9**	**4026**	**101**	**644**	**41**	**6**

The following chapters based on substantial input from Machacek and Kalvig 2017: EURARE provide more details about individual applications.

21.3.2.1 Magnets, electric motors and generators

Permanent magnets are materials, which are able to retain magnetic properties after inserted in a strong magnetic field, also once that the external magnetic field expires. There are different characteristics which make magnets suitable for different applications, such as magnetic strength, resistance to demagnetisation, higher temperatures, chemical corrosion, relative density etc.

"*Permanent magnets have a variety of uses, and are e.g. used in the following major groups: acoustic transducers, motors and generators, magneto mechanical devices, and magnetic field and imaging systems. In cars, magnets are being utilized in permanent magnet motors, controlling the power window, windshield wipers, and used for generators, as well as utilized in various types of sensors. Also magnets are used in amplifiers and loudspeakers, smartphones and other communication technology. The wind-turbine sector is a major consumer of permanent magnets. In addition, an emerging technology using REE-magnets, i.e. magnetic refrigeration, could potentially improve the energy efficiency of refrigerators for home and commercial use*" (Machacek and Kalvig 2017: EURARE).

The most important REE for permanent magnets are neodymium, praseodymium, dysprosium, samarium and also other REE used in minor amounts. NdFeB magnets are the strongest known types of permanent magnets were invented in the 1980s by General Motors Corporation, US and Sumitomo Special Metals, Japan. A NdFeB magnet can lift 1300 times its own mass. NdFeB alloyed with up to 4 wt% dysprosium can dramatically increase the maximum operating temperature from 80°C up to 200 °C.

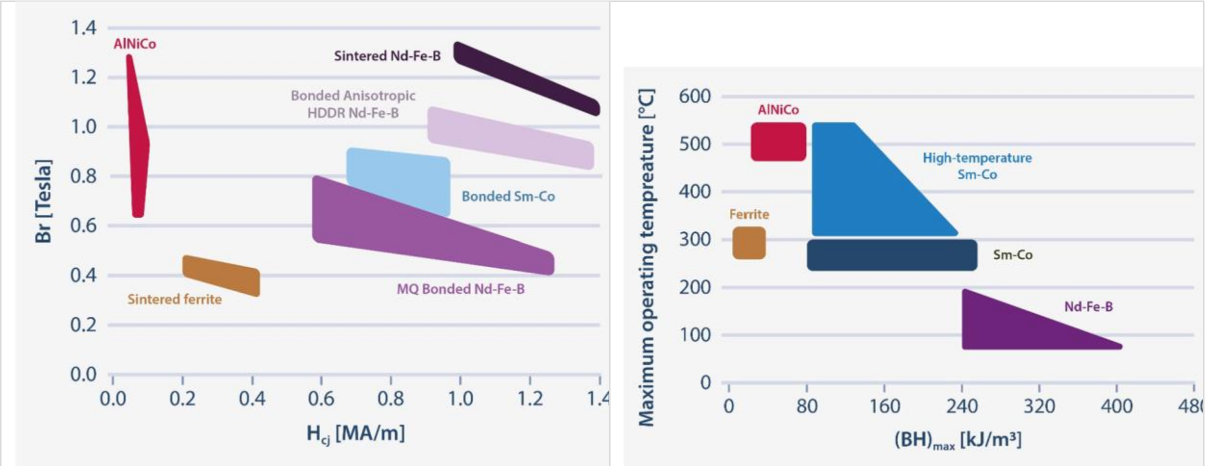


Figure 387: (left) Comparison of the properties of different types of magnets. Br = remanence (magnetization left after an external magnetic field is removed); Hcj = coercivity (a measure of the resistance of a ferromagnetic material to becoming demagnetized) (Binnemans 2018). (right) Comparison of the maximum operating temperatures of NdFeB and Sm–Co magnets (Binnemans 2018).

Global production of NdFeB magnets is around 80,000 tpa (Binnemans 2015) worth USD 13.4 billion in 2015 (Global Information Inc. 2016), representing around 66% of the market value (Global Market Insights Inc., 2017). Although ferrites remain the most used raw material for permanent magnets (in 2012 they accounted for about 80% of the global permanent magnets production) (Grand View Research, 2014), mainly because they are cheap and largely used in the fast growing automotive market. Minor production shares then relates to AlNiCo and SmCo magnets (around 1,000 tpa) (Binnemans 2015).

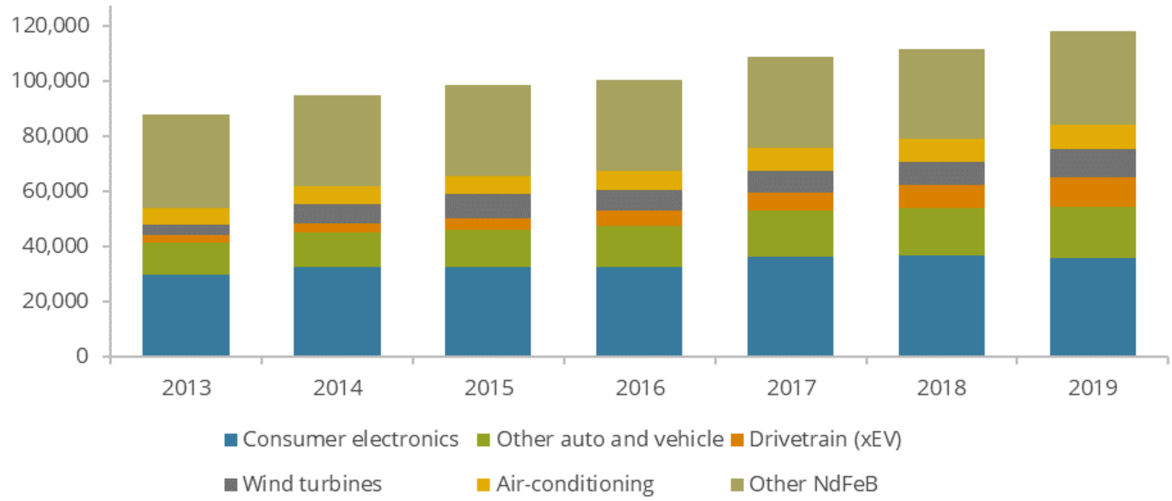


Figure 388: NdFeB magnets demand per application in tonnes in 2013-2019 (Roskill 2019)

Electric motors

In the next decade, the most disruptive technology for the consumption of REE is forecast to be the growth in hybrid electric vehicles (HEVs) and full electric vehicles (EVs), which are expected to cause wholesale changes in the volumes and types of raw materials consumed by the automotive industry. Production of HEVs and EVs is forecast to increase from 2.3 million units in 2016 to over 10.1 million units in 2026 (Roskill 2016a), as nearly all major automotive manufactures have developed HEV and EV models.

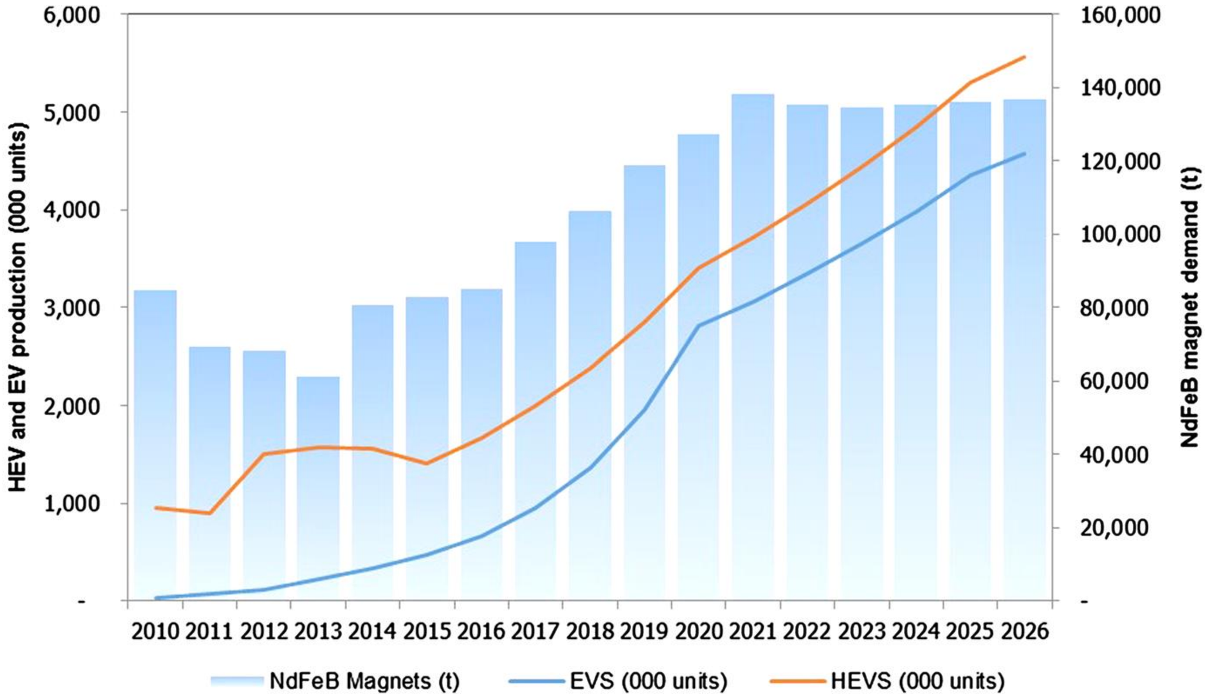


Figure 389: Forecast production of HEVs and EVs versus NdFeB magnet demand, 2010–2026. (Goodenough et al. 2017).

Hybrid electric vehicles (HEVs), plug-in hybrids (PHEVs), and pure electric vehicles (EVs) all require electric motors.

In 2018, 93% of all passenger EVs sold globally used permanent magnet traction motors (PMSM) containing rare earth permanent magnets (e.g. in BMW i3). Permanent magnet synchronous motors are up to 15% more efficient than induction motors and are the most power-dense type of traction motor commercially available (in kW/kg and kW/cm3). Other rare earths free alternatives are induction motors (IM) (used in Tesla model S or Renault Twizzy), and electrically-excited synchronous motors (EESM) (used in Renault Zoe and Fluence, or Smart Fortwo).

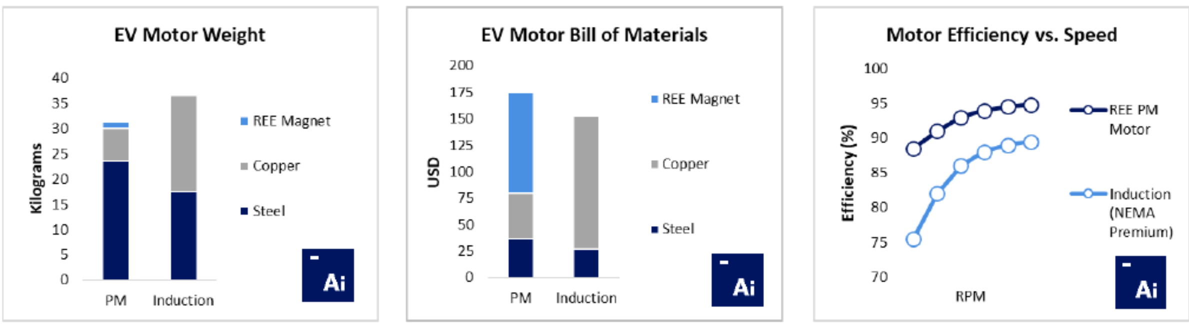


Figure 390: Comparison of EV traction motor weights, costs and efficiencies (UBS, Control Engineering in Adamas Intelligence, 2019)

A high-performance magnet for use in motor applications has a composition close to 31%Nd–4.5%Dy–2%Co–61.5%Fe–1%B (wt%). The dysprosium is critical in this application to provide very high coercivities in order to achieve a service temperature of 160 °C.

Hybrid EVs and pure battery EVs use between 1-3kg of neodymium-iron-boron (NdFeB) magnets in standard drivetrain motors[228]. Binnemans (2018) states that for a 55-kW motor, 0.65 kg of Nd–Dy–Co–Fe–B alloy is required, which represents 200 g of neodymium (3.6 g/kW) and 30 g of dysprosium (0.55 g/kW) per motor.

Adamas Intelligence (2019) assumes that to produce 1.6 kg of NdFeB alloy requires approximately 0.5 kg of rare earth metal inputs (primarily NdPr with lesser Dy and minor Tb), plus an additional 15 to 20% to compensate for losses incurred during production of NdPr metal and Ferro-Dy alloy input materials, bringing total consumption to approximately 0.6 kg of rare earth metals per 100 kW of peak motor power (6 g/kW).

	Material Intensity (Per 100 kW) *	Avg. EV Motor in 2018 (93 kW)	Avg. EV Motor in 2025 (131 kW)
NdFeB	1.6 kg	1.5 kg	2.0 kg
NdPr metal	0.6 kg	0.5 kg	0.8 kg
NdPr oxide	0.7 kg	0.7 kg	1.0 kg

* Magnet, metal and oxide mass estimates account for material losses from oxide to metal to alloy to finished NdFeB
* Numbers may not calculate exactly as shown due to rounding
Source: Adamas Intelligence research

Figure 391: Rare earths materials used in a permanent magnet traction motor. (Adamas Intelligence 2019).

The global electric car fleet exceeded 5.1 million in 2018[229], up by 2 million since 2017, almost doubling the unprecedented amount of new registrations in 2017. China remained the world's largest electric car market with nearly 1.1 million electric cars sold in 2018 and, with 2.3 million units, it accounted for almost half of the global electric car stock. Europe followed with 1.2 million electric cars and the United States with 1.1 million on the road by the end of 2018 and market growth of 385 000 and 361 000 electric cars from the previous year. Norway remained the global leader in terms of electric car market share at 46% of its new electric car sales in 2018, more than double the second-largest market share in Iceland at 17% and six-times higher than the third-highest Sweden at 8%.

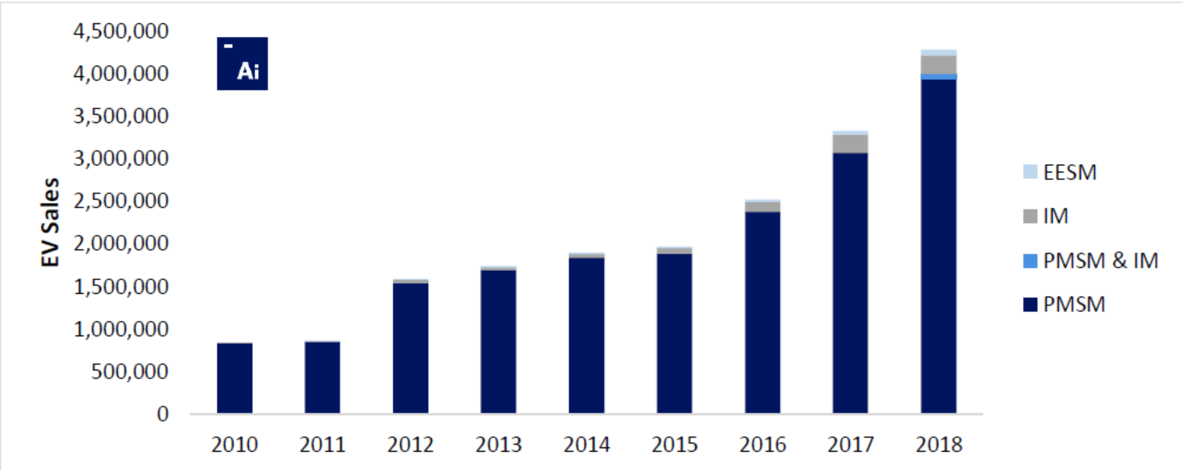


Figure 392: Global sales of electric vehicles 2010-2018 (Adamas Intelligence, 2019). Permanent magnet synchronous motors ("PMSMs"), induction motors ("IMs"), and electrically-excited synchronous motors ("EESMs"). Of the three

[228] https://roskill.com/news/rare-earths-bmws-fifth-generation-ree-free-electric-drivetrain/ posted on 4 January 2019
[229] https://www.iea.org/publications/reports/globalevoutlook2019/

motor types, PMSMs are the only variety that contain rare earth permanent magnets.

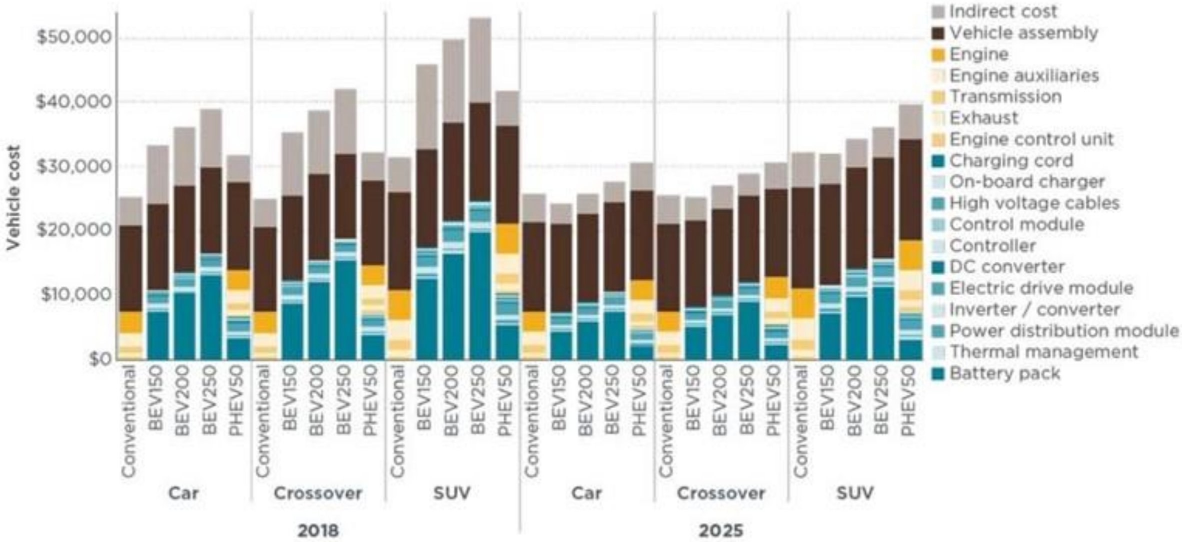


Figure 393: Vehicle technology costs for conventional and electric vehicles in 2018 and 2025 for cars, crossovers and SUVs (ICCT)[230]

A new and rapidly growing market for NdFeB magnets is electric bicycles, which contain lightweight, compact, Nd–Fe–B-based, miniature electric motors. They use approximately 350 g of NdFeB or 86 g of neodymium per electric bicycle. So far, there are no alternatives to NdFeB magnets in bicycles due to space and weight considerations. (Binnemans 2018)

Electricity generators

Wind turbine producers choose between doubly fed induction generator (DFIG) turbines, which require no permanent magnets (PMs); direct-drive turbines, which require large NdFeB PMs; hybrid drive turbines, which require smaller PMs; and turbines that use large PMs, but require no Dy, as high temperatures are unlikely to occur in a well-designed wind turbine.

Direct-drive wind turbines contain 700–1200 kg of NdFeB magnets per MW, which corresponds to 175–420 kg of pure neodymium per MW.

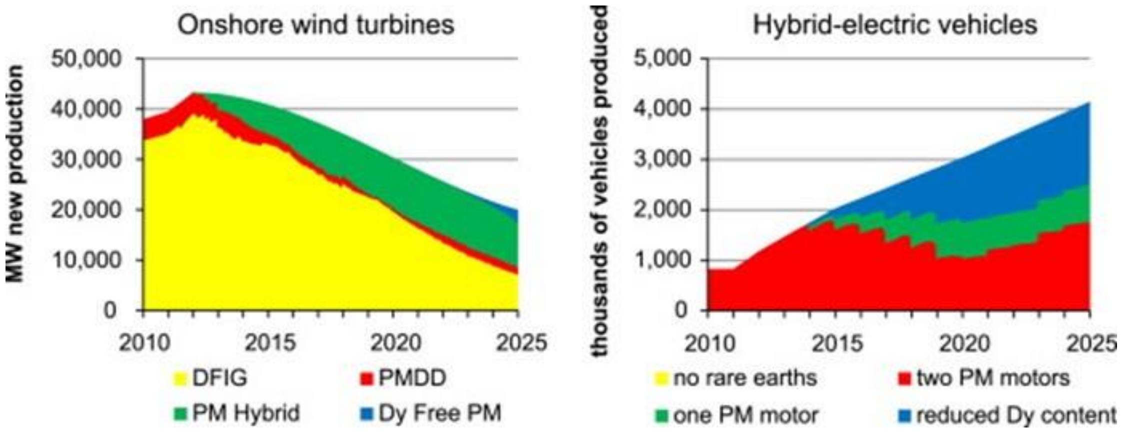


Figure 394: Production of onshore wind turbines and hybrid electric vehicles using different technologies: average baseline scenario projections. (Notes:

[230] https://thedriven.io/2019/04/04/electric-cars-could-cost-half-of-equivalent-petrol-vehicles-by-2030/ posted on 4 April 2019

DFIG=doubly-fed induction generator, PMDD=permanent magnet direct drive, and PM=permanent magnet) (Riddle et al. 2015).

Europe installed 11.7 GW (10.1 GW in the EU) of gross power capacity in 2018[231], which was 33% less than in 2017. With a total net installed capacity of 189 GW, wind energy remains the second largest form of power generation capacity in Europe, set to overtake gas installations in 2019.

In November 2018[232], a 3.6MW wind turbine in Denmark had its permanent magnet generator replaced by a high-temperature superconductor (HTS) based generator as part of the EU-funded EcoSwing project. The superconductor reduces the size of the generator and replaces about 1t of neodymium (Nd) used in NdFeB permanent magnets with about 1kg of the rare earth gadolinium (Gd) used in the superconducting composite tape: gadolinium–barium–copper oxide (GdBaCuO).

21.3.2.2 Metallurgy

"*REE are used in the manufacture of iron and steel to improve performances and properties of the final products. Among their different applications in metallurgical industry, REE are employed in construction and automotive sector, including Hybrid Electric Vehicles (HEV) and Electric Vehicles (EV), in portable electronics, in fuel cell components, in high strength metals for aircraft manufacture and in magnesium alloys*" (Machacek and Kalvig 2017: EURARE).

"*Ce and La are by far the most used REE in this field. In metallurgical applications REE are usually applied as mischmetal or as REE-silicide. Mischmetal is an alloy made by a mixture of REE obtained by an electrolytic extraction; although different composition are available on the market based on Ce content, a typical mischmetal composition is: 48-56% Ce, 25-34% La, 11-17% Nd, 4-7% Pr, minor amounts of other REE, 0.2-0.5% Fe and other impurities such as Si, Mg, S and P (MSE Supplies LLC, 2017; Metall Rare Earth Ltd, 2017). REE-silicide, which is usually less reactive than mischmetal, is instead constituted by REE, silicon and iron in about equal proportions*" (Machacek and Kalvig 2017: EURARE).

"*In particular, the overall amount of REE (mischmetal or REE-silicides) used to remove impurities in iron and steel casting have partially declined, due to the shift by foundries in Europe and North- America to magnesium ferrosilicon (FeSiMg) nodulisers containing much smaller amounts of REE. Moreover, the employment of Ce to remove traces of sulphur from the molten materials, typically after deoxidation and desulphurisation stages, or to improve the mechanical properties (e.g. corrosion resistance) of the final product is decreasing. REE are where possible substituted by less expensive metals such as magnesium, calcium and other Group II metals are commonly used for such purposes. Information about purity is based on American Elements and Metall Rare Earth Ltd."* (Machacek and Kalvig 2017: EURARE).

21.3.2.3 Batteries

"*Nickel-metal hydride (NiMH) batteries were introduced to the market in the 1990's, as an improvement of the existing nickel hydrogen technology, mainly based on nickel-cadmium (NiCd) batteries. Both are rechargeable batteries with almost similar electrochemical*

[231] https://windeurope.org/about-wind/statistics/european/wind-energy-in-europe-in-2018/

[232]https://roskill.com/news/rare-earths-ndfeb-wind-turbine-generator-replaced-by-high-temperature-superconductor/

behaviour. But the NiMH batteries have better performances due to longer life-cycle, higher stability and lack of persistence issues. Moreover, the Cd-anode in the Ni-Cd-battery is replaced with a metal hydride in the NiMH battery, making the latter 'greener'. Due to such enhancements, NiMH batteries have been increasingly deployed in different growing markets (e.g. portable tools and consumer electronic applications), even if their largest use is in the emerging sector of HEVs.

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

Lithium-ion (Li-ion) batteries are increasingly replacing NiMH batteries in computing, communication and consumer products (e.g. mobile phones and laptops) due to their easier manufacture in special shapes: indeed, electronics covers about 50% of the global market associated to lithium-ion batteries (Allied Market Research, 2016).

Although the manufacturing costs of Li-ion are still higher than the ones associated to NiMH batteries, Li-ion batteries are partially replacing NiMH batteries also in PHEVs and EVs, mainly because of their higher energy density and longer lifespan. Indeed, such types of electric vehicles can be charged by plugging them in a grid-provided electricity system and thus require batteries with higher energy density in order to guarantee a range as wide as possible between charging stations. The battery for HEVs are charged through the gasoline combustion engine, and for this purpose the high-power density NiMH batteries are more suited, and therefore still represent the most used batteries in HEVs, although in 2013 lithium-ion batteries accounted for about 20% of all batteries used in HEVs (CEC, 2015). However, NiMH batteries maintain a relevant role in large-size, stationary applications in which power-to-weight is less important (e.g. back-up units), as well as in high-temperature applications where Li-ion batteries are unsafe. China currently leads the production of small-size NiMH batteries, while the large-size ones are mainly manufactured in Japan. Information about purity is based on American Elements and Metall Rare Earth Ltd". (Machacek and Kalvig 2017: EURARE).

21.3.2.4 Catalysts

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

The two main areas of applications for REE in the catalysis sector are associated to the formulation of catalysts for the Fluid Catalytic Cracking (FCC) in the petroleum processing, as well as in catalysts aiming at reducing emissions of pollutants within the exhaust gases originated from automobiles and other combustible engines. Several of the REE are used in catalysts formulation, both in processing and in automotive applications: they are mainly La, Ce, Nd and Pr. Information about purity is based on American Elements and Metall Rare Earth Ltd." (Machacek and Kalvig 2017: EURARE).

Fluid Catalytic Cracking (FCC) catalysts

"FCC process is used in the petroleum industry to obtain light fractions such as LPG and gasoline from high-molecular weight hydrocarbon fractions. Due to the higher octane

rating of gasoline and higher yield in olefinic gases, this process has gradually substituted the thermal cracking. In particular, the employment of La, Ce and Nd rose in the 1960s, when zeolite-based cracking catalysts started to be used in oil refineries. These kinds of catalysts are typically constituted by a crystalline zeolite (representing 5-40% of the catalyst weight), i.e. the active component acting as a sieve to filter the crude oil, by a matrix typically of alumina (5-25 wt%), by a binder such as silica sol or gel (5-25 wt%) and by an inert matrix, i.e. the clay (Trigueiro et al., 2013; Henriques, 2012; Roskill, 2016)". (Machacek and Kalvig 2017: EURARE).

Car catalysts

"*Along with applications in petroleum processing, catalysts for automotive engineering represent another large market for REO, aiming at reducing emissions of pollutants within the exhaust gases originated from automobiles and other combustible engines. In particular, Ce, La, Nd and mainly REO and RE-compounds are used; dominant purity specifications are 3-4Ns and 2-5Ns respectively. CeO2 or other Ce-compounds are used to (i) keep up the catalysts efficiency by avoiding the formation alpha alumina phase; (ii) improve the oxidant features of the overall system and facilitates a water-gas shift on reaction."* (Machacek and Kalvig 2017: EURARE).

