***SCRREEN2***

*This project has received funding from the European*

*Union's Horizon 2020 research and innovation programme*

*under grant agreement No 958211.*

Start date: 2020-11-01 Duration: 36 Months

# FACTSHEETS UPDATES **BASED ON THE EU FACTSHEETS 2020**

# RARE EARTH ELEMENTS

AUTHOR(S):

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# RARE EARTH ELEMENTS (REE)

## OVERVIEW

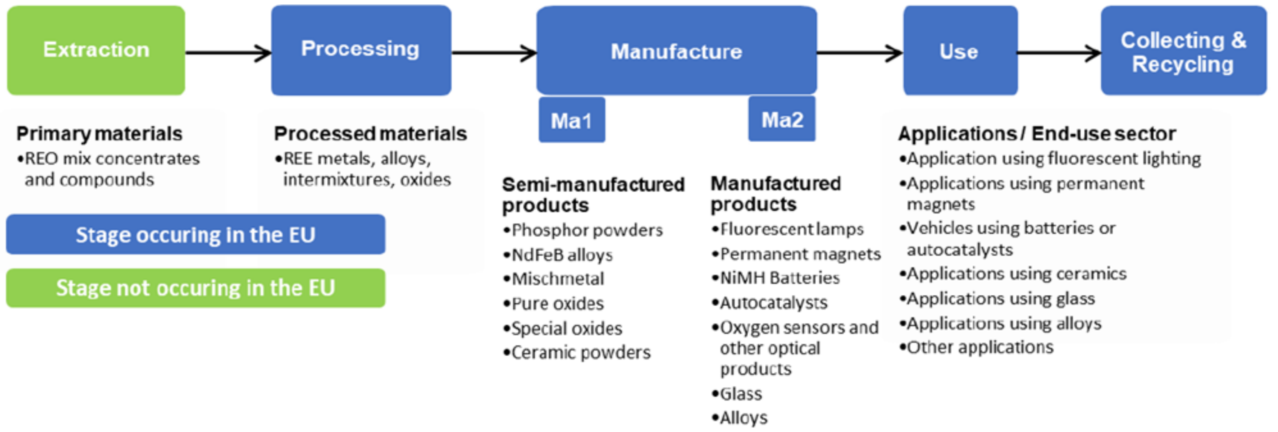


**Figure 1. Simplified value chain for REE in the EU**

**Table 1. REE supply and demand in metric tonnes, 2016-2020 average (in metal content, EUROSTAT 2022)**

| REE | Global production (in tonnes) | Global Producers | EU consumption | EU Share | EU Suppliers | Import reliance |
|---|---|---|---|---|---|---|
| **Ce** | 57740 | China 68%<br>Australia 10%<br>USA 9%<br>Myanmar 8%<br>Russia 2% | 4086 | | Russia 64%<br>China 18%<br>Other countries 7%<br>UK 4% | 100 |
| **Nd** | 26845 | | 119 | | China 80%<br>Ohter countries 11%<br>UK 3%<br>USA 2% | 100 |
| **La** | 42823 | | 2234 | | | |
| **Pr** | 6860 | | 107 | | | |
| **Sm** | 3343 | | 26.5 | | | |
| **Eu** | 381 | | 3.86 | | China 64%<br>Japan 17%<br>UK 8%<br>Russia 5%<br>South Korea 3% | 100 |
| **Tb** | 182 | | 5.9 | | | |
| **Gd** | 1974 | | 170 | | | |
| **Er** | 478 | | 111 | | | |
| **Y** | 5133 | | 224 | | | |
| **Ho** | 123.11 | | 0.23 | | | |
| **Lu** | 15.49 | | 20.5 | | | |
| **Tm** | 15.44 | | 0.74 | | | |
| **Yb** | 186 | | 27 | | | |
| **Dy** | 708 | | 1.13 | | China 65%<br>Japan 18%<br>Russia 21%<br>UK 8% | 100 |

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

Global mine production is estimated at 280,000 tonnes of REO equivalent in 2021, significantly increased in comparison to 2020 (240,000 tonnes). Production of REO in China was estimated to be 168,000 tonnes (USGS, 2022). China provided around 62% of the world's primary production of REEs in 2020

EU imports 100% of its REEs. 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 to manufacture REE-based products for various industries (phosphors, catalysts, polishing powders, etc.). There are also alloys makers and magnet manufacturers (in Germany and Slovenia) operating from imported processed materials. Just outside of the EU there is metal and alloy-making capability in the UK.

The EU consumption of REE is 4,734 tonnes/y of compounds (expressed in rare-earth oxide or REO equivalent content) and 683 tonnes/y of REE metals and interalloys during the 2016-2018 period, and is entirely based on imports, which amount to 9,438 tonnes/y for REO compounds and 1,162 tonnes/y of REE metals and interalloys.

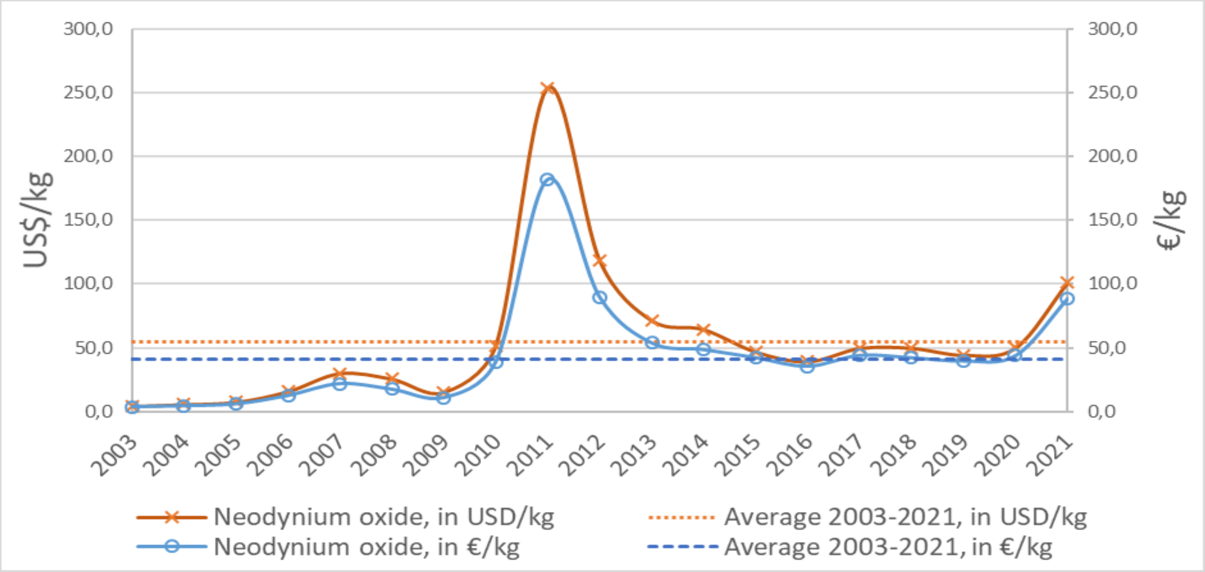


**Figure 2. Annual average price of Nd2O3 between 2000 and 2020 (S&P Global, 2022).**

**Prices:** Prices of REEs experienced great variations in the last decade. In 2010-2011 a 12-fold increase was observed, mainly triggered by misinterpretation by the global market of a significant reduction in Chinese export quotas in 2010 (not actual exports) and geopolitical tension in a period of high demand for permanent magnets, driven by the expected growth of the renewable energy and EV market. From early 2012, prices were already down by half and went down almost continuously until 2019, showing relatively short-term volatility. Neodymium prices graphic is given as illustration on Figure 2

**Primary supply:** 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%. In recent years, China's share of global REE mine production has fallen slightly as a handful of new or re-activated REE mines have come on stream outside China. However, China has continuously expanded its share of downstream value-adding production of oxides, metals, alloys and magnets (Mancheri et all 2019).

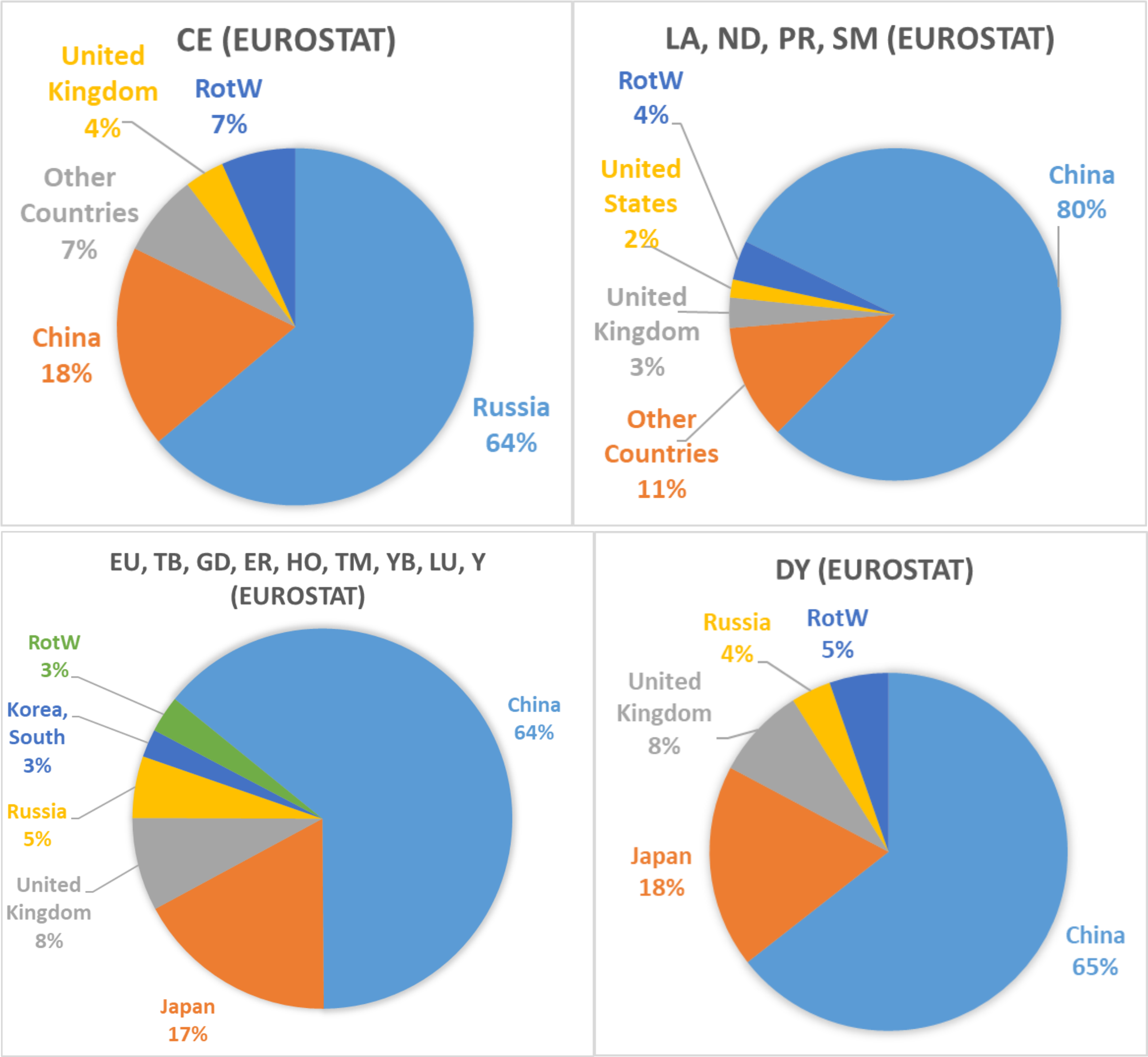


Figure 3. EU imports of REE by country (2016-2020) (EUROSTAT 2022). Net import value for each REE given in Table 1

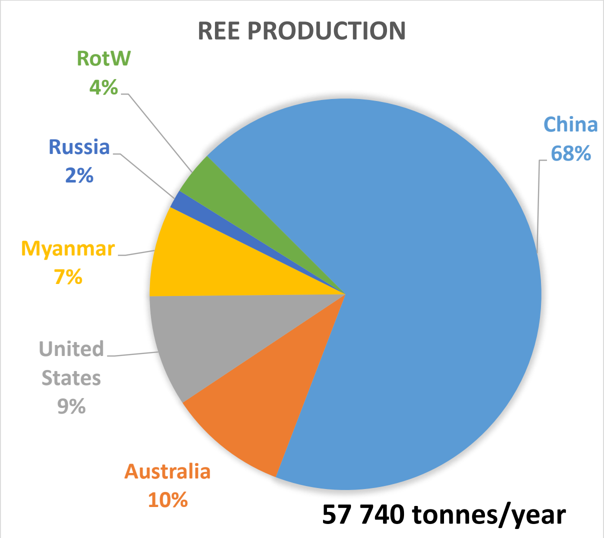


Figure 4. Global mine production of REE (2016-2020)

**Secondary supply:** Today, recycling 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 reported only thanks to recycling of fluorescent lamps. 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

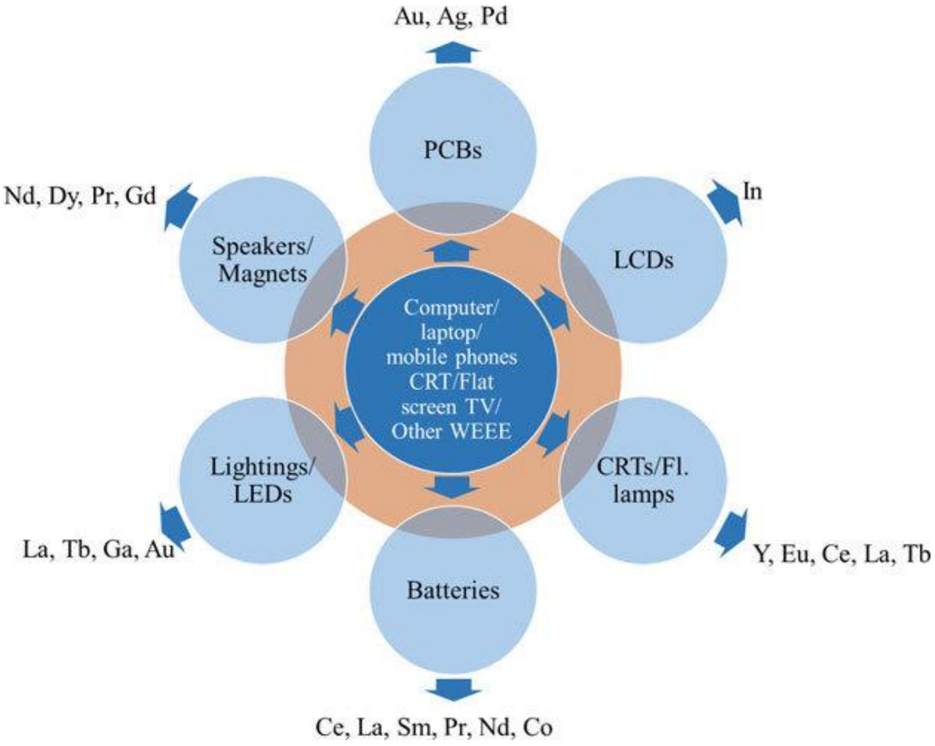
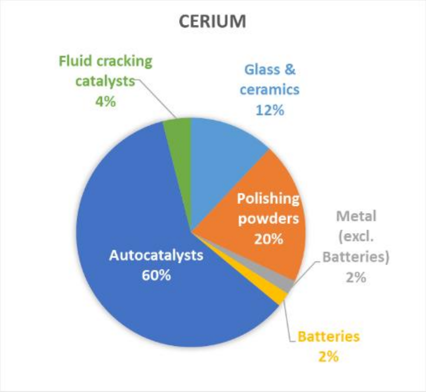
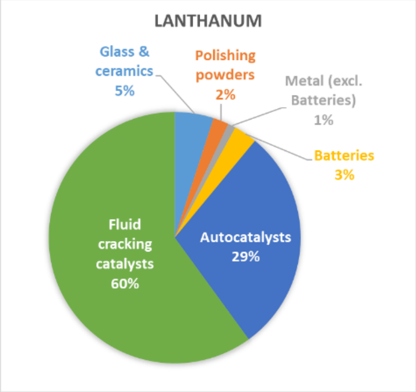
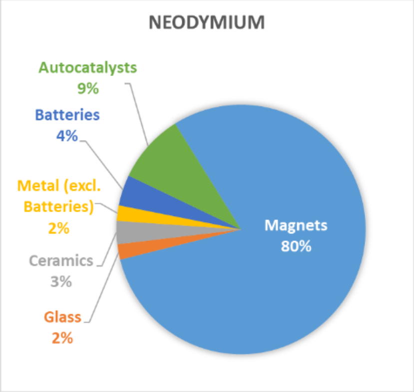


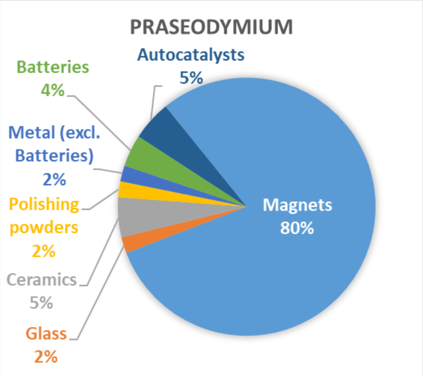
Figure 5: Recycling of REEs

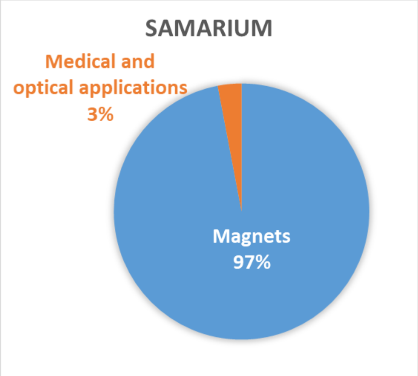
**Uses:** Like the global consumption, the main usage of REEs in EU are auto catalysts, glass i and FCC catalysts by quantity wise.

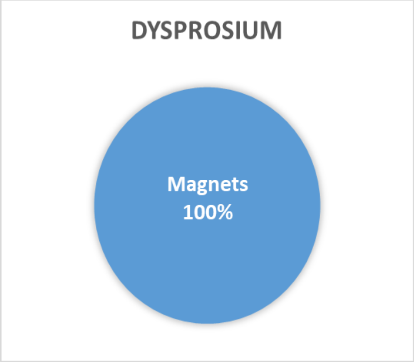

CERIUM
Fluid cracking catalysts 4%
Glass & ceramics 12%
Polishing powders 20%
Metal (excl. Batteries) 2%
Batteries 2%
Autocatalysts 60%

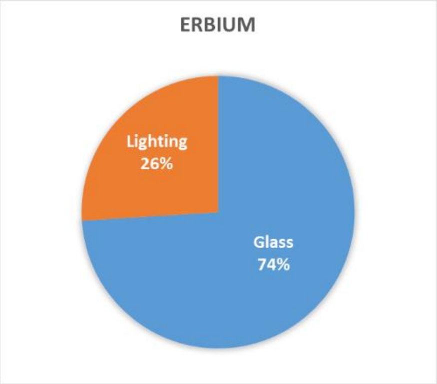

LANTHANUM
Glass & ceramics 5%
Polishing powders 2%
Metal (excl. Batteries) 1%
Batteries 3%
Autocatalysts 29%
Fluid cracking catalysts 60%

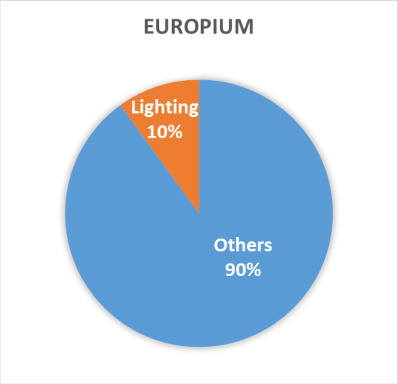

NEODYMIUM
Autocatalysts 9%
Batteries 4%
Metal (excl. Batteries) 2%
Ceramics 3%
Glass 2%
Magnets 80%

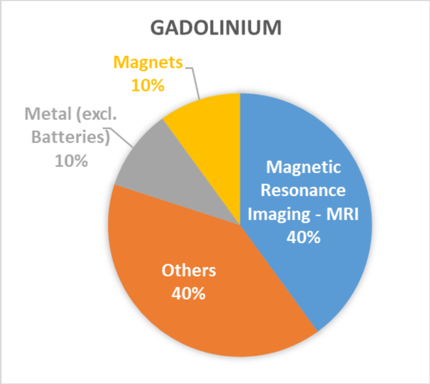

PRASEODYMIUM
Batteries 4%
Autocatalysts 5%
Metal (excl. Batteries) 2%
Polishing powders 2%
Ceramics 5%
Glass 2%
Magnets 80%

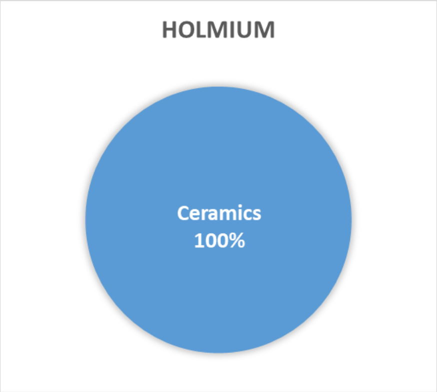

SAMARIUM
Medical and optical applications 3%
Magnets 97%

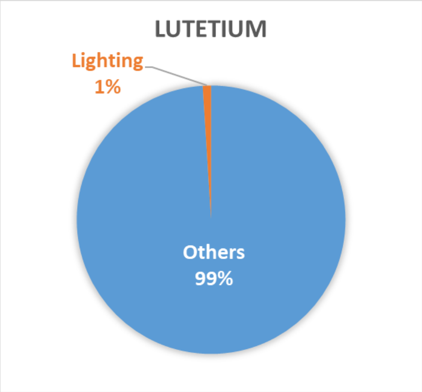

DYSPROSIUM
Magnets 100%

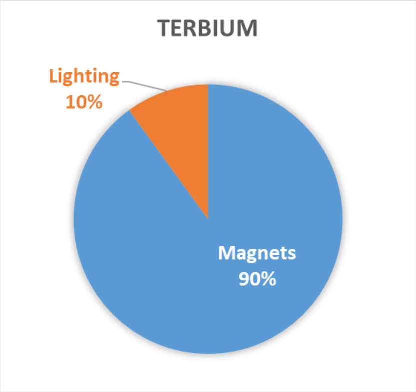

ERBIUM
Lighting 26%
Glass 74%


EUROPIUM
Lighting 10%
Others 90%


GADOLINIUM
Magnets 10%
Metal (excl. Batteries) 10%
Magnetic Resonance Imaging - MRI 40%
Others 40%


HOLMIUM
Ceramics 100%


LUTETIUM
Lighting 1%
Others 99%


TERBIUM
Lighting 10%
Magnets 90%

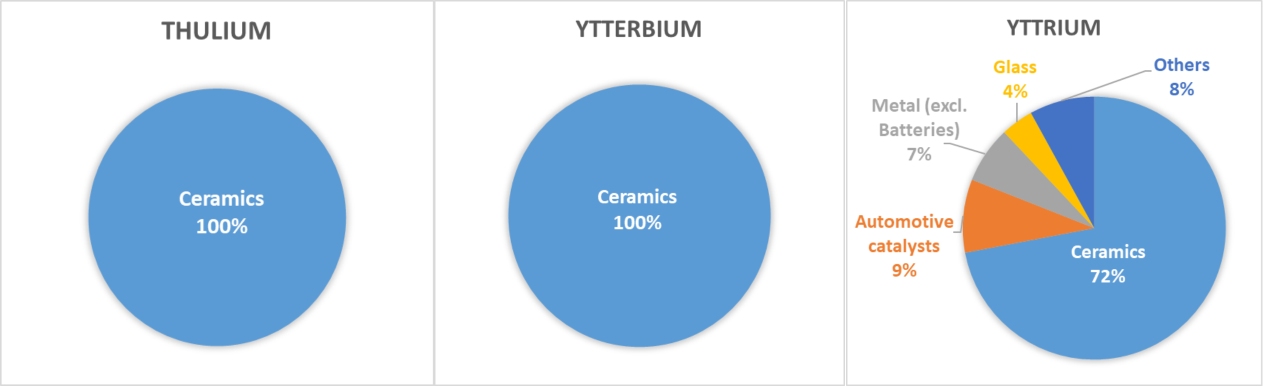


Figure 5: EU uses of rare earth

**Substitution:** 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.

Table 2. Uses and possible substitutes

| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
|---|---|---|---|---|---|---|
| Ce | Autocatalysts | 60% | Lanthanum | 5% | Similar or lower costs | Similar |
| Ce | Autocatalysts | 60% | Neodymium | 3% | Very high costs | Similar |
| Ce | Autocatalysts | 60% | Praseodymium | 2% | Very high costs | Similar |
| Ce | Glass & ceramics | 12% | Lanthanum | 28% | Similar or lower costs | Similar |
| Ce | Glass & ceramics | 12% | Praseodymium | 3% | Very high costs | Similar |
| Ce | Glass & ceramics | 12% | Other REO | 5% | Slightly higher costs | Similar |
| Ce | Glass & ceramics | 12% | Calcium oxide | 1% | Similar or lower costs | Reduced |
| Ce | Glass & ceramics | 12% | MgO | 1% | Similar or lower costs | Reduced |
| Ce | Glass & ceramics | 12% | Zirconium | 1% | Very high costs | Similar |
| Ce | Polishing powders | 20% | Iron oxide | 13% | Similar or lower costs | Similar |
| Ce | Polishing powders | 20% | Alumina | 13% | Similar or lower costs | Similar |
| Ce | Polishing powders | 20% | Silica powder | 13% | Similar or lower costs | Similar |
| Ce | Polishing powders | 20% | Magnesia | 13% | Similar or lower costs | Similar |
| Ce | Fluid cracking catalysts | 4% | Lanthanum | 68% | Similar or lower costs | Similar |
| Ce | Batteries | 2% | Lanthanum | 5% | Similar or lower costs | Similar |
| Ce | Batteries | 2% | Li-ion batteries | 85% | Slightly higher costs | Similar |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| La | Fluid cracking catalysts | 60% | Cerium | 32% | Similar or lower costs | Similar |
| La | Autocatalysts | 29% | Cerium | 5% | Similar or lower costs | Similar |
| La | Batteries | 3% | Li-ion batteries | 85% | Slightly higher costs | Similar |
| La | Batteries | 3% | Cerium | 5% | Similar or lower costs | Similar |
| La | Glass & ceramics | 5% | Cerium | 65% | Similar or lower costs | Similar |
| La | Glass & ceramics | 5% | Praseodymium | 3% | Very high costs | Similar |
| La | Glass & ceramics | 5% | Other REO | 5% | Very high costs | Similar |
| La | Glass & ceramics | 5% | Calcium oxide | 1% | Similar or lower costs | Reduced |
| La | Glass & ceramics | 5% | MgO | 1% | Similar or lower costs | Reduced |
| La | Glass & ceramics | 5% | Zirconium | 1% | Very high costs | Similar |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Nd | Magnets | 80% | Praseodymium | 8% | Slightly higher costs | Reduced |
| Nd | Magnets | 80% | Ferrite | 2% | Similar or lower costs | Reduced |
| Nd | Magnets | 80% | Sm-Co | 2% | Similar or lower costs | Reduced |
| Nd | Magnets | 80% | AlNiCo | 1% | Similar or lower costs | Reduced |
| Nd | Ceramics | 3% | Cerium | 40% | Similar or lower costs | Similar |

| | | | | | | |
|---|---|---|---|---|---|---|
| Nd | Ceramics | 3% | Yttrium | 10% | Similar or lower costs | Similar |
| Nd | Ceramics | 3% | Calcium oxide | 1% | Similar or lower costs | Reduced |
| Nd | Ceramics | 3% | MgO | 1% | Similar or lower costs | Reduced |
| Nd | Batteries | 4% | Li-ion battery | 85% | Slightly higher costs | Similar |
| Nd | Batteries | 4% | Lanthanum | 1% | Similar or lower costs | Reduced |
| Nd | Batteries | 4% | Cerium | 1% | Similar or lower costs | Reduced |
| Nd | Batteries | 4% | Praseodymium | 1% | Slightly higher costs | Similar |
| Nd | Metal (excl. Batteries) | 2% | Cerium | 13% | Similar or lower costs | Reduced |
| Nd | Metal (excl. Batteries) | 2% | Lanthanum | 13% | Similar or lower costs | Reduced |
| Nd | Metal (excl. Batteries) | 2% | Magnesium | 0% | Slightly higher costs | Similar |
| Nd | Metal (excl. Batteries) | 2% | Calcium | 0% | Slightly higher costs | Reduced |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Sm | Magnets | 97% | NdFeB | 15% | Very high costs | Similar |
| Sm | Magnets | 97% | Ferrites | 2% | Similar or lower costs | Reduced |
| Sm | Magnets | 97% | AlNiCo | 1% | Similar or lower costs | Reduced |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Dy | Magnets | 100% | Terbium | 25% | Very high costs | Similar |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Er | Glass | 74% | No substitute | 100% | | |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Eu | Lighting | 10% | Manganese | 0% | Similar or lower costs | Reduced |
| Eu | Lighting | 10% | Silicate barium phosphors | 0% | Similar or lower costs | Reduced |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Gd | Magnets | 10% | Terbium | 25% | Very high costs | Similar |
| Gd | Magnets | 10% | Dysprosium | 25% | Very high costs | Similar |
| Gd | Metal (excl. Batteries) | 10% | Praseodymium | 25% | Slightly higher costs | Similar |
| Gd | Metal (excl. Batteries) | 10% | Neodymium | 25% | Slightly higher costs | Similar |
| Gd | Magnetic Resonance Imaging - MRI | 40% | Manganese | 0% | Similar or lower costs | Similar |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Ho | Ceramics | 100% | No substitute | 100% | | |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Lu | Others | 99% | No substitute | 100% | | |
| Lu | Lighting | 1% | No substitute | 100% | | |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Tb | Magnets | 90% | Dysprosium | 75% | Slightly higher costs | Similar |
| Tb | Lighting | 10% | LEDs | 70% | Similar or lower costs | Similar |
| Tb | Lighting | 10% | La | 2% | Similar or lower costs | Similar |
| Tb | Lighting | 10% | Ce | 2% | Similar or lower costs | Similar |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Yb | Ceramics | 100% | No substitute | 100% | | |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Y | Automotive catalysts | 9% | No substitute | 100% | | |
| Y | Ceramics | 72% | Calcium oxide | 10% | Similar or lower costs | |
| Y | Ceramics | 72% | MgO | 10% | Slightly higher costs | Reduced |

## MARKET ANALYSIS, TRADE AND PRICES

### GLOBAL MARKET

**Table 3. REE supply and demand in metric tonnes, 2016-2020 average (in metal content, EUROSTAT 2022)**

| REE | Global production (in tonnes) | Global Producers | EU consumption | EU Share | EU Suppliers | Import reliance |
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| **Ce** | 57740 | China 68%<br>Australia 10%<br>USA 9%<br>Myanmar 8%<br>Russia 2% | 4086 | | Russia 64%<br>China 18%<br>Other countries 7%<br>UK 4% | 100 |
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| **Tb** | 182 | | 5.9 | | | |
| **Gd** | 1974 | | 170 | | | |
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| **Y** | 5133 | | 224 | | | |
| **Ho** | 123.11 | | 0.23 | | | |
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| **Tm** | 15.44 | | 0.74 | | | |
| **Yb** | 186 | | 27 | | | |
| **Dy** | 708 | | 1.13 | | China 65%<br>Japan 18%<br>Russia 21%<br>UK 8% | 100 |

Rare-earth elements (REEs) are essential in the production of high-tech, low-carbon-enabling goods such as electric vehicles (EVs), wind turbines, batteries and energy-efficient light bulbs. They are also indispensable in the defence sector (European Commission, 2020). Significant market demand for certain REEs is particularly supported by national and international targets aiming to reduce carbon emissions as REE-based permanent magnets play a critical role in the decarbonisation of the transport industry and the generation of renewable energy (Roskill, 2021).

Although there are a significant number of REE mineral deposits around the world, production along the entire value chain is heavily concentrated in China. This includes mining, concentration, extraction, separation, metal and alloy making, magnet manufacturing and recycling. The largest REE mines and processing entities operating in China are state-owned and significantly sustained by government subsidies (ERMA, 2021). The Chinese government, being the major player in the market, awards production quotas to only six known companies which are: China Minmetals Rare Earth, Chinalco Rare Earth & Metals, Guangdong Rising Nonferrous, China Northern Rare Earth Group, China Southern Rare Earth Group and Xiamen Tungsten (LePan, 2021). In 2021, the government approved the merger of three of these enterprises – specifically China

Minmetals Rare Earth, Chinalco Rare Earth & Metals, and China Southern Rare Earth Group, along with two other companies, Ganzhou Zhonglan Rare Earth New Material Technology and Jiangxi Ganzhou Rare Metal Exchange. The newly formed mega-company, China Rare-Earths Group, will subsequently control 70% of China's REE output (Chang, 2022). The only large-scale producer of separated REE compounds outside China is the Australian company Lynas Rare Earths, Ltd. (Woodall, 2020). Establishing refining facilities in other regions is still challenging due to extensive permitting hurdles, a lack of investment in upstream mining and refining projects and fierce competition with established producers in China. Therefore, although market players outside China are establishing mines and processing plants, a significant portion of that output will still end up in China (Chen & Erickson, 2022). The foresight study undertaken by the European Commission shows that China also dominates the production of NdFeB magnets with 85-90% of total capacity (European Commission, 2020). The Covid-19 pandemic further highlighted the vulnerability of the supply chain as Chinese domestic consumers were preferentially supplied with REE magnets over international customers (Woodall, 2020).

REEs are not yet commodities, rather they are customer-specific chemical compounds, 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 (European Commission, 2020). It is therefore a volatile market with high uncertainty and opacity. In addition, several participants have often cited market manipulation and a lack of transparency in the supply chain (U.S. Department of Energy, 2020). Overall, determining the market and dynamics dominated by China is complicated 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 and differentiation of types and quality of REE products (e.g., mixed REE 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.

## EU TRADE

For the purpose of this assessment, REEs are evaluated at both extraction and processing stage as CN trade codes do not differentiate between REE ores, concentrate and purified oxides.

Figure 6 shows EU trade in cerium compounds between 2000 and 2021. Over the whole period, the EU was a net importer of cerium compounds. The EU stat shows that EU import of cerium constantly declined from its peak in 2000 of about 20,000 tonnes to less than 2,000 tonnes in 2015 and slightly increased the import there after reaching to 11,743 tonnes in 2021.  While the EU export remained less than 2,000 tonnes in past 20 years with a slight increase to 5,224 tonnes in 2021.

Table 4. Relevant Eurostat CN trade codes for rare earth elements

| Processing/refining | |
|---|---|
| **CN trade code** | **Title** |
| **28461000** | Cerium compounds |
| **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 |
| **28053010** | Intermixtures or interalloys of rare-earth metals, scandium an yttrium |
| **28053020** | Cerium, lanthanum, praseodymium, neodymium and samarium, of a purity by weight of >=95% (excl. Intermixtures or interalloys) |
| **28053030** | Europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium or yttrium, of a purity by weight of >=95% (excl. Intermixtures or interalloys) |

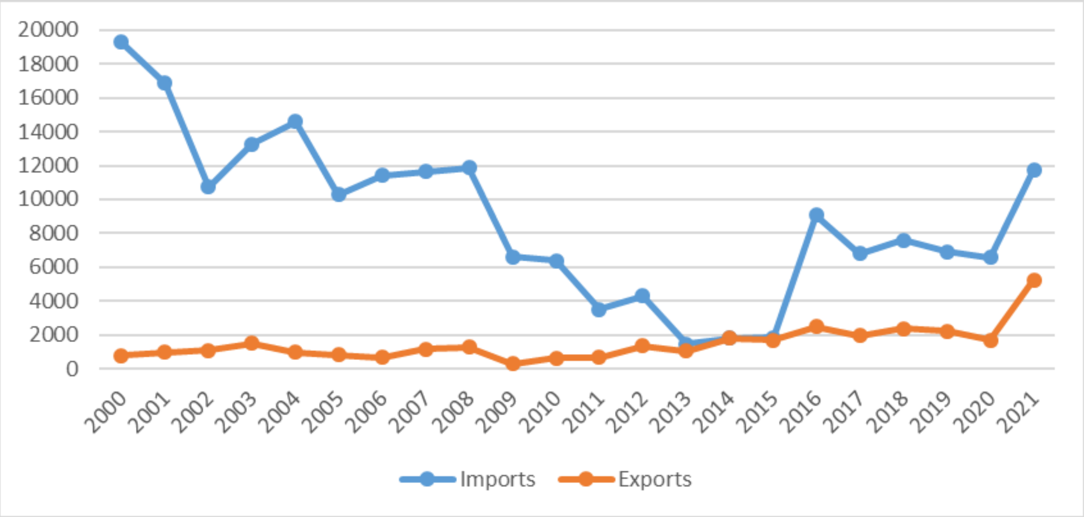

Figure 6. EU trade flows of cerium compounds (in tonnes) (CN 28461000) from 2000 to 2021 (Eurostat, 2022)

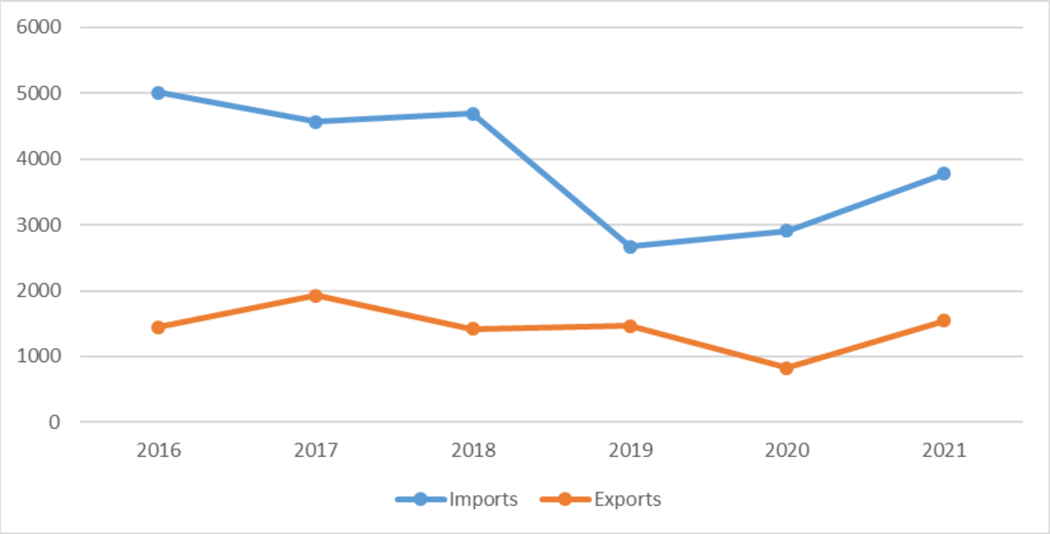

Figure 7. EU trade flows of light rare earth compounds excluding cerium in tonnes (CN 28469010) from 2016 to 2021 (Eurostat, 2021)

Figure 7 shows the EU import and export of compounds of light REEs such as lanthanum, praseodymium, neodymium and samarium. The imports remain within the range of 4,000 to 5,000 tonnes within the 2016-2021 time period. The majority of these could be lanthanum compounds as lanthanum is used in comparatively large quantities as fluid cracking catalysts (FCCs) by the petroleum refining industry. The data also shows an EU export of an average 1,500 tonnes of these materials per year for the same period.