"*The amount of REE required for automotive catalysts' formulation depends on vehicle type (petrol, diesel or hybrid vehicle) and size. China is currently leading the worldwide vehicle markets (in 2015 it accounted for about 27% of the global production) (OICA, 2015). In addition, the demand for automotive catalysts is further affected by the fact that, unlike European customers, Chinese customers usually prefer large-size vehicles (e.g. SUVs), entailing major amounts of catalysts (Roskill, 2016). The automotive sector is influenced by changes in emissions standards: even though European regulations are more stringent, USA and BRIC countries are fostering a tighter emission control (e.g. India's and China's emission standards are now respectively equivalent to the ones of Euro III and Euro IV), thus offering opportunities for REE (mainly Ce) to be used in catalysts*." (Machacek and Kalvig 2017: EURARE). Information about purity is based on American Elements and Metall Rare Earth Ltd.

21.3.2.5 Polishing

"*REE-based polishing powders are essentially employed to finish the surface of glass products and electrical components, such as display panels, flat glass, optical glass and consumer electronics. Moreover, REE (i.e. CeO2) can also be used in jewellery as alternative to jeweller's rouge, i.e. a very fine powder of ferric oxide, to polish precious metals and stones (Roskill, 2016).*

Although CeO2 is the most used REE compound, polishing powders can also contain traces of other REE with minor polishing properties (i.e. La, Pr, Nd). The main advantages in using CeO2-based polishes, making them the most used glass polishes, are related to the faster polishing operations, in which CeO2 is mixed with water, and easier cleaning after use. In particular, most of the Ce is employed in traditional glass polishing applications (e.g. display panels, flat glass and optical glass, silicon microprocessors and disk drives), while the rest of the Ce is used in consumer electronics.

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

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

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

Within the same approach, polishing industry developed solutions enabling the recovery and re-use of slurries from polishing operations: this led to the implementation of recycling steps within several polishing plants. Information about purity is based on American Elements and Metall Rare Earth Ltd." (Machacek and Kalvig 2017: EURARE)

21.3.2.6 Glass

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

Ce is the dominant REE used in this sector, though also La, Er and minor amounts of Gd, Nd, and Y are also employed in different technological applications within the glass sector. Moreover, small quantities of other REE can be used: they include Pr, Sm, Eu, Ho and Tm.

Ce is utilised as a glass stabiliser to contrast effects of UV and high-energy rays (for example in display panels and in the bottling industry) or as decolouring agent to remove natural impurities from glass, such as iron oxides. In particular, a specific market for CeO_2 exists in Japan, where UV-resistant glass for vehicles is required by legislation to be used in vehicle front windscreens.

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

USA represents the principal market for glass coating based on REE (e.g. used in scientific lenses, laser cavity mirrors, laser printer mirrors, slides for electron microscopy) mainly related to the defence sector. For glass coating, only high purity 4N-products of CeO_2, Ce-fluoride, La_2O_3 and Nd- fluoride, with addition of iron oxide, can be employed (Roskill, 2016). Information about purity is based on American Elements and Metall Rare Earth Ltd." (Machacek and Kalvig 2017: EURARE)

21.3.2.7 Phosphors

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

Y_2O_3 is by far the most used REO in phosphors, followed by Pr_6O_{11}, CeO_2, La_2O_3 and Eu_2O_3. However, the type of REE to be used in phosphors, their relative composition and content are dependent on the specific application and are typically considered proprietary

information. Generally, the oxides of Y, Gd, and La are mainly employed as host materials in phosphor production. Several other REE find application in the phosphor sector primarily as activators, with a relevant role covered by Eu-activated red phosphors. Eu is widely used in TV and PC monitor screen panels and to a lesser extent in lighting and medical imaging, such as X-ray. Information about purity is based on American Elements and Metall Rare Earth Ltd." (Machacek and Kalvig 2017: EURARE)

21.3.2.8 Ceramics

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

Around 0.4% of REE are used as pigments to stain ceramic tiles and to impart colour/improve the finish of ceramic glazes (Roskill, 2016).

Given the wide range of different ceramics products and applications in which REE are involved, including several niche markets, as well as the increasing boost towards the substitution of metals with engineering ceramics, an effective estimation of REE consumption trends for ceramics is quite difficult. However, in the ceramic capacitor-market, for example, base metal (BM) capacitors are gradually replacing precious metal (PM) counterparts, which will reduce the demand for Nd_2O_3 *substantially. Information about purity is based on American Elements and Metall Rare Earth Ltd*." (Machacek and Kalvig 2017: EURARE)

21.3.2.9 Photonics and 5G

REE doped laser crystals are used in many applications.

Nd oxide is used as dopant in yttrium aluminum garnet (YAG - neodymium-doped yttrium aluminum garnet; $Nd:Y_3Al_5O_{12}$) lasers to improve absorption and emission performance. Frequently used in material processing and in medical applications. (Machacek and Kalvig 2017: EURARE)

Y and Nd: Used as dopants to cause fluorescence (purity 5N or higher). (Machacek and Kalvig 2017: EURARE)

5G networks would require small cells, rather than geographically dispersed cell towers that characterize LTE networks and its predecessors. 5G communications require a multi Gb/s data transmission in its small cells. For this purpose millimeter wave (mm-wave) radio frequency signals are the best solutions to be utilized for high speed data transmission. Photonic based solutions can generate such signals using REE doped lasers (Er, Th, Yb). (Alavi et al. 2016)

21.3.2.10 Other applications

"*Minor amounts of REE are applied in other market sectors and products, such as microwave crystals and garnets, nuclear applications, carbon arc lights, textiles additives, medical applications, fertilisers, chemical compounds as reagents or paints drying agents, alloys for magnetic refrigeration, and other. In particular, Ce is largely the most used REE in other applications, followed by La and other minor amounts of Gd, Y, Pr, Nd and other REE.* (Machacek and Kalvig 2017: EURARE)

Table 152: Consumption of REE in miscellaneous sectors (Machacek and Kalvig 2017: EURARE)

Main area of application	Main RE products	Main uses
Microwave devices	Y, Gd, Nd, Ho, Tm, Er, Yb	Crystals and garnets for microwaves and laser: Y, Gd and Nd. followed by Ho, Tm, Er and Yb compounds as dopant agents. Yttrium-iron-garnet (YIG) used for microwaves and cell phones and laser. Gd-iron-garnet (GIG): Similar applications as above. Y- and Gd-based garnets: used as resonators in frequency meters, magnetic field measurement devices, tuneable transistors, and Gunn oscillators.
Nuclear applications	Gd, Sm, Eu, Dy, Er, Y	Neutron absorbers in nuclear reactors: Frequently used REE are: Gd, Sm, Eu and Dy. Control rods: Sm, Eu, Er and Gd. Shielding purposes and neutron absorbing coatings: Gd and Eu, while Y can be utilised in piping. Detection of radiation leaks: Gd.
Lighting applications	Ce, La, Eu, Pr, Yb	Industrial lighting and projectors: Several LREE-compounds (e.g. Ce, La, Eu, Pr and Yb) are mainly used in these fields, improves the lighting performance, in terms of e.g. quality and intensity. (Rare Earth Technology Alliance, 2014).
Medical applications	Ce, Nd, La, Eu	Drug formulations: e.g. Ce-oxalate in motion sickness drugs, Nd-isonicotinate to treat thrombosis), and in medical applications (e.g. La nitrate used as an antiseptic, Ce-141 used in biological and medical research). Living tissue research: Highly sensitive luminescence is provided by Eu. (Rare Earth Technology Alliance, 2014).
Fertilisers	La, Ce	Fertilizer for cottons and oil-plants in China: REE-oxides added to improve the overall plant growth. Superphosphate: REE compounds are added to calcium superphosphate, thus obtaining a REE-phosphate fertiliser (REPF).
Magnetic refrigeration	Gd, Nd, Tb, Er, La, Pr	Magnetic refrigeration technology: Gd-alloy used as a refrigerant surrounded by NdFeB magnets, which cause the heating and the cooling of the refrigerant itself by respectively increasing and decreasing the magnetic field generated by their movement. Alternative alloys are: e.g. Gd-Si-Ge alloy, Gd-Tb alloy, Gd-Er alloy, La alloys doped with Fe or Pr alloys doped with Ni.
Other applications	Ce, La, Nd, (Pm), Gd, Pr, Ho, Yb	Synthetic gemstones: A niche market for Y. Paint dries: Ce, La and Nd can be included in the formulation. Polymer colorant: Ce sulphide is used in polymer colorants in substitution of Cd compounds. Textiles: Mainly Ce and Pr, are used in textiles as dyes (e.g. Ce compounds), they are mainly used to give "protection" properties (water- or mildew-proof) to the fabric, as well as to face creasing effects or bleaching caused by sunlight; this application is restricted to China.

		Water treatment: Ce and La are also used in the formulation of products for water treatment of pools, spa, municipal and industrial wastewaters, aiming at removing e.g. phosphates.

21.3.3 Applications of individual REE

21.3.3.1 Cerium applications

The end-use of cerium products in the EU are presented in Figure 395 and relevant industry sectors are described using the NACE sector codes in Table 153.

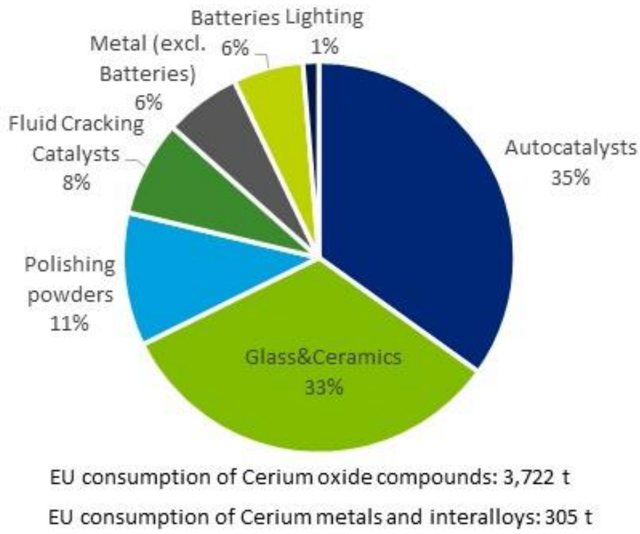


Figure 395: EU end-uses of cerium. Average 2016-2018 (Eurostat, 2019a; Guyonnet et al. 2015)

Table 153: Cerium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2019c).

Applications	2-digit NACE sectors	Value added of NACE 2 sector (millions €)	4-digit NACE sectors
Autocatalysts	C20 - Manufacture of chemicals and chemical products	105,514	C2029 - Manufacture of other chemical products n.e.c.
Glass& Ceramics	C23 - Manufacture of other non-metallic mineral products	57,255	C2310 - Manufacture of glass and glass products
Polishing powders	C26 - Manufacture of computer, electronic and optical products	65,703	C2670 - Manufacture of optical instruments and photographic equipment
Fluid Cracking Catalysts	C19 - Manufacture of coke and refined petroleum products	17,289	C1920 - Manufacture of refined petroleum products
Metal (excl. Batteries)	C24 - Manufacture of basic metals	55,426	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Batteries	C27 - Manufacture of electrical equipment	80,745	C2720 - Manufacture of batteries and accumulators
Lighting	C27 - Manufacture of electrical equipment	80,745	C2740 - Manufacture of electric lighting equipment

Cerium is used for a variety of applications, but the four main uses are polishing, metallurgy other than batteries, autocatalysts and glass (European Commission, 2017). Other uses for cerium include batteries, fluid cracking catalysts, other catalysts, phosphors, ceramics, fertiliser, water treatment, paints and coatings (European Commission, 2017).

In recent years, demand for cerium used in the glass polishing sector has declined. It is likely to increase in the automotive catalyst sector due to low prices, good availability and stricter regulation on transportation emissions ARAFURA (2016).

21.3.3.2 Dysprosium applications

The main and almost exclusive use of dysprosium is in permanent magnets NdFeB (Figure 396). Dysprosium is added to NdFeB magnets (2-11% w/w) to increase the Curie temperature, which means that it allows the use of those magnets at up to 200°C. The main finished products driving dysprosium consumption for magnets include new generations of wind turbines, industrial motors, etc. Relevant industry sectors are described using the NACE sector codes in Table 154.

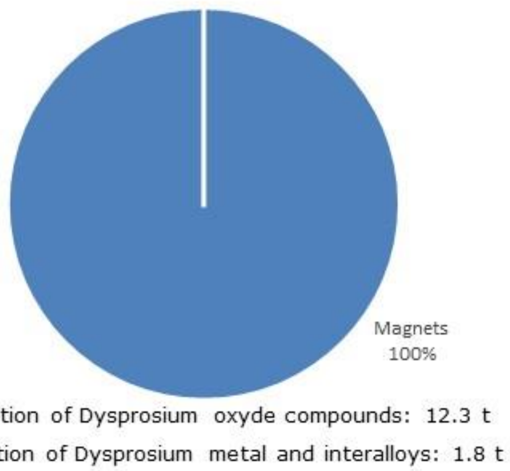


Figure 396: EU end-uses of dysprosium. Average 2016-2018 (Eurostat, 2019; Guyonnet et al. 2015)

Table 154: Dysprosium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2019c).

Applications	2-digit NACE sectors	Value added of sector (millions €)	4-digit NACE sectors
Magnets	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351	C2599 - Manufacture of other fabricated metal products not elsewhere classified

21.3.3.3 Erbium applications

The majority of erbium is used in glass for optical application (74%), although phosphors for lighting applications are also an important use (EC, 2017), see Figure 397. Other uses for erbium include the nuclear industry (neutron-absorbing control rods), and metallurgy (metallurgical additive, erbium-nickel alloy) (BRGM, 2015).

The principal optical uses involve its pink-colored Er^{3+} ions, which have optical fluorescent properties particularly useful in certain laser applications (BRGM, 2015):

- Colorant for glass: erbium oxide has a pink color, and is sometimes used as a colorant for glass, cubic zirconia and porcelain.
- Erbium-doped optical silica-glass fibers are the active element in erbium-doped fiber amplifiers (EDFAs), which are widely used in optical communications.
- Co-doping of optical fiber with Er and Yb is used in high-power Er/Yb fiber lasers or
- Medical applications (i.e. dermatology, dentistry) with erbium-doped lasers Er:YAG

Information about the breakdown of the European market by application was not available at the time of writing.

Relevant industry sectors are described using the NACE sector codes in Table 155.

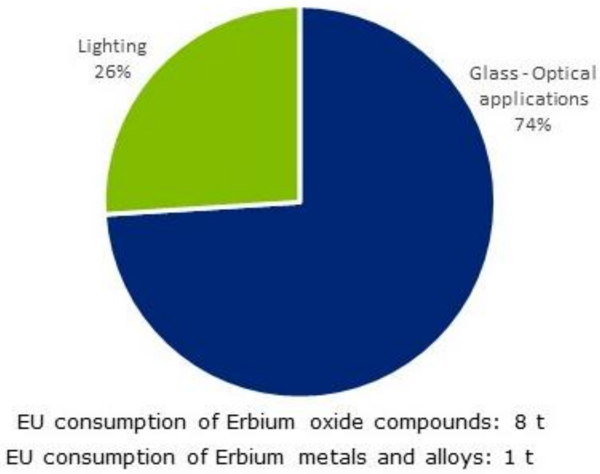


Figure 397: EU end-uses of erbium. Average 2016-2018 (Eurostat, 2019; Guyonnet et al. 2015)

Table 155: Erbium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2019c).

Applications	2-digit NACE sector	Value added of sector (millions €)	4-digit NACE sectors
Optical applications	C23 - Manufacture of other non-metallic mineral products	57,255	C2310 - Manufacture and processing of other glass, including technical glassware
Lighting	C27 - Manufacture of electrical equipment	80,745	C2740 - Manufacture of electric lighting equipment

21.3.3.4 Europium applications

Europium is used in the in the world and in EU almost exclusively in lighting applications (BRGM, 2015), see Figure 398. It represents 5% of the composition of phosphors used for lighting. Some other uses in nuclear and optic industries can be mentioned, as well as protection for fraud of Euro banknotes (BRGM, 2015).

Relevant industry sectors are described using the NACE sector codes in Table 156.

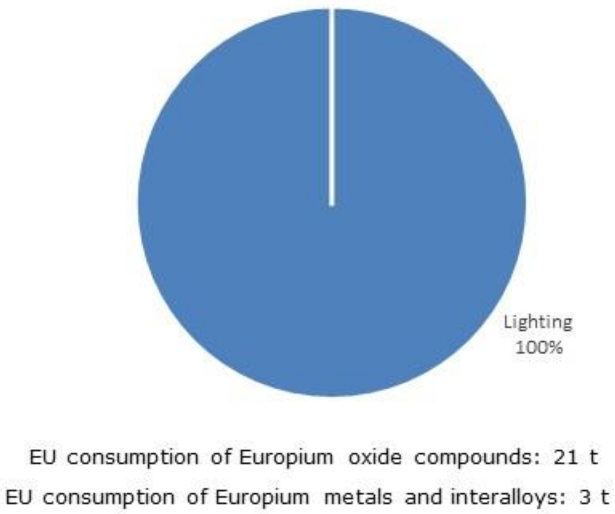


Figure 398: EU end-uses of europium. Average 2016-2018 (Eurostat, 2019; Guyonnet et al. 2015)

Table 156: Europium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2019c).

Applications	2-digit NACE sector	Value added of sector (millions €)	4-digit NACE sectors
Lighting	C27 - Manufacture of electrical equipment	80,745	C2740 - Manufacture of electric lighting equipment

21.3.3.5 Gadolinium applications

Gadolinium is mainly used for NdFeB permanent magnets, for lighting applications and for metallurgy (see Figure 399), relevant industry sectors are described using the NACE sector codes in Table 157.

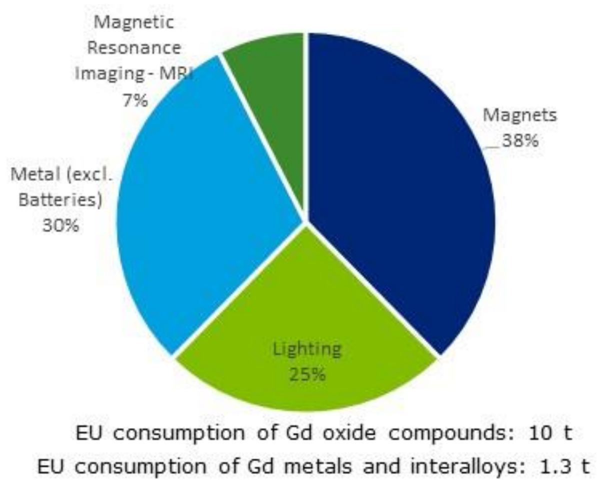


Figure 399: EU end-uses of gadolinium. Average 2016-2018 (Eurostat, 2019; Guyonnet et al. 2015)

The major applications for gadolinium can be described in more detail as follows:

- Gd is primarly used in NdFeB alloys (Kiggins, 2015) but also in SmCo alloys (Humphries, 2013) for temperature compensation and resistance to corrosion (BRGM, 2015).
- Gadolinium oxide is used as a luminophore and gives the green color in television tubes (BRGM, 2015).
- Gadolinium metal possesses unusual metallurgic properties, to the extent that as little as 1% gadolinium can significantly improve the workability and resistance to high temperature oxidation of iron, chromium, and related alloys. Gadolinium is used in metallurgical applications for improving the mechanical characteristics of alloyed steel, for desulphurisation, or for binding trace elements in stainless steel.
- Gd is used as a medical contrasting agent for MRIs (EC, 2017).
- Other uses of gadolinium include optics and nuclear industry. Indeed, gadolinium as a metal or salt has exceptionally high absorption of neutrons and therefore is used for shielding in neutron radiography and in nuclear reactors (EC, 2017).

Information about the breakdown of the European market by application was not available at the time of writing.

Table 157: Gadolinium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2019c).

Applications	2-digit NACE sector	Value added of sector (millions €)	4-digit NACE sectors
Magnets	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351	C2599 - Manufacture of other fabricated metal products not elsewhere classified
Lighting	C27 - Manufacture of electrical equipment	80,745	C2740 - Manufacture of electric lighting equipment
Metal (excl. Batteries)	C24 - Manufacture of basic metals	55,426	C2410 - Manufacture of basic iron and steel and of ferro-alloys
MRI	C21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations	80,180	C2100 - Manufacture of pharmaceutical preparations

21.3.3.6 Holmium, Lutetium, Ytterbium and Thulium applications

The use of holmium, thulium, ytterbium and lutetium in individual applications is too small to be estimated with accuracy. Their major uses are as follows:

- Holmium: pigments, magnets, lasers and nuclear.
- Thulium has no real commercial use; but glass, phosphors and fibre optics have potential.
- Ytterbium: fibre optics, lasers, photovoltaics, stress gauges.
- Lutetium: phosphors, PET detectors, glass.

Each one of these elements are used in niche applications mostly related to their optical properties (Laser dopants, fiber optics, radiography, etc.) – Figure 400.

Information about the breakdown of the European market by application was not available at the time of writing.

Relevant industry sectors are described using the NACE sector codes in Table 158.

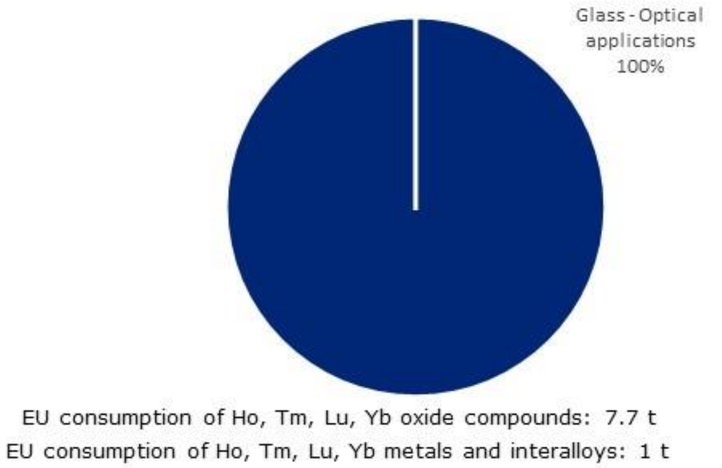


Figure 400: EU end-uses of Ho, Tm, Lu, Yb. Average 2016-2018 (Eurostat, 2019; Guyonnet et al. 2015)

Table 158: Ho, Lu, Tm, Yb applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2019c).

Applications	2-digit NACE sector	Value added of sector (millions €)	4-digit NACE sectors
Glass - Optical applications	C23 - Manufacture of other non-metallic mineral products	57,255	C2310 - Manufacture and processing of other glass, including technical glassware

21.3.3.7 Lanthanum applications

Lanthanum is used for a variety of applications; its three main uses are in FCCs, nickel-metal hydride batteries and glass & ceramics. Other uses for lanthanum include autocatalysts, polishing powders, lighting applications, metallurgical uses, fertiliser, algal control and cement (EC, 2017). Relevant industry sectors are described using the NACE sector codes in and Table 159.

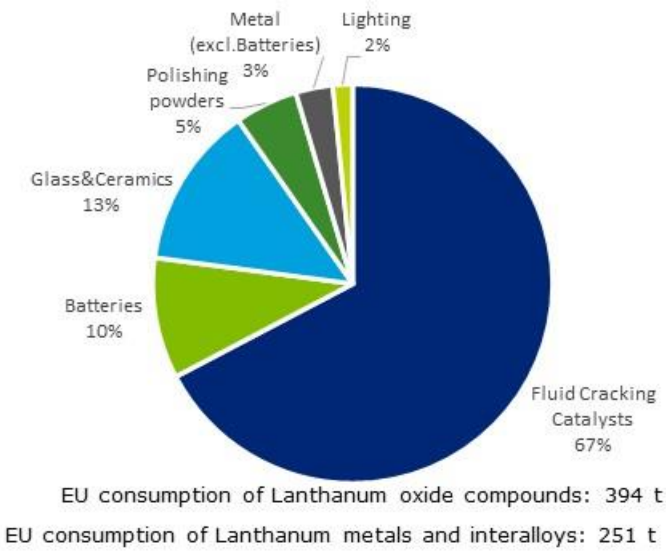


Figure 401: EU end-uses of La. Average 2016-2018 (Eurostat, 2019; Guyonnet et al. 2015)

Table 159: La applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2019c).

Applications	2-digit NACE sector	Value added of sector (M€)	4-digit NACE sectors
Fluid Cracking Catalysts	C19 - Manufacture of coke and refined petroleum products	17,289	C2029 - Manufacture of other chemical products not elsewhere classified
Batteries	C27 - Manufacture of electrical equipment	80,745	C2720 - Manufacture of batteries and accumulators
Glass& Ceramics	C23 - Manufacture of other non-metallic mineral products	57,255	C2331 - Manufacture of ceramic tiles and flags
Polishing powders	C26 - Manufacture of computer, electronic and optical products	65,703	C2670 - Manufacture of optical instruments and photographic equipment
Metal (excl. Batteries)	C24 - Manufacture of basic metals	55,426	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Lighting	C27 - Manufacture of electrical equipment	80,745	C2740 - Manufacture of electric lighting equipment

21.3.3.8 Neodymium applications

The main application of neodymium in the EU is for NdFeB permanent magnets (37% of total use). The main finished products driving neodymium consumption for magnets include industrial motors, hard drives, automobiles and wind turbines.

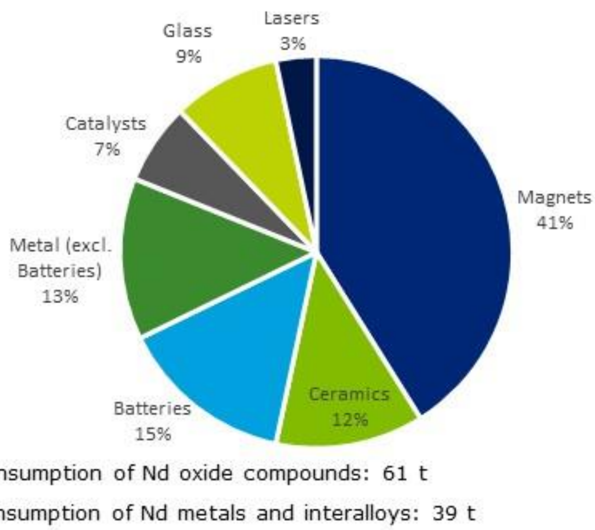


Figure 402: EU end-uses of Nedoymium. Average 2016-2018 (Eurostat, 2019; Guyonnet et al. 2015)

Neodymium is also used in NiMH batteries (Umicore, 2016), as a part of the batteries' cathode (13% of total use) although this use is declining (Higgins, 2016). In ceramics applications (11% of total use), neodymium is mainly used as a blue pigment in ceramic tiles (Yoldjian, 1985). In electronic ceramics, it is used as an insulator. Other applications include the manufacture of metals, catalysts, glass and lasers (BRGM, 2015).

Relevant industry sectors are described using the NACE sector codes in Table 160.

Table 160: Neodymium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2019c).

Applications	2-digit NACE sector	Value added of sector (M€)	4-digit NACE sectors
Magnets	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351	C2599 - Manufacture of other fabricated metal products not elsewhere classified
Ceramics	C23 - Manufacture of other non-metallic mineral products	57,255	C2331 - Manufacture of ceramic tiles and flags
Batteries	C27 - Manufacture of electrical equipment	80,745	C2720 - Manufacture of batteries and accumulators
Metal (excl. batteries)	C24 - Manufacture of basic metals	55,426	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Catalysts	C20 - Manufacture of chemicals and chemical products	105,514	C2029 - Manufacture of other chemical products not elsewhere classified
Glass	C23 - Manufacture of other non-metallic mineral products	57,255	C2310 - Manufacture of glass and glass products
Lasers	C26 - Manufacture of computer, electronic and optical products	65,703	C2670 - Manufacture of optical instruments and photographic equipment

21.3.3.9 Praseodymium applications

Praseodymium is used in the EU in many applications. Most praseodymium is used in magnet applications in NdFeB magnets (27%), although ceramics, batteries and metallurgical uses other than batteries are also important applications. Other uses for praseodymium include catalysts, polishing and fiber amplifiers. In ceramics applications, praseodymium is mainly used as a yellow pigment in ceramic tiles (Yoldjian, 1985).

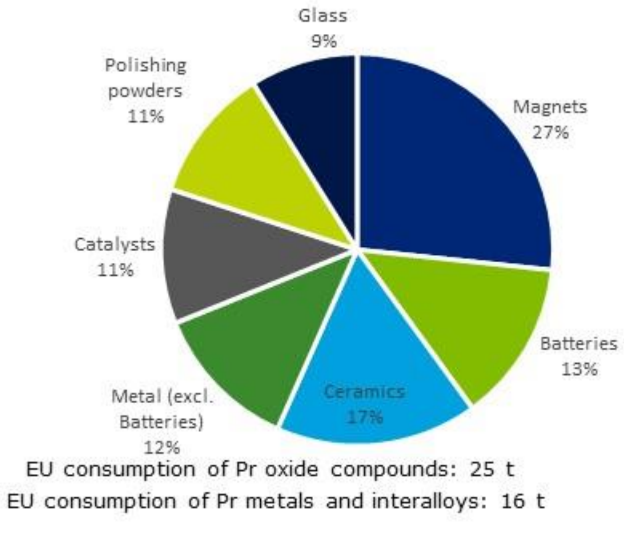


Figure 403: EU end-uses of Praseodymium. Average 2016-2018 (Eurostat, 2019; Guyonnet et al. 2015)

Table 161: Praseodymium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2019c).

Applications	2-digit NACE sector	Value added of sector (M €)	4-digit NACE sectors
Magnets	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351	C2599 - Manufacture of other fabricated metal products not elsewhere classified
Ceramics	C23 - Manufacture of other non-metallic mineral products	57,255	C2331 - Manufacture of ceramic tiles and flags
Batteries	C27 - Manufacture of electrical equipment	80,745	C2720 - Manufacture of batteries and accumulators
Metal (excl. batteries)	C24 - Manufacture of basic metals	55,426	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Catalysts	C20 - Manufacture of chemicals and chemical products	105,514	C2029 - Manufacture of other chemical products not elsewhere classified
Glass	C23 - Manufacture of other non-metallic mineral products	57,255	C2310 - Manufacture of glass and glass products
Polishing powders	C26 - Manufacture of computer, electronic and optical products	65,703	C2670 - Manufacture of optical instruments and photographic equipment

21.3.3.10 Samarium applications

The main application for samarium is SmCo permanent magnets. SmCo magnets have high permanent magnetization, which is about 10,000 times that of iron and is second only to that of neodymium magnets. However, samarium-based magnets have higher resistance to demagnetization, as they are stable to temperatures above 700 °C (cf. 300–400 °C for neodymium magnets) (BRGM, 2015). These magnets are found in small motors, headphones, and high-end magnetic pickups for guitars and related musical instruments.

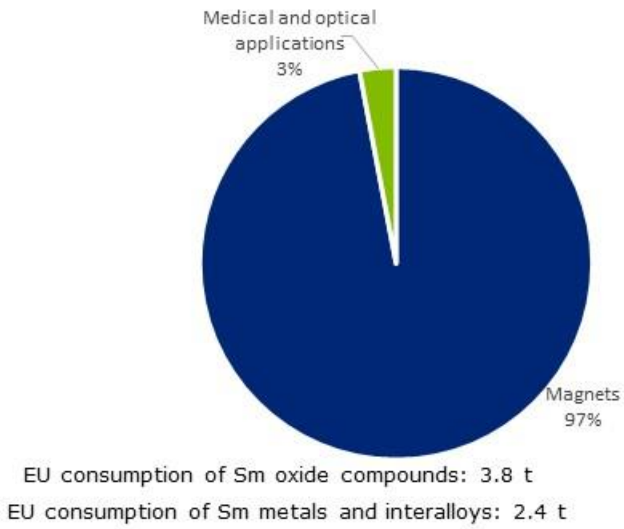


Figure 404: EU end-uses of Samarium. Average 2016-2018 (Eurostat, 2019; Guyonnet et al. 2015)

Other uses of Sm are niche applications mostly related to its optical properties (laser dopant, radiography, etc.) and nuclear industry (EC, 2017).

Relevant industry sectors are described using the NACE sector codes in Table 162.

Table 162: Samarium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2019).

Applications	2-digit NACE sector	Value added of sector (M€)	4-digit NACE sectors
Magnets	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351	C2599 - Manufacture of other fabricated metal products not elsewhere classified
Medical and optical applications	C26 - Manufacture of computer, electronic and optical products	65,703	C2670 - Manufacture of optical instruments and photographic equipment

21.3.3.11 Terbium applications

Terbium is used in the EU for NdFeB permanent magnets (BRGM, 2015; CRS, 2013) and for lighting applications (BRGM, 2015):

- Like dysprosium, terbium is used in NdFeB magnets to increase the Curie temperature and thus enable the use of those magnets at elevated temperatures. However, Dy is favoured over Tb because it is cheaper (BRGM, 2015).
- Terbium oxide gives the yellow or green color in neons and fluo-compact lamps. It represents 4% of the composition of luminophores used for lighting (BRGM, 2015).

Relevant industry sectors are described using the NACE sector codes in Table 163.

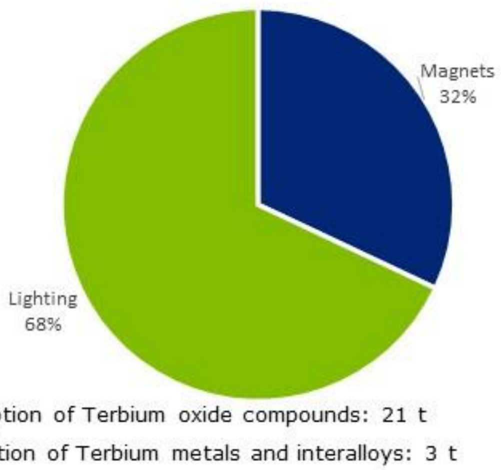


Figure 405: EU end-uses of Terbium. Average 2016-2018 (Eurostat, 2019a; Guyonnet et al. 2015)

Table 163: Terbium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2019c).

Applications	2-digit NACE sector	Value added of sector (millions €)	4-digit NACE sectors
Magnets	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351	C2599 - Manufacture of other fabricated metal products not elsewhere classified
Lighting	C27 - Manufacture of electrical equipment	80,745	C2740 - Manufacture of electric lighting equipment

21.3.3.12 Yttrium applications

Yttrium is used in the EU for lighting and ceramics applications mainly; other uses include the manufacture of glass and alloys:

- Y is the most used REE for the production of luminophores (70%-80%). Y-compounds are doped with other REE (Eu and Ce mainly) to produce luminophores. Y is used in both fluorescent and LED lamps.
- The major use of Y in ceramics is yttria in Ytrria-Stabilised-Zirconia (YSZ) for refractory uses. Y is also used in electronics for the manufacture of oxygen sensors in vehicles.
- Yttrium oxide is added to the glass used to make camera lenses heat and shock resistant.
- Yttrium is also used as an additive in alloys. It increases the strength of aluminum and magnesium alloys.

Relevant industry sectors are described using the NACE sector codes in Figure 406.

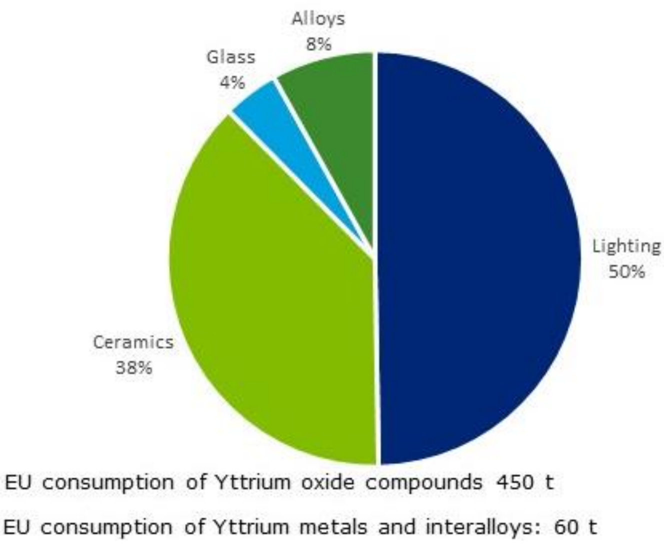


Figure 406: EU end-uses of Yttrium. Average 2016-2018 (Eurostat, 2019a; Guyonnet et al. 2015)

Table 164: Yttrium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2019c).

Applications	2-digit NACE sector	Value added of sector (M€)	4-digit NACE sectors
Lighting	C27 - Manufacture of electrical equipment	80,745	C2740 - Manufacture of electric lighting equipment
Ceramics	C23 - Manufacture of other non-metallic mineral products	57,255	C2331 - Manufacture of ceramic tiles and flags
Alloys	C24 - Manufacture of basic metals	55,426	C2410 - Manufacture of basic iron and steel and of ferro-alloys
Glass	C23 - Manufacture of other non-metallic mineral products	57,255	C2310 - Manufacture of glass and glass products

21.3.4Substitution

In most of their applications, REE are not substitutable without losses of performance. However, for economic reasons, many R&D strategies have focused on reducing the amount of REE used in their different applications. These particular aspects are summarised in Table 165. The chapter contains substantial input from Machacek and Kalvig (2017: EURARE) providing more datails about individual applications.

Table 165: Individual Substitution Indexes

REE	LREE					HREE						
	Ce	La	Nd	Pr	Sm	Dy	Er	Eu	Gd	Ho, Tm, Lu, Yb	Tb	Y
[SI(SR)]	0.99	0.97	0.98	0.97	0.98	1.00	0.99	0.95	0.99	1.00	0.95	0.99
[SI(EI)]	0.95	0.89	0.93	0.93	0.98	0.95	0.96	0.79	0.92	1.00	0.79	0.98

Table 166: Summary of REE substitutes

Use	Substitutes			
	General comment	**REE**	**Substitution elements**	**Alternative technologies**
Fluid cracking catalysts	Not easily substitutable	La	Ce	-
		Ce	La	
Autocatalysts	Some dematerialisation is possible	Ce	La, Nd, Pr	-
Other catalysts	Not easily substitutable	-	-	-
Glass	Not easily substitutable	Er, Lu, Ce …	-	-
Batteries	There is a growing shift to Li-ion batteries in the major markets for NiMH batteries	Ce	-	Li-ion batteries. NiCd or lead-acid batteries are also an alternative
		Pr	-	
		La	Co	
		Nd	Co	
Metallurgy	Some dematerialisation is possible	Ce	Ca, La, Nd, Gd	-
		Gd	Pr	
		Pr	Gd	-
		La	Ce, Nd, Gd, Ca	-
Polishing	Some dematerialisation is possible	Ce	La, Zr, Pr, FeO, Al_2O_3	-
		La	Ce, FeO, Al_2O_3	-
Phosphors (lighting and displays)	The falling cost of LEDs means that there is now a viable competitor for fluorescent lamps for low-energy lighting	Er	Y, Gd	LED, that contain 1000 times less phosphor than fluorescent lamps
		Gd	Eu, Y, Tb	
		Tb	Eu, Y	
Ceramics	Not easily substitutable in either construction or electronics	Ce, La	-	-
Magnets	Several options exist to reduce or replace the rare earth content of magnets, either by material substitution or by using alternative magnet technology	Dy	Tb, Gd	wind turbine exempt of Dy using a cooling system to reduce the temperature of the use
		Gd	Dy, Tb	-
		Nd	Pr, Ce, La	ferrite or SmCo magnets
		Pr	Nd	ferrite or SmCo magnets
		Sm	-	NdFeB, ferrite or AlNiCo magnets
		Tb	Dy, Ga	-
Others	Some of the minor markets have substitutes.			
	YAG-lasers (as dopants, but with a different wavelength)	Nd, Y	- not replacable for the same Wave length	

21.3.4.1 Permanent magnets

Permanent magnets are key components of electric motors and power generators (wind turbines). The widely used high performance REE magnets are NdFeB, where neodymium improves magnet's strength (maximum energy product (BH)max) and allows to make magnets smaller compared to other types. Dysprosium and finer grain size are improving thermal coercivity (stability) of NdFeB magnets at higher temperatures.

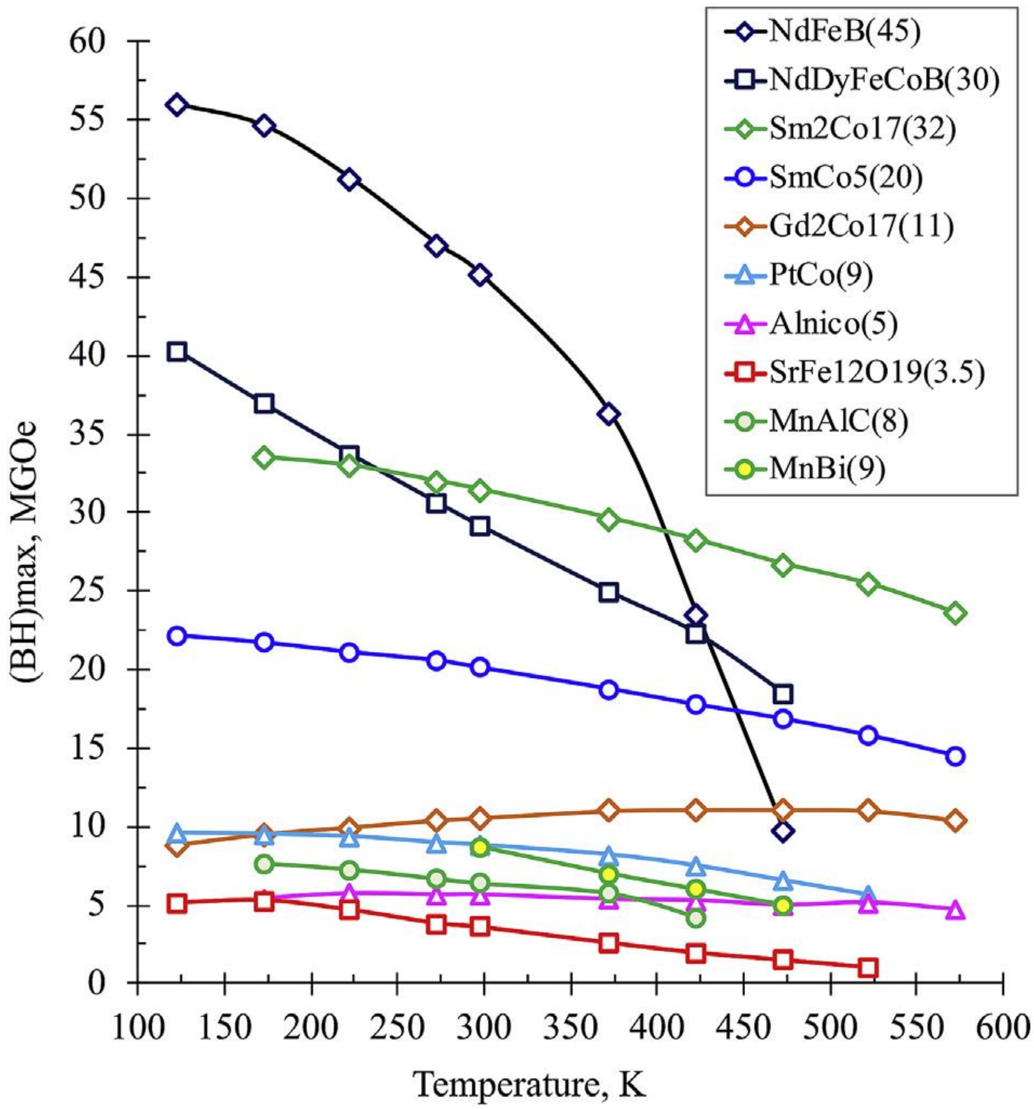


Figure 407: Magnets strength (BH)max of most commercial permanent magnets changing with temperature. The value in parentheses in (BH)max at 298 K (25ºC). (Cui et al. 2018)

A long-term approach to reducing use of REE is to develop non-RE magnets that can fill in this gap between hard ferrite and REE magnets.

Table 167: Comparison of motor magnet price and maximum energy product (BH)max in 2016 and 2022 (estimated). (Cui et al. 2018)

	$(BH)_{max}$, MGOe		Price, $/kg	
	2016	2022	2016	2022
NdFeBDy(NH42SH)	40–42	42	$60	$120
SmCo (SC-3215)	31–32	34	$128	$210
AlNiCo-9	9	11	$71	$80
Ferrite (Sr-8B)	3.8	3.8	$4	$4

Substitution strategies for NdFeB permanent magnets in electric motors and power generators aim at reducing the use of Nd and Dy, using other REE, developing magnets without REE, or developing motors without REE permanent magnets.

Improving resource efficiency

REE resource efficiency in permanent magnets reducing supply risk and costs, whilst maintaining or increasing their performance, has been a strong driver of industry R&D over the last decade.

Two main approaches are used to reduce the use of Nd and Dy in NdFeB magnets, by diffusion of Dy into the magnet material in place of direct alloying, and reducing the grain size in the magnets to nanoscale (Kozawa 2010). An example is Hitachi Metals (Gehm 2013) who have developed magnets which reduce Dy content in NdFeB magnets, without a reduction in their high temperature coercivity.

Substitution by other REE

Up to 25% of Nd can be substituted by Pr without significantly affecting magnetic properties of materials (Binnemans, 2014b).

Substitution of Nd and Dy by other REE (Ce, Gd) in NdFeB magnets leads to reduction of the magnetic properties.

SmCo magnets could replace NdFeB magnets for selected applications, but SmCo magnets are twice as expensive, and have around 50-75% magnetic strength of NdFeB magnets.

Substitution by REE-free magnets

In the last years, great progress has also been made toward improving the microstructure and physical properties of non-REE magnets. They are not as strong as NdFeB magnets, but some of them are much cheaper and contain abundant elements. The general goal for the development of non-REE magnets is to fill in the gap between the most cost-effective, but low performing hard ferrite magnet, and the most expensive, but high performing REE magnets. Several new candidate materials systems were investigated, including Mn based, high magnetocrystalline anisotropy alloys (MnBi and MnAl compounds), spinodally decomposing alloys (Alnico), high-coercivity tetrataenite L10 phase (FeNi and FeCo), and nitride systems (iron nitride $Fe_{16}N_2$) or carbid sytems (Co_2C/Co_3C). However it is not clear how practical or close to market these materials are and it can be argued that commercialisation is likely to take several years, even once significant improvements have been achieved.

Table 168: The REE substitution in the permanent magnet sector (Cui et al. 2018; Machacek and Kalvig 2017: EURARE)

Existing solutions	Challenges and comparison with NdFeB magnets
Ferrite magnets could substitute NdFeB magnets for selected applications, such as in wind turbines.	Ferrite magnets are more than 10 times cheaper, but NdFeB magnets are 10 times stronger
AlNiCo magnets (developed first in 1931) could substitute NdFeB magnets for selected applications where high temperatures and mechanical properties are required.	AlNiCo-9 magnets are similarly expensive, but NdFeB magnets are 4 times stronger. However, magnets' remarkable temperature stability (even at 500°C) and good mechanical properties earned its small market share (5%). Cobalt, the most expensive component with high supply risk, is needed for magnetisation and coercivity.
MnAl alloys (stabilised with C, Ga, Cu, Fe, Ni, Co, Cr, Ti, Mo, B or Zn)	MnAl alloys have good resistance to corrosion and low density, raw materials are abundant; but NdFeB magnets are 5 times stronger, and the metallurgy and magnetism of the MnAl are very complex.
MnBi alloys	MnBi has low decomposition temperature of 535 K (262°C) which makes the bulk magnet production difficult. NdFeB magnets are 5 times stronger.
Tetrataenite $L1_0$ FeNi found in a meteorite in 2010	$L1_0$-FeNi is one of the few non-REE materials that has the potential to reach the strength of REE permanent magnets. It is intensively studied, but it is very challenging to reproduce the lattice structure with alternating monatomic layers of Fe and Ni formed over billion years in meteorites. Main issues are purity of the feedstock powder and thermal stability of the desired phase during bulk magnet fabrication process. Best approaches achieved only 19% of the $L1_0$-FeNi phase.
Iron Nitride ($Fe_{16}N_2$) alloy discovered in 1950's, once commercially available as permanent magnets, could substitute NdFeB magnets in temperatures up to 355K (82 °C).	Iron Nitride ($Fe_{16}N_2$) magnets could theoretically be three times stronger than NdFeB magnets enabling size and weight reduction in motors without compromising power or torque. However, they are difficult to produce, they decompose quickly above 300°C, coercivity needs to be improved, they will need the same corrosion protection as raw iron. US Niron Magnetics (2020) company is developing by arc melting, melt spinning, and nitriding the world's first commercial, bulk Iron Nitride ($Fe_{16}N_2$) permanent magnets, owning 17 granted and 35 pending patents. (Niron Magnetics, 2020).
$HfCo_7$ and Zr_2Co_{11} compounds known since 1970's can have potential uses in the form of thin films for microelectromechanical systems (MEMS), data storage, and spintronics applications.	$HfCo_7$ and Zr_2Co_{11} nanoparticle films reach 30-40% magnetic strength of NdFeB magnets, but stability and control of phase purity of these compounds have been always a challenge. Higher material cost of Co and Hf and high supply risk is an important issue for using Hf-Co, Zr-Co as bulk magnets.
Carbides	Co3C and Co2C

Substitution by technology change

Next to materials substitution, other REE-free motor technologies could represent viable option to REE based motors. Producers are re-designing machines in order to make them compatible with ferrite magnets (servo motors in cars and motors in industrial applications; ERECON 2015).

There are many alternatives for permanent magnet synchronous generators (PMSG) in wind turbines that require less or no REE: doubly-fed induction generator (DFIG), electrically excited synchronous generator (EESG), squirrel-cage induction generators linked to a full converter, PMSG substitution with high-temperature superconductors (HTS; Pavel et al. 2016a).

Permanent magnets are widely used in electric vehicles in highly efficient PM synchronous-traction motor (PSM). There are some alternative electric motors: Tesla S uses an asynchronous motor (ASM), the Renault Zoe has an electrically exited synchronous motor (EESM). Another substitute for PSM are: ASM with high rpm, PMS with low-cost magnets, hybrid motor, the transversal flux motor (TFM) and the switched reluctance motor (SRM, still in research phase; Pavel et al. 2016a).

An EU project ReFreeDrive[233] also aims at developing new electric drives based on free of rare earth technologies, namely induction machines and synchronous reluctance machines. In order to develop and integrate the new powertrains for a final in-vehicle validation for two use cases (75kW, medium power range, and 200kW high power range).Another alternative technology for traction motors is switched reluctance motor.

Table 169: Comparison of electric motor technologies which reduce or eliminate rare earth magnets. (Widmer et al. 2015)

Motor technology	**Reduced NdFeB magnet**	**Ferrite permanent magnet**	**Copper rotor induction**	**Wound rotor synchronous**	**Switched reluctance**
Peak power	80 kW	80 kW	50 kW	50 kW	75 kW
Peak efficiency	98%	96%	96%	96%	97%
Active material cost	$223	$154	$144	$144	$118
Active material cost per kW	$2.78/kW	$1.93/kW	$2.88/kW	£2.88/kW	£1.57/kW
Torque density	15 Nm/kg	11 Nm/kg	10 Nm/kg	10 Nm/kg	15 Nm/kg

21.3.4.2 Batteries

"Lithium-ion (Li-ion) batteries are increasingly replacing NiMH batteries in computing, communication and consumer products (e.g. mobile phones and laptops), due to their easier manufacture in special shapes: indeed, electronics covers about 50% of the global market associated to lithium-ion batteries (Allied Market Research, 2016).

Although the manufacturing costs of Li-ion are still higher than the ones associated to NiMH batteries, Li-ion batteries are partially replacing NiMH batteries also in PHEVs and EVs, mainly because of their higher energy density and longer lifespan. Indeed, such types of electric vehicles can be charged by plugging them in a grid-provided electricity system

[233] http://www.refreedrive.eu

and thus require batteries with higher energy density in order to guarantee a range as wide as possible between charging stations. The battery for HEVs are charged through the gasoline combustion engine, and for this purpose the high- power density NiMH batteries are more suited, and therefor still represent the most used batteries in HEVs, although in 2013 lithium-ion batteries accounted for about 20% of all batteries used in HEVs (CEC, 2015).

However, NiMH batteries maintain a relevant role in large-size, stationary applications in which power-to-weight is less important (e.g. back-up units), as well as in high-temperature applications where Li-ion batteries are unsafe. China currently leads the production of small-size NiMH batteries, while the large-size ones are mainly manufactured in Japan." (Machacek and Kalvig 2017: EURARE)

21.3.4.3 Catalysts

"La is crucial for FCC catalysts because it provides thermal stability and selectivity, and substitutes for La in FCC catalysts are known (Öko Institut, 2011). The only alternative can be considered the use of fluid cracking catalysts based on zeolites without REE, but this leads to products with poor, yet still acceptable, performance (Binnemans et al. 2013a).

In automotive catalysts REE (mostly cerium) are responsible for enhanced thermal stability and emission reduction. Currently no substitution materials are known for the REE used for automotive catalysts (Öko Institut, 2011)." (Machacek and Kalvig 2017: EURARE)

21.3.4.4 Polishing

"The price spike in 2011 boosted the industrial research both for improved technical solutions enabling the reduction of Ce use, as well as for alternative materials such as zirconia (especially for lower quality products). However, as price decreased again, these efforts to find substitutes were put on hold and the traditional use of $CeO2$ were maintained." (Machacek and Kalvig 2017: EURARE)

21.3.4.5 Glass

"Research activities focusing substitution and reduction of REE have been performed only for the past five years. In particular, Chinese industry is pursuing improvements in La-based optical glass, considering the foreseen future growth in demand for optical glass associated to the increasingly diffusion of smartphones, tablets and other electronic displays. The very specific role covered by REE-based additives used in glass manufacturing hinders the potential substitution of such compounds with other materials for most of the applications within this sector". (Machacek and Kalvig 2017: EURARE)

21.3.4.6 Phosphors

"The research of alternative materials to substitute REE in phosphors applications have been mainly boosted by price spike in 2011. Despite some improvements in efficiency have been reached in lighting applications, thus enabling to partially reduce REE consumption, the identification of substitutes for REE is very hard, essentially due to the high purity required for phosphors." (Machacek and Kalvig 2017: EURARE)

21.4 Supply

21.4.1 Global supply

The global mine production is estimated at 170,000t of rare-earth-oxide equivalent (REO[234]) in 2018 (Zion Markey Research 2019). According to China's Ministry of Commerce, production of REO in China was estimated to be at least 180,000 tonnes based on magnet material production.

Before the 1990s, less than 10% of total REE production were separated REE, in 2011 it was already 60% (Kingsnorth, 2012). Now, production of lanthanum and cerium oxides accounts for about 70%, praseodymium and neodymium oxides for around 20%, and other elements account for around 10%.

China provides around 80-90% of the world production of the whole range and purity of REE and their compounds, including the official production quota of 132,000 tonnes for 2019 and undocumented production.