Figure 8 shows EU 27 imports and export of heavy REE compounds of europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium and yttrium. EU imports show a declining trend until 2020 but an increase in 2021. Imports were approximately 1,200 tonnes in 2016, which declined to 559 tonnes in 2020, but increased to 718 tonnes in 2021. The EU also exported minor quantities of heavy REE compounds. The exports were equal to 209 tonnes in 2016 and 94 tonnes in 2021.

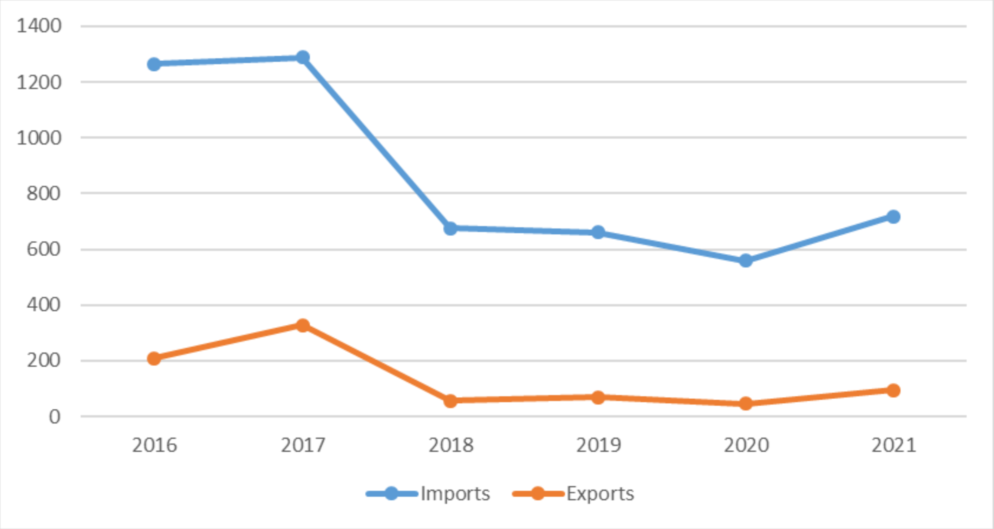

**Figure 8. EU trade flows of heavy rare earth compounds in tonnes (CN 28469020) from 2016 to 2021 (Eurostat, 2022)**

Figure 8 shows that the EU imports and exports minor quantities of light REE metals (i.e., cerium, lanthanum, praseodymium, neodymium and samarium). Imports were approximately 150 tonnes of REE metals in 2016, decreasing to 33 tonnes in 2021. EU exports were 24 tonnes in 2016 and 7 tonnes in 2021.

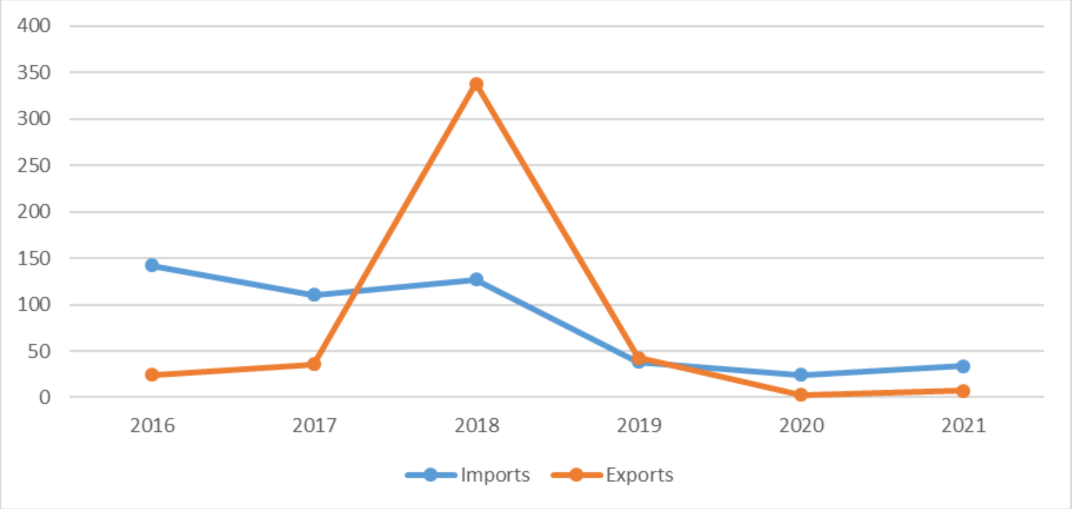

**Figure 9. EU trade flows of light rare earth metals of a purity by weight of >=95% (CN 28053020) in tonnes from 2016 to 2021 (Eurostat, 2022)**

Figure 10 shows EU import and export of heavy REEs metals of europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium and yttrium, of a purity by weight of >=95% (excluding intermixtures or interalloys). EU imports were approximately 21 tonnes in 2016, increasing to 70 tonnes in 2019 but declining sharply to 7 tonnes in 2021.

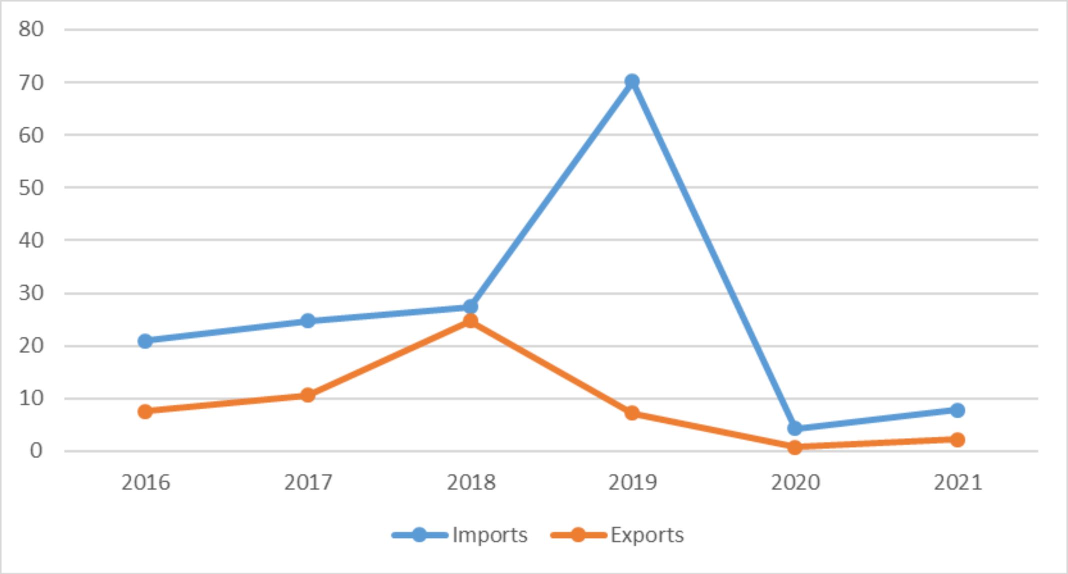

**Figure 10. EU trade flow of heavy earth metals of a purity by weight of >=95% (CN 28053030)in tonnes from 2016 to 2021 (Eurostat, 2022)**

Figure 11 shows the EU imports of cerium compounds by country for the period 2000-2021. The major supplier to the EU of cerium compounds was China, which used to supply more than 90%. However, China's share in this product group has declined in recent years. Russia, Malaysia, and the UK also contribute to the EU import basket. EU imports of cerium compounds from China declined to 16% in 2021 and the imports from Malaysia and Russia were approximately 42 and 39 percent respectively.

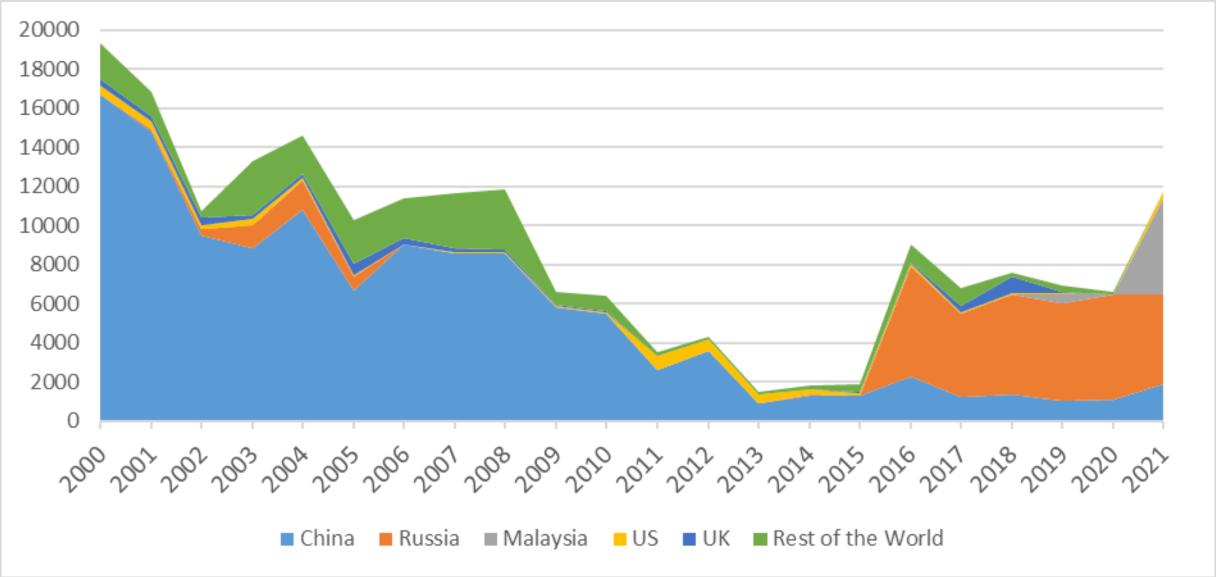

**Figure 11. EU imports of cerium compounds in tonnes by country (CN 28461000) by country between 2000-2021 (Eurostat, 2021)**

Figure 12 shows that China is the major import source of light REE compounds for the EU. 65% of imports originated from China in 2016 in this product category. However, the import share from China increased to 88% in 2021 followed by the USA (4%), Japan (3%), India (2%) and rest of the world (3%).

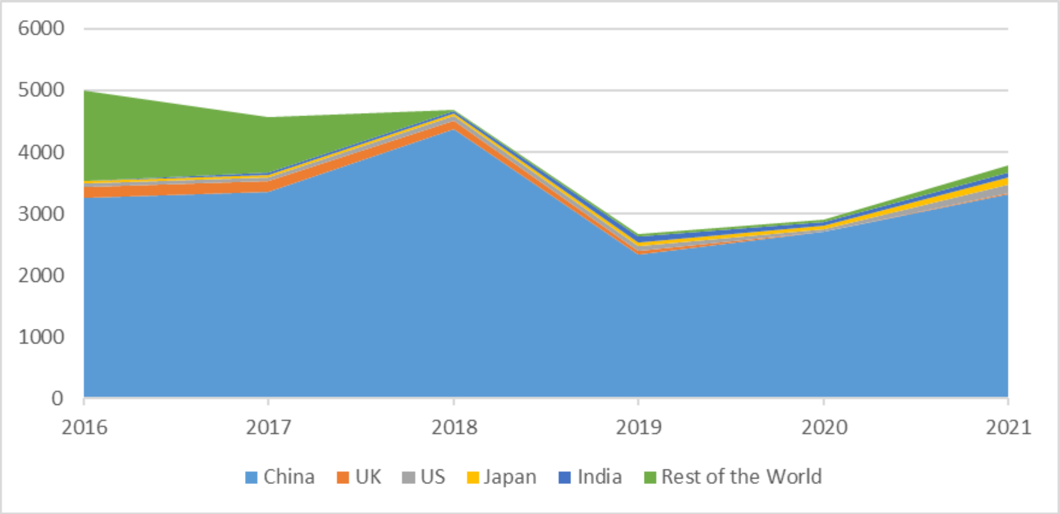

Figure 12. EU imports of light rare earth compounds excluding cerium (CN 28469010) in tonnes by country between 2016-2021 (Eurostat, 2022)

For the import of heavy REE compounds, Figure 12 shows that China contributed approximately 25% in 2016, followed by Japan which contributed approximately 21%. The rest of the world provided approximately 50% of EU import requirements.  However, in 2021 China's share increased to 64% followed by Korea (8%), UK (2%) and the rest of the world (26%)

Figure 13 shows that most of the EU imports of light REE metals (i.e., cerium, lanthanum, praseodymium, neodymium and samarium), of a purity by weight of >=95%, also originated from China. China's share was 67% in 2016 with a rest of the world share of 33%. Though the overall import quantity declined in the period between 2016-2021, China's share increased to 97% in 2021, with 2% of imports from the USA.

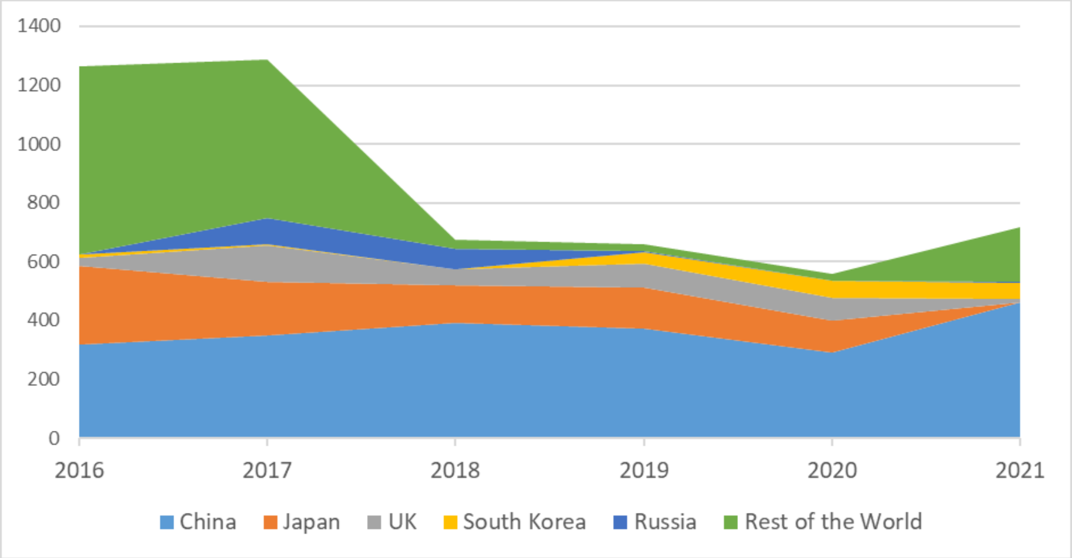

Figure 13. EU imports of heavy rare earth compounds in tonnes (CN 28469020) by country between 2016-2021 (Eurostat, 2022)

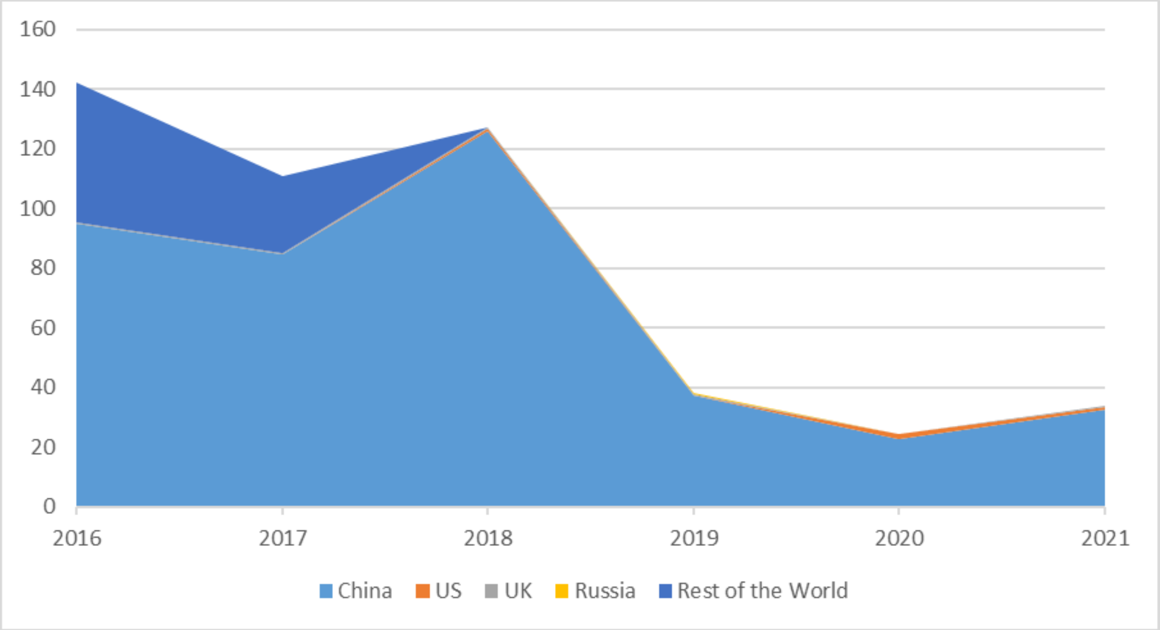

**Figure 14. EU imports of light rare earth metals in tonnes (CN 28053020) by country between 2016-2021 (Eurostat, 2022)**

As shown in Figure 15, the EU imports minor quantities of the heavy REE metals (i.e., europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium and yttrium), of a purity by weight of >=95%. The EU imported approximately 35% of these metals from China in 2016 and in 2021 China's share was 95 percent.

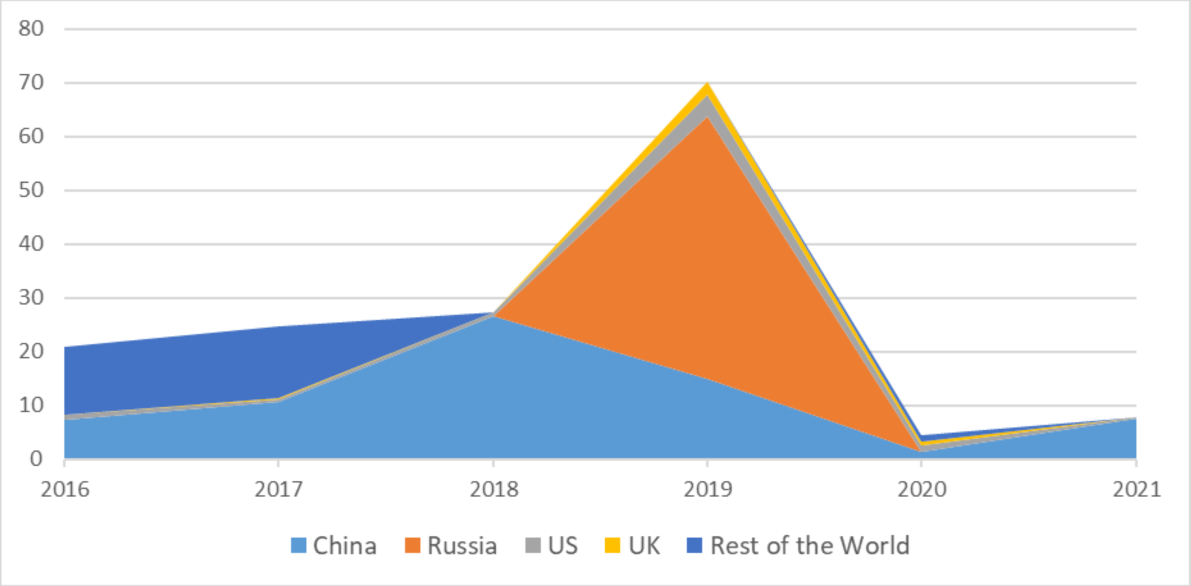

**Figure 15. EU imports of heavy rare earth metals in tonnes (CN 28053030) by country between 2016-2021 (Eurostat, 2022)**

## PRICE AND PRICE VOLATILITY

Prices of REEs experienced great variations in the last decade. In 2010-2011 a 12-fold increase was observed, mainly triggered by misinterpretation by the global market of a 16ignificant reduction in Chinese export quotas in 2010 (not actual exports) and geopolitical tension in a period of high demand for permanent magnets, driven by the expected growth of the renewable energy and EV markets. From early 2012, prices were already down by half and went down almost continuously until 2019, showing relatively short-term volatility.

## MAGNET RARE EARTHS (ND, PR, TB, DY)

The prices of magnet REEs experienced great variations between 2010 and 2016. In 2010, China used its REE monopoly as a diplomatic tool by severely limiting REE exports to Japan for a short period, during disagreements over disputed territory. The prices reached an all-time high in 2011. Even after this incident, the Chinese government retained a REE export quota for the next four years which resulted in consistently high REE prices. In 2015, the World Trade Organization proclaimed that China's REE export quotas were unlawful, which then restored REE prices to historical levels (Kim & Jariwala, 2021). With tensions rising between the USA and China in 2019, the Chinese government showed that it could once again use its dominant position as an exporter of REEs. China raised tariffs on imports from the USA from 10% to 25%, which meant that REEs exported to China would be substantially more expensive following subsequent processing. In addition, there were also conversations about a potential embargo on REE exports from China (Cohen & Grant, 2021). The situation caused a significant spike in the prices of many REEs on the global market, most likely due to speculators buying stocks in anticipation of the shortage of Chinese supplies. Even though these events did not have as much impact as the 2010 crisis, it made it very clear that the REE market is quite volatile and significantly dependent on Chinese foreign policy (Kim & Jariwala, 2021). A coup d'état in Myanmar, the main foreign supplier of heavy REE feedstocks into China, tightened supply and also helped push the prices of dysprosium and terbium up in 2021. Due to these insecurities, in addition to the surging demand for magnet applications in EVs and wind power, the prices of REEs have been consistently on the rise since 2019 (Mitchell, 2021).

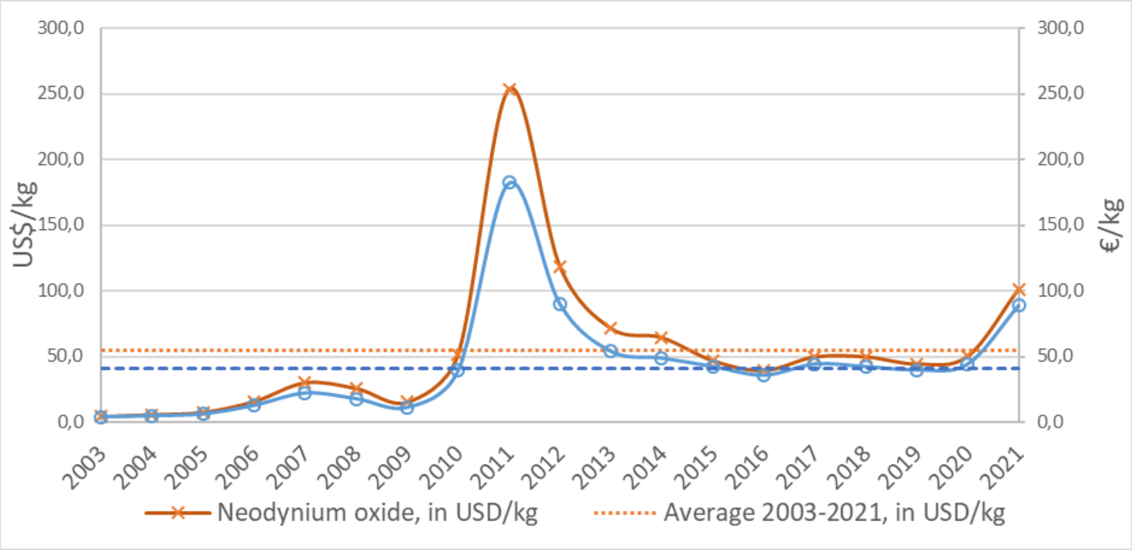

**Figure 16. Annual average price of neodymium oxide 99%min FOB China between 2003 and 2021, in US$/kg and €/kg (S&P Global, 2022). Dash lines indicates average price for 2003-2021.**

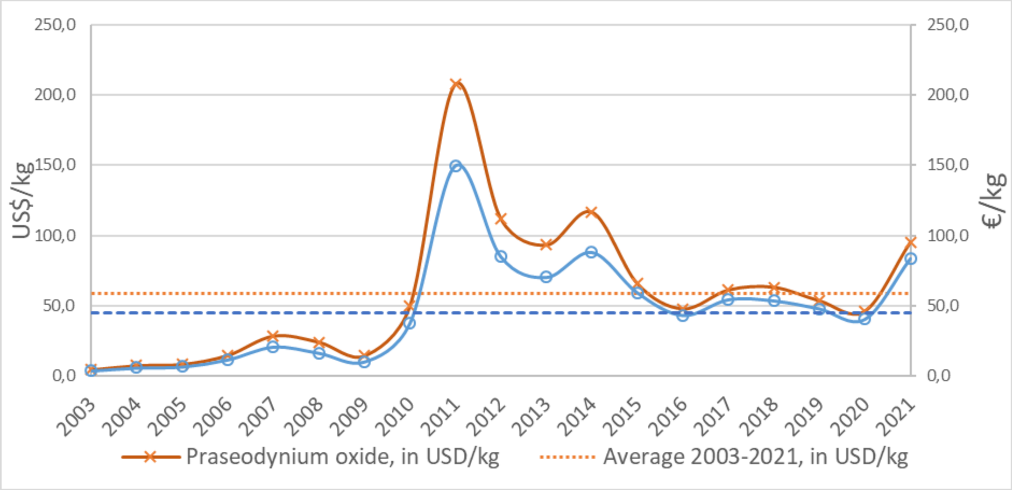

**Figure 17. Annual average price of praseodymium oxide 99%min FOB China between 2003 and 2021, in US$/kg and €/kg (S&P Global, 2022). Dashed lines indicates average price for 2003-2021.**

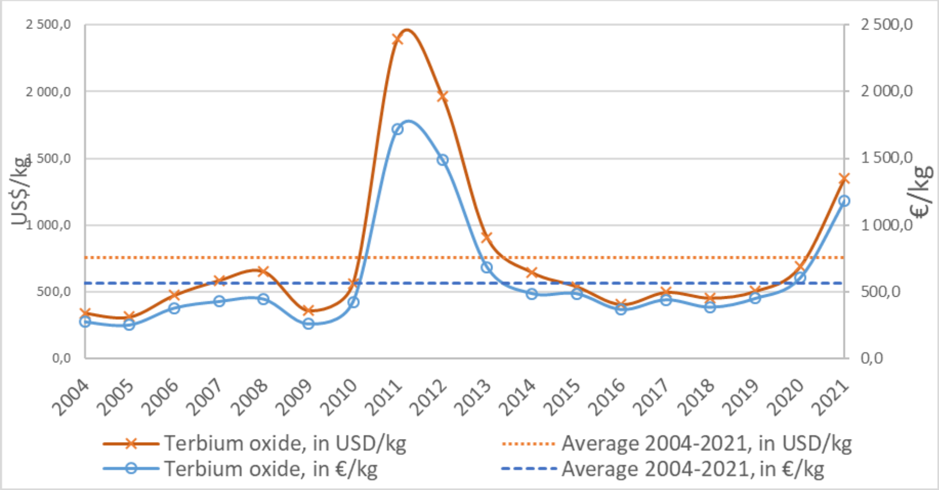

**Figure 18. Annual average price of terbium oxide 99%min FOB China between 2004 and 2021, in US$/kg and €/kg (S&P Global, 2022). Dashed lines indicates average price for 2004-2021.**

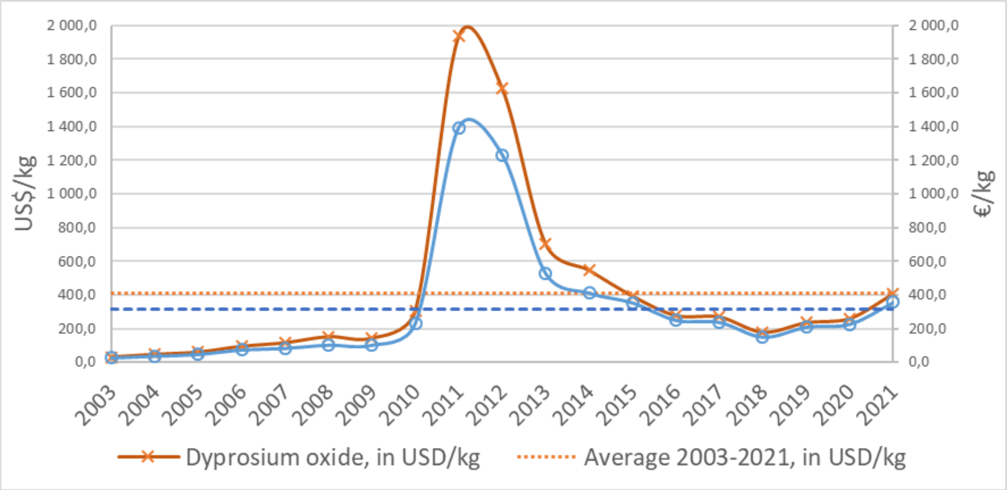

**Figure 19**. Annual average price of dysprosium oxide 99%min FOB China between 2003 and 2021, in US$/kg and €/kg **(Argus Media, 2018)**; **(DERA, 2022)**. Dashed lines indicates average price for 2003-2021.

## HEAVY RARE EARTHS (HREES)

HREE prices reached an all-time high in 2011 due to export quota restrictions in China. Since then, prices have continuously decreased. Yttrium's price recently recovered in 2020 driven by reduced spot supplies of high-purity yttrium oxide and stronger demand globally. Demand for yttrium for applications in the coating and ceramics industries has increased. Chinese and international buyers are eager to restock yttrium due to concerns regarding further supply cuts and higher freight costs (Argus Media, 2021). Even though 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. Therefore, its price has not shown signs of recovery.

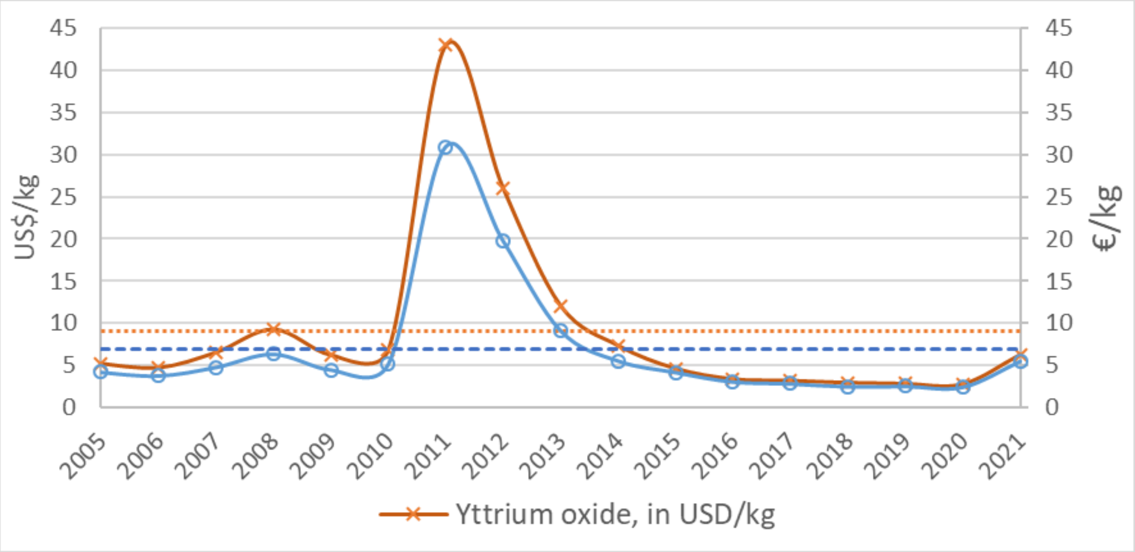

**Figure 20. Annual average price of yttrium oxide 99%min FOB China between 2005 and 2021, in US$/kg and €/kg (S&P Global, 2022). Dashed lines indicates average price for 2005-2021.**

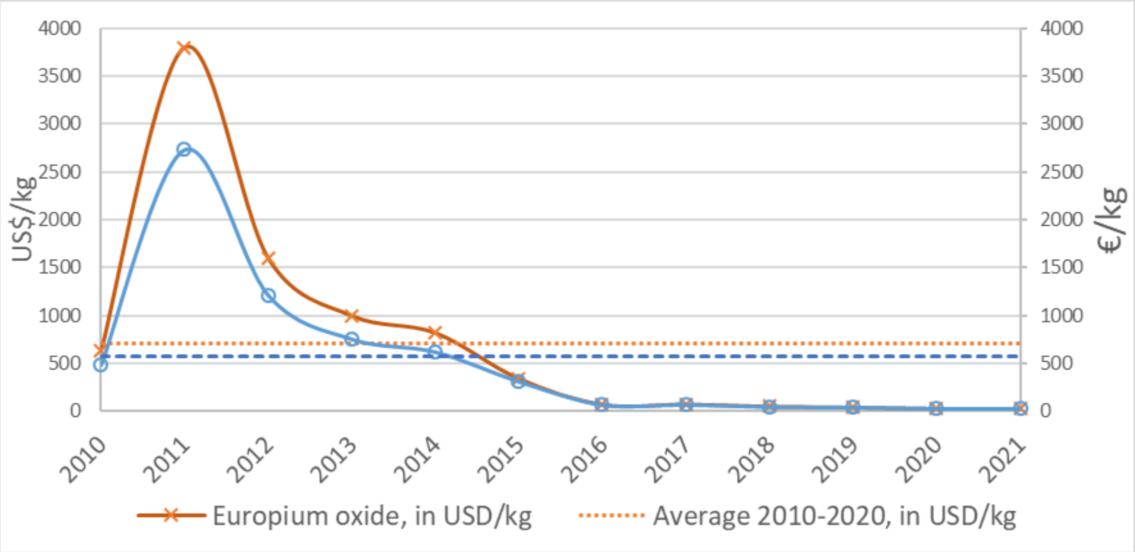

**Figure 21. Annual average price of europium oxide 99%min FOB China between 2010 and 2021, in US$/kg and €/kg (USGS, 2022). Dashed lines indicates average price for 2010-2021.**

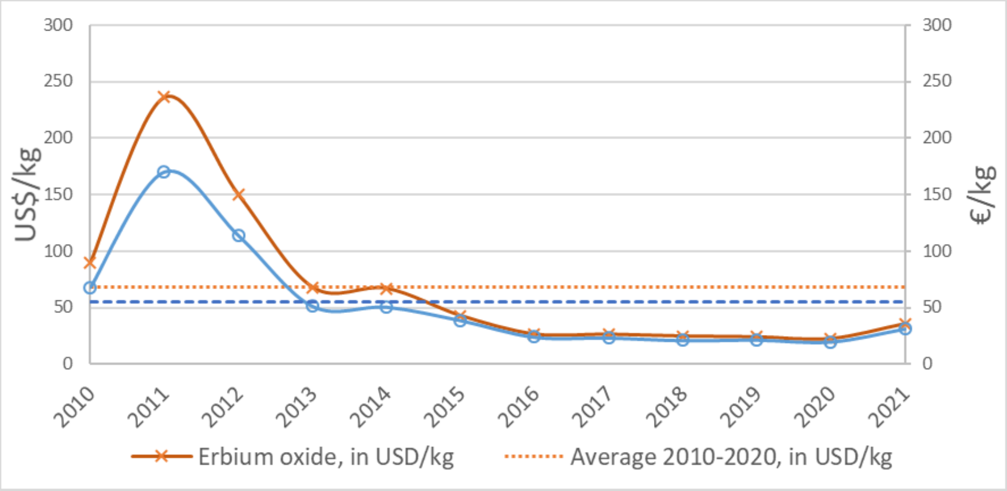

**Figure 22. Annual average price of erbium oxide 99%min FOB China between 2010 and 2021, in US$/kg and €/kg (DERA, 2022), (Statista, 2022). Dashed lines indicates average price for 2010-2021.**

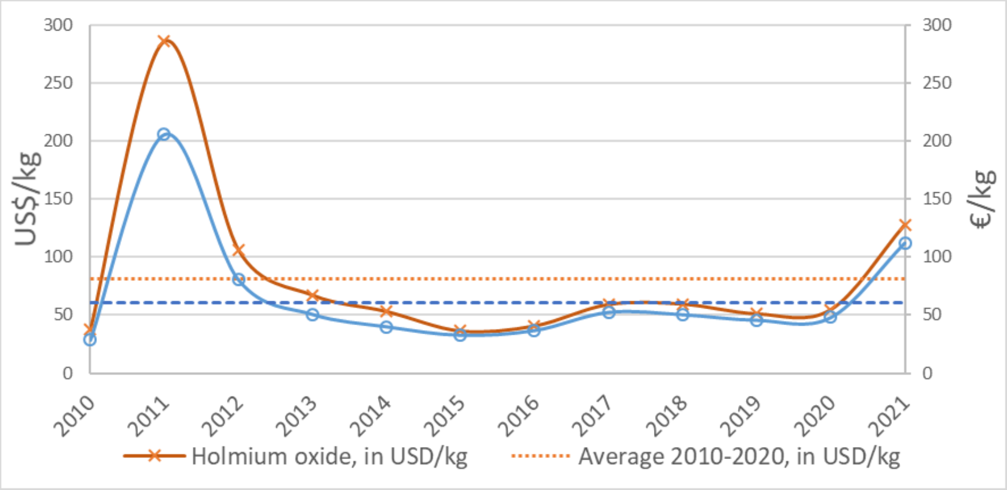

**Figure 23. Annual average price of holmium oxide 99%min FOB China between 2010 and 2021, in US$/kg and €/kg (DERA, 2022). Dashed lines indicates average price for 2010-2021.**

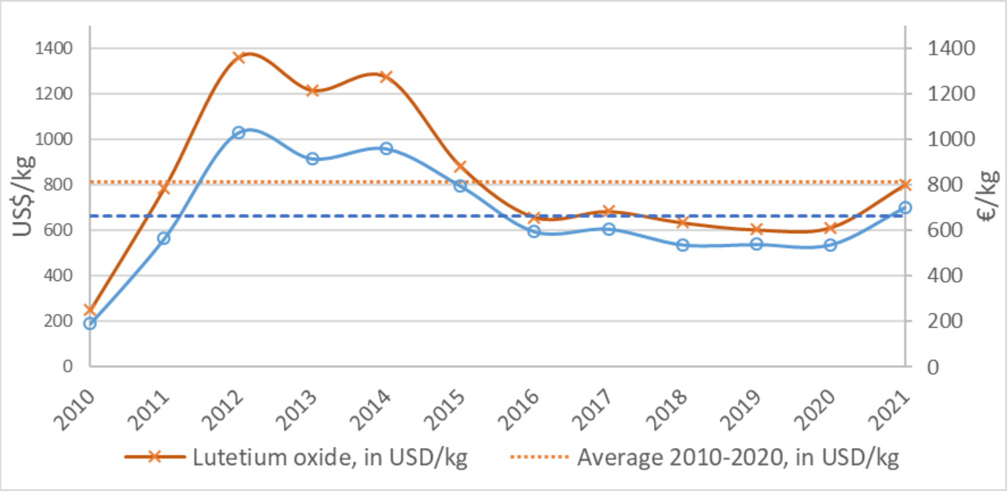

**Figure 24. Annual average price of lutetium oxide 99%min FOB China between 2010 and 2021, in US$/kg and €/kg (DERA, 2022). Dashed lines indicates average price for 2010-2021.**