In recent years, China's share of global rare earth mine production has fallen slightly as a handful of new rare earth mines have come on stream outside China. However, China's has continuously expanded share of downstream value-adding production of oxides, metals, alloys and magnets, where profit margins are greater and activities are environmentally cleaner. (Adamas Intelligence, 2019)

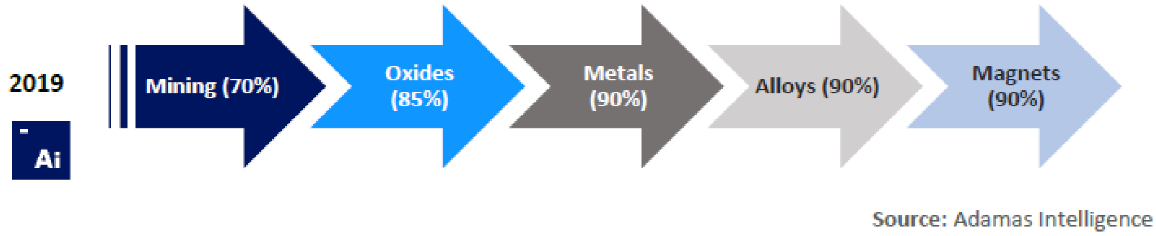


Figure 408: Share of Chinese production in rare earths value chain (Adamas Intelligence, 2019)

Until 2000, China exported mainly primarily mixed REE mineral concentrates, REE-containing components such as magnets, phosphors and polishing powders. Since the turn of the century, REE-exports by China increasingly included advanced REE-containing final consumer products such as batteries, mobile phones and LCDs. (Kingsnorth, 2012)

Lynas is the second largest global REE producer and the major producer outside China with an integrated production from mining to separated LREE and mixed HREE products (Neodymium and Praseodymium (NdPr) used in magnets, Lanthanum (La), Cerium (Ce) and Mixed Heavy Rare Earths (SEG)). Their assets include REE mines in Mt Weld, Western Australia and a concentration Plant– commissioned in 2011 and located 1.5km from the mine site; and separation and processing facility located in the Gebeng Industrial Estate near the Port of Kuantan in Malaysia producing since 2012. Other producers are small and offer limited range and quality of REE products.

[234] Average conversion factor of REE metal vs. Rare Earth Oxides (REO) is estimated at 0.85 (Guyonnet, et al. 2015).

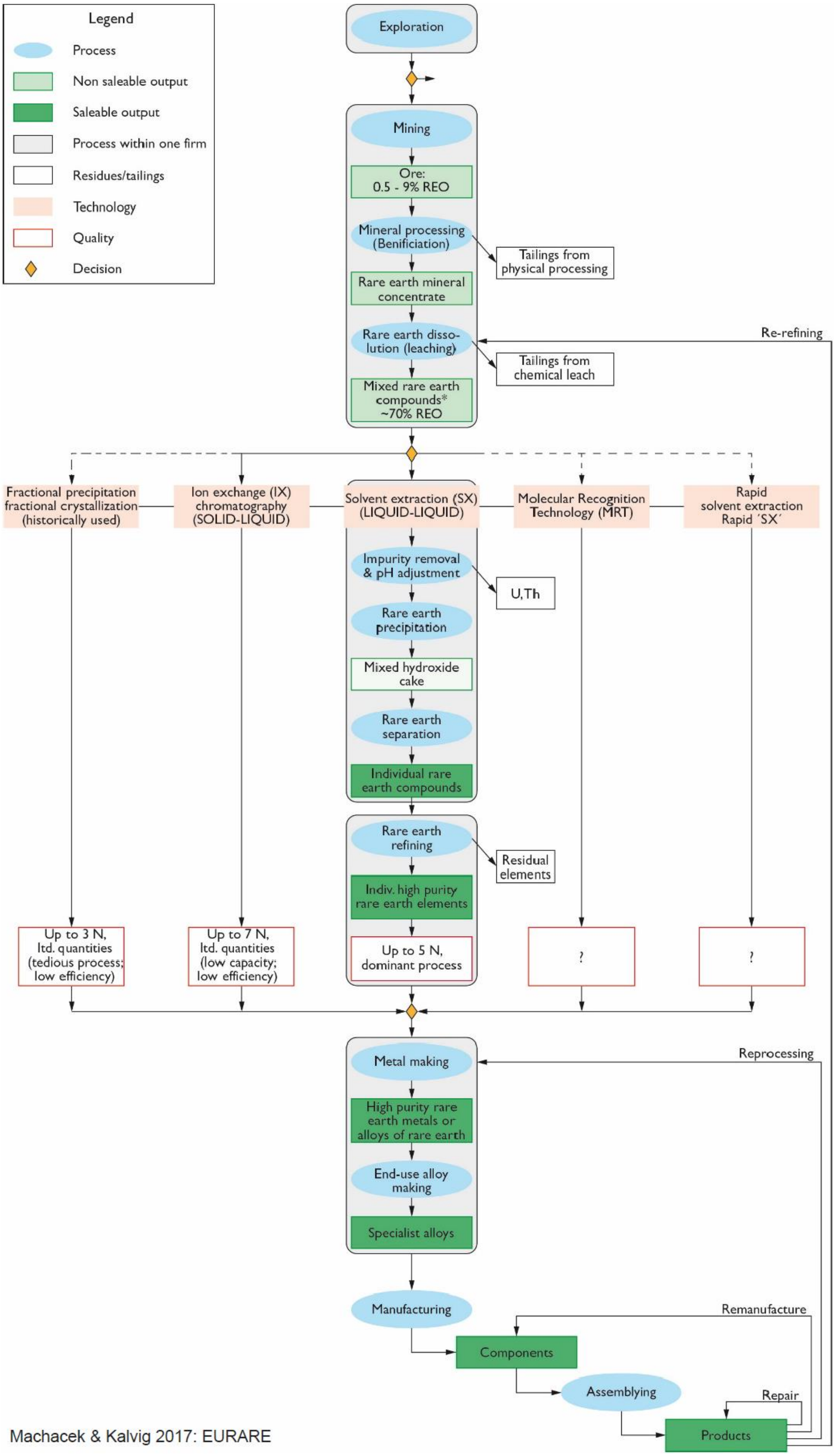


Figure 409: Generic material supply chain for REE. Source: MiMa-GEUS, 2016 based on Gupta and Krishnamurty, 2005 (Machacek and Kalvig 2017: EURARE)

21.4.2EU supply chain

EU imports 100% of REE. In the EU, a few players are found at different stages of the REE value chain. Some have the ability to separate individual REOs (in Estonia and France) and manufacture REE-based products for various industries (phosphors, catalysts, polishing powders, etc.). There are also alloys makers and magnets manufacturers (in Germany, the UK, Slovenia) operating from imported processed materials. The ASTER project specifies 6,000 REE metals and compounds produced in EU (separation products), by Estonia and France (Guyonnet, 2015). There is no critical mass of REE transformation and manufacturing in the EU; although critical in many industries, a large proportion of REE consumption comes from finished products imports to the EU (magnets, alloys, hard drives, laptops, electric or hybrid vehicles, etc.).

However, a few players are found at different stages of the REE value chain for the elements described hereunder.

21.4.2.1 Cerium

EU consumed in average around 3700 tonnes per year of cerium compounds (oxide content) and 305 tonnes of cerium metals and interalloys between 2016-2018 for wide range of applications (autocatalysts, glass and ceramics, polishing powders, fluid cracking catalyst, metals, batteries and lighting). According to statistics EU imported 5,241 tonnes of cerium compounds and 522 t of cerium metals and interalloys, while exports around 1500 tonnes and 217 tonnes respectively between 2016-2018.

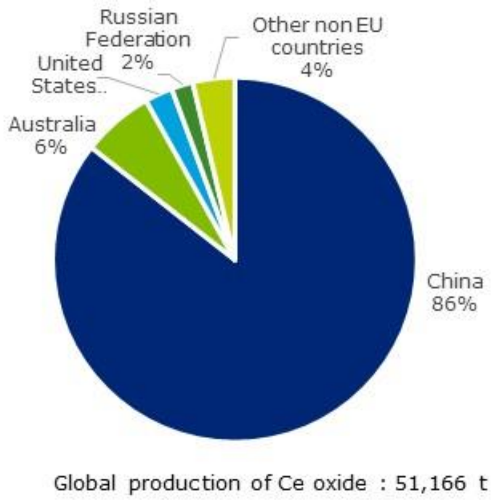


Figure 410: Global production of Cerium oxide, average 2012-2016 (WMD, 2019)

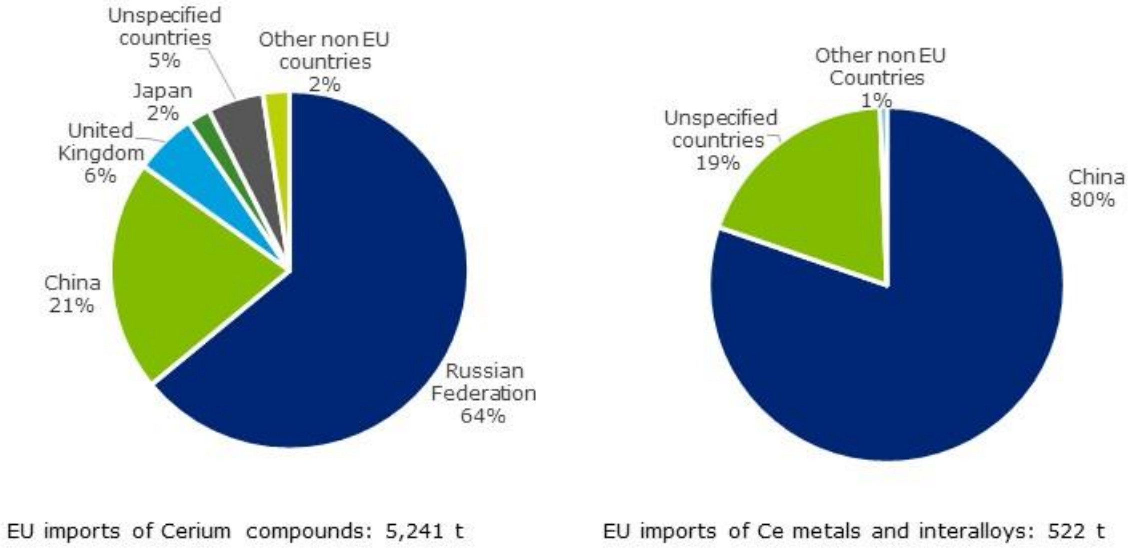


Figure 411: EU import of Cerium compounds (oxide content) and Cerium metals and interalloys (Eurostat, 2019a)

Two companies have the ability to separate individual REOs (in Estonia and France) and manufacture REE-based products for various industries. In particular, the EU is likely to use more cerium for catalysts uses in the petroleum industry than in the rest of the world (BRGM, 2015).

21.4.2.2 Dysprosium

EU consumed in average around 12 tonnes per year of dysprosium compounds (oxide content) and 2 tonnes of dysprosium metals and interalloys between 2016-2018 and used in the magnets. According to statistics EU imported around 15 tonnes of dysprosium compounds and 2.5 tonnes of dysprosium metals and interalloys, while exports around 3 tonnes and 0.7 tonnes respectively between 2016-2018.

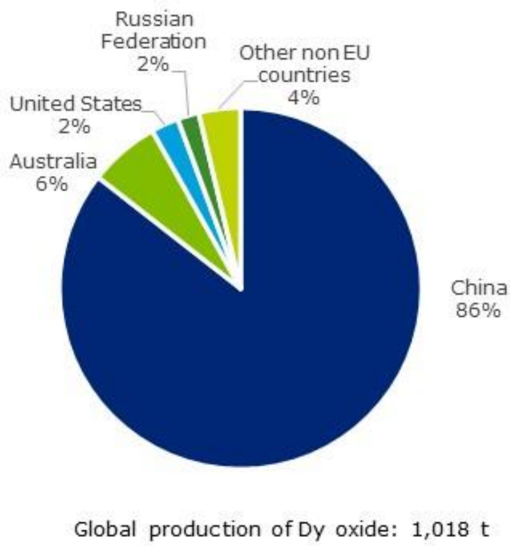


Figure 412: Global production of Dysprosium oxide, average 2012-2016 (WMD, 2019)

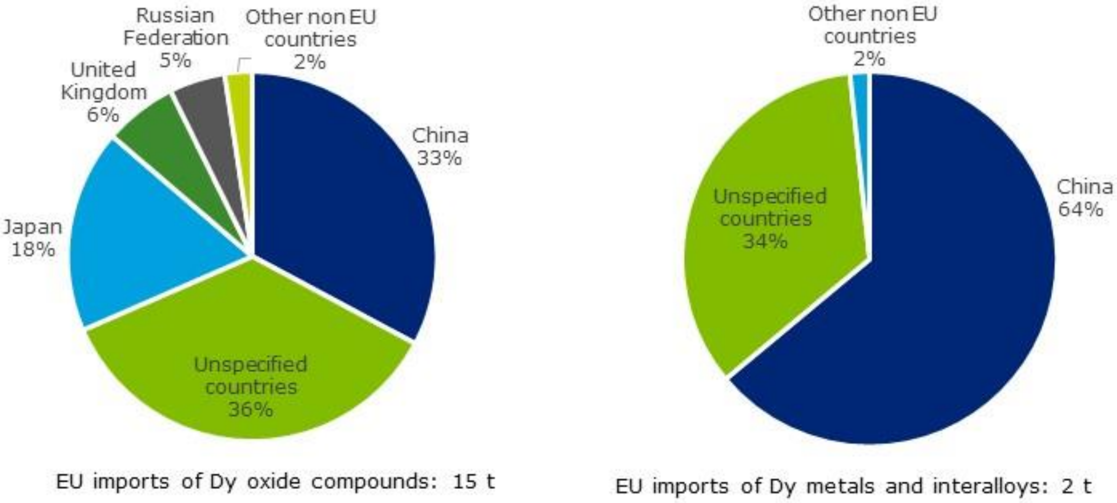


Figure 413: EU import of dysprosium compounds (oxide content) and dysprosium metals and interalloys (Eurostat, 2019a)

There are several alloys makers and magnets manufacturers (in Germany, the UK, and Slovenia) likely to use imported quantities of dysprosium alloys and compounds (BRGM, 2015).

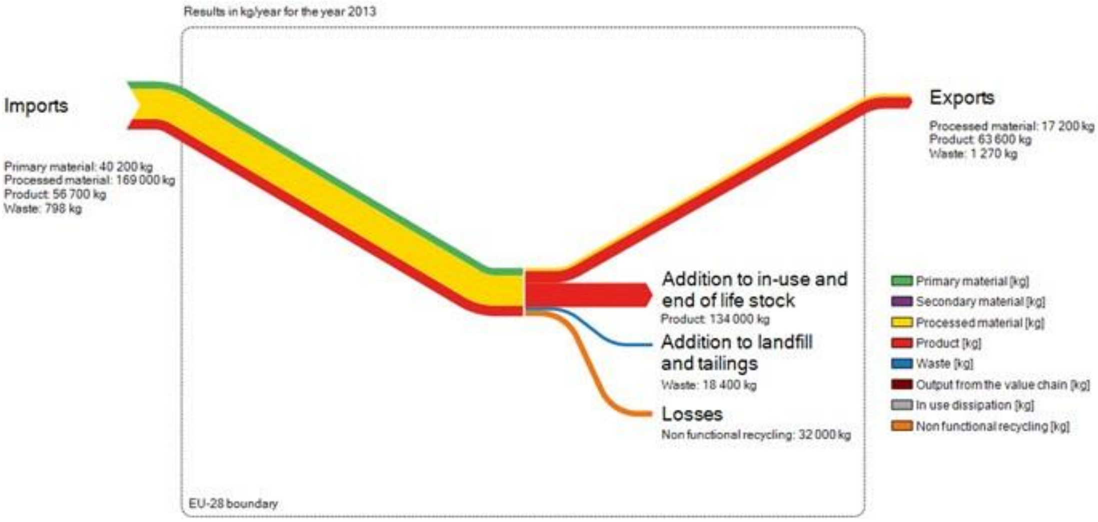


Figure 414: Simplified MSA. (Bio Intelligence Service, 2015)

21.4.2.3 Erbium

EU consumed in average around 8 tonnes per year of erbium compounds (oxide content) and 1 tonne of erbium metals and interalloys between 2016-2018 for glass and optical applications and lighting. According to statistics EU imported around 11 tonnes of erbium compounds and 2 tonnes of erbium metals and interalloys, while exports around 3.7 tonnes and around 1 tonne respectively between 2016-2018.

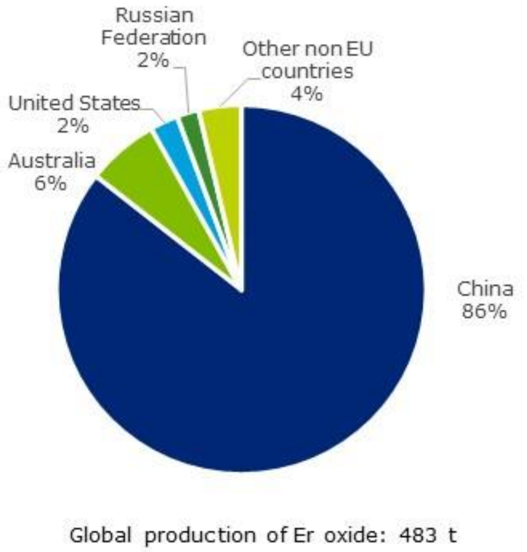


Figure 415: Global production of erbium oxide, average 2012-2016 (WMD, 2019)

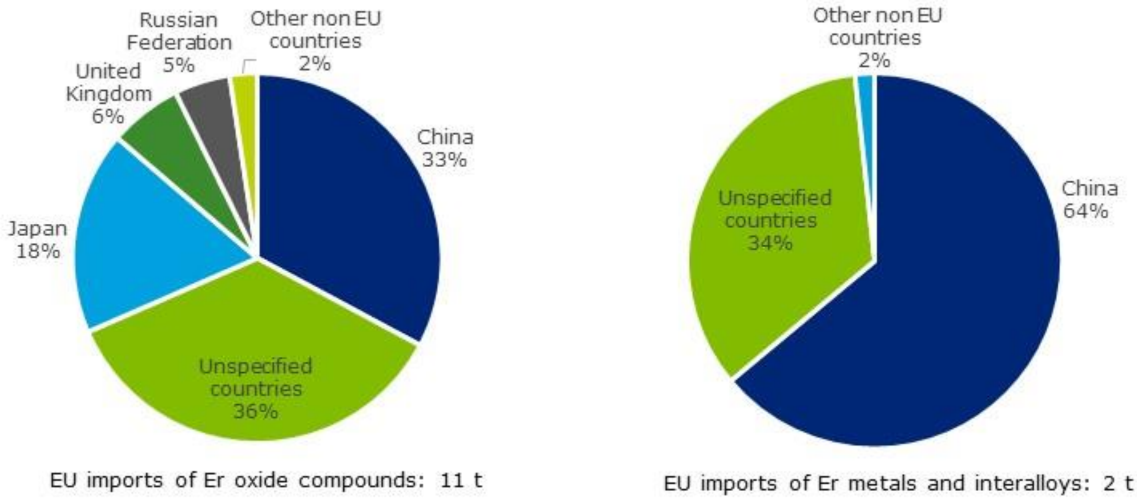


Figure 416: : EU import of erbium compounds (oxide content) and erbium metals and interalloys (Eurostat, 2019a)

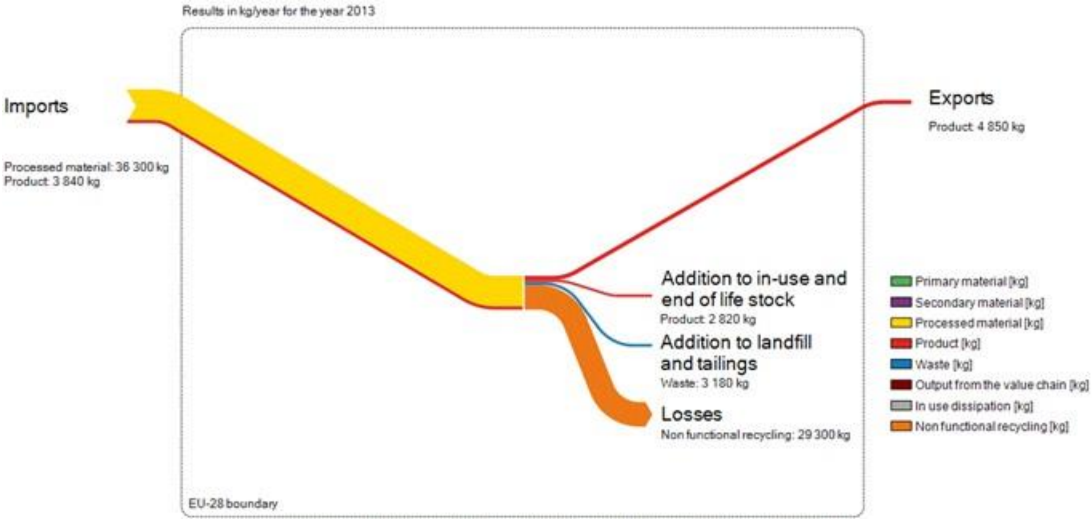


Figure 417: Simplified MSA. (Bio Intelligence Service, 2015)

21.4.2.4 Europium

EU consumed in average around 21 tonnes per year of europium compounds (oxide content) and 3 tonnes of europium metals and interalloys between 2016-2018 for lighting applications. According to statistics EU imported around 30 tonnes of europium compounds and 5 tonnes of europium metals and interalloys, while exports around 10 tonnes and around 2.5 tonnes respectively between 2016-2018.

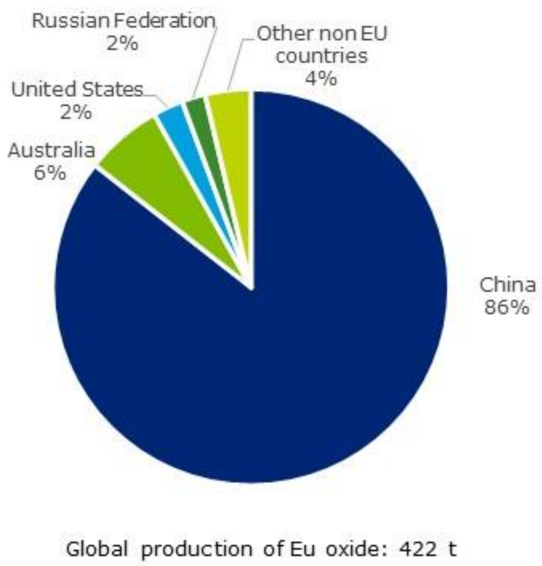


Figure 418: Global production of europium oxide, average 2012-2016 (WMD, 2019)

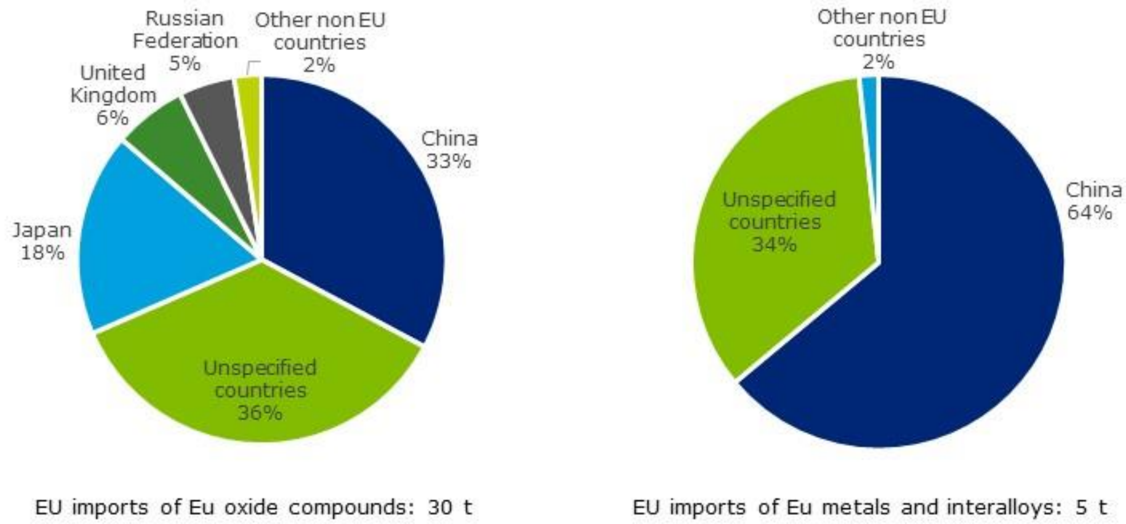


Figure 419: EU import of europium compounds (oxide content) and europium metals and interalloys (Eurostat, 2019a)

The separation of europium was performed in the Solvay plant in La Rochelle and was estimated at around 14 t/yr in the EU (Guyonnet et al., 2015) for the 2010-2014 period, but it discontinued after 2015.

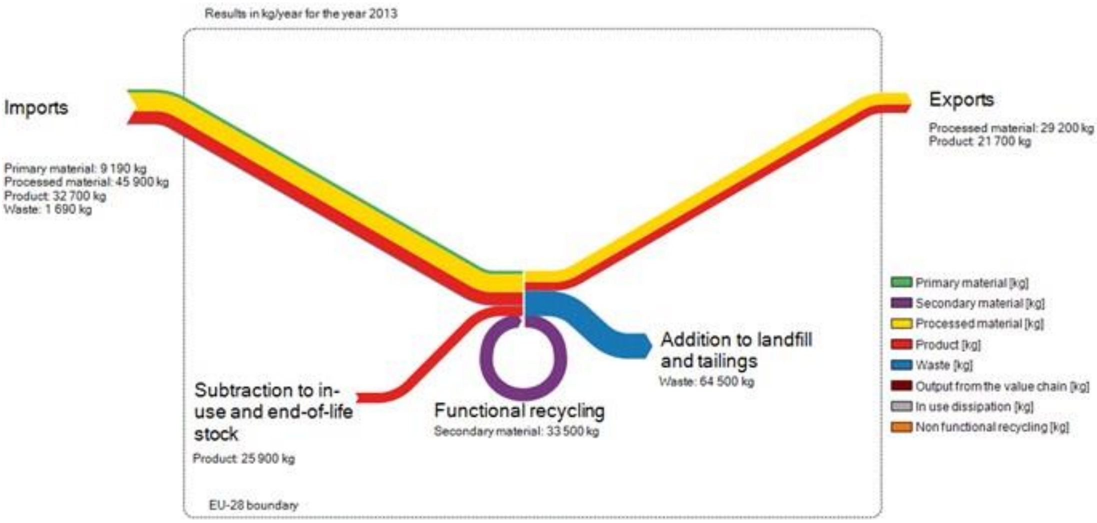


Figure 420: Simplified MSA. (Bio Intelligence Service, 2015)

21.4.2.5 Gadolinium

EU consumed in average around 10 tonnes per year of gadolinium compounds (oxide content) and 1.3 tonnes of gadolinium metals and interalloys between 2016-2018 for magnets, lighting, metals and magnetic resonance imaging applications. According to statistics EU imported around 15 tonnes of gadolinium compounds and 3 tonnes of gadolinium metals and interalloys, while exports around 4.9 tonnes and around 1.2 tonnes respectively between 2016-2018.