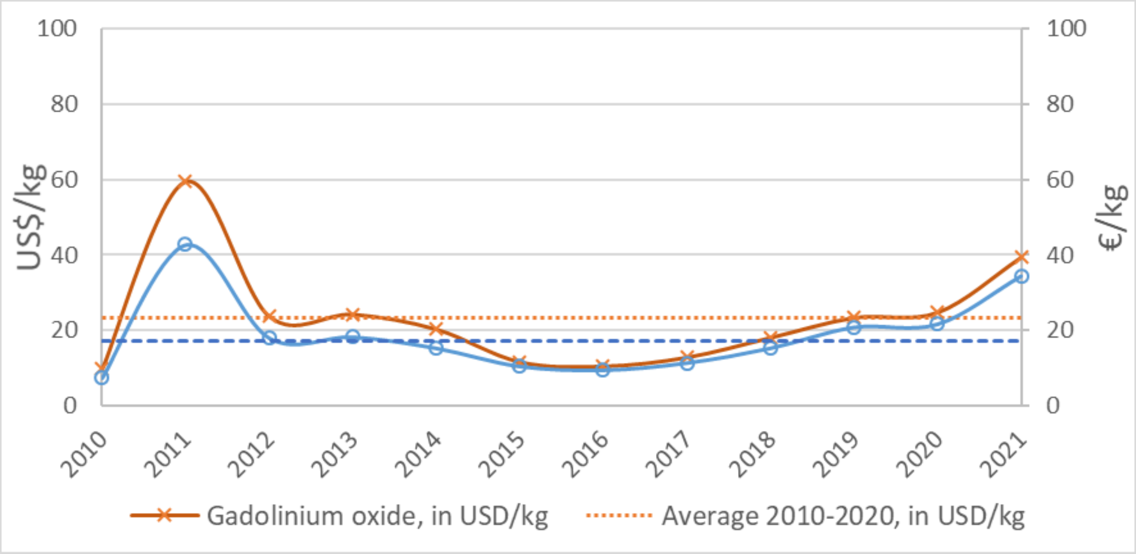

**Figure 25. Annual average price of gadolinium oxide 99%min FOB China between 2010 and 2021, in US$/kg and €/kg** (DERA, 2022)**. Dashed lines indicates average price for 2010-2021.**

## LIGHT RARE EARTHS (LREES)

The skyrocketing of prices in 2010-2011 was triggered by the misinterpretation of a significant reduction of Chinese export quotas. Prices were then subsequently restored in 2015 due to the intervention of the World Trade Organization. Since then, LREE prices have stayed relatively flat remaining below the average for the period 2003-2021. The co-mining of REEs means that the supply of each REE is solely dependent on the total amount of ore mined and the concentration of the desired element in the ore (Alonso, et al., 2012). Therefore, the drive to produce larger quantities of magnet materials has also resulted in large quantities of LREEs produced. This has led to an oversupply of certain LREEs on the market which translates to consistently low prices (Roskill, 2019).

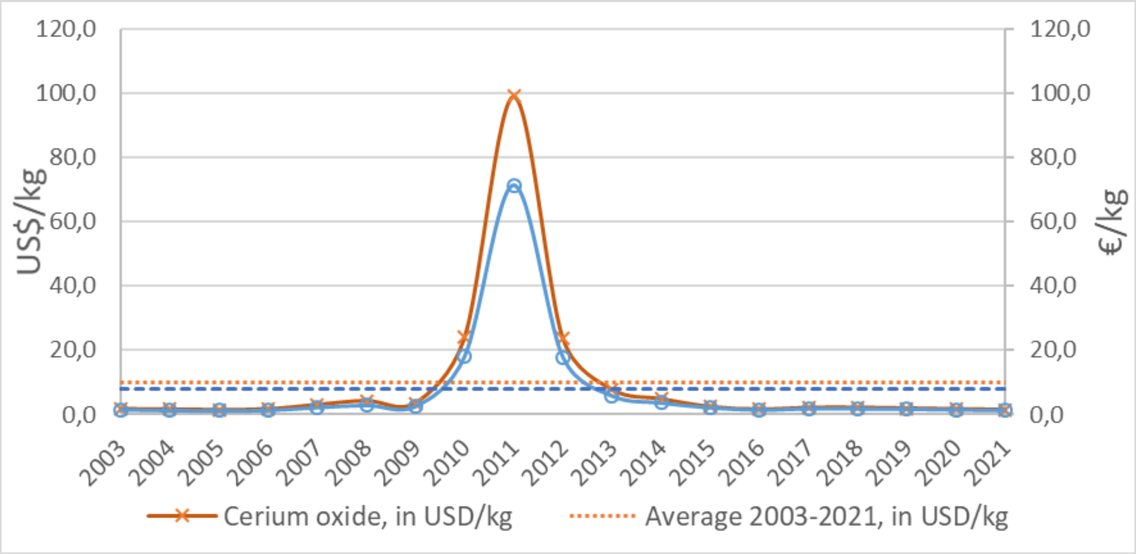

**Figure 26. Annual average price of cerium oxide 99%min FOB China between 2003 and 2021, in US$/kg and €/kg** (S&P Global, 2022)**. Dashed lines indicates average price for 2003-2021.**

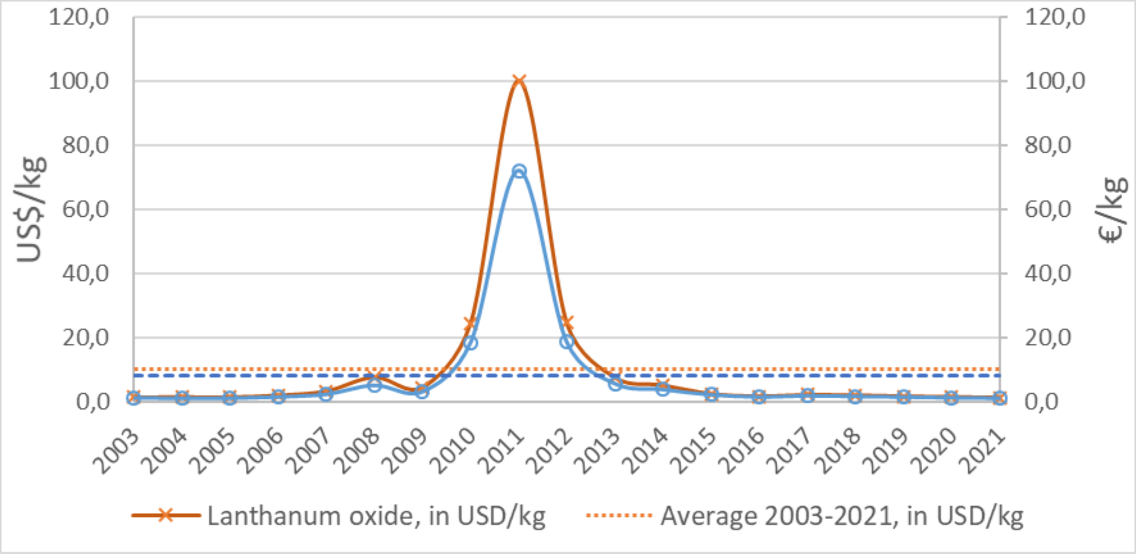

**Figure 27. Annual average price of lanthanum oxide 99%min FOB China between 2003 and 2021, in US$/kg and €/kg (S&P Global, 2019). Dashed lines indicates average price for 2003-2021.**

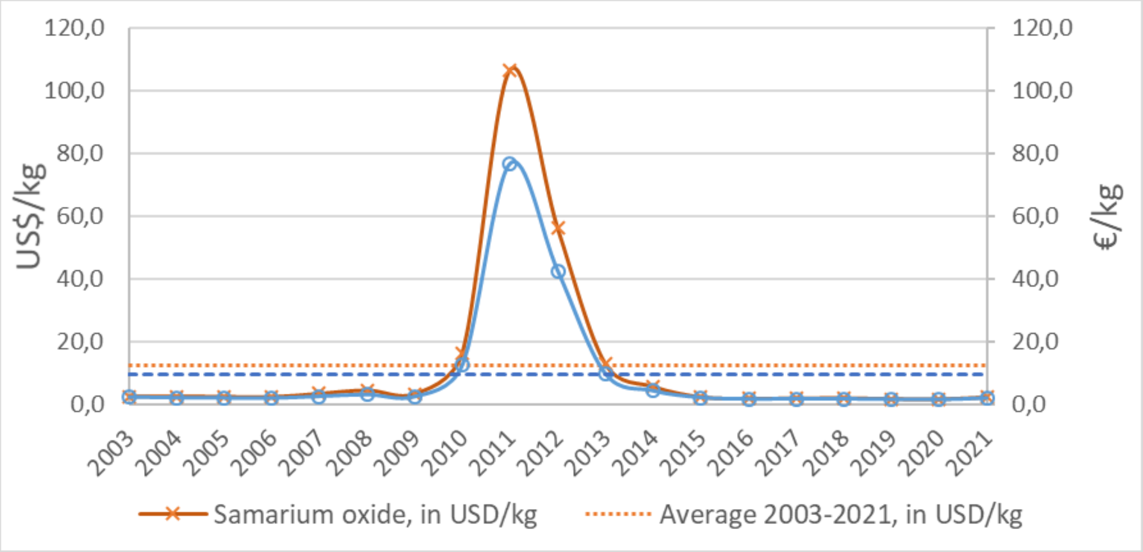

**Figure 28. Annual average price of samarium oxide 99%min FOB China between 2003 and 2021, in US$/kg and €/kg (S&P Global, 2022). Dashed lines indicates average price for 2003-2021.**

## OUTLOOK

In 2021, China merged three major state-owned REE companies. The newly established megafirm is expected to have increased pricing power of key REEs, such as dysprosium and terbium and will most likely result in changes to the whole supply chain. It is expected that with this merger, the Chinese government ultimately seeks for REE prices to be rationalized (Zhou & Brooke, 2022). It is forecasted that, from 2022 through 2035, the global demand for NdFeB magnets will increase at a compound annual growth rate (CAGR) of 8.6%, boosted by the growth of the EV and wind-power sectors, which translates to comparable demand growth for magnet REEs. Over the same period, the global production of magnet REEs is expected to collectively increase at a slower CAGR of just 5.4% as the supply side of the market increasingly struggles to keep up with rapidly growing demand (Adamas Intelligence, 2022)

## DEMAND

### GLOBAL AND EU DEMAND AND CONSUMPTION

The EU consumption of REE is 4,734 tonnes/y of compounds (expressed in rare-earth oxide or REO equivalent content) and 683 tonnes/y of REE metals and interalloys during the 2016-2018 period, and is entirely based on imports, which amount to 9,438 tonnes/y for REO compounds and 1,162 tonnes/y of REE metals and interalloys[1]. Consumption of individual REEs is presented in Table 5.

**Table 5: EU consumption of REEs (average 2016-2020 in metal content, criticality assessment 2023)**

| REE | EU consumption | EU Suppliers |
|---|---|---|
| **Ce** | 2.5 tonnes | Taiwan 48%<br>Norway 43%<br>Canada 8%<br>Russia 4% |
| **Nd** | 80.2 tonnes | China 80%<br>UK 3%<br>USA 2% |
| **La** | 2242 | |
| **Pr** | 67 tonnes | |
| **Sm** | 2.79 | |
| **Eu** | 1.04 | China 64%<br>Japan 18%<br>UK 8%<br>Russia 4%<br>South Korea 2.5%<br>Norway 1.5% |
| **Tb** | 1.56 | |
| **Gd** | 44.7 | |
| **Er** | 30.65 | |
| **Y** | 56 | |
| **Ho** | 0.06 | |
| **Lu** | 5.61 | |
| **Tm** | 0.2 | |
| **Yb** | 7.37 | |
| **Dy** | 2.32 | China 61%<br>Russia 21%<br>Japan 7%<br>UK 5%<br>USA 4% |

*‘‘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; many 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 CeO2, 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*

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

*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). Generally, 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).*

## LIGHT REE GLOBAL AND EU CONSUMPTION

Light-REE-extraction stage (oxide level) EU consumption is presented by HS codes CN 28461000 Cerium compounds and CN 28469010 Compounds of lanthanum, praseodymium, neodymium or samarium, inorganic or organic. The associated import and export data shown in Figure 28 is extracted from Eurostat Comext (2022). Production data is extracted from Eurostat Prodcom (2022) using PRCCODE 20136510 for Cerium compounds and using PRCCODE 20136520 for Compounds of lanthanum, praseodymium, neodymium or samarium, inorganic or organic.

Based on Eurostat Comext (2022) and Eurostat Prodcom (2022) data, average import reliance of light REEs at the extraction stage (oxide) was 56.8 % for 2019-2020.

Light-REE-processing stage EU import and export is presented by HS Code CN 28053020 Cerium, lanthanum, praseodymium, neodymium and samarium, of a purity by weight of >=95% (excl. Intermixtures or interalloys).

However, EU consumption cannot be determined due to lack of production data from Eurostat Prodcom (2022).

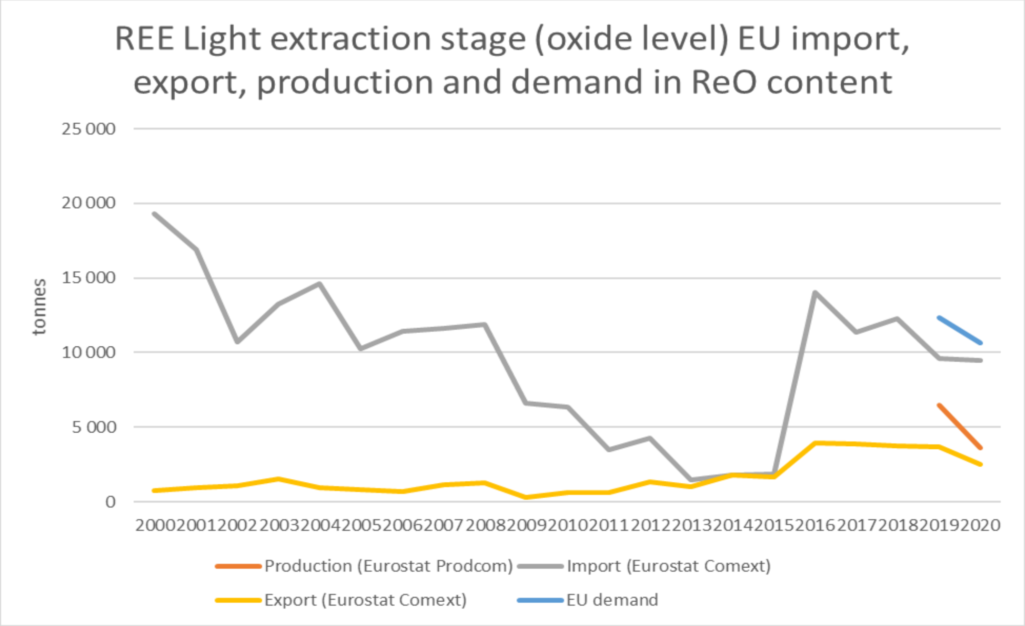


**Figure 29. Light REE (CN 28461000 and CN 28469010) extraction stage apparent EU consumption. Import and export data for CN 28469010 is available only for 2016-2020. Production data through Eurostat Prodcom (2022) is only available for 2019-2020. Consumption is calculated in REO content (EU production+import-export).**

## HEAVY REE GLOBAL AND EU CONSUMPTION

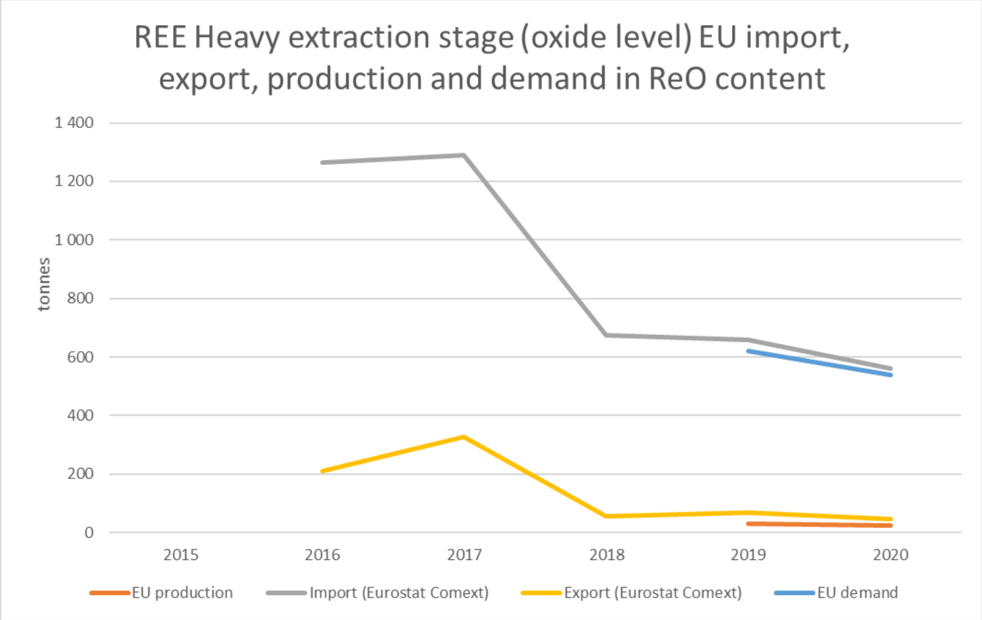


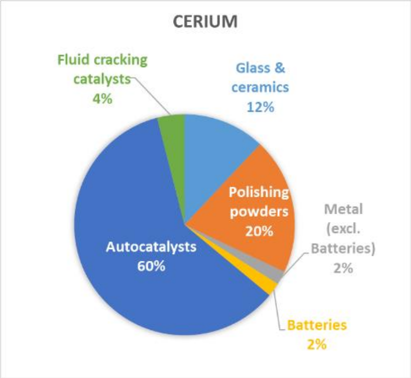
**Figure 30. Heavy REE (CN 28469020) extraction stage apparent EU consumption. Import and export data for CN 28469020 is available only for 2016-2020. Production data through Eurostat Prodcom (2022) is only available for 2019-2020. Consumption is calculated in REO content (EU production + import-export).**

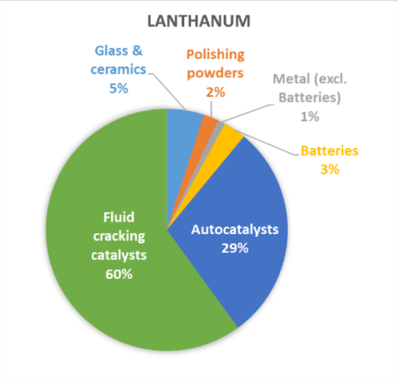
Heavy-REE-extraction stage (oxide level) EU consumption is presented by HS code CN 28469020 Compounds of europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium or yttrium, inorganic or organic. Import and export data is extracted from Eurostat Comext (2022). Production data is extracted from Eurostat Prodcom (2022) using PRCCODE 20136550 for Compounds, inorganic or organic, of rare-earth metals or of mixtures of these metals. Compounds of europium, gadolinium, terbium, dysprosium, holmium.

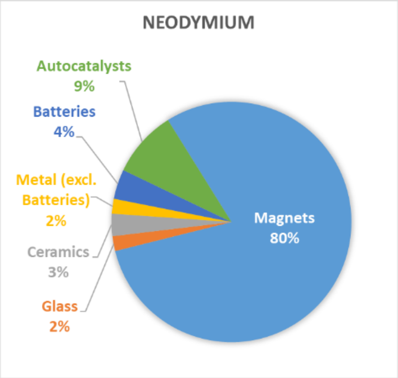
Based on Eurostat Comext (2022) and Eurostat Prodcom (2022) average import reliance of heavy REE at extraction stage (oxide) is 95.5 % for 2019-2020.

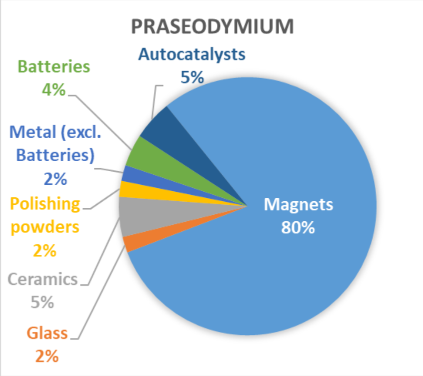
Heavy REE processing stage EU import and export is presented by HS Code CN 28053030 Europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium or yttrium, of a purity by weight of >=95% (excl. Intermixtures or interalloys). However, EU consumption cannot be determined due to lack of production data from Eurostat Prodcom (2022).

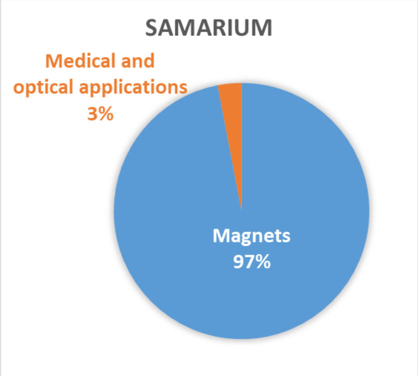
## EU USES AND END-USES

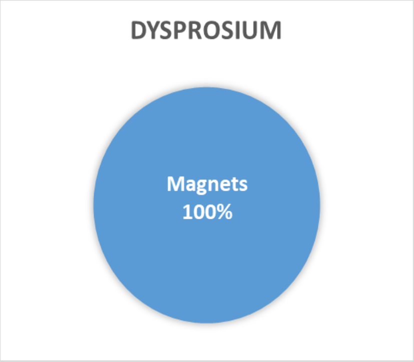


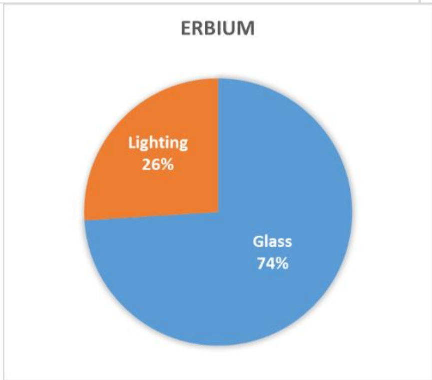


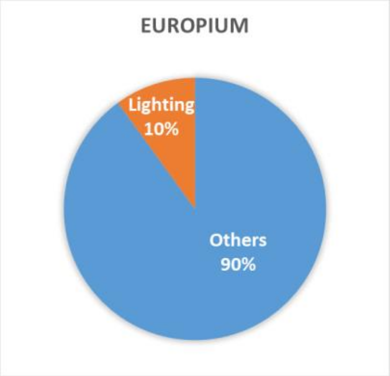


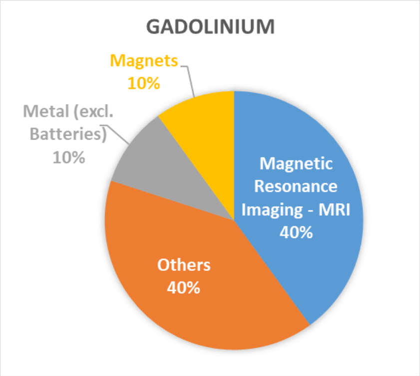












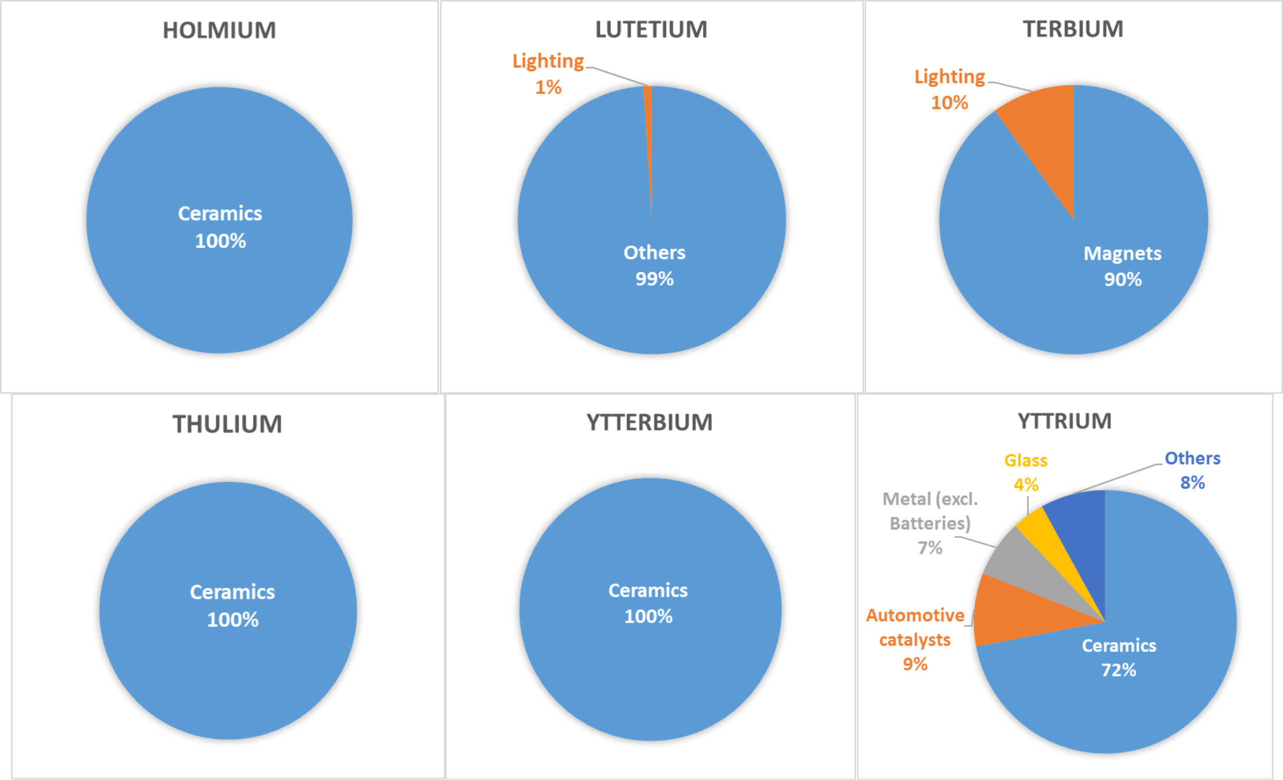


**Figure 31: EU end uses of REEs, average 2016-2020 (criticality assessment 2023)**

## CERIUM APPLICATIONS

The end uses of cerium products in the EU are presented in Figure 31 and relevant industry sectors are described using the NACE sector codes in Table 6.

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 (Table 6).

**Table 6. Cerium 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 (millions €) | Examples of 4-digit NACE sector |
|---|---|---|---|
| Fluid Cracking | C19 - Manufacture of coke and refined petroleum products | 25,475.50 | C2029 - Manufacture of other chemical products not elsewhere classified |
| Batteries | C27 - Manufacture of electrical equipment | 98,417.10 | C2720 - Manufacture of batteries and accumulators |
| Autocatalysts | C20 - Manufacture of chemicals and chemical products | 117,093.2 | C2029 - Manufacture of other chemical products not elsewhere classified |
| Glass&Ceramics | C23 - Manufacture of other non-metallic mineral products | 69,888.20 | C2331 - Manufacture of ceramic tiles and flags |
| Polishing powders | C26 - Manufacture of computer, electronic and optical products | 84,020.90 | C2670 - Manufacture of optical instruments and photographic equipment |

| | | | |
|---|---|---|---|
| Metal (excl. Batteries) | C24 - Manufacture of basic metals | 71,390.80 | C2410 - Manufacture of basic iron and steel and of ferro-alloys |
| Lighting | C27 - Manufacture of electrical equipment | 98,417.10 | C2740 - Manufacture of electric lighting equipment |

Cerium compounds have several practical applications, but the four main uses are polishing, metallurgy other than batteries, autocatalysts and glass.

Other uses for cerium include **batteries, fluid cracking catalysts, other catalysts, phosphors, ceramics, fertiliser, water treatment, paints and coatings**. The dioxide is used in the optical industry for fine polishing of glass, as a decolorizer in glassmaking, in petroleum cracking catalysts and in three-way auto-emission catalysts, which utilises its dual-valency properties (3+ / 4+). Cerium, together with the other REEs, is part of many iron alloys to trap sulphur and oxygen and to crosslink cast iron. It is also used in non-ferrous alloys, especially for improving the high-temperature oxidation resistance of superalloys. Mischmetal (typically 50% cerium, 25% lanthanum, 18% neodymium, 5% praseodymium and 2% other rare earths) is mainly used for lighter flintstones and alloying additions (European Commission, 2017).

In metallurgy, cerium is used as an **additive for aluminium alloys and high-temperature-resistant iron-based alloys.** It supports the separation of sulphur and oxygen in the melting process. The iron-mischmetal alloy Cereisen serves as the starting material for flints for use in lighters and for generating sparks on roller coasters and in movie scenes (accident scenes). Cereisen has a composition of 70% cerium and 30% iron (ISE, 2022).

Small additions of (pure) cerium compounds impart certain properties to other materials (ISE, 2022):

1. Ceria ($CeO_2$) is used to stabilize the alumina ceramic catalyst support for automotive exhaust catalysts
2. Part of some special lenses, for example UV filters and windshields, and dehumidifiers in glass manufacturing
3. For colouring enamel
4. Ceria is used as a polishing agent in glass processing
5. Cerium-doped fluorescent dyes (phosphors) in picture tubes and white LEDs
6. as doping in mantles
7. Self-cleaning ovens contain a cerium-containing coating
8. Cerium (IV) sulphate as oxidizing agent in quantitative analysis (cerimetry)
9. As a contrast agent at nuclear resonance
10. As a phosphor in gas-discharge tubes
11. Added to the regeneration of soot particle filters dissolved in the fuel
12. As part of non-precious metal-containing bonding alloys in dental technology (ceramics)
13. As an oxidant for organic syntheses with CAN (cerium ammonium nitrate), $(NH_4)_2[Ce(NO_3)_6$

### 4.2.2 DYSPROSIUM APPLICATIONS

The end-use of dysprosium products in the EU are presented in Figure 31 and relevant industry sectors are described using the NACE sector codes in Table 7.

**Table 7. Dysprosium 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 €) | Examples of 4-digit NACE sector |
|---|---|---|---|
| Magnets | C25 - Manufacture of fabricated metal products, except machinery and equipment | 183,015.50 | C2599 - Manufacture of other fabricated metal products not elsewhere classified |

Typical finished products driving dysprosium consumption for magnets include wind turbines and industrial motors.

Dysprosium isalmost exclusively used as an alloying addition (2-11%) to NdFeB permanent-magnet materials (i.e., part of the neodymium is replaced by dysprosium) to increase both the maximum operating temperature and the coercivity (resistance to demagnetisation), thereby improving the high-temperature behaviour of the alloy. The metal is also part of the magnetostrictive material Terfenol-D ($Tb_{0.3}Dy_{0.7}Fe_2$). Dysprosium is used in nuclear-reactor control rods because of its relatively high neutron-absorption cross section; its compounds have been used in the manufacture of laser materials and phosphorus activators as well as in metal halide lamps (EC, 2020).

The economic and technical importance of dysprosium are relatively low. Its output is estimated at less than 100 tonnes per year. It is used in various alloys, in magnets and with lead alloyed as shielding material in nuclear reactors. However, its use in magnets for wind turbines and EV powertrains has made this REE a rare commodity. In addition, the world's largest supplier China is slowing down its delivery to increase its own added value (ISE, 2022).

### ERBIUM APPLICATIONS

The end-use of erbium products in the EU are presented in Figure 31 and relevant industry sectors are described using the NACE sector codes in Table 8.

**Table 8: Erbium 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 (millions €) | Examples of 4-digit NACE sector |
|---|---|---|---|
| Optical applications | C23 - Manufacture of other non-metallic mineral products | 69,888.20 | C2310 - Manufacture and processing of other glass including technical glassware |
| Lighting | C27 - Manufacture of electrical equipment | 98,417.10 | C2740 – Manufacture of electric lighting equipment |

Most of the erbium is used in glass for optical application (74%), although phosphors for lighting applications are also an important use (EC, 2017), see Figure 3.

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-coloured 3+ ions, which have optical fluorescent properties particularly useful in certain laser applications as follows (BRGM, 2015):

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

More detailed information regarding optical properties of Erbium is given as follows (ISE, 2022):

The optical properties of erbium 3+ ions make up most applications of the element. Erbium-doped glasses and crystals are used as laser-gain media, optical fibres and amplifiers in fibre-optic communication systems. Erbium lasers are also widely used in medicine, dermatology and dentistry, and stronger erbium-ytterbium lasers are used in metal cutting and welding. The same different absorption and emission spectra that make erbium useful for functional optical applications result in the distinct pink colouration of erbium 3+ compounds, so erbium can also be used aesthetically as a dye for glasses, ceramics and zirconia.

In addition to its optical properties, erbium is useful for its ability to readily absorb free neutrons, making it suitable for use in control rods in nuclear reactors. Furthermore, erbium alloys are used in cryocoolers for use at liquid-helium temperatures because of their high specific heat capacity.

Erbium-doped optical fibres are used for optical amplifiers that can amplify a light signal without first converting it into an electrical signal. Gold as a host material doped with a few hundred ppm of erbium is used as a sensor material of magnetic calorimeters for high-resolution particle detection in physics and engineering.

Erbium is used alongside other REEs such as neodymium or holmium to dope laser crystals in solid-state lasers. The Er:YAG laser is mainly used in human medicine. It has a wavelength of 2,940 nm and thus an extremely high absorption in tissue water of approximately 12,000 per cm. It causes abrupt vaporisation and thus photoablation of tissue in thin layers. It is suitable for the ablation of many benign skin lesions. A biopsy is required beforehand to rule out malignancy. Ablated melanomas, for example, are strongly suspected of forming metastases via the bloodstream due to cells detached during ablation.

Erbium also used in the treatment of hard tissues such as bone, tooth enamel and dentin (healthy and carious). Another erbium-based laser is the Er:CrYSGG laser, which has a slightly shorter wavelength of 2,790 nm but serves the same medical or dental indications.

## EUROPIUM APPLICATIONS

The end-use of europium products in the EU are presented in Figure 31 and relevant industry sectors are are described using the NACE sector codes in Table 9

**Table 9: Europium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2022).**

| Applications | 2-digit NACE sector | Value-added of sector (millions €) | Examples of 4-digit NACE sector |
|---|---|---|---|
| Lighting | C27 - Manufacture of electrical equipment | 98,417.10 | C2740 - Manufacture of electrical lighting equipment |

- Europium (III)-doped yttrium oxide sulphide $Y_2O_2S:Eu^{3+}$ forms the red phosphor (luminophore) in colour picture tubes.
- Europium (II) doped barium fluorobromide $BaFBr:Eu^{2+}$ is used for photostimulated luminescence (PSL)
- $Eu^{3+}$ doped solids usually show a red luminescence, $Eu^{2+}$ can emit depending on the host lattice in the entire optical spectral range (UV to red).
- Doping element in phosphors for light sources such as high-pressure mercury lamps and energy-saving lamps.
- Doping material in scintillation crystals (as activator).
- Organic compounds as shift reagent in NMR spectroscopy.
- Europium-tetracycline complexes in fluorescence spectroscopy for the detection of hydrogen peroxide
- TRFIA = time-resolved fluoroimmunoassay. $Eu^{3+}$ ions fluoresce only briefly in water. Therefore, one uses chelating agents, which build around the $Eu^{3+}$ ions in a hydrophobic environment. This leads to a longer duration of fluorescence. This makes it possible to distinguish it from all other, shorter-lived fluorescence that can occur in organic mixtures.

Europium is used globally (and in the EU) almost exclusively in lighting applications (BRGM, 2015). It represents 5% of the composition of phosphors used for lighting. Europium used as a dopant to produce phosphors are used, for example, in cathode ray tube screens, which were previously mainly used for computer screens and televisions, as well as for aircraft instruments, and in compact fluorescent lamps. Phosphors with both bivalent and trivalent europium are used for different colours. For red phosphors, yttrium oxide doped with europium ($Y_2O_3:Eu^{3+}$) is mainly used; yttrium oxysulfide or, as the first important red phosphor, yttrium vanadate:$Eu^{3+}$ were also used in the past. $Eu^{2+}$ is mostly used as a blue phosphor in compounds such as strontium chlorophosphate $Sr_5(PO_4)_3Cl:Eu^{2+}$, strontium chloroapatite (SCAP) and barium magnesium aluminate $BaMgAl_{10}O_{17}: Eu^{2+}$ (BAM).

Plasma picture screens require phosphors that convert the VUV radiation emitted by the noble gas plasma into visible light. For this purpose, europium-doped phosphors are used for both the blue and red spectrum - BAM for blue light, $(Y,Gd)BO_3:Eu^{3+}$ for red.

More information of europium use is given (ISE, 2022):

Due to its neutron absorption, europium can be used in control rods for nuclear reactors. Control rods containing europium were tested in various Soviet test reactors such as BOR-60 and BN-600. As EuropiumHexaBorid, it is also offered as a coating to produce oxide cathodes for glow emission. Europium fluorescence is used to prevent counterfeiting of euro banknotes. This property can also be used in fluorescence spectroscopy. For this purpose, the europium is bound in a suitable complex, for example, which reacts preferentially at the desired location, for example with a certain protein, and accumulates there.

In terms of connections from europium the following can be said (ISE, 2022):

Compounds in the oxidation states +2 and +3 are known, whereby, as with all lanthanides, although the trivalent state is the more stable, the divalent state is also unusually stable and therefore many Eu (II) compounds exist. The ionic radii differ depending on the oxidation state, with $Eu^{2+}$ ions being larger than $Eu^{3+}$ ions. With the coordination number six the radii are 131 pm for $Eu^{2+}$ and 108.7 pm for $Eu^{3+}$. The effective ion radius (which uses an O140 ion which is 14 pm larger by 2 pm as a reference) is accordingly 117 pm or 94,7 pm for the coordination number six. The ionic radii are larger in higher coordination numbers; for Eu2 + in the coordination number eight it is 139 pm.

Regarding oxygen compounds of europium - Europium (III) oxide, $Eu_2O_3$, is the technically most important europium compound and serves as a starting material to produce other europium compounds and as a dopant for fluorescent dyes such as $Y_2O_3$:$Eu^{3+}$, which has a particularly intense red fluorescence with a europium (III) oxide content of around 10%. Like the other lanthanoid oxides, it crystallizes in the cubic lanthanoid C structure.