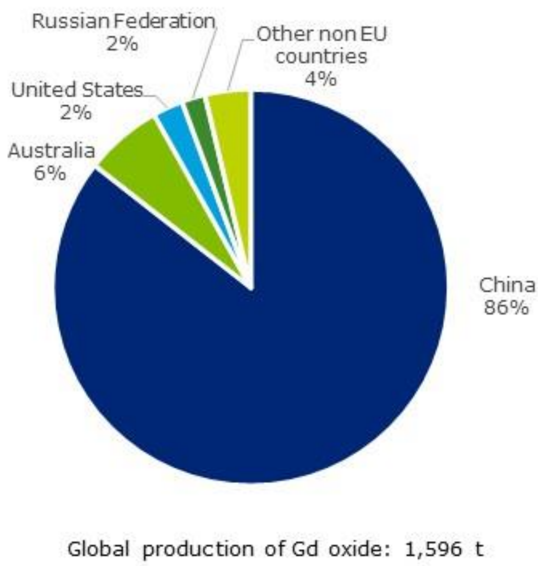


Figure 421: Global production of gadolinium oxide, average 2012-2016 (WMD, 2019)

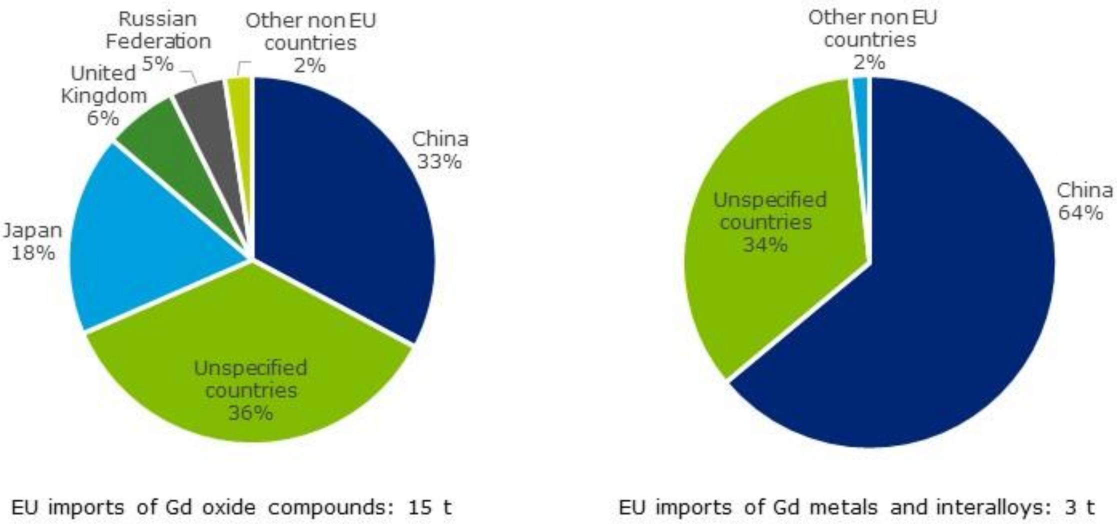


Figure 422: EU import of gadolinium compounds (oxide content) and gadolinium metals and interalloys (Eurostat, 2019a)

21.4.2.6 Holmium, Lutetium, Ytterbium and Thulium

EU consumed in average around 8 tonnes per year of holmium, lutetium, ytterbium and thulium compounds (oxide content) and 1 tonne of holmium, lutetium, ytterbium and thulium metals and interalloys between 2016-2018 for glass-optical applications. According to statistics EU imported around 11 tonnes of holmium, lutetium, ytterbium and thulium compounds and 2 tonnes of holmium, lutetium, ytterbium and thulium metals and interalloys, while exports around 3.7 tonnes and around 1 tonne respectively between 2016-2018.

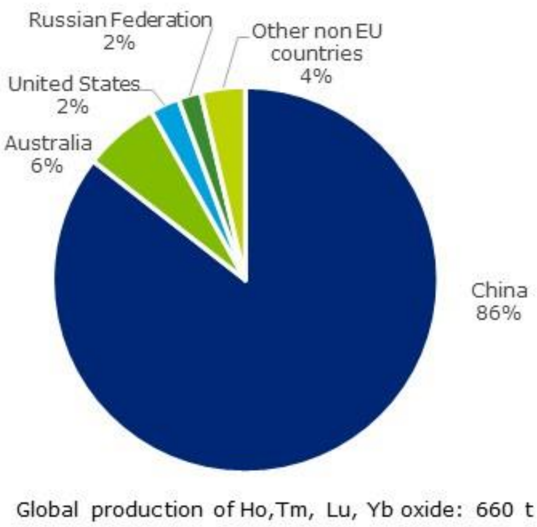


Figure 423: Global production of Ho, Tm, Lu, Yb oxide, average 2012-2016 (WMD, 2019)

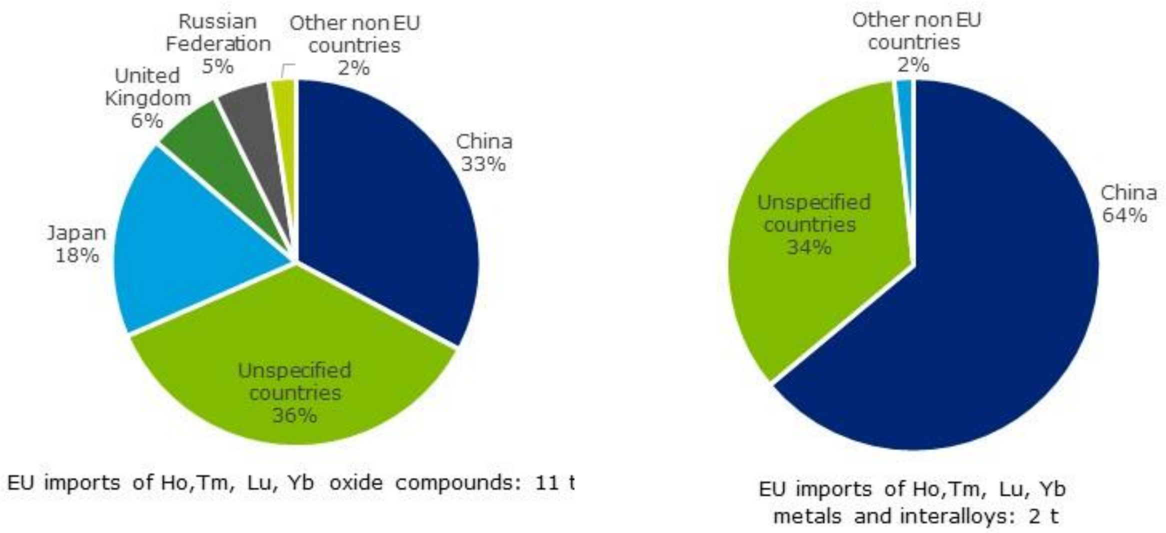


Figure 424: EU import of Ho, Tm, Lu, Yb compounds (oxide content) and Ho, Tm, Lu, Yb metals and interalloys (Eurostat, 2019a)

21.4.2.7 Lanthanum

EU consumed in average around 394 tonnes per year of lanthanum compounds (oxide content) and 251 tonnes of lanthanum metals and interalloys between 2016-2018 for magnets, ceramics, batteries, metals, catalysts, glass, lasers applications. According to statistics EU imported around 2.8 kt of lanthanum compounds and 579 tonnes of lanthanum metals and interalloys, while exports around 2.4 kt and around 328 tonnes respectively between 2016-2018.

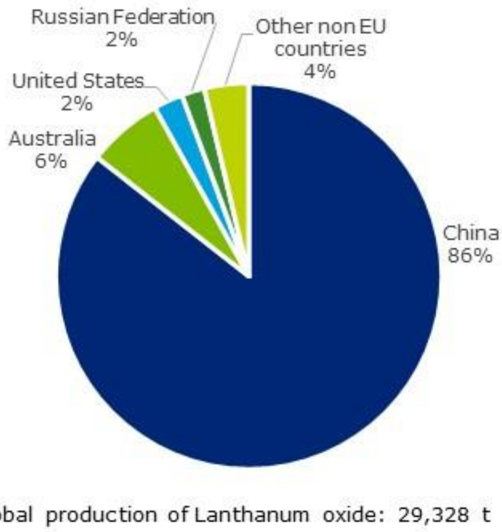


Figure 425: Global production of lanthanum oxide, average 2012-2016 (WMD, 2019)

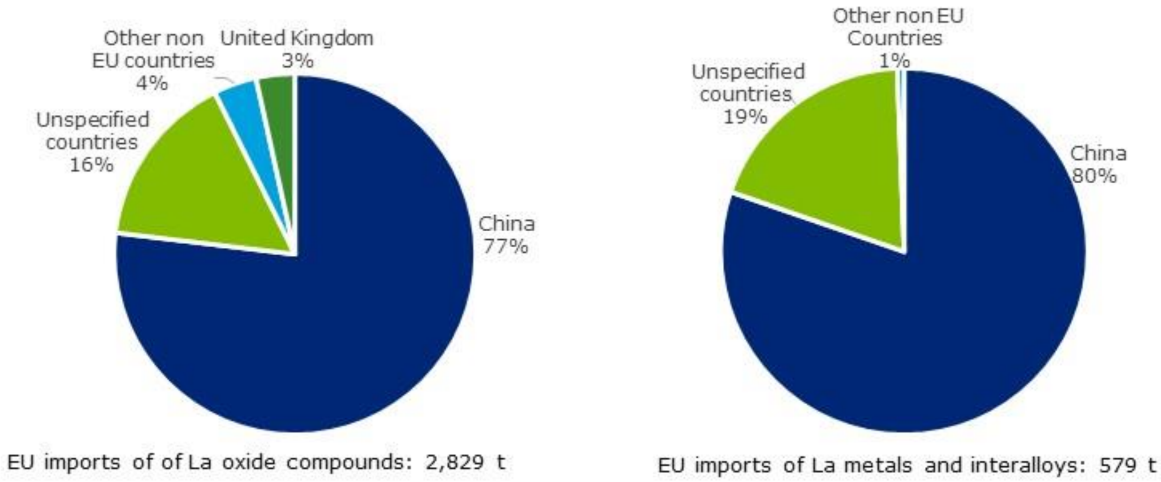


Figure 426: EU import of lanthanum compounds (oxide content) and lanthanum metals and interalloys (Eurostat, 2019a)

21.4.2.8 Neodymium

EU consumed in average around 91 tonnes per year of neodymium compounds (oxide content) and 39 tonnes of neodymium metals and interalloys between 2016-2018 for magnets, ceramics, batteries, metals, catalysts, glass, lasers applications. According to statistics EU imported around 442 tonnes of neodymium compounds and 90 tonnes of neodymium metals and interalloys, while exports around 380 tonnes and around 51 tonnes respectively between 2016-2018.

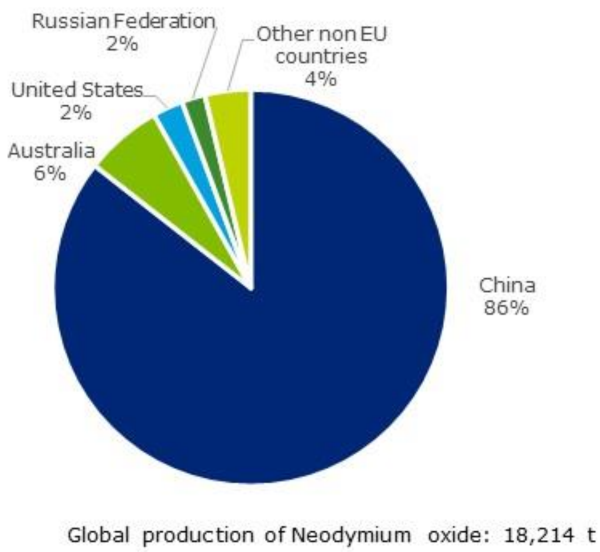


Figure 427: Global production of neodymium oxide, average 2012-2016 (WMD, 2019)

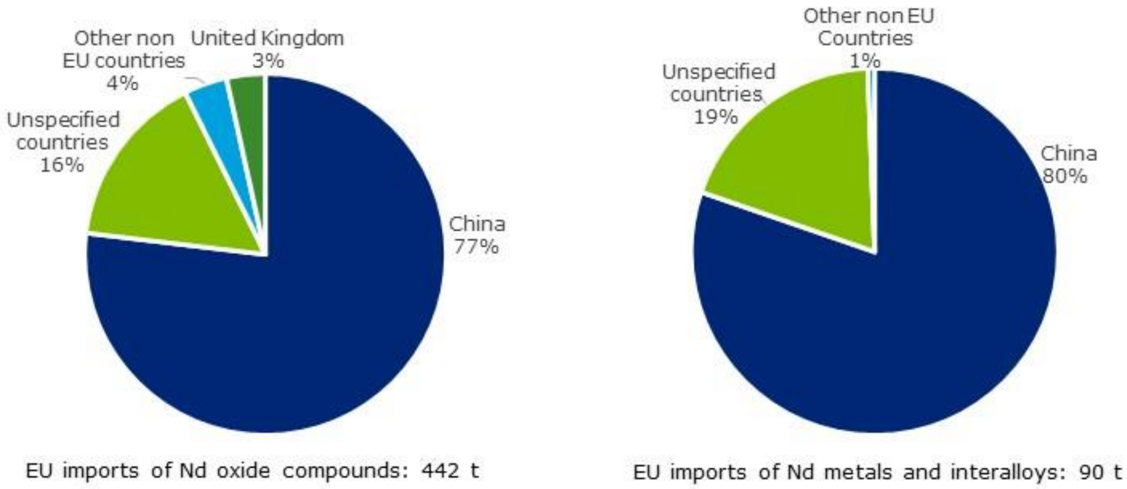


Figure 428: EU import of neodymium compounds (oxide content) and neodymium metals and interalloys (Eurostat, 2019a)

Some companies have the ability to separate individual REOs (in Estonia and France) or to produce neodymium metal (in Estonia the company Silmet is separating rare-earth mixtures to produce neodymium metal (300-400 t/yr) (Guyonnet et al., 2015).

Downstream, there are also alloy makers and magnet manufacturers (in Germany, the UK, Slovenia) operating from imported processed materials.

Other manufacturers of REE-based products are present in various industries (phosphors, catalysts, polishing powders, etc.) and are potential users of neodymium.

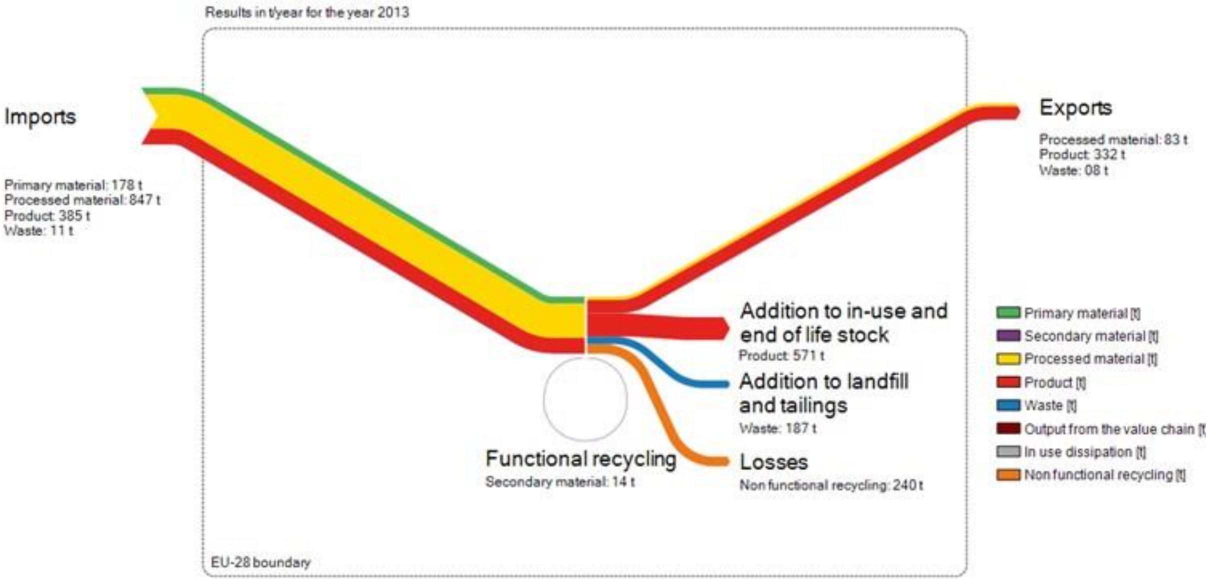


Figure 429: Simplified MSA. (Bio Intelligence Service, 2015)

21.4.2.9 Praseodymium

EU consumed in average around 25 tonnes per year of praseodymium compounds (oxide content) and 16 tonnes of praseodymium metals and interalloys between 2016-2018 for magnets, batteries, ceramics, metals, catalysts, polishing powders, glass applications. According to statistics EU imported around 179 tonnes of praseodymium compounds and 37 tonnes of praseodymium metals and interalloys, while exports around 154 tonnes and around 21 tonnes respectively between 2016-2018.

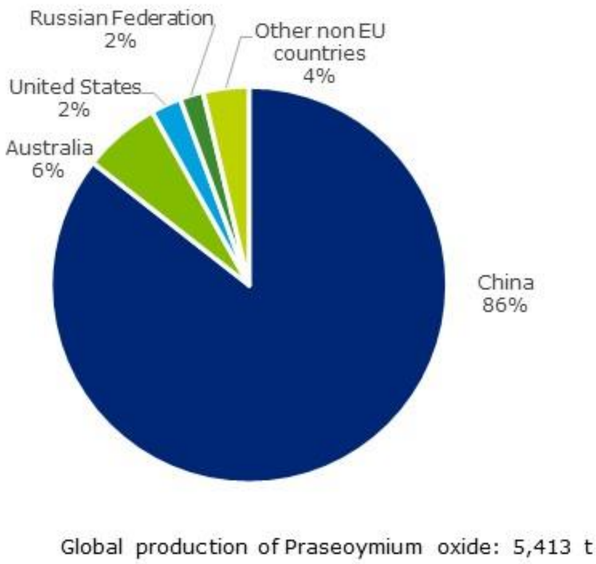


Figure 430: Global production of praseodymium oxide, average 2012-2016 (WMD, 2019)

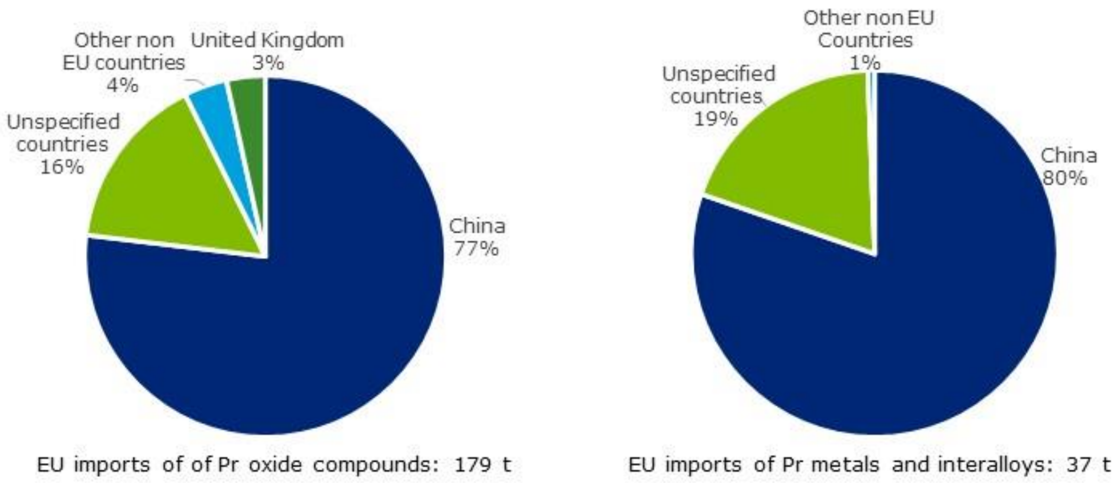


Figure 431: EU import of praseodymium compounds (oxide content) and praseodymium metals and interalloys (Eurostat, 2019a)

21.4.2.10 Samarium

EU consumed in average around 3.8 tonnes per year of samarium compounds (oxide content) and 2.4 tonnes of samarium metals and interalloys between 2016-2018 for magnets, ceramics, batteries, metals, catalysts, glass, lasers applications. According to statistics EU imported around 28 tonnes of samarium compounds and 6 tonnes of samarium metals and interalloys, while exports around 24 tonnes and around 3 tonnes respectively between 2016-2018.

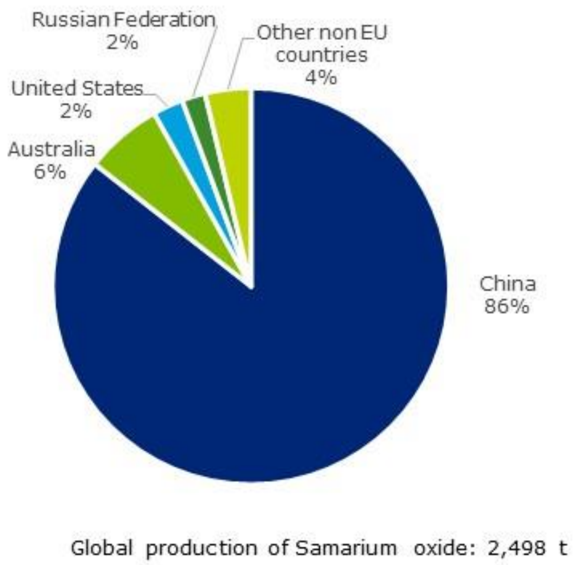


Figure 432: Global production of samarium oxide, average 2012-2016 (WMD, 2019)

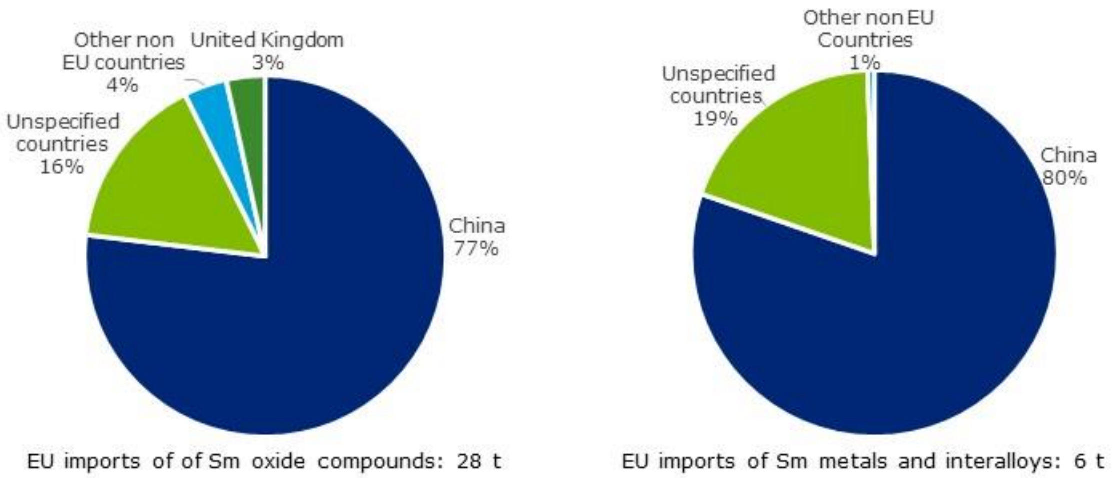


Figure 433: EU import of samarium compounds (oxide content) and samarium metals and interalloys (Eurostat, 2019)

21.4.2.11 Terbium

EU consumed in average around 21 tonnes per year of terbium compounds (oxide content) and 3 tonnes of terbium metals and interalloys between 2016-2018 for magnets and lighting applications. According to statistics EU imported around 30 tonnes of terbium compounds and 5 tonnes of terbium metals and interalloys, while exports around 10 tonnes and around 2.5 tonnes respectively between 2016-2018.

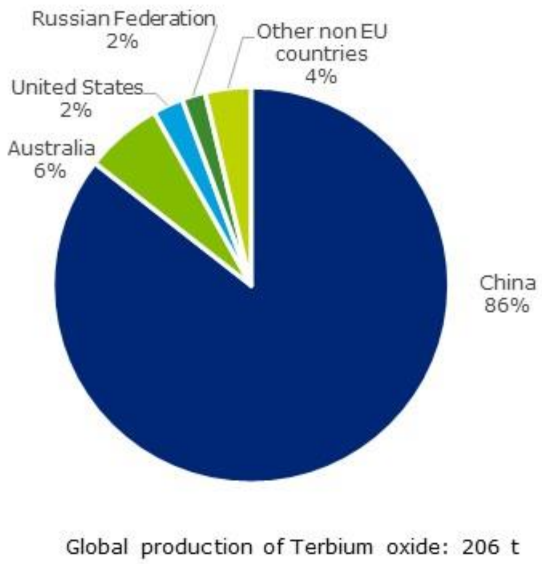


Figure 434: Global production of terbium oxide, average 2012-2016 (WMD, 2019)

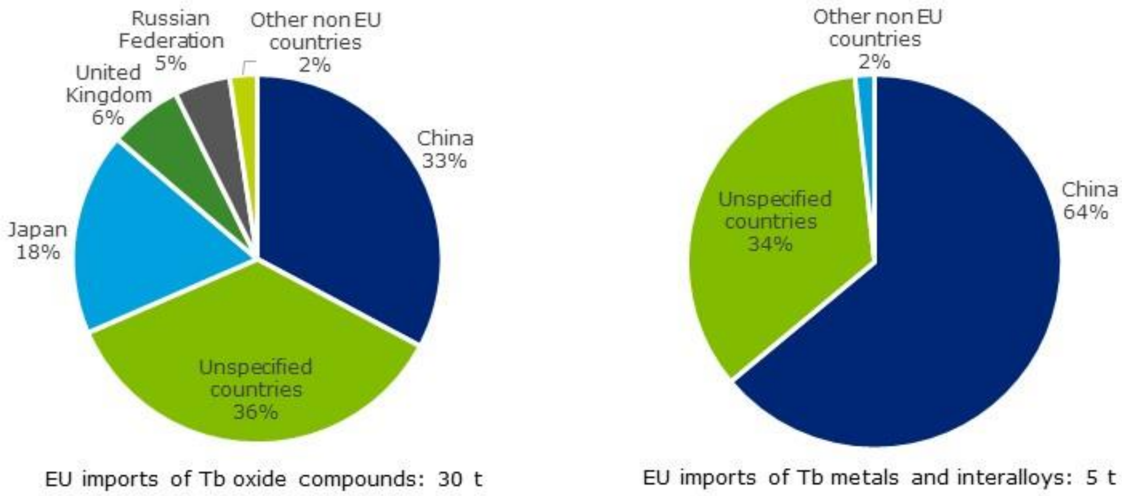


Figure 435: EU import of terbium compounds (oxide content) and terbium metals and interalloys (Eurostat, 2019a)

The separation of terbium metal was estimated at around 14 t/yr in the EU (Guyonnet et al., 2015) for the 2010-2014 period. Separation was performed in the Solvay plant in La Rochelle.

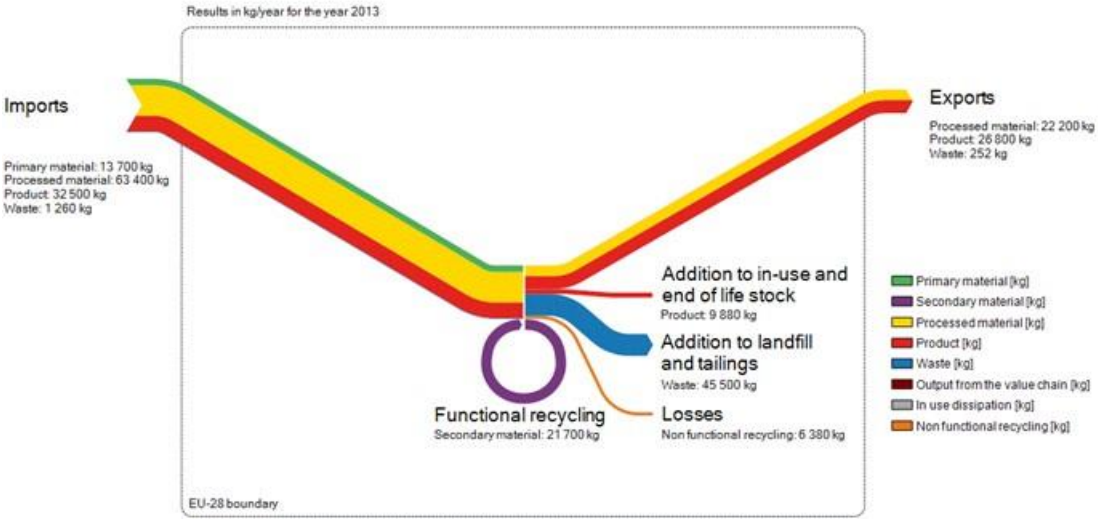


Figure 436: Simplified MSA. (Bio Intelligence Service, 2015)

21.4.2.12 Yttrium

EU consumed in average around 450 tonnes per year of yttrium compounds (oxide content) and 60 tonnes of yttrium metals and interalloys between 2016-2018 for magnets and lighting applications. According to statistics EU imported around 663 tonnes of yttrium compounds and 115 tonnes of yttrium metals and interalloys, while exports around 214 tonnes and around 56 tonnes respectively between 2016-2018.

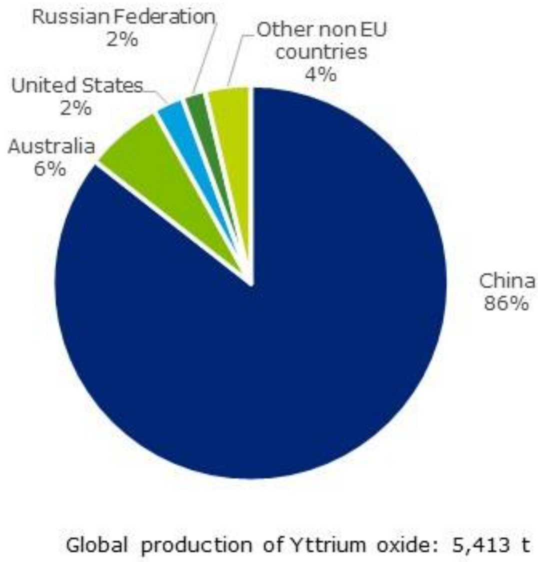


Figure 437: Global production of yttrium oxide, average 2012-2016 (WMD, 2019)

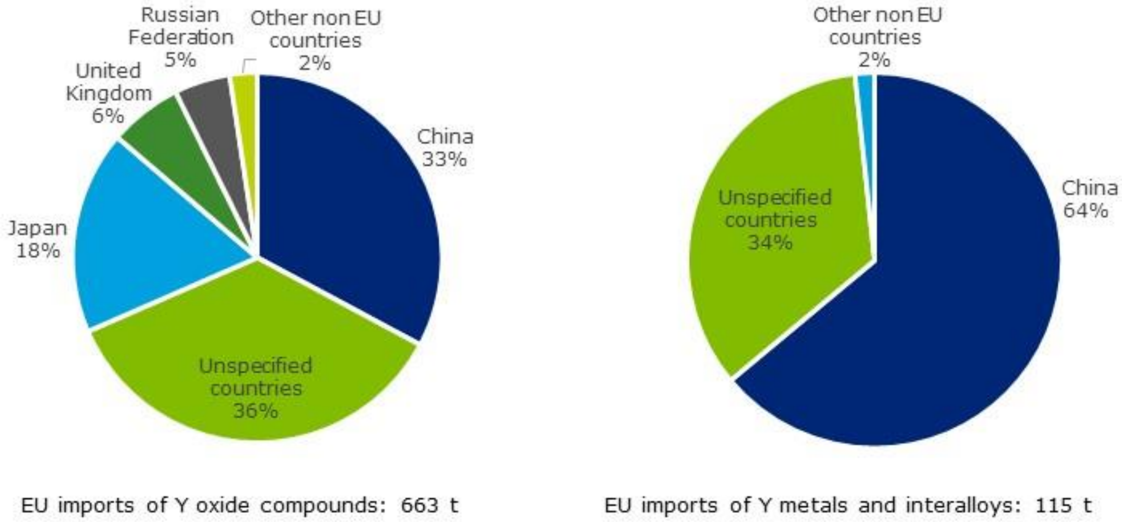


Figure 438: EU import of terbium compounds (oxide content) and terbium metals and interalloys (Eurostat, 2019a)

The separation of yttrium metal was estimated at around 500 t/yr in the EU (Guyonnet et al., 2015) for the 2010-2014 period. Separation was mainly performed in the Solvay plant in La Rochelle.

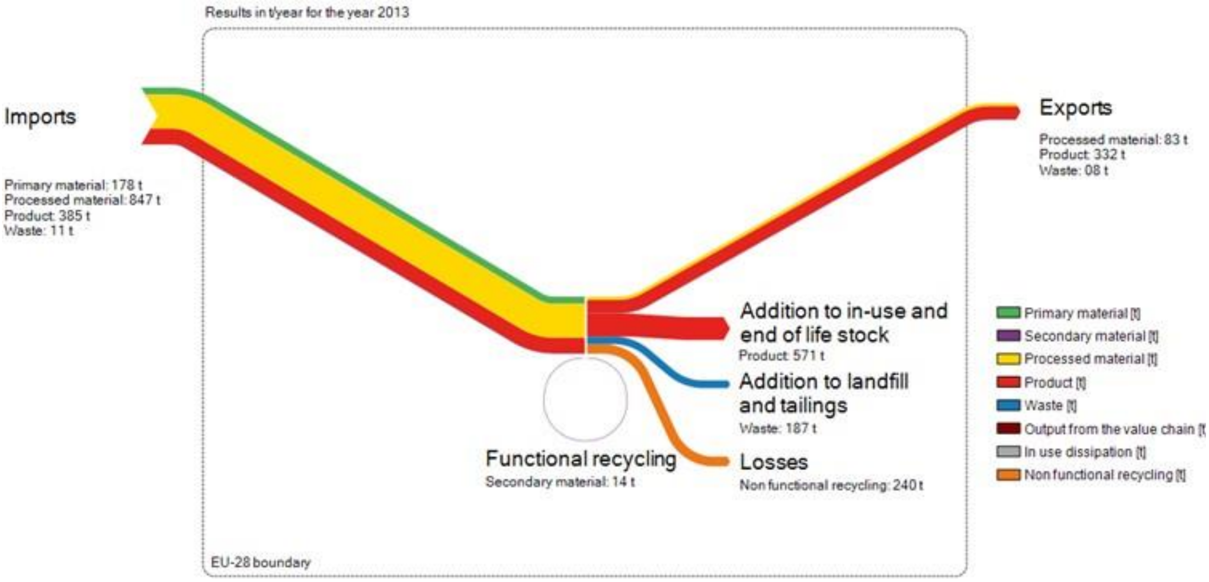


Figure 439: Simplified MSA. (Bio Intelligence Service, 2015)

21.4.3Supply from primary materials

The stages of production for hard rock deposits in the rare earth sector generally comprise mining, beneficiation, hydrometallurgical processing, separating, refining, alloying, and manufacturing rare earths into end-use items and components:

- mining of ores from the mineral deposits;
- beneficiation of the ore minerals into a mineral concentrate;
- hydrometallurgical processing to extract and concentrate the rare earths into a mixed chemical concentrate;
- separating and refining into individual REO. The oxides can be dried, stored and shipped for further processing into metals;
- converting the REO into metals with different purity levels;
- forming the metals into rare earth alloys;
- manufacturing the alloys into devices and components, such as permanent magnets.

21.4.3.1 Geology, resources and reserves of REE

Geological occurrence and deposits:

Concentration of individual REE in the upper crust is summarized in Table 170.

Table 170: Uppercrustal concentration of rare earth elements (Rudnick, 2003)

REE		Concentration (ppm)
LREE	Ce	63
	Nd	27
	La	31
	Pr	7.1

	Sm	4.7
	total LREE	132.8
HREE	Eu	1
	Tb	0.7
	Gd	4
	Er	2.3
	Dy	3.9
	Y	21
	Ho, Tm, Lu, Yb	very low
	total HREE	32.9
	Total	**165.7**

REE ore deposits occur in a wide variety of rocks and genetic types (Wall, 2014; BRGM, 2015). In summary, the most important ones for commercial exploitation are carbonatite-associated deposits (including weathered carbonatites), ion adsorption deposits, alkaline igneous rocks (including alkaline granites), placer deposits, and more anecdotic hydrothermal deposits and seafloor deposits.

Deposits vary in terms of size and grade. Carbonatite-associated deposits tend to be medium to large tonnage and high grade. The main examples are the Bayan Obo mine in China (accounting for about 60% of LREE global production in 2014) and Mountain Pass in the USA, with bastnaesite as the main ore mineral. They are typically enriched in LREE.

Alkaline rock deposits are generally larger tonnage but lower grade. An example is the nepheline syenite deposit of Lovozero in Russia, where loparite is the main ore mineral.

Beach sand placer deposits are variable in size and generally low grade; the main REE-bearing mineral in those deposits is monazite (with potential thorium content) which is exploited as a by-product of rutile, ilmenite and others.

Ion adsorption deposits are rather small and low grade but relatively rich in HREE contained in ion-adsorption clays and xenotime mineralization. The majority is located in Southern China. They are mostly artisanal small-scale mines, however accounting for 98% of HREE global production.

The concentration of rare earth elements varies with each type of mineralisation, and also between each individual ore body.

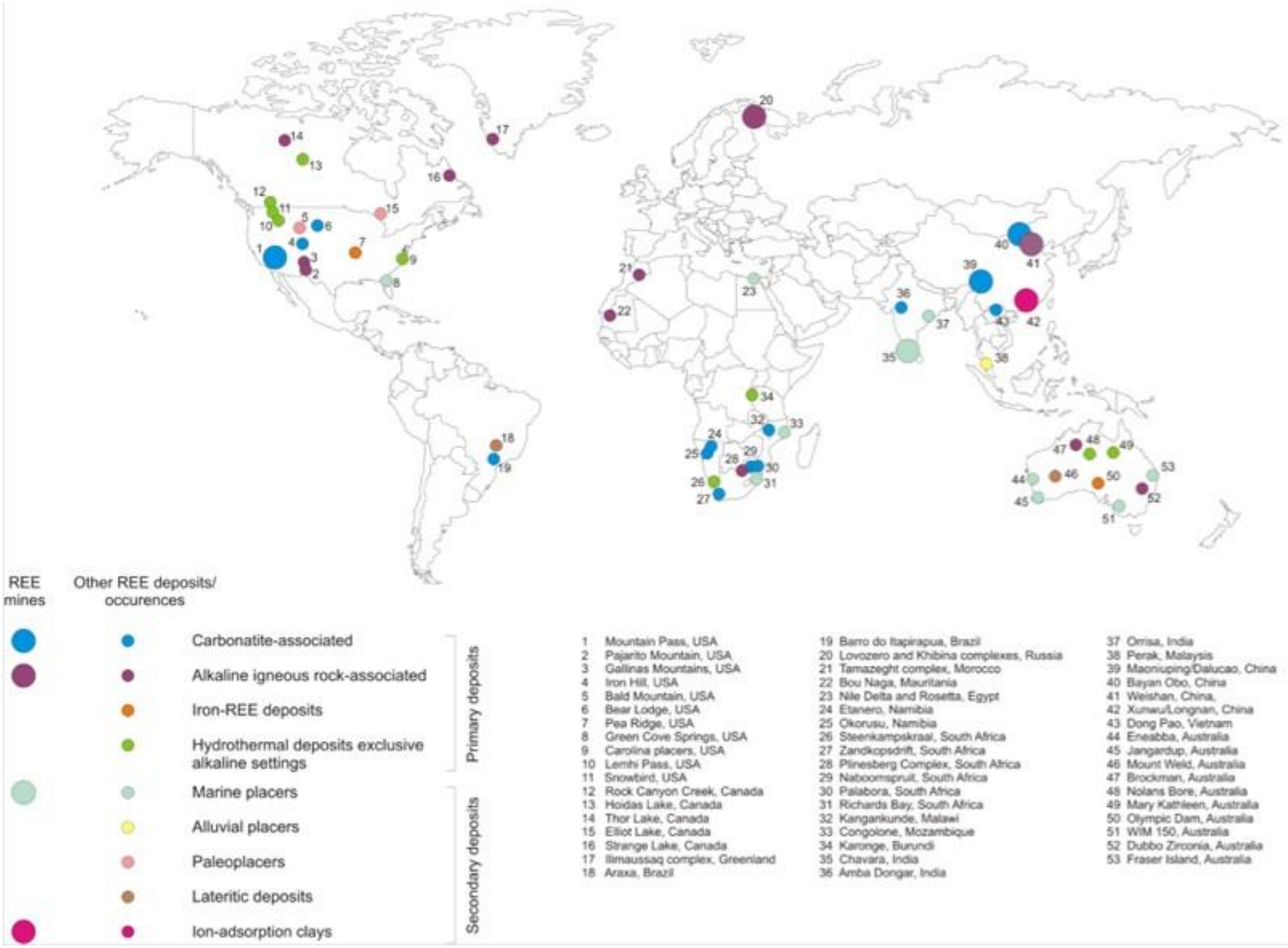


Figure 440: Global REE deposits (BGS 2019)

Global resources and reserves[235]

There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of REE in different geographic areas of the EU or globally.

Most of the REO-equivalent reserves estimates range from 80 million tonnes (BRGM, 2015) to 120 million tonnes (USGS 2020), as presented in **Error! Reference source not found.**. The USGS collects information about the quantity and quality of mineral resources, but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Association of China Rare Earth Industry (ACREI 2019) refers to 246 million tonnes of global REO reserves, including 169 million tonnes in China in 2018. Weng et al. (2015) published a global REO resources figure of 619.5 Mt, split between 267 deposits and grading 0.63% TREO and hosting c. 554 Mt TREO, based on JORC, NI43-101, SAMREC and CRIRSCO mineral resource data gathered in 2013-2014.

Individual companies may publish regular mineral resource and reserve reports under various reporting systems, which makes their comparison and summing up difficult. Figures for countries where no reporting obligation apply are the most difficult to evaluate and can vary from one source to another (e.g. Brazil, China, India) which explain some differences.

Looking from a tonnage point of view alone it appears that the global REE-reserve is sufficient for about 500 of years of production. However, neither the tonnage nor the grade alone makes a mine, because the REE-distribution, as well as many other parameters, should be considered. World resources are contained primarily in bastnäsite and monazite (USGS, 2016), and bastnäsite is the main source of LREE. (Machacek and Kalvig 2017: EURARE)

Table 171: Estimates of the global REO reserves in million tonnes

Country	BRGM (2015)	USGS (2020)		TMR (2015)	Adamas Intelligence (2016)
Australia	2.563	3.3		3.21	4.45
Brazil	7.46	22		2.64	2.29
Canada	0.805	0.83		35.44	38.19
China	65.84	44			

[235] There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of fluorspar in different geographic areas of the EU or globally. The USGS collects information about the quantity and quality of mineral resources but does not directly measure reserves, and companies or governments do not directly report reserves to the USGS. Individual companies may publish regular mineral resource and reserve reports, but reporting is done using a variety of systems of reporting depending on the location of their operation, their corporate identity and stock market requirements. Translations between national reporting codes are possible by application of the CRIRSCO template.[235], which is also consistent with the United Nations Framework Classification (UNFC) system. However, reserve and resource data are changing continuously as exploration and mining proceed and are thus influenced by market conditions and should be followed continuously.

Gabon					2.64
Germany				0.02	0.02
Greenland	1.528	1.5		35.57	41.3
India		6.9			
Kenya				4.25	6.14
Kyrgyzstan					0.05
Madagascar					0.57
Malaysia	0.043	0.03			
Malawi					0.58
Mozambique					0.02
Namibia					0.02
Norway				4	0.90
Russia	0.153	12			
Sweden	0.14			0.24	0.24
Turkey				0.35	0.35
Tanzania	0.94	0.89		1.77	4.63
South Africa	0.064	1.8		1.24.29	1.34
USA	1.694	1.4		4.291.2	3.93
Vietnam		22			
Other Countries		0.31		1.24	
Total	81.23	120		90.99	108

REE-enriched deposits are the result of primary (magmatic and hydrothermal) or secondary (weathering and sedimentary transport) geological processes.

A brief summary of the seven main geological types of REE deposits (Machacek and Kalvig 2017: EURARE):

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

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

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

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

Iron oxide-apatite deposits of the Kiruna type in the Svecofennian belt are also enriched in the REE due to apatite, including Kiruna and Malmberget in northern Sweden and the Grängesberg-Blötberget deposits in South Central Sweden (Goodenough et al. 2016). Some Iron-Oxide Copper Gold (IOCG) deposits such as Olympic Dam, Australia, carry the mineral apatite, which has the potential to produce REE as a by-product. The REE-bearing apatite is currently treated as waste during iron ore processing, there is however, as earlier mentioned, an on-going pilot-project to start a small rare earths production from iron-ore mining wastes.

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

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

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

EU resources and reserves[236]:

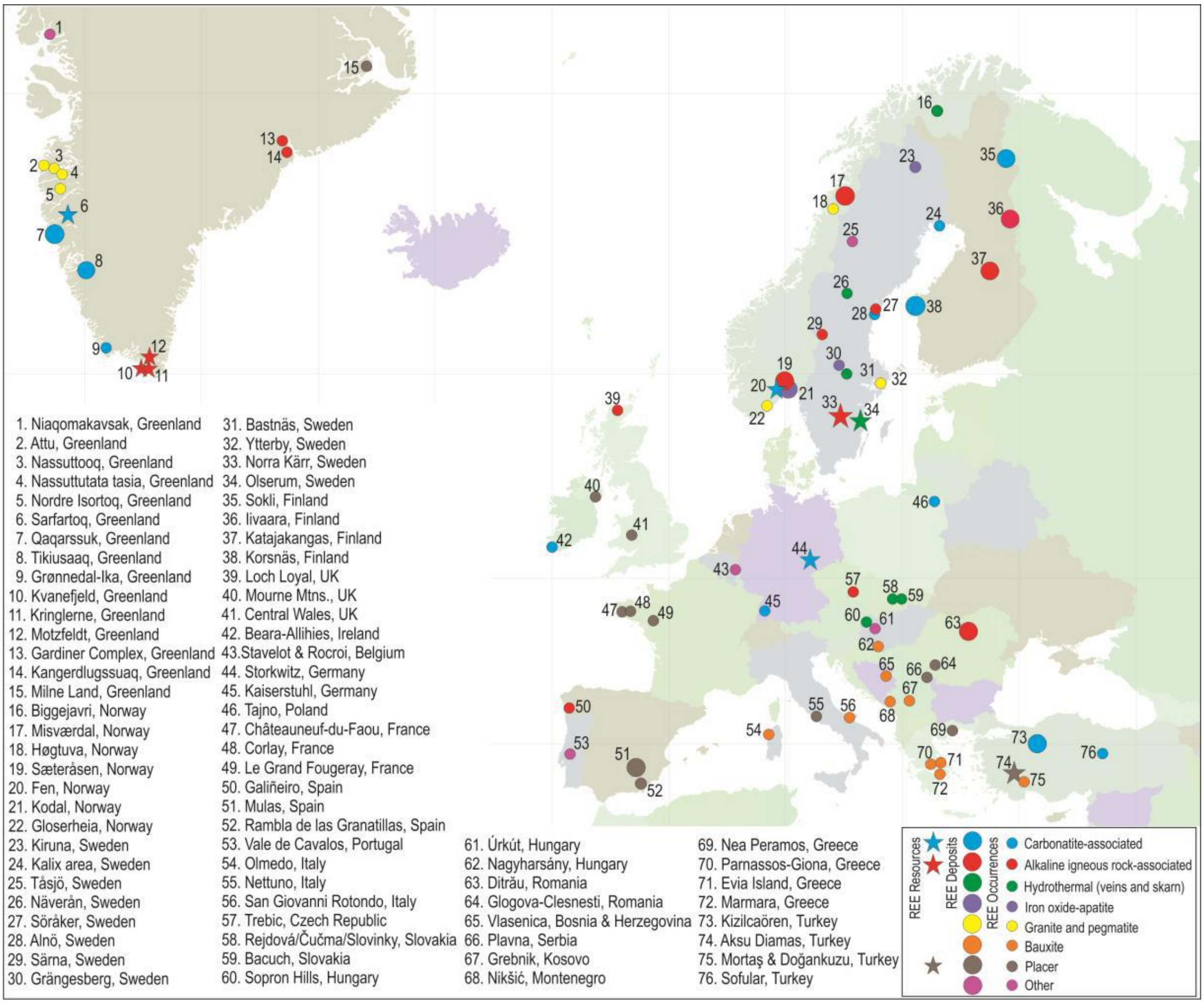


Figure 441: REE deposits in the EU according to the EURare project. (BGS NERC 2019: SCRREEN)

[236] For Europe, there is no complete and harmonised dataset that presents total EU resource and reserve estimates for REEs. The Minerals4EU project is the only EU-level repository of some mineral resource and reserve data for REEs, but this information does not provide a complete picture for Europe. It includes estimates based on a variety of reporting codes used by different countries, and different types of non-comparable datasets (e.g. historic estimates, inferred reserves figures only, etc.). In addition, translations of Minerals4EU data by application of the CRIRSCO template is not always possible, meaning that not all resource and reserve data for REEs at the national/regional level is consistent with the United Nations Framework Classification (UNFC) system (Minerals4EU 2019). Many documented resources in Europe are based on historic estimates and are of little current economic interest. Data for these may not always be presentable in accordance with the UNFC system. However a very solid estimation can be done by experts.

Sweden and Greenland present interesting potential for REE exploitation, although currently penalized by low market conditions or environmental issues. The Minerals4EU website only provides some data about Yttrium lanthanide and yttrium ore reserves in Ukraine, at about 417 kt (RUS A) (Minerals4EU, 2019). However, only Greenland and Sweden assessments of rare earths reserves (respectively 1,528,000 tonnes and 140,000 tonnes of REO – see Table 172) have been performed using international reporting code and can be qualified as reliable at the present date.

Table 172: REE exploration projects in EU in a harmonized UNFC format (based on responses from EU RMSG in 2019)

Countries	Projects	Commercial projects (E1; F1; G1,2,3)[1]	Potentially commercial projects (E2; F2; G1,2,3)[1]	Non-Commercial projects (E3; F2; G1,2,3)[1]	Exploration projects (E3; F3; G4)[1]	E3, F4, G1, G2
		Estimate of quantities (tonnes, REO)				
Finland	Katajakangas			11040		
	Kontioaho			34605		
	Korsnas					7740
	Konvela		1160			
Germany	Storkwitz		9900			
	Storkwitz		9900			
Greenland	Kringlerne		28200000			
	Kvanefjeld	632100				
	Kvanefjeld	896000				
Norway	Fen			907200		
	Kodal			756000		
	Misværdalen			21000		
Portugal	Vale de Cavalos				10320	
Spain	Matamulas		35890			
	Gemas, Tesorillo			25000		
Sweden	Norra Kärr		202519			
	Grängesberg				280000000	
	Olserum		27000			
	Olserum		20790			
	Tasjo		82500			

Importance of REE mineralogy

The REE can be incorporated into a range of different mineral types, such as carbonates, oxides, silicates, phosphates, each of them related to specific geological environments. More than 200 REE- bearing minerals have been identified (Kanazawa and Kamitani, 2006), though only a few are currently considered feasible for the extraction of REE. Bastnäsite (carbonate mineral), is currently the most important REE ore mineral and is extracted at the Chinese mining operations in Bayan Obo, Weishan and Maoniuping, and until 2015 was also mined at Mountain Pass (USA). Monazite and xenotime (phosphate minerals), and loparite (oxide mineral) are also exploited.

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

1.4 million tonnes of red mud waste generated annually in the EU by alumina production from 3.5 million tonnes bauxite through the Bayer process may also be interesting alternative, containing on average 900 ppm REE compared with typical values of <100 ppm to ~500 ppm REE in bauxites. (Deady et al. 2014)

Similarly, phosphates are a perspective source of REE, for example the EU project SecREEts amis to unlock potential of REE in 650,000 tons of phosphate rock mined annuallyin Norway, containing about 0.3 -1.0 percent of REE.

The REE ore grade impacts on the economic viability of each deposit. REE-distribution can be even more important than the REE-grade. There is an oversupply of cerium and lanthanum, while there is a demand for REE used in magnets (Pr, Nd, Sm and Dy), and phosphors (Eu, Gd, Tb and Y).

Each of the REE-minerals has a characteristic REE-ratio (Kanazawa and Kamitani, 2006), e.g. bastnäsite and monazite are dominated by LREE, whereas xenotime is relatively rich in HREE. Substantial variations in REE-distribution can occur within one type of REE-mineral, e.g. the eudialyte minerals from Kringlerne, Kipawa and Norra Kärr, or bastnäsite in Bayan Obo, China and Mountain Pass, USA have different REE-compositions.

Presence of radioactive elements, mainly uranium and thorium are addressed in the chapter on Environmental, health and safety issues.

Table 173: Some of the most common REE minerals (Wall, 2014) (Machacek and Kalvig 2017: EURARE).

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

Benchmarking REE-exploration projects

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

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

The Criteria for a Sustainable Economically Sound Rare Earths Project (Kingsnorth 2018)

- Ore grade (%), meaning the REE content of one unit of the ore;
- Ore tonnage, meaning the volume of the ore (the economic part of the rock hosting REE-minerals)
- Composition of the REE mineral: the mis-match between the ratio of the rare earths produced and those consumed is a major issue for the industry. Accordingly, given the high growth in demand for neodymium and praseodymium it is desirable that the composition of a project's rare earths ores are high in these elements. High concentrations of lanthanum and cerium are a 'problem' as a significant proportion of these elements are discarded. Normally, no value is attributed to the five HREE with limited, niche markets (Ho, Er, Tm, Yb, Lu).
- Individual REE-grade (%) based on the individual REE as a fraction of REE, frequently expressed as HREE/LREE-%, reflecting the REE-distribution.
- Ore value or gross metal value (GMV): REO-value per unit mass of mineral resource (EUR/tonne), reflecting the in-situ value of the ore material, thus considering the ore grade, but not the tonnage and recovery of the ore. A high-grade ore dominated by LREE may reach a lower GMV than a low-grade ore dominated by HREE. Further, high GMV does not guarantee a market for the products.
- Basket price (EUR/kg), reflecting the potential price if one kilogram of the REO is extracted from the ore – not accounting for the ore grade or the total recovery rates. From this it follows that low grade ore may well result in high basket price and vice versa.
- Mineralogy of the ore: To date there have only been 4 minerals (bastnastite, monazite, xenotime and the ionic clays in China) that have been successfully processed commercially. It has taken Alkane Resources over 10 years of pilot plant work to

develop a potentially commercial process for the extraction of rare earths, zirconium, hafnium and niobium from the eudialyte at Dubbo, New South Wales, Australia.

- Pilot plant: The successful operation of a pilot plant is required to demonstrate the technical, financial and social viability of a project. The operation will provide samples for customer approval, while providing the required data for the estimation of capital and operating costs.
- Demonstrable Radioactivity and Environmental Management: All rare earth ores contain some uranium and thorium so it is incumbent on the project developer to demonstrate that this aspect of the project is manageable.
- Realistic start-up schedule: including adequate working capital.
- Marketing: The marketing plan must be realistic in terms of market share and product quality.

It should be noted that, as a result of poor market transparency, there is no standard set of prices for the REE-commodities, and thus metrics such as GMV and basket price are both dynamic parameters and may reflect company views.

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

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

21.4.3.2 World and EU mine production

Global mine production

According to USGS (2020) the global mine production of REO equivalent in 2019 reached 210,000 tonnes.

China official mine production quota for REO in 2019 was 132, 000 tonnes, which is over 60% of global production, compared to 120,000 tonnes in 2018, and 105,000 tonnes in 2017. Additional undocumented annual production in China is estimated at 60,000-80,000 tonnes (Kingsnorth, 2018). ACREI (2019) reports that the production capacity of the six Chinese rare earth producers was 227000 tons in 2018, while the capacity of the whole industry including comprehensive recycling of rare earth resources was estimated to be about 300,000 tonnes.

After a break in 2015-2017, US restarted mining in Mountain Pass reaching 18,000 tons in 2018, and 26,000 t in 2019 (USGS, 2020). But their ores and concentrates are shipped to China for refining, from where it sources 80% refined rare earths. In 2019, Australia mined 21,000 tonnes of REO, Myanmar 22000 tonness, India 3000 tonnes, Russia 2,700 tonnes and Madagascar 2,000 tonnes and Thailand 1,800 tonnes. Brasil, Burundi, Malaysia, Vietnam and other countries produced 1000 tonnes or less (USGS, 2020).