Europium (II) oxide, EuO, is a purple-black ferromagnetic solid with a Curie temperature of 70 K that crystallizes in a sodium-chloride structure. It can be obtained by reducing europium (III) oxide with europium and is the only divalent oxide of the lanthanoids that is stable under normal conditions. In addition to these two oxides, the mixed-valence oxide europium (II, III) oxide, $Eu_3O_4$, is also known

## GADOLINIUM APPLICATIONS

The end-use of gadolinium products in the EU are presented in Figure 31 and relevant industry sectors are are described using the NACE sector codes in Table 10

**Table 10: Gadolinium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2022).**

| Applications | 2-digit NACE sector | Value-added of sector (millions €) | Examples of 4-digit NACE sector |
|---|---|---|---|
| Magnets | C25 - Manufacture of fabricated metal products, except machinery and equipment | 183,015.50 | C2599 - Manufacture of other fabricated metal products not elsewhere classified |
| Lighting | C27 - Manufacture of electrical equipment | 98,417.10 | C2740 - Manufacture of electric lighting |
| Metal (excl. Batteries) | C24 - Manufacture of basic metals | 71,390.80 | C2410 - Manufacture of basic iron and steel and of ferro-alloys |
| MRI | C21 - Manufacture of basic pharmaceutical products and pharmaceutical preparation | 94,337.60 | C2100 - Manufacture of pharmaceutical preparation |

Gd is primarily used in NdFeB alloys (Kiggins, 2015) but also in SmCo alloys (Humphries, 2013) for temperature compensation and resistance to corrosion (BRGM, 2015). The major applications for gadolinium can be described in more detail as follows:

Gadolinium is used to make gadolinium yttrium garnet for microwave applications. Gadolinium oxide is used as a luminophore and gives the green colour in television tubes (BRGM, 2015). Oxysulfides are used to produce green phosphor for luminescent screens (radar).

Gd is used as a medical contrasting agent for magnetic resonance imaging (MRI) (EC, 2017). Intravenously injected gadolinium (III) compounds, such as gadopentetate dimeglumine, serve as contrast agents in MRI examinations. For this purpose, complexing agents with high complexing constants, such as, for example, the chelates DTPA (diethylenetriaminepentaacetic acid) and DOTA (1,4,7,10-tetraazacyclododecane-1,4,7,10-tetraacetic acid, with Gd = gadoteric acid) are used because of the high toxicity of free gadolinium ions. Due to the seven unpaired electrons in the shell, gadolinium is highly paramagnetic. The contrast agent thus allows the surrounding protons - essentially water - to relax more quickly. This significantly increases the contrast differences between different tissues in an MRI scan (ISE, 2022).

These contrast agents can also be used for studies on the brain, since the gadolinium complexes do not overcome the blood-brain barrier in healthy patients and thus a blood-brain barrier disorder - an indication of a pathological event (e.g., deficient circulation, tumour, inflammation) – can be made visible. Gadolinium gallium garnet was used to make magnetic bubble stores. It is also used in the production of rewritable compact discs.

Gadolinium is used in metallurgical applications for improving the mechanical characteristics of alloyed steel, for desulphurisation, or for binding trace elements in stainless steel. 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. Additions of 1% gadolinium increase the machinability and the high temperature and oxidation resistance of iron and chromium alloys. Corresponding gadolinium iron cobalt alloys can be used for optomagnetic data storage. Moreover, gadolinium is used in the form of gadolinium oxide in modern fuel assemblies as a burnable absorber material which, after a fuel change at the beginning of the operating cycle, limits the excess reactivity of the reactor due to an excess of nuclear fuel (ISE, 2022).

## HOLMIUM, LUTETIUM, YTTERBIUM AND THULIUM APPLICATIONS

The end-use of these products in the EU are presented in Figure 31 and relevant industry sectors are described using the NACE sector codes in Table 11.

**Table 11: 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 €) | Examples of 4-digit NACE sector |
|---|---|---|---|
| Glass – Optical applications | C23 - Manufacture of other non-metallic mineral products | 69,888.20 | C2310 - Manufacture of other glass including technical glassware |

The use of holmium, thulium, ytterbium and lutetium in individual applications is too small to be estimated with accuracy. Each one of these elements are used in niche applications mostly related to their optical properties (Laser dopants, fibre optics, radiography, etc.). Their major uses are as follows (ISE, 2022):

Holmium can be used for pigments, magnets, lasers and nuclear. Because of its excellent magnetic properties, pole pieces made of holmium are used for certain niche high-performance magnets to generate the strongest magnetic fields. Other applications are:

- magnetic bubble storage using thin-film alloys of holmium-iron, holmium-nickel and holmium-cobalt.
- control rods in breeder reactors.
- doping of yttrium iron garnet (YIG), yttrium aluminium garnet (YAG) and yttrium lithium fluoride (YLF) for solid-state lasers (holmium laser with an emission wavelength of 2.1 µm and microwave components in medical technology.
- holmium oxide to produce yellow glass, among other things because of its sharp absorption bands for calibration functions for photometers.

Lutetium can be used as phosphors, PET detectors, glass. Lutetium is used in scintillator crystals for positron emission tomography. One of the most prominent examples is cerium-doped lutetium oxyorthosilicate (LSO). The radionuclide $^{177}$Lu can be used as a therapy against neuroendocrine tumours.

Ytterbium in general is used as fibre optics, lasers, photovoltaics, stress gauges. Ytterbium can be used for grain refining and to improve the mechanical properties of stainless steels. The radioactive isotope $^{169}$Yb (half-life 32 days) is occasionally used as a source of γ-radiation in nuclear medicine. Ytterbium-cobalt-iron-manganese alloys are suitable for high-quality permanent magnets. Ytterbium-doped crystals (mainly Yb: YAG) are used as reinforcing material in lasers.

Thulium offers few commercial applications:

- $^{170}$Tm removed from nuclear reactors is used as a source of X-rays (gamma emitters in materials testing).
- Thulium-doped yttrium tantalate or lanthanum oxybromide (LaOBr) serves as a scintillator in X-ray intensifying screens or fluorescent screens in X-ray technology
- Thulium-doped calcium sulphate is used as a detector in personal dosimeters for measuring low radiation doses.
- Thulium crystals can be used as active medium in diode-pumped solid-state lasers (wavelength 2 µm) with an overall efficiency of up to 10% at a maximum light output of 60 W.
- Thulium-doped silica glass as active medium in fibre lasers (wavelength 2 µm) was operated with a differential efficiency of 53.2% at a power > 1 kW.

### 4.2.7 LANTHANUM APPLICATIONS

The end-uses of lanthanum products in the EU are presented in Figure 31 and relevant industry sectors are described using the NACE sector codes in Table 12.

**Table 12: 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 (millions €) | Examples of 4-digit NACE sector |
|---|---|---|---|
| Fluid Cracking | C19 - Manufacture of coke and refined petroleum products | 25,475.50 | C2029 - Manufacture of other chemical products not elsewhere classified |
| Batteries | C27 - Manufacture of electrical equipment | 98,417.10 | C2720 - Manufacture of batteries and accumulators |
| Glass&Ceramics | C23 - Manufacture of other non-metallic mineral products | 69,888.20 | C2331 - Manufacture of ceramic tiles and flags |
| Polishing powders | C26 - Manufacture of computer, electronic and optical products | 84,020.90 | C2670 - Manufacture of optical instruments and photographic equipment |
| Metal (excl. Batteries) | C24 - Manufacture of basic metals | 71,390.80 | C2410 - Manufacture of basic iron and steel and of ferro-alloys |
| Lighting | C27 - Manufacture of electrical equipment | 98,417.10 | C2740 - Manufacture of electric lighting equipment |

Lanthanum is used for a variety of applications; its three main uses are in FCCs, nickel-metal hydride batteries and glass & ceramics (EC, 2017). Lanthanum is a component in misch metal. Pyrophoric flint materials contain 25-45 weight % lanthanum. In addition, it finds use as a reducing agent in metallurgy. As a cast-iron addition, it supports the formation of spheroidal graphite, as an alloying additive, it improves the oxidation resistance. Lanthanum admixtures reduce the hardness and temperature sensitivity of molybdenum.

High-quality cathodes for generating free electrons consist of lanthanum hexaboride as a substitute for tungsten wire. High-purity lanthanum oxide is used in the glass industry to produce high-quality glasses with a high refractive index for the optics z. B. used for camera lenses (ISE, 2022).

Lanthanum can be used in combination with cobalt and titanium: The cobalt-lanthanum alloy $LaCo_5$ is used as a magnetic material, lanthanum-doped barium titanate to produce PTC thermistors (temperature-dependent resistors). In conjunction with cobalt, iron, manganese, strontium and others, it serves as a cathode for high-temperature fuel cells (SOFC). An alloying metal with material compositions of lanthanum and titanium, the effect is attributed to the fact that with chip-forming processing, the chip length is reduced. This should facilitate the processing of the metal. In the field of medicine, corrosion-resistant and easily sterilizable instruments are produced from the alloying metal. This titanium-based metal alloy is said to be particularly well-suited for surgical tools and apparatus because the allergy propensity of using such metal alloy with titanium relative to other alloys should be low (ISE, 2022).

Finally, lanthanum oxide can be used as follows (ISE, 2022):

- production of glasses (Lanthanglas) with comparatively high refractive index, which in turn changes only slightly with the wavelength (low dispersion), for cameras, telescope lenses and for spectacle lenses
- Production of crystal glass and porcelain stains. It replaces more toxic lead compounds with simultaneous improvement of chemical resistance (improvement of alkali resistance, "dishwasher safe")
- Catalyst addition to zeolites during fluid catalytic cracking in the oil refinery
- Production of ceramic condenser masses and silicate-free glasses
- Component of glass polishers
- Production of hot cathodes for electron tubes (also lanthanum borides)
- Drug for lowering the phosphate level in dialysis patients (so-called phosphate binder)

### 4.2.8 NEODYMIUM APPLICATIONS

The end-uses of neodymium products in the EU are presented in Figure 31 and relevant industry sectors are described using the NACE sector codes in Table 13.

**Table 13: Neodymium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2022).**

| Applications | 2-digit NACE sector | Value-added of sector (millions €) | Examples of 4-digit NACE sector |
|---|---|---|---|
| Magnets | C25 - Manufacture of fabricated metal products, except machinery and equipment | 183,015.50 | C2599 - Manufacture of fabricated metal products not elsewhere classified |
| Ceramics | C23 - Manufacture of other non-metallic mineral products | 69,888.20 | C2331 - Manufacture of ceramic tiles and flags |

| | | | |
|---|---|---|---|
| Batteries | C27 - Manufacture of electrical equipment | 98,417.10 | C2720 - Manufacture of batteries and accumulators |
| Metal (excl. batteries) | C24 - Manufacture of basic metals | 71,390.80 | C2410 - Manufacture of basic iron and steel and of ferro-alloys |
| Catalysts | C20 - Manufacture of chemicals and chemical products | 117,093.2 | C2029 - Manufacture of other chemical products not elsewhere classified |
| Glass | C23 - Manufacture of other non-metallic mineral products | 69,888.20 | C2310 - Manufacture of glass and glass products |
| Lasers | C26 - Manufacture of computer, electronic and optical products | 84,020.90 | C2670 - Manufacture of optical instruments and photographic equipment |

Neodymium-iron-boron compounds are used to produce strongest magnets. They are used for magnetic resonance tomographs, micromotors and hard disks (positioning of the read / write heads), permanent magnet rotors (e.g., stepper and servo motors, efficient permanent magnet DC machines, e.g., in some wind turbine types, for the propulsion of battery and hybrid EVs as well as model vehicles), linear motors for positioning the axes of CNC machines, high quality speakers and headphones. Compared to samarium-cobalt magnets, they are stronger and much cheaper, but are also much more sensitive to heat. Additionally, the following applications can be mentioned (ISE, 2022):

- Neodymium (III) oxide for glass staining produces very warm violet to maroon and grey tones. Such glasses have sharp absorption bands and are used in astronomy for calibration.
- Discoloration of ferrous glass
- UV-absorbing glasses (solar control glass)
- Part of the industrially widespread neodymium-YAG laser
- Neodymium oxide doped barium titanate for capacitor dielectrics
- Because of its pyrophoric properties also as alloying partner with cerium in flint stones
- For the preparation of neodymium-catalysed polybutadiene rubber (Nd-PBR)
- Neodymium Iron Boron (Nd2Fe14B) is currently the strongest material for Neodymium Nickel Magnets
- Permanent magnets. You can achieve a remanence of up to 1,4 Tesla. The coercive force jHc varies in the range from 870 to 2750 kA / m.

## PRASEODYMIUM APPLICATIONS

The end-uses of products in the EU are presented in Figure 31 and relevant industry sectors are described using the NACE sector codes in Table 14.

**Table 14: Praseodymium applications, 2-digit NACE sectors, 4-digit NACE sectors and value added per sector (Eurostat, 2022).**

| Applications | 2-digit NACE sector | Value-added of sector (millions €) | Examples of 4-digit NACE sector |
|---|---|---|---|
| Magnets | C25 - Manufacture of fabricated metal products, except machinery and equipment | 183,015.50 | C2599 - Manufacture of fabricated metal products not elsewhere classified |
| Ceramics | C23 - Manufacture of other non-metallic mineral products | 69,888.20 | C2331 - Manufacture of ceramic tiles and flags |

| | | | |
|---|---|---|---|
| Batteries | C27 - Manufacture of electrical equipment | 98,417.10 | C2720 - Manufacture of batteries and accumulators |
| Metal (excl. batteries) | C24 - Manufacture of basic metals | 71,390.80 | C2410 - Manufacture of basic iron and steel and of ferro-alloys |
| Catalysts | C20 - Manufacture of chemicals and chemical products | 117,093.2 | C2029 - Manufacture of other chemical products not elsewhere classified |
| Glass | C23 - Manufacture of other non-metallic mineral products | 69,888.20 | C2310 - Manufacture of glass and glass products |
| Polishing powders | C26 - Manufacture of computer, electronic and optical products | 84,020.90 | C2670 - Manufacture of optical instruments and photographic equipment |

Praseodymium is used in the EU in many applications. Most praseodymium is used in magnet applications as a substitute for neodymium in NdFeB magnets (27%, see figure 9). Additionally, praseodymium is used in alloys with magnesium to produce high-strength metal for aircraft engines. Praseodymium compounds are used for colouring glass and enamel (for example in green-coloured headlamp lenses in lighting technology). The compounds also improve UV absorption and are used for eye protection glasses during welding.

### SAMARIUM APPLICATIONS

The end-use of products in the EU are presented in Figure 31 and relevant industry sectors are described using the NACE sector codes in Table 15.

**Table 15: 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 (millions €) | Examples of 4-digit NACE sector |
|---|---|---|---|
| Magnets | C25 - Manufacture of fabricated metal products, except machinery and equipment | 183,015.50 | C2599 - Manufacture of fabricated metal products not elsewhere classified |
| Medical and optical applications | C26 - Manufacture of computer, electronic and optical products | 84,020.90 | C2670 - Manufacture of optical instruments and photographic equipment |

The main application for samarium is SmCo permanent magnets. SmCo magnets have high permanent magnetization, second only to that of NdFeB 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. Other uses of Sm are niche applications mostly related to its optical properties (laser dopant, radiography, etc.) and nuclear industry (EC, 2017).

### TERBIUM APPLICATIONS

The end-use of terbium products in the EU are presented in Figure 31 and relevant industry sectors are described using the NACE sector codes in Table 16.

Table 16: 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 (millions €) | Examples of 4-digit NACE sector |
|---|---|---|---|
| Lighting | C27 - Manufacture of electrical equipment | 98,417.10 | C2740 - Manufacture of electrical lighting equipment |
| Ceramics | C23 - Manufacture of other non-metallic mineral products | 69,888.20 | C2331 - Manufacture of ceramic tiles and flags |
| Alloys | C24 - Manufacture of basic metals | 71,390.80 | C2410 - Manufacture of basic iron and steel and of ferro-alloys |
| Glass | C23 - Manufacture of other non-metallic mineral products | 69,888.20 | C2310 - Manufacture of glass and glass products |

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

Like dysprosium, terbium is used in NdFeB magnets to increase the intrinsic coercivity and 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 colour in neons and fluo-compact lamps. It represents 4% of the composition of luminophores used for lighting (BRGM, 2015). In that way, terbium is used to dope calcium fluoride, calcium tungstate and strontium molybdate for use in semiconductors (solid-state devices). Together with zirconium (IV) oxide, it is used to stabilise the structure in high-temperature fuel cells. The oxide is added to the green phosphor in picture tubes and fluorescent lamps. Sodium terbium borate is used as a laser material to generate coherent light with a wavelength of 546 nm. Terbium-iron-cobalt or terbium-gadolinium-iron-cobalt alloys are used as coatings on rewritable magneto-optical (MO) discs. Alloys containing terbium-dysprosium show strong magnetostriction (change in length due to a magnetic field or magnetic pulses when the length changes). Such alloys are used in materials testing technology (ISE, 2022).

## SUBSTITUTION

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 aspects are summarised in Table 17. The chapter contains substantial input from Machacek and Kalvig (2017: EURARE) providing more details about individual applications.

Table 17: Summary of REE substitutes (source: EC, 2020)

| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
|---|---|---|---|---|---|---|
| Ce | Autocatalysts | 60% | Lanthanum | 5% | Similar or lower costs | Similar |
| Ce | Autocatalysts | 60% | Neodymium | 3% | Very high costs | Similar |
| Ce | Autocatalysts | 60% | Praseodymium | 2% | Very high costs | Similar |
| Ce | Glass & ceramics | 12% | Lanthanum | 28% | Similar or lower costs | Similar |
| Ce | Glass & ceramics | 12% | Praseodymium | 3% | Very high costs | Similar |
| Ce | Glass & ceramics | 12% | Other REO | 5% | Slightly higher costs | Similar |
| Ce | Glass & ceramics | 12% | Calcium oxide | 1% | Similar or lower costs | Reduced |
| Ce | Glass & ceramics | 12% | MgO | 1% | Similar or lower costs | Reduced |
| Ce | Glass & ceramics | 12% | Zirconium | 1% | Very high costs | Similar |
| Ce | Polishing powders | 20% | Iron oxide | 13% | Similar or lower costs | Similar |

| | | | | | | |
|---|---|---|---|---|---|---|
| Ce | Polishing powders | 20% | Alumina | 13% | Similar or lower costs | Similar |
| Ce | Polishing powders | 20% | Silica powder | 13% | Similar or lower costs | Similar |
| Ce | Polishing powders | 20% | Magnesia | 13% | Similar or lower costs | Similar |
| Ce | Fluid cracking catalysts | 4% | Lanthanum | 68% | Similar or lower costs | Similar |
| Ce | Batteries | 2% | Lanthanum | 5% | Similar or lower costs | Similar |
| Ce | Batteries | 2% | Li-ion batteries | 85% | Slightly higher costs | Similar |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| La | Fluid cracking catalysts | 60% | Cerium | 32% | Similar or lower costs | Similar |
| La | Autocatalysts | 29% | Cerium | 5% | Similar or lower costs | Similar |
| La | Batteries | 3% | Li-ion batteries | 85% | Slightly higher costs | Similar |
| La | Batteries | 3% | Cerium | 5% | Similar or lower costs | Similar |
| La | Glass & ceramics | 5% | Cerium | 65% | Similar or lower costs | Similar |
| La | Glass & ceramics | 5% | Praseodymium | 3% | Very high costs | Similar |
| La | Glass & ceramics | 5% | Other REO | 5% | Very high costs | Similar |
| La | Glass & ceramics | 5% | Calcium oxide | 1% | Similar or lower costs | Reduced |
| La | Glass & ceramics | 5% | MgO | 1% | Similar or lower costs | Reduced |
| La | Glass & ceramics | 5% | Zirconium | 1% | Very high costs | Similar |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Nd | Magnets | 80% | Praseodymium | 8% | Slightly higher costs | Reduced |
| Nd | Magnets | 80% | Ferrite | 2% | Similar or lower costs | Reduced |
| Nd | Magnets | 80% | Sm-Co | 2% | Similar or lower costs | Reduced |
| Nd | Magnets | 80% | AlNiCo | 1% | Similar or lower costs | Reduced |
| Nd | Ceramics | 3% | Cerium | 40% | Similar or lower costs | Similar |
| Nd | Ceramics | 3% | Yttrium | 10% | Similar or lower costs | Similar |
| Nd | Ceramics | 3% | Calcium oxide | 1% | Similar or lower costs | Reduced |
| Nd | Ceramics | 3% | MgO | 1% | Similar or lower costs | Reduced |
| Nd | Batteries | 4% | Li-ion battery | 85% | Slightly higher costs | Similar |
| Nd | Batteries | 4% | Lanthanum | 1% | Similar or lower costs | Reduced |
| Nd | Batteries | 4% | Cerium | 1% | Similar or lower costs | Reduced |
| Nd | Batteries | 4% | Praseodymium | 1% | Slightly higher costs | Similar |
| Nd | Metal (excl. Batteries) | 2% | Cerium | 13% | Similar or lower costs | Reduced |
| Nd | Metal (excl. Batteries) | 2% | Lanthanum | 13% | Similar or lower costs | Reduced |
| Nd | Metal (excl. Batteries) | 2% | Magnesium | 0% | Slightly higher costs | Similar |
| Nd | Metal (excl. Batteries) | 2% | Calcium | 0% | Slightly higher costs | Reduced |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Sm | Magnets | 97% | NdFeB | 15% | Very high costs | Similar |
| Sm | Magnets | 97% | Ferrites | 2% | Similar or lower costs | Reduced |
| Sm | Magnets | 97% | AlNiCo | 1% | Similar or lower costs | Reduced |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Dy | Magnets | 100% | Terbium | 25% | Very high costs | Similar |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Er | Glass | 74% | No substitute | 100% | | |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Eu | Lighting | 10% | Manganese | 0% | Similar or lower costs | Reduced |
| Eu | Lighting | 10% | Silicate barium phosphors | 0% | Similar or lower costs | Reduced |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Gd | Magnets | 10% | Terbium | 25% | Very high costs | Similar |
| Gd | Magnets | 10% | Dysprosium | 25% | Very high costs | Similar |
| Gd | Metal (excl. Batteries) | 10% | Praseodymium | 25% | Slightly higher costs | Similar |
| Gd | Metal (excl. Batteries) | 10% | Neodymium | 25% | Slightly higher costs | Similar |
| Gd | Magnetic Resonance Imaging - MRI | 40% | Manganese | 0% | Similar or lower costs | Similar |

| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
|---|---|---|---|---|---|---|
| Ho | Ceramics | 100% | No substitute | 100% | | |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Lu | Others | 99% | No substitute | 100% | | |
| Lu | Lighting | 1% | No substitute | 100% | | |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Tb | Magnets | 90% | Dysprosium | 75% | Slightly higher costs | Similar |
| Tb | Lighting | 10% | LEDs | 70% | Similar or lower costs | Similar |
| Tb | Lighting | 10% | La | 2% | Similar or lower costs | Similar |
| Tb | Lighting | 10% | Ce | 2% | Similar or lower costs | Similar |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Yb | Ceramics | 100% | No substitute | 100% | | |
| REE | Application | Share | Substitutes | SubShare | Cost | Performance |
| Y | Automotive catalysts | 9% | No substitute | 100% | | |
| Y | Ceramics | 72% | Calcium oxide | 10% | Similar or lower costs | |
| Y | Ceramics | 72% | MgO | 10% | Slightly higher costs | Reduced |

## PERMANENT MAGNETS

neodymium-based high-performance magnets are widely used, with maximum available magnetic field strength per unit mass. Heavy REE additions such as dysprosium or terbium and finer grain size can improve intrinsic coercivity  of NdFeB magnets at higher temperatures.

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

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

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

## BATTERIES

“Lithium-ion (Li-ion) batteries have largely replaced 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 batteries are still higher than those associated to NiMH batteries, Li-ion batteries have largely replaced NiMH batteries in EVs, mainly because of their higher energy density and longer lifespan. Indeed, such types of EVs can be charged by plugging them in a grid-provided electricity system and thus require batteries with higher energy density to guarantee a range as large as possible between charging stations.

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),

### CATALYSTS

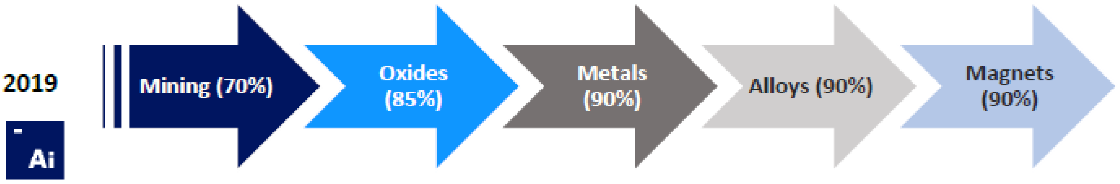
"La is crucial for FCC catalysts because it provides thermal stability and selectivity, and substitutes for La in FCC catalysts are known (Öko Institut, 2011). The only alternative can be considered the use of fluid cracking catalysts based on zeolites without REE, but this leads to products with poor,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

## SUPPLY

### GLOBAL SUPPLY

Global mine production is estimated at 280,000 tonnes of REO equivalent in 2021, significantly increased in comparison to 2020 (240,000 tonnes). Production of REO in China was estimated to be 168,000 tonnes (USGS, 2022). China provided around 62% of the world's primary production of REEs in 2020 (WMD, since 1984).

Before the 1990s, less than 10% of total REE production were separated REE. Iin 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%. In recent years, China's share of global REE mine production has fallen slightly as a handful of new or re-activated REE mines have come on stream outside China. However, China has continuously expanded its 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 42).



Source: Adamas Intelligence

Figure 42: 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 from 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. Their assets include a REE mine at Mt Weld in Western Australia and a concentration plant, commissioned in 2011, and located

1.5km from the mine site. They also include a cracking / leaching / separation facility located in the Gebeng Industrial Estate near the Port of Kuantan in Malaysia, which has been producing since 2012. Other producers are small and offer limited range and quality of REE products. More recently Lynas has constructed a crack / leach plant in Kalgoorie, Western Australia, as a replacement for the same operations in Malaysia.

## EU SUPPLY CHAIN

EU imports 100% of its REEs. 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 to manufacture REE-based products for various industries (phosphors, catalysts, polishing powders, etc.) but not metallic rare earths. There are also alloys makers and magnet manufacturers (in Germany and Slovenia) operating from imported processed materials (strip cast alloy). Just outside of the EU there is metal and alloy-making capability in the UK (Less Comon Metals, LCM). 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 imported into to the EU (magnets, alloys, hard drives, laptops, electric or hybrid vehicles, etc.).

### CERIUM

The EU consumed on average approximately 4000 tonnes per year of cerium compounds (metal equivalent) for a wide range of applications (autocatalysts, glass and ceramics, polishing powders, fluid cracking catalyst, metals, batteries and lighting).

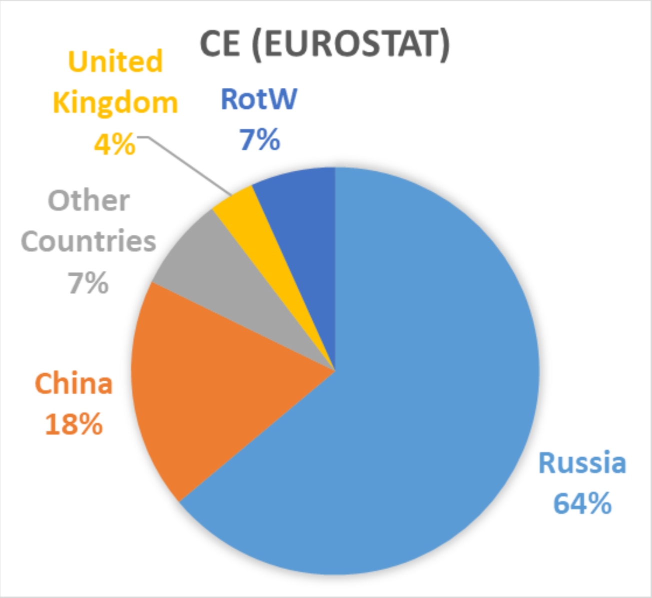


Figure 43: EU import of Cerium, all forms in Ce content (EC criticality evaluation 2023)

Two companies have the ability to separate individual REEs (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).

## LANTHANUM

The EU consumed on average approximately 2240 tonnes per year of lanthanum under all forms (metal equivalent) for ceramics, batteries, metals, catalysts, glass, lasers applications.

## NEODYMIUM

The EU consumed on average approximately 80 tonnes per year of neodymium under all forms (metal equivalent) for magnets, ceramics, batteries, metals, catalysts, glass, lasers applications.

## PRASEODYMIUM

The EU consumed on average approximately 67 tonnes per year of praseodymium under all forms (metal equivalent) for magnets, batteries, ceramics, metals, catalysts, polishing powders, glass applications.

## SAMARIUM

The EU consumed on average approximately 2.8 tonnes per year of samarium under all forms (metal equivalent) for magnets, ceramics, batteries, metals, catalysts, glass, lasers applications.

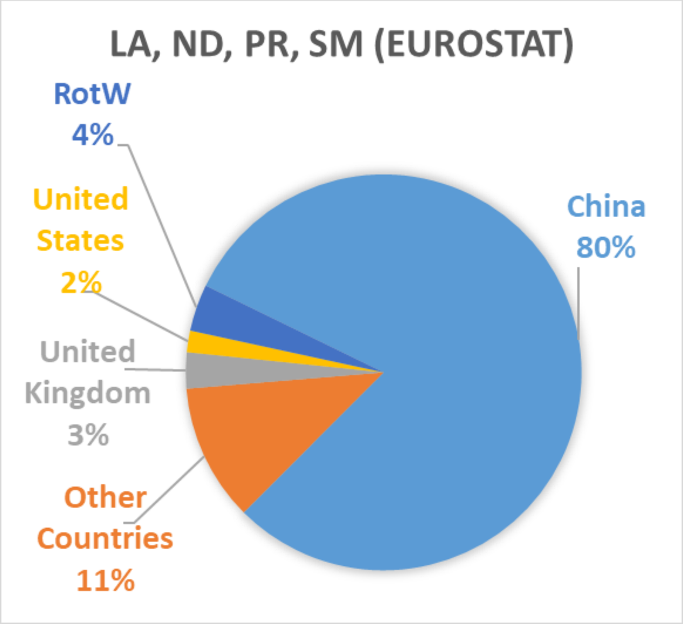


**Figure 32: EU import of lanthanum, neodymium, praseodymium and samarium under all forms (EC criticality evaluation 2023)**

## DYSPROSIUM

EU consumed on average approximately 2.3 tonnes per year of dysprosium under all forms (metal equivalent) used in magnets.

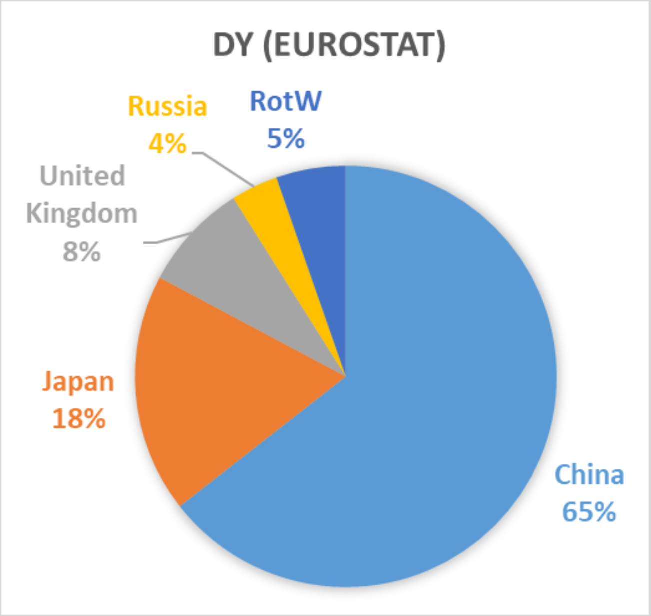


Figure 44: EU import of dysprosium under all forms (EC criticality evaluation 2023))

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

## ERBIUM

EU consumed in average approximately 30.6 tonnes per year of erbium under all forms (metal equivalent) for glass and optical applications and lighting.

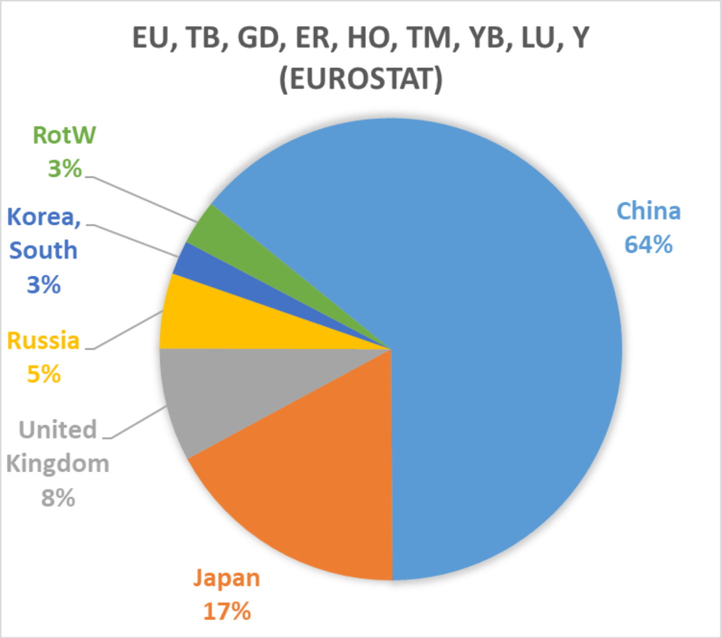


Figure 46: EU import of europium, terbium, gadolinium, erbium, holmium, thullium, ytterbium, lutetium and yttrium (EC criticality evaluation 2023)

### EUROPIUM

The EU consumed on average approximately 1 tonne per year of europium under all forms (metal equivalent) for lighting applications.

### GADOLINIUM

The EU consumed on average approximately 45 tonnes per year of gadolinium under all forms (metal equivalent) for magnets, lighting, metals and magnetic-resonance imaging applications.

### HOLMIUM, LUTETIUM, YTTERBIUM AND THULIUM

The EU consumed on average approximately 60 kg of holmium, 200 kg of thulium, 5.6 tonnes of lutetium and 7.4 tonnes of ytterbium under all forms (metal content) mainly  for glass-optical applications.

### TERBIUM

The EU consumed on average approximately 1.6 nnes per year of terbium under all forms (metal equivalent) for magnets and lighting applications.

### YTTRIUM

The EU consumed on average approximately 56 tonnes per year of yttrium under all forms (metal equivalent) magnets and lighting applications.

## SUPPLY FROM PRIMARY MATERIALS

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

- mining of ores from the mineral deposits;
- beneficiation of the ore minerals into mineral concentrates;
- hydrometallurgical processing to extract and concentrate the REEs into mixed chemical concentrates;
- separating and refining into individual REOs. The REOs are dried, stored and shipped;
- converting certain REOs into metals with different purity levels;
- forming the metals into REE alloys;
- manufacturing some of thse alloys into devices and components such as permanent magnets.

### GEOLOGY, RESOURCES AND RESERVES OF REES

### GEOLOGICAL OCCURRENCE AND DEPOSITS:

The average concentration of individual REEs in the Earth’s upper crust is summarized in Table 18.

**Table 18: 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 for commercial exploitation are carbonatite-associated deposits (including weathered carbonatites), ion-adsorption deposits, alkaline igneous rocks (including alkaline granites), and placer 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 and Mountain Pass in the USA, with bastnaesite as the main ore mineral. They are typically enriched in LREEs.

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) along with some xenotime, which are both exploited as a by-product of rutile, ilmenite and others.

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

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

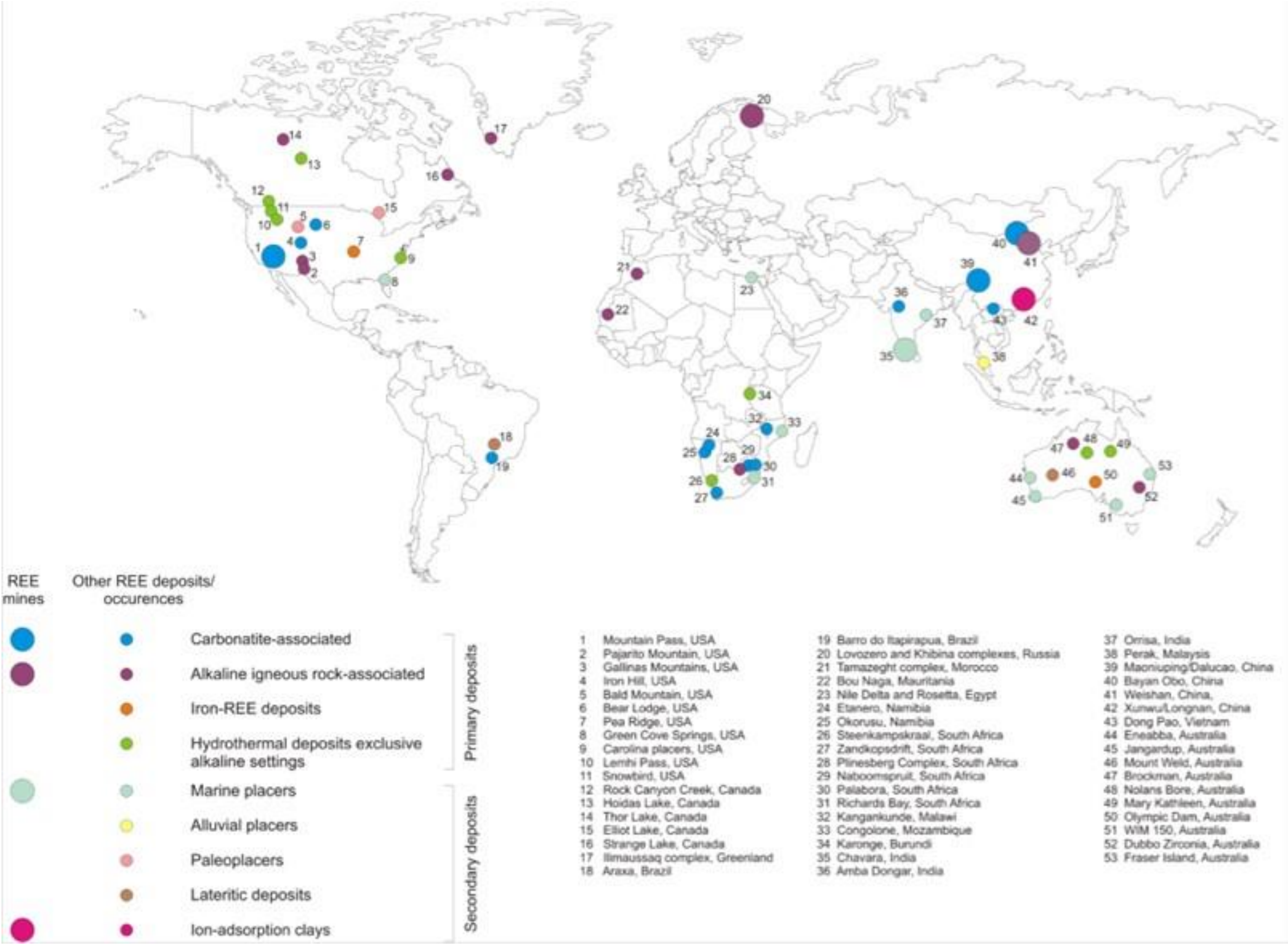