As shown in the following table, there is an issue with existing statistics due to confusion between REE and REO, as well as inconsistency with respect to the commodities included; e.g. in some cases REE-mineral concentrates are included, in other cases not. (Machacek and Kalvig 2017: EURARE)

Table 174: Variation in REE mine production statistics (2014) (USGS,2016; Brown *et al.*, 2016; Adamas Intelligence, 2016) (Machacek and Kalvig 2017: EURARE)

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

"*The main discrepancy in the annual production statistics may be due to the illegal operations which are in general not included, except for Admas Intelligence, 2016. The extensive contribution to the mine production is supported by Kingsnorth (2016), estimating the illegal figure to be about 30% of the national production quotas.*

Development of new REE operations outside China is facing strong competition from the state-controlled and vertically integrated Chinese REE-industry, which controls the REE-supply chain from mining to manufactured goods. Outside China, only two new producers of primary REE have begun production in the past five years – Lynas Corp at Mount Weld, Australia, and Molycorp at Mountain Pass, USA, of which the latter went bankrupt in 2015, and operations suspended in 2016." (Machacek and Kalvig 2017: EURARE)

Table 175: World REE-mining companies (Adamas 2015; Jesper Zeuthen, pers. Comm. Oct. 2016) (Machacek and Kalvig 2017: EURARE)

Country	Company	Mine/ Region	Geol. type	Capacity (REO tpa)	LREE/HREE enrichment	Product
Australia	Lynas Corp	Mount Weld	Carb./laterite	22,000	LREO	Mixed and separated REO
Brazil	Nuclear Industries of Brazil	Buena Norté		1,500	LREO	Mixed and separated REO
China	Baotou Steel Rare Earth Co[237]	Bayan Obo	Carbonatite	59,500	LREO	Mixed and separated REO
China	Jiangzi Copper Rare Earth	Maoniuping	Carbonatite	2,500	LREO	Mixed and separated REO
China	Minmetals Ganzhou Rare Earth Co.	Jiangxi	Ion-adsorp.	9,000	HREO	Mixed and separated REO
China	Xiamen Tungsten Co.	Fujian	Ion-adsorp.	2,000	HREO	Mixed and separated REO
China	Guangdong Rare Earth Industry Group	Guangdong	Ion-adsorp.	2,000	HREO	Mixed and separated REO
China	Chinalco Rare Earth Co.	Guangzi	Ion-adsorp.	2,500	HREO	Mixed and separated REO
China	China Minmetals Rare Earth Co.	Hunan	Ion-adsorp.	2,000	HREO	Mixed and separated REO
China	China Iron and Steel Research Institute Group	Weishan	Ion-adsorp.	2,600	HREO	Mixed and separated REO
China	China Minmetals Rare Earth Co.	Yunnan	Ion-adsorp.	200	HREO	Mixed and separated REO
India	Indian Rare Earth Ltd	Tamil Nadu	Placer	2,800	LREO	Mineral concentrate
India	Kerala Metals and Minerals	Kerala	Placer	240	LREO	Mineral concentrate
Malaysia	Pegang Mining Co.	Kinta Valley	Placer	100	LREO	Mineral concentrate
Russia	Lovozerskiy GOK	Lovozero	Alkaline	2,400	LREO	Mineral concentrate
USA	Molycorp *(operation restarted in 2018)*	Mountain Pass	Carbonatite	26,000	LREO	Mixed and separated REO
Vietnam	Lavreco/Sojitz/Toy ota	Dong Pao	Placer	220	LREO	Minex and separated REO

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

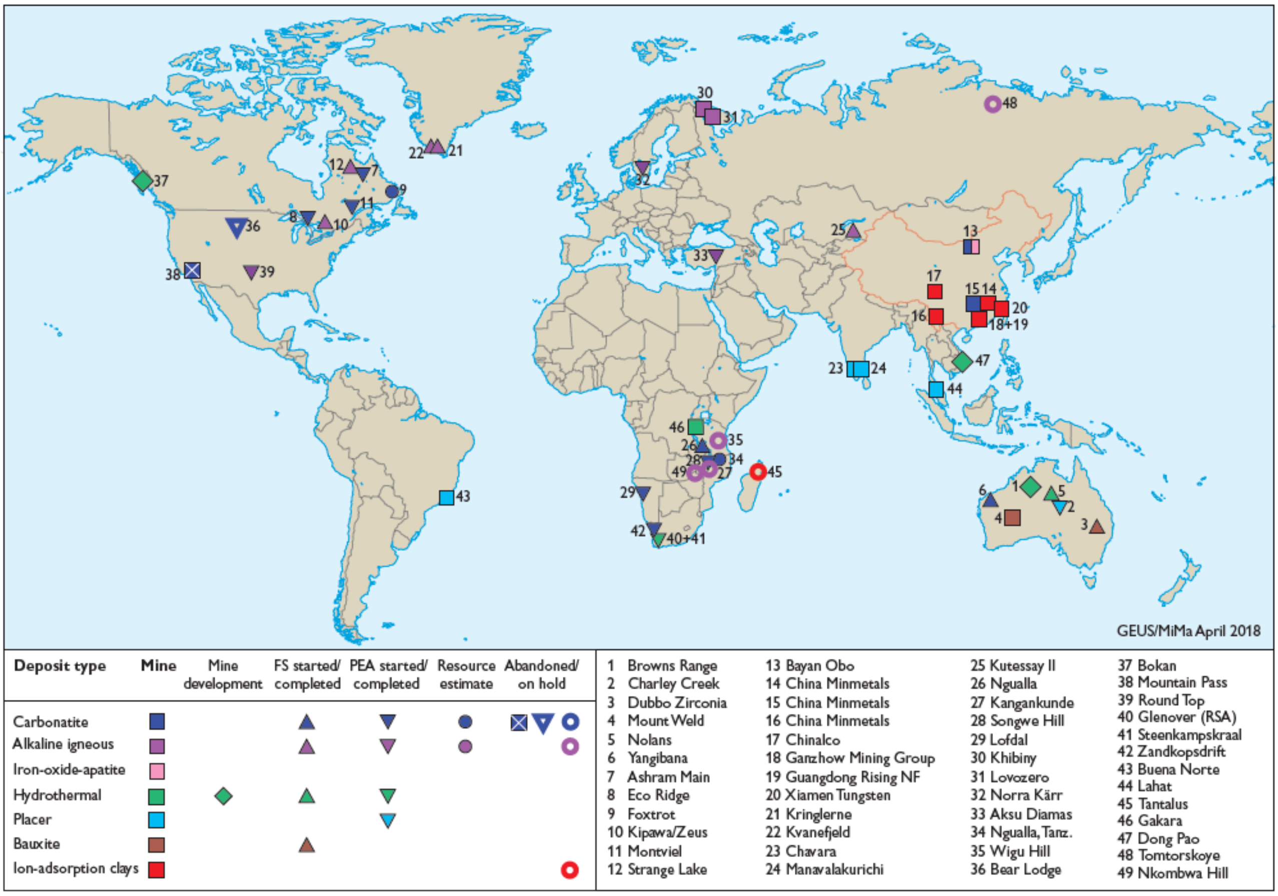


Figure 442: Major global rare-earth element mines and advanced exploration projects (GEUS/MiMa, 2018) (Machacek and Kalvig 2017: EURARE).

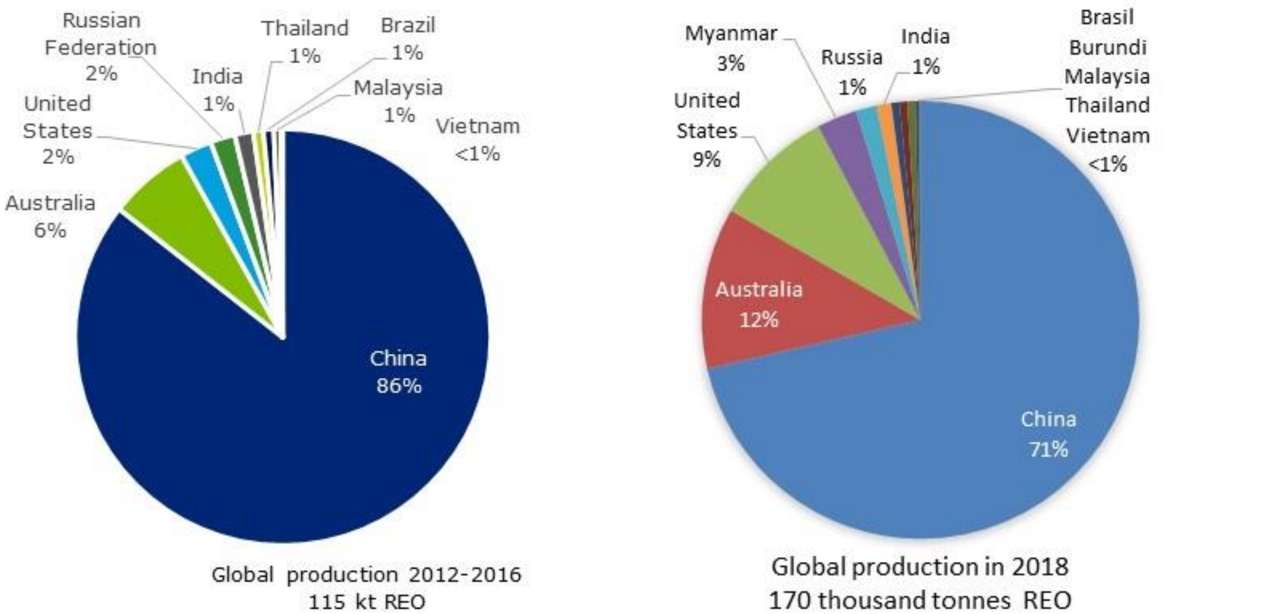


Figure 443: Global mine production of REOs, average 2012–2016. No EU mine production of rare earths. Compilation of data (World Mining Data 2018, USGS 2019)

Kingsnorth (2013, 2018) reported on undocumented extraction of REE in China, which at some periods could have accounted for 30-40% of Chinese production. USGS reported that according to China's Ministry of Commerce, production of REO in China in 2018 was estimated to be at least 180,000 tons based on magnet material production, including undocumented production.

Table 176: Global production of REO (WMD 2019 and USGS 2016[1]; Roskill 2019[2])

REE		Production (t) [1]	% of global production[1]	Production (t) [2]	% of global production[2]
LREE	La	28,328	24.5	45,469	25.0
	Ce	51,167	44.3	76,677	42.1
	Pr	5,413	4.7	9,757	5.4
	Nd	18,214	15.8	30,687	16.8
	Sm	2,498	2.2	3,041	1.7
	total LREE	105,620	91.5	165,631	90.9
HREE	Eu	422	0.4	364	0.2
	Gd	1,596	1.4	2,431	1.3
	Tb	206	0.2	400	0.2
	Dy	1,018	0.9	1,397	0.8
	Er	484	0.4	830	0.5
	Y	5,413	4.7	10,414	5.7
	Ho, Tm, Lu, Yb	660	0.6	727	2.7
	total HREE	9,799	8.6	16,563	9.1
	Total	**115,419**	**100**	**182,194**	**100**

As there is no data available at the global level for individual production of REE, individual figures of REE production were obtained relying on several sources and hypotheses (BGS, 2016; BRGM, 2015; Bio Intelligence Service, 2015; Roskill 2019).

Most REE mines, such as Bayan Obo, Mountain Pass and Mount Weld, are open-cast operations, involving conventional blast, and load and haul techniques. No underground mines have ever been designed for the exclusive production of REE but there are, or has been, production of REE from a few underground mines. For example, the former thorium mine at Steenkampskraal, South Africa, and the former uranium mines at Elliot Lake, Ontario, Canada.

Different mining techniques are used for the beach sand placer deposits because they are generally much less consolidated than carbonatites, alkaline rocks or hydrothermal deposits. They are also often under water. Mining techniques include dredging and excavation by bucket wheel or by excavator. Some crushing may be required.

There are few details available of mining techniques for ion adsorption deposits in China but many are small-scale operations, with much of the mining done by manual labor. The clay deposits are excavated and leached to extract REE, mostly using in-situ leaching techniques, sometimes on large areas.

Some ores are mined as the main product from hard-rock deposits (e.g. Lovozero, Russia); some are mined as by-products from large-scale iron mining operations as in Bayan Obo, China; some are extracted as by-products from heavy-mineral sand dredging operations, such as

Manavlakurichi and Chavara in India; and some are leached out from ion-adsorption clay deposits, e.g. Xunwu/Longnan in South-East China.

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

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

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

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

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

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

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

EU mine production

The EU has no mining of rare earths, but imports ores and concentrates for refining. An iron ore producer - LKAB in Sweden, and phosphates fertilisers producer - Yara in Norway, currently develop processes to start a small rare earths production from their mining wastes. Potential exists also in coal and aluminium ore mining wastes.

21.4.4Supply from secondary materials/recycling

Recycling R&D on new processes were initiated in 2011 in a context of high prices and uncertainty of supply, when China announced a reduction of export quotas. There are several groups of products providing potential for recycling of REE, such as neodymium, dysprosium, praseodymium, samarium, gadolinium, europium, terbium, but also cerium and lanthanum.

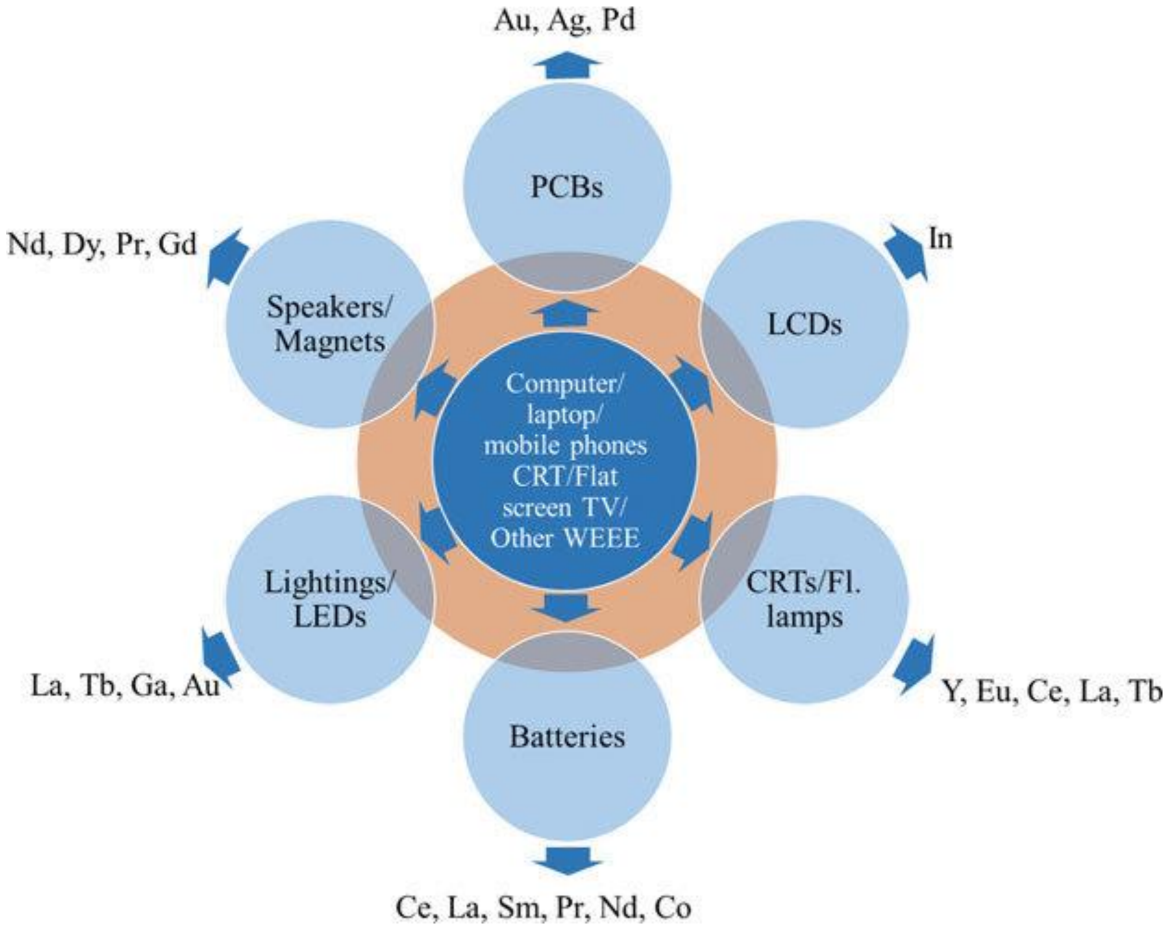


Figure 444: Example of different types of WEEE and potential for recyling raw materials, includingh rare earths. (Sethurajan et al., 2019)

Today, rescycling input rate is still very low, usually under 1%, especially in Europe because of the lack of efficient collecting systems and prohibitive costs of building REE recycling capacities (ERECON, 2014). Higher recycling input rates for europium, yttrium and terbium are repprted only thanks to recycling of fluorescent lamps.

Rhodia-Solvay, one of the main REE-based phosphors producers in the EU developed a recycling unit together with Umicore in France in 2012, but had to stop operations by January 2016 because it had become uneconomic (Delamarche, 2016). Solvay still produces several REE products, such as gadolinium, lutetium and yttrium oxides, cerium oxides and hydroxides, and neodymium versatate and neodymium phosphate used in chemical, medical, nuclear, glass and electronic applications. However, a lot of research projects are on-going to identify the best targets and processes (ERECON, 2014)

Recycling is often difficult because of the way that REE are incorporated as small components in complex items or are part of complex materials. The processes required are energy intensive and complex (Schüler et al., 2011).

Nevertheless, as for many metals, new scraps generated during the manufacture of alloys are an important secondary source, mainly in a closed loop (30% of magnet alloys end up in scraps during manufacture) (Higgins, 2016).

End-of-life recycling input rate of individual REE are summarized in Table 177.

Table 177: EOL-RIR of individual REE (1 - UNEP, 2013; 2 - Bio Intelligence Service, 2015; 3 - BRGM, 2015)

REE	LREE					HREE						
	Ce[1]	La[1]	Nd[2]	Pr[3]	Sm[1]	Dy[2]	Er[1]	Eu[2]	Gd[1]	Ho, Tm, Lu, Yb[1]	Tb[2]	Y[2]
End of life recycling input rate (EOL-RIR)	1%	1%	1%	10%	1%	0%	1%	38%	1%	1%	6%	31%

21.4.4.1 Magnets

Permanent magnets are the main secondary resources for the recovery of neodymium, praseodymium, dysprosium and samarium.

Swarf coming from shaping and cutting of the final magnet is a potential source of secondary materials, although its exploitation at large scales is hindered by some issues, such as: the swarf often needs further treatment steps before being introduced in the formulation of new magnet alloys, mainly because of its content in dysprosium or in other alloying elements; improvements in cutting tools and relative yields are lowering the availability of swarf as source of secondary materials.

Magnets extraction technology from the end-products has been already developed, but further improvements required to efficiently separate and recover REE from the magnets: in this latter field, several industries from Japan, as well as the French industry Rhodia-Solvay, have developed processes, but mainly targeting a technology to recover REE from magnets used in air-conditioning units (Roskill, 2016).

Two different methodologies have been developed for the recycling of end of life permanent magnets containing REE (Samouhos et al. 2019: SCRREEN).

The first, called direct recycling process, aims to the magnets reuse after their demagnetization, thermal treatment and re-alloying by the addition of extra amount of pure REE in the end of life material. The low environmental impact consists the main advantage of the direct recycling process. Researchers at the University of Birmingham optimised the direct recycling of NdFeB magnets via hydrogen decrepitation technology.

The second recycling methodology concerns the elemental recovery of Nd, Pr, Dy and Sm through classic hydro and pyro metallurgical techniques. Delft University developed a metallurgical route which is based on scrap leaching and REE extraction through selective precipitation. Several technological barriers should be overcome prior to the commercialization of REE extraction by EoL magnets. The most significant are: (a) the automation of magnets dismantling, (a) the reducing of leaching environmental impact and (c) the effective separation/purification of REE in the leachate.

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

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

An important boost to magnets recycling could come from the expansion of the market associated to large-size NdFeB magnets for wind turbines and HEVs: although the major size of such kinds of magnets makes their collection easier, their long life span (around 25 years) significantly impacts on the time in which a real recycling of the recovered magnets into lower-power applications can be carried out (Roskill, 2016).

21.4.4.2 Batteries

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

The recovery of metallic neodymium and praseodymium from metal hydride and Li-ion batteries has been commercially attempted by limited number of European companies. The recovery of Nd, Pr, Dy and Sm from EoL permanent magnets via numerous novel processes is described in literature. These processes have been successfully tested at laboratory or pilot scale, using shredered scrap that is pure and is composed by single devices. The investigation of Nd, Pr, Dy and Sm recovery at actual conditions using multi-composed scrap is necessary in order for the recycling sustainability to be proved. (Samouhos et al. 2019: SCRREEN)

21.4.4.3 Catalysts

The large amount of REOs (up to 4 wt% according to the features of the petroleum treated) contained in the FCC catalysts represents a valuable potential for recycling. Currently some research activities are moving in the REE recycling in FCC sector (Innocenzi et al., 2014; Zhao et al., 2016).

It is an open question whether a recovery of the REE (mostly La) from FCC catalysts could be interesting from an economic point of view in the next years. This is mainly depending on the price development of La (ÖkoÖko Institut, 2011). La/Ce Recycling will not be feasible as with rising volumes mined for NdPr, Ce/La gets more abundant (Balance problem of RE separation).

Currently, recycling activities on catalysts from the automotive sector are based only on the recovery of platinum group metals (PGM) from catalytic converters. "Cerium oxide is not commercially recovered from catalytic converters; instead, it is sent to landfills along with the waste produced by processing the monoliths for their PGM content" (Biswas, 2013).

The recycling of catalytic converters will continue to rely on the economic viability of recovering their PGM content (Biswas, 2013). There are currently no commercially viable technologies to recover the cerium content of catalytic converters (Biswas, 2013).

21.4.4.4 Polishing:

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

Regarding secondary supply of cerium, recycling has developed for polishing powders since 2011, mostly in Japan, where cerium can be re-used in the form of mishmetal (BRGM, 2015).

21.4.4.5 Glass

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

21.4.4.6 Phosphors

Phosphors originated from end-of-life LCDs, computers, X-ray tubes, light bulbs and TV-sets is a significant secondary resource of yttrium. Yttrium is currently industrially extracted from various electric and electronic scrap materials in EU (Rhodia-Solvay, Narva Light Sources GmbH, Eco Recycling in Northern Italy).

Europium, terbium and yttrium from end-of-life lamps had been recycled at the Rhodia-Solvay plant in La Rochelle from 2011 until its closure in 2016 (Usine Nouvelle, 2016). Rhodia-Solvay developed a patented process (2012) to recover and recycle REE from fluorescent lamps; recovering up to 95% of REE contained in a fluorescent lamp (Walter, 2011). The plant reached its full capacity (i.e. 2,500 tpy of processed power) in 2013 (Binnemans et al., 2013c). Around 2011, primary europium oxide, terbium oxide and yttrium oxide were expensive (around 5,900 $/kg for europium oxides, and 5,000 $/kg for terbium oxides,) (BRGM, 2015) and there was a demand for cheaper, recycled the rare earth oxides. However, by 2015 prices of prices of primary terbium dropped to around 500 $/kg lasting until today, and primary europium dropped significantly to 445 $/kg in 2015 and 30 $/kg in 2019, thus rendering the recycling process far less competitive than during the crisis (2011-2014). Solvay announced in early 2016 the closure of the plant by the end of 2016. Solvay however still offers yttrium oxides amongst their products.

A number of patents in the literature describe the development of dismantling machines for the automated mechanical treatment of EoL fluorescent lamps. Some current strategies for Y recycling are acid/basic leaching or solvent extraction. In the last years, several European projects were carried out to improve and develop novel strategies for recycling REE. For example, in the SepSELSA project a successful new approach called solid-state chlorination was developed, which could provide various advantages in terms of costs and disposal.

Concerning cerium extraction from scrap, the recycling of ceriume containing LEDs has been attempted at pilot scale. The developed process comprises a combination of manual and mechanical processing steps aiming to the removal of non-metallic components and the enrichment of the recycling stream. The results of this research consists a useful tool for the further development of the dismantling and pretreatment processes in case of other electronic wastes. However today, the market price of cerium is very low (6$/kg for the pure metal, 2$/kg for the pure oxide), limiting the potential development of a recycling market. In terms of environmental impact, if the recycling strategies rely on the same process used for the primary production, no significant difference is expected. Only a breakthrough in the selected processes could bring an added value for the development of a sustainable secondary production of cerium. (Samouhos et al. 2019: SCRREEN)

21.4.4.7 Other applications

A minor part of recycled yttrium comes from oxygen sensors contained in end-of-life vehicles (Bio Intelligence Service, 2015).

Ho, Tm, Yb and Lu recovery from scrap has not been attempted even at laboratory scale due to the limited number of end-of-life devices containing these REE and their low concentrations. Specific attention should be given to the collection, classification and dismantling of end-of-life scraps containing Ho, Tm, Yb and Lu as a first recycling-action. (Samouhos et al. 2019: SCRREEN)

21.4.5Processing and separation

21.4.5.1 World

There is no data on production of high purity single REE, but it is believed that only China holds industrial scale separation plants for the whole range of REE (this is the current bottleneck).

Lynas Malaysia is one of the largest rare earths separation plants in the world treating the Mt WeldA ustralia concentrate and produce separated light REO products for sale to customers in locations including Japan, Europe, China and North America. It was designed and built in two phases, with full Phase 2 capacity capable of producing up to 22,000 tonnes per annum of separated REO products. Commissioning of Lynas Malaysia started in late 2012. Currently, the most valuable product produced at the plant is praseodymium/neodymium, NdPr. Lynas produced its first Rare Eaths products for customers in February 2013.

USA Rare Earth LLC and Texas Mineral Resources Corp. announced in December 2019 the opening of a REE pilot separation plant in Wheat Ridge, Colorado from the Round Top deposit, El Paso, Texas containing HREE and LREE, lithium, uranium, beryllium, gallium, hafnium and zirconium.

Texas Mineral Resources have also purchased the neodymium iron boron (NdFeB) permanent magnet manufacturing equipment with capacity of 2,000 tonnes per year (17% of the current U.S. market, $140 million in annual sales at 2019 prices), formerly owned and operated in North Carolina by Hitachi Metals America, Ltd. USA Rare Earth (NdFeB) Permanent Magnet Plant. In late 2011, Hitachi announced the phased construction of a state-of-the-art sintered rare earth magnet manufacturing facility, planning to spend up to $60 million over four years. However, following settlement of the rare earth trade dispute between China and Japan, Hitachi closed the plant in 2015 after less than two years of operation.

21.4.5.2 EU

The EU has no mining of rare earths, but imports ores and concentrates for refining. Over the last decade, the EU reduced the rare earths processing and refining capacity, such as Solvay operation in La Rochelle. NPM Silmet operation in Estonia is still operational.

At the mining stage, REE are assessed as mixes of REO or low purity single REE ores and concentrates (this roughly corresponds to mining + first stages of processing / separation). CN8 codes used for this stage are: 28461000 "Cerium compounds", 28469010 "Compounds of lanthanum, praseodymium, neodymium or samarium, inorganic or organic" and 28469020 "Compounds of europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium or yttrium, inorganic or organic". Eurostat data have been reported as REO content by using the conversion factors (see Table 182).

The use of term "compound" opens for various interpretations, such as to whether it refers to different types of compounds (metals, alloys, oxides, salts), and thus, REE that encompasses all types of compounds, or whether it refers to rare earth metals, as metals of individual elements in form of alloys.

At the refining stage, we consider mixes of high purity single REE (this correspond to advanced separation / refining). The trade codes used for EU trade are CN8: 28053010 "Intermixtures or interalloys of rare-earth metals, scandium and yttrium", 28053020 "Cerium, lanthanum, praseodymium, neodymium and samarium, of a purity by weight of >=95% (excl. intermixtures and interalloys)", 28053030 "Europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium and yttrium, of a purity by weight of >=95% (excl. intermixtures and interalloys)".

EURARE (2017) reports a global production of 50 kt of REE metals in 2015 mostly centered in China holding industrial scale separation plants (Barakos, 2018). Estonia and United Kingdom produced 500 tonnes in the same period.

REE have a complex supply chain, and products are sold at several stages along the processing and separation sequence. The first step is the processing of the ore to produce mineral concentrates containing mixed rare earth oxides (REOs). Those concentrates can be sold at this stage to downstream processors. However, an increasing proportion of ore is now processed in vertically integrated companies (both in China and the rest of the world) partly due to the difficulty (and cost) to have the specific technology and knowledge to process each individual type of ore (Roskill, 2015).

Further processing lead to REE compounds such as rare earth carbonates, nitrates and chlorides. Those products can be sold to end users such as catalyst manufacturers or are supplied to downstream processors for separation.

The goal of separation is to obtain individual rare earths compounds to a degree of purity of 99.9% (3N) to 99.9999% (6N). The majority of production is in the oxide form but individual rare earth carbonates, chlorides or fluorides can also be produced. This step is technically difficult and costly in comparison to others. It involves various phases; initial separation results in the isolation of lighter elements such as lanthanum and cerium, as well as intermediate products such as mischmetal (La-Ce, La-Ce-Pr or La-Ce-Pr-Nd) and didymium (Pr-Nd). These products are combinations of individual rare earths and can be supplied directly either to magnet alloy producers or in the iron and steel industry. The heavier fractions (Sm-Eu-Gd) are separated in the end. The main method used for separation is solvent extraction (SX), suitable at the industrial scale to produce large tonnages of individual compounds. Ion adsorption is more adequate to extract small quantities of HREE of 6N purity (BRGM, 2015).

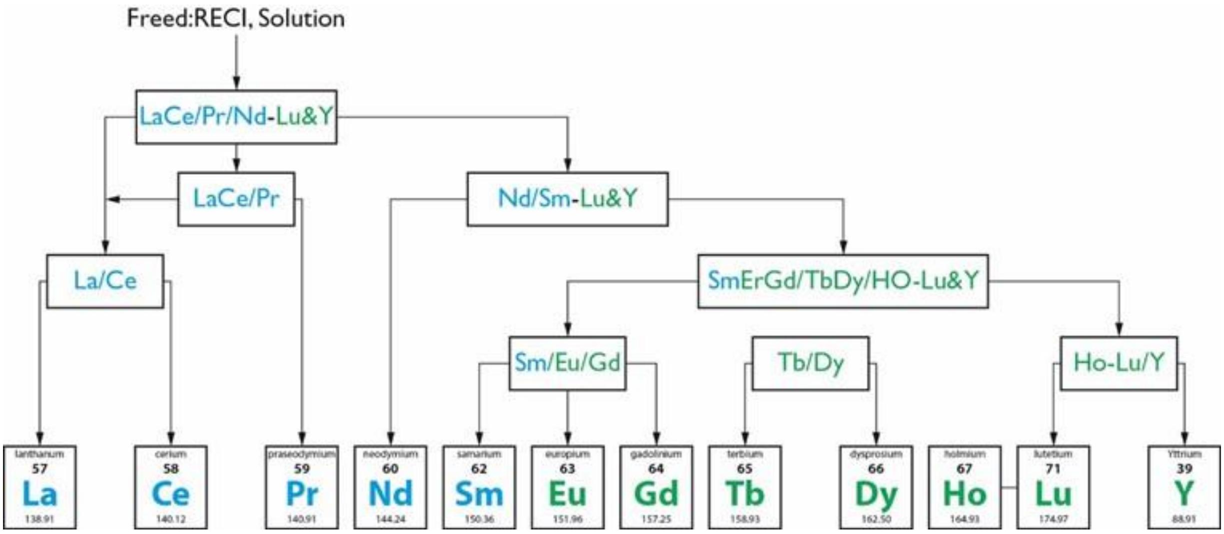


Figure 445: Example of a schematic REE solvent extraction (SX) separation process (Machacek and Kalvig 2017: EURARE adapted from Zhang and Zhao, 2016)

Further refining is needed for the production of REE metals and alloys. It is also a very costly and complicated step. Most of the time, metallothermic reduction is used for preparation, followed by further reduction where boron, iron or cobalt can be added to form the desired magnets alloys. Pure REE metals (99,999% or more) are the most expensive products and usually purchased for very specific applications.

21.4.5.3 Chemical separation methods

"*With respect to physical and chemical properties, the REE have strong similarities; this makes the chemical separation of the individual REE a complicated process. Three types of separation technologies are applied by the industry: (i) the fractional step method; (ii) the ion exchange method (IX), and (iii) the solvent extraction method (SX). The IX and SX methods constitute the processing technologies applied on an industrial scale, close to 100% of which occurs in China (Izatt et al., 2016).*

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

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

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

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

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

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

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

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

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

A new separation technology has been developed by the EURARE project, which has the potential to be an alternative to the MRT technology. The EURARE-technology involves appropriate ligands being grafted onto magnetic silica nanoparticles, which are introduced to the REE solutions. The produced adsorbents demonstrated rather quick adsorption kinetics, achieving at least 80% of maximal capacity within some few minutes. Considerable selectivity is observed, favoring retention of HREE (Dy in comparison with Nd and La) with distribution coefficients achieving values over 80:1. The magnetic nature of the nanoparticle allows for simple and robust solid/liquid separation with use of magnets. The principles of the EURARE technology are shown *in Figure 446. Application of this technology in processing REE from both ore leachate and from dissolved components in recycling processes should offer efficient uptake and controlled release under precisely defined pH conditions."* (Machacek and Kalvig 2017: EURARE)

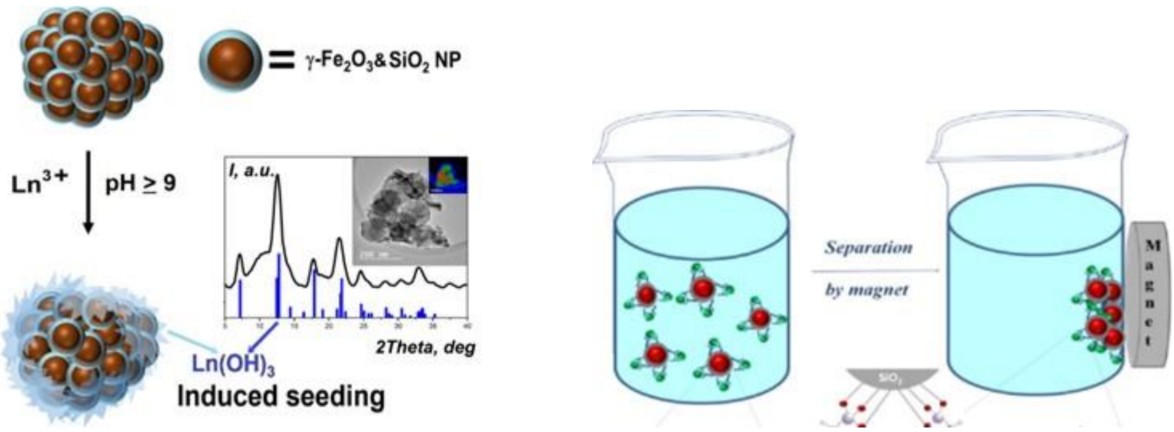


Figure 446: Principles in the magnetic nanoparticle separation technology (Machacek and Kalvig 2017: EURARE)

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

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

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

21.5 Other considerations

21.5.1 Standardisation – Technical committee ISO/TC 298 on Rare earths

The International Organization for Standardization (ISO) has formed a technical committee (ISO/TC 298[238]) in September 2015, following the proposal from China, to explore the possibility of international standardization of rare earth products. The Standardization Administration of China (SAC) has been appointed as the secretariat. Currently, nine countries, including Denmark, are participating members of the technical committee and there are 24 observing members, including 10 from EU. 11 ISO standards are under development in the fields of rare earth mining, concentration, extraction, separation and conversion to useful rare earth compounds/materials (including oxides, salts, metals, master alloys, etc.).

Participating Members (9)	Australia (SA) Canada (SCC) China (SAC)	Denmark (DS) India (BIS) Japan (JISC)	Korea, Republic of (KATS) Russian Federation (GOST R) United States (ANSI)
Observing Members (24)	Argentina (IRAM) Armenia (SARM) Brazil (ABNT) Cuba (NC) Czech Republic (UNMZ) Egypt (EOS) Finland (SFS) France (AFNOR)	Germany (DIN) Iran, Islamic Republic of (ISIRI) Israel (SII) Italy (UNI) Malaysia (DSM) Mexico (DGN) Netherlands (NEN) Pakistan (PSQCA)	Poland (PKN) Portugal (IPQ) Saudi Arabia (SASO) South Africa (SABS) Spain (UNE) Sweden (SIS) Switzerland (SNV) Viet Nam (STAMEQ)

21.5.2 Environmental and health and safety issues

21.5.2.1 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 (ERECON 2015).

EIA directive 2014/52/EU [239] 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

[238] https://www.iso.org/committee/5902483.html

[239] Directive 2014/52/EU of the European Parliament and of the Council of 16 April 2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment. – Official Journal of the European Union, L 124/1, 25.4.2014

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 2006/21/EC[240] 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.[241] 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 2013/59/Euratom [242] 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.

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. (ERECON 2015)

[240] Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC. - Official Journal of the European Union, L 102/15, 11.4.2006

[241] European Commission: Best Available Techniques document for the Management of Waste from the Extractive Industries, in accordance with Directive 2006/21/EC, abbreviated as MWEI BREF. Reviewed in 2018.

[242] Directive 2013/59/Euratom - protection against ionising radiation of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation, and repealing Directives 89/618/Euratom, 90/641/Euratom, 96/29/Euratom, 97/43/Euratom and 2003/122/Euratom

21.5.2.2 Toxicity and radioactivity

REE extraction and processing faces environmental and health and safety challenges. At present, however, information regarding the environmental aspects of REE mining is limited. Toxicological data about the effects of REE on aquatic, animal, or human health are also limited (USGS 2017b).

REE-minerals are in many cases associated with uranium (U) and thorium (Th), either incorporated into the lattice of the REE-minerals or in associated minerals within the ore mineral assemblage. This is particularly the case for the alkaline igneous and carbonatite-associated REE mineralization, and also typically for placers. During the precipitation and selective dissolution, U and Th will exit the solvent extraction circuit and become radioactive waste. Some of the Th and U are removed during all the purification steps (precipitation, selective dissolution), but due to the strong extraction of Zr^{4+}, Th^{4+}, UO^{22+} and Fe^{3+} these metals will be extracted together with the HREE fraction (Email communication with respondent of Mintek, 2013). The radioactive elements can remain a part of the REE concentrate. Once they are liberated, they act as individual elements. For instance, the decay daughter of U-235, actinium isotope Ac-227 behaves like lanthanum and remains with the REE. U and Th are used as indicators for the presence of other radiogenic daughter products. (Machacek and Kalvig 2017: EURARE)

Radioactivity is one of the issues that has to be addressed with care as it is a matter of real concern to local communities. Rare earth minerals are frequently collocated with naturally occurring radioactive material, monazite has the highest thorium content, while bastnäsite contains relatively low concentrations of both thorium and uranium. The thorium content in mineral concentrates varies from less than 0.1 to about 10%, while the uranium content varies from very low values to 1% (IAEA, 2011).

Depending on minerals and process used, their extraction, separation and refining may result in waste containing higher levels of radioactive material which can have serious health and environmental impacts (Koltun & Tharumarajah, 2014) (IEA, 2011). Rim, Koo, and Park (2013) state that the whole process poses a great risk to miners and residents of mining towns who inhale higher amounts of radioactive dust. However, currently available methodologies in life cycle assessment are insufficient to account for the impact of naturally occurring radioactive materials on both humans and ecosystems (Frischknect, 2000) (Garnier-Laplace et al., 2009). A newly devised NORM impact category addresses this issue (Goronovski et al., 2018; Joyce et al., 2017). However, it is been shown that the materials found in REE are not more radioactive than the radioactivity humans are exposed to daily.

Toxicity is another issue for the REE which has been exposed via life cycle assessment. However, the models for toxicity of metals are not robust enough to be taken at face value. There is a big question of interpretation for these categories within life cycle assessment (Santero and Hendry, 2016). All REE can cause organ damage if inhaled or ingested in large quantities; some must be handled with extreme care to avoid poisoning or combustion (Geological Survey of Finland, 2014) (Higgins, 2015).

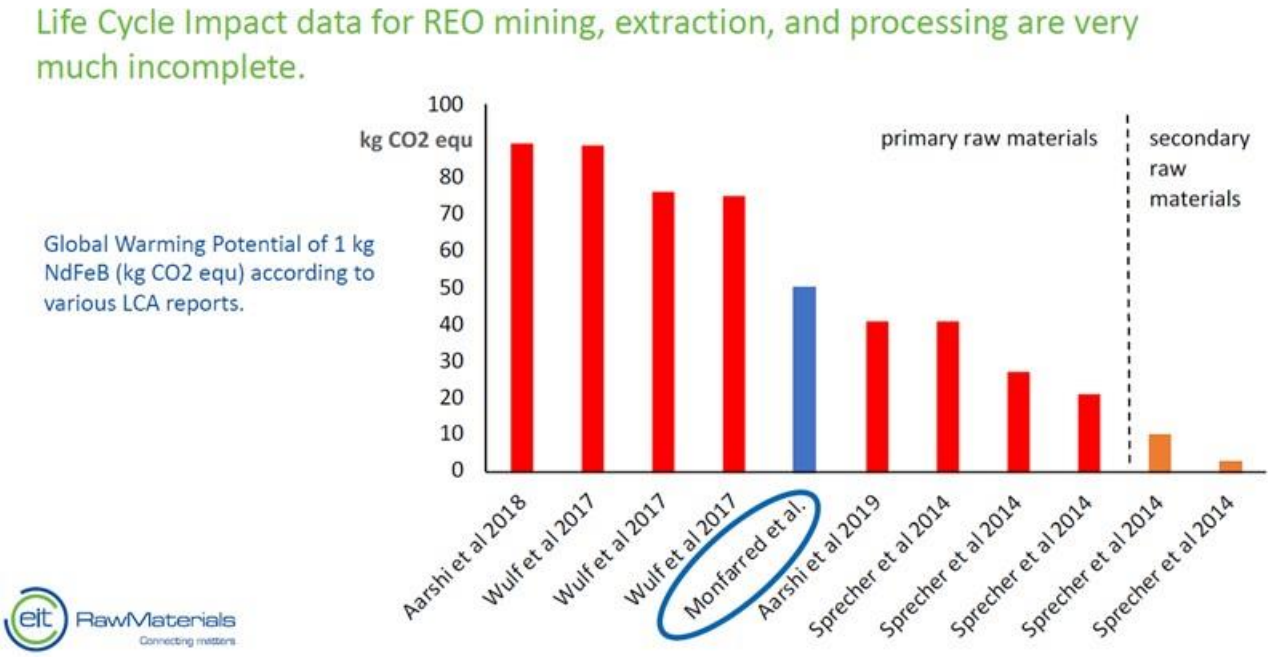


Figure 447: LCA-studies (EIT RM)

21.5.2.3 Enabling climate targets

Over the past two to three years, an ever-growing list of countries have announced impending bans on sales of new gasoline- and diesel-powered vehicles by as early as 2025. And similarly, an ever-growing list of cities have announced impending bans that will prohibit use of gasoline- and diesel- (or just diesel-) powered vehicles within city limits by as early as 2024.

The nine countries and one U.S. state in the list on the left collectively have potential to fuel electric vehicles sales to upwards of 10 million per annum by 2030 and 20 million per annum by 2040 and in doing so, would collectively make a major contribution towards meeting the Paris Climate Commitment targets. Such a massive deployment of electric vehicles could create demand for approximately 25,000 tonnes of NdFeB annually by 2025 and 60,000 tonnes by 2030. (Adamas Intelligence, 2019)

Country	Ban Commences	Passenger Vehicle Market Size (2018)
Norway	2025	0.2 million
Germany	2030	3.8 million
Ireland	2030	0.2 million
Israel	2030	0.3 million
India	2030	4.0 million
Netherlands	2030	0.4 million
U.K.	2040	2.9 million
France	2040	2.6 million
Taiwan	2040	0.3 million
U.S. (California)	2040	2.0 million

City	Ban Commences	Population (2018)
Rome	2024	2.9 million
Paris	2025	2.1 million
Madrid	2025	3.2 million
Mexico City	2025	8.9 million
London	2030	8.1 million
Los Angeles	2030	4.0 million
Hainan	2030	8.7 million
Seattle	2030	0.7 million
Vancouver	2030	0.7 million
Amsterdam	2030	0.8 million

Figure 448: list of countries and cities have announced impending bans on sales or use of gasoline- and diesel-powered vehicles (Marklines, The World Bank, United Nations, Adamas Intelligence research)

21.5.3Socio-economic issues

There are few recent studies conducted regarding the social issues pertaining to the extraction and production of REE-containing products. Werker et al. (2019) conducts a social LCA on three different REE mine and magnet production sites. The impact categories evaluated are numerous ranging from issues of social responsibility, fair competition and corruption. Overall, out of the three sites evaluated, the US value chain indicates the lowest level of social risk along the supply chain (Werker et al., 2019). Across all three cases, the mineral, fossil fuel and chemical sectors are shown to be problematic in terms of impact to society.

Recently, Bailey (2019) developed a methodology for performing life cycle assessment for the entire life cycle and cost of REE inside magnets and motors, using economical and environmental models for cost-efficient and environmentally-friendly direct and indirect recycling routes.

Another study evaluates the importance of the REE and other CRMs supply risk using the World Governance Index (WGI) (Mancini et al., 2018). The purpose of the supply risk based characterization factors (CFs) provided by Mancini et al. (2018) is to warn practitioners of the use of CRMs, rather than to measure an environmental impact.

Mancini et al. (2018) developed these CFs by dividing the supply risk by the world governance index, which is a modified Herman Hirshfindaal indicatior (HHI) on concentration of supply. This data provided in European Commission (2017) and appropriated them as midpoint CFs. The list of CFs are included in the methodology are as follows:

SR_{WGI} is supply risk based on WGI

- SR_{WGI} = supply risk due to low governance

- $SR_{WGI^{\wedge}6}$ = supply risk due to low governance exponential
- SR_{WGI}/Production = supply risk related to global mine production
- SR_{WGI}/Reserves = supply risk related to geological reserve data

The SR_{WGI} dataset denotes a risk of supply disruptions due to supply concentration and political instability of the producing country. This supply risk aspect is characterized using SR_{WGI} data provided in the European Commission study on CRM and appropriates each SR_{WGI} value for each material or resource as midpoint CFs (European Commission, 2017). The SR_{WGI} has low variability; therefore, the difference between materials or resources in terms of security is not evident when these values are applied as linear weighting factors, so a subjective exponent of 6 was added to this assessment to be able to better view the supply security (Mancini et al., 2018). The SR_{WGI}/Production divides the supply risk by the size of the market, that is, the global mine production in a given year, in order to better capture niche materials having small markets (Mancini et al., 2018). Despite the imprudent use of reserves data as an indicator for prodection potential, the SR_{WGI}/Reserves method divides the supply risk by geological reserve data to be able to include, "an element related to resource availability" (Mancini et al., 2018). Thus, when applying an element of criticality and resource efficiency to an environmental assessment, then the supply risk for REE is important which also reveals the benefits of recycling.

21.5.4R&D

ERECON

ERECON was an EU funded action to create a network of REE stakeholders finished in 2015. After the end of ERECON, a large number ofstakeholder platforms, industry activities and research projects have emerged as a response to increasing concerns over supply security of REE.

The EU financed REE related R&D projects for over a decade.

The project targeted primary and secondary production of rare earths and magnets, substitution of REE and expert networks. Below in Table 178 some of the relevant projects are listed.

However, to our knowledge there is still no mainstream solution today for recovering REE applied on the EU primary resources and end-of life products.

Table 178: Overview of projects from the 7th Framework Programme, Horizon 2020, ERA-MIN, ERA-MIN 2 as well as EIT Raw Materials that are concerned with supply security of REE (European Commission 2018).

project	*budget (million €)*	*metals secured*	*information and transparency*	*secondary supply*	*industry and innovation*
EURARE	13.8	REE	x		
MIDAS	12.3	Co, Mn, REE	x		
REE4EU	9.1	REE		x	
REEcover	7.9	REE (Y, Tb, Nd, Dy)		x	
SCALE	7.7	REE (Sc)		x	
FAME	7.5	unspecified	x		
NOVAMAG	7.1	REE,			x
ADIR	6.6	Ta, REE, Ge, Co, Pd, Ga, W		x	
REProMag	5.7	REE			x

project	*budget (million €)*	*metals secured*	*information and transparency*	*secondary supply*	*industry and innovation*
HiTech AlkCarb	5.4	REE (Sc), Nb, Hf, Ta, Zr	x		
PARTIAL-PGMs	5.0	PGM (Pt, Pd, Rh), REE			x
AMPHIBIAN	4.9	REE			x
COLABATS	4.6	Co, REE, Ni, Li		x	
RECYVAL-NANO	4.4	In, REE (Y, Nd)		x	
EREAN	3.9	REE		x	
DEMETER	3.8	REE (Nd, Sm)		x	
HYDROWEEE DEMO	3.8	REE : Ce,Eu, La, Tb, Y ; In, Li, Co, Zn, Cu, Au, Ag, Ni, Pb, Sn, PGM (Pt, Pd)		x	
REDMUD	3.7	Fe, Al, Ti, REE (Sc)		x	
REMAGHIC	3.7	REE		x	
ProSUM	3.7	secondary CRMs and other materials		x	
MAG-DRIVE	3.6	REE (Nd, Dy)			x
ARMEVA	3.6	REE			x
SCRREEN	3.0	all CRMs	x	x	x
VENUS	2.9	REE			x
SMART GROUND	2.5	Unspecified		x	
SOLCRIMET	2.5	REE, Ta, Nb, Co, In, Ga, Ge, Sb		x	
ENVIREE	2.5	REE	x	x	
NOVACAM	2.4	PGMs (Pt, Pd, Rh), REE			x
REE-CYCLE	2.3	REE		x	
MinFuture	1.2	unspecified	x	x	
RAREASH	1.1	REE		x	
AMDREY	1.0	REE (Y)	x	x	
HYTECHCYCLING	0.5	unspecified		x	
CAPTURE	0.3	REE, Cu, Zn, Ni	x		
REMSIL	0.2	REE		x	
QUMEC	0.2	unspecified		x	
REE Value Chain	0.2	REE	x	x	
MINEPEP	0.2	REE (La, Y)		x	
BATRe ARES	n.a.	REE		x	
FREECATS	n.a.	PGM, REE, Cr			x
inSPECtor	n.a.	REE, others	x		
INSPIRE	n.a.	unspecified	x	x	
PCRec	n.a.	unspecified		x	
SPARK	n.a.	REE		x	x
STRADE	1.9	unspecified	x	X	
ReCREW	n.a.	unspecified	X	x	
MINATURA 2020	2.0	unspecified	x	X	

project	*budget (million €)*	*metals secured*	*information and transparency*	*secondary supply*	*industry and innovation*
INTRAW	2.1	unspecified	X	X	x
REMENANCE	4.9	REE	X	x	X
REMinE	n.a.	unspecified	X		x
CERA	n.a.	unspecified	x		X
EMFIS	1.0	unspecified	x		X
IRTC	n.a	unspecified	x		X
SIMS	16.1	unspecified			x
SMART GROUND	2.4	unspecified			x

21.6 Comparison with previous EU assessments

A revised methodology was introduced in the 2017 assessment of critical raw materials in Europe and both the calculations of economic importance and supply risk are different compared to the results of the previous assessments. Therefore, the changes observed are largely due to the revised methodology and not due to significant market changes.

The individual assessment results of each of the 15 REE indicate that each one should be considered critical, with the exception of lanthanum.

The main driver for the Supply Risk result for the overall REEs group is explained by important EU reliance on Chinese production, which are characterised by the quotas / export taxes from China enacted during the 2012 – 2016 period. Generally speaking, there is no significant REE transformation and manufacturing activity in the EU; a large proportion of EU consumption / imports of REE comes from finished products to the EU (e.g. magnets, alloys, hard drives, laptops, electric or hybrid vehicles, etc.). Further, in most of their applications, REE are not substitutable without losses of performance. However, for economic reasons, many R&D strategies have focused on reducing the amount of REEs used in their different applications.

The results of the 2020 assessment and the previous assessments are shown in Table 179.

Table 179: Economic importance and supply risk results for REE in the assessments of 2011, 2014 (European Commission, 2011; European Commission, 2014) and 2017.

Assessment year	2011		2014		2017		2020	
Indicator	EI	SR	EI	SR	EI	SR	EI	SR
LREEs	5.78	4.86	5.37	4.67	3.6	4.9	4.3	6.0
HREEs			5.21	3.13	3.7	4.8	3.9	5.6

21.7 Data sources

21.7.1 Data sources used in the factsheet

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21.7.2 Data sources used in the criticality assessment

The calculation of economic importance is based on the use of the NACE 2-digit codes and the value added at factor cost for the identified sectors (See chapter 3.2 for the applications, 2-digit NACE sectors and value added per sector for each rare earth element). The value added data correspond to 2013 figures.

Data sources for the estimation of REE supply are summed up in Table 180.

Table 180: Sources of data for the estimation of REE supply.

		Data for all REEs (mixed)		Data for individual REEs	
		Nature of data	Data source	Nature of data	Data source
Scope of supply	Global	Production	BGS, USGS, Roskill, BRGM, ASTER project	Relative concentration of the individual REE in the total world production of REEs	EC (2014) Report on critical raw materials
	EU	Imports to the EU	EUROSTAT	Share of the individual REE in the total EU use of REEs	ASTER project

The codes used for the EUROSTAT extraction (COMEXT database) and the REO content are reported in Table 181 (sources: Guyonnet et al., 2015; updated in Bio Intelligence Service, 2015 for the conversion factors).

Table 182: EUROSTAT codes for REE and REO conversion factors

NC8 Code	Description	Estimated REO conversion factor
28461000	Cerium compounds	0.72
28469000	Compounds, inorganic or organic, of rare-earth metals, of yttrium or of scandium or of mixtures of these metals (excl. cerium)	0.63

The disaggregation factors for individual REEs reported in Table 183 were estimated according to TMR Advanced Rare-Earth Projects Index[243] (TMR, 2015). The share of the individual REE in the total EU use of REEs is based on the ASTER project (Guyonnet et al., 2015).

Table 183: Disaggregation factors for individual REEs

REE	Relative concentration of the individual REE in the total world production of REEs	Share of the individual REE in the total EU use of REEs
La	24.5%	41.0%
Ce	44.3%	39.4%
Pr	4.7%	2.6%
Nd	15.8%	6.4%
Eu	0.4%	0.4%
Gd	1.4%	0.2%
Tb	0.2%	0.4%
Dy	0.9%	0.2%
Y	4.7%	8.8%
Sm	2.2%	0.4%
Er	0.4%	0.2%
Ho, Tm, Yb, Lu	0.6%	0.2%

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[243] http://www.techmetalsresearch.com/metrics-indices/tmr-advanced-rare-earth-projects-index/ last updated on November 19, 2015, (Accessed June 2019).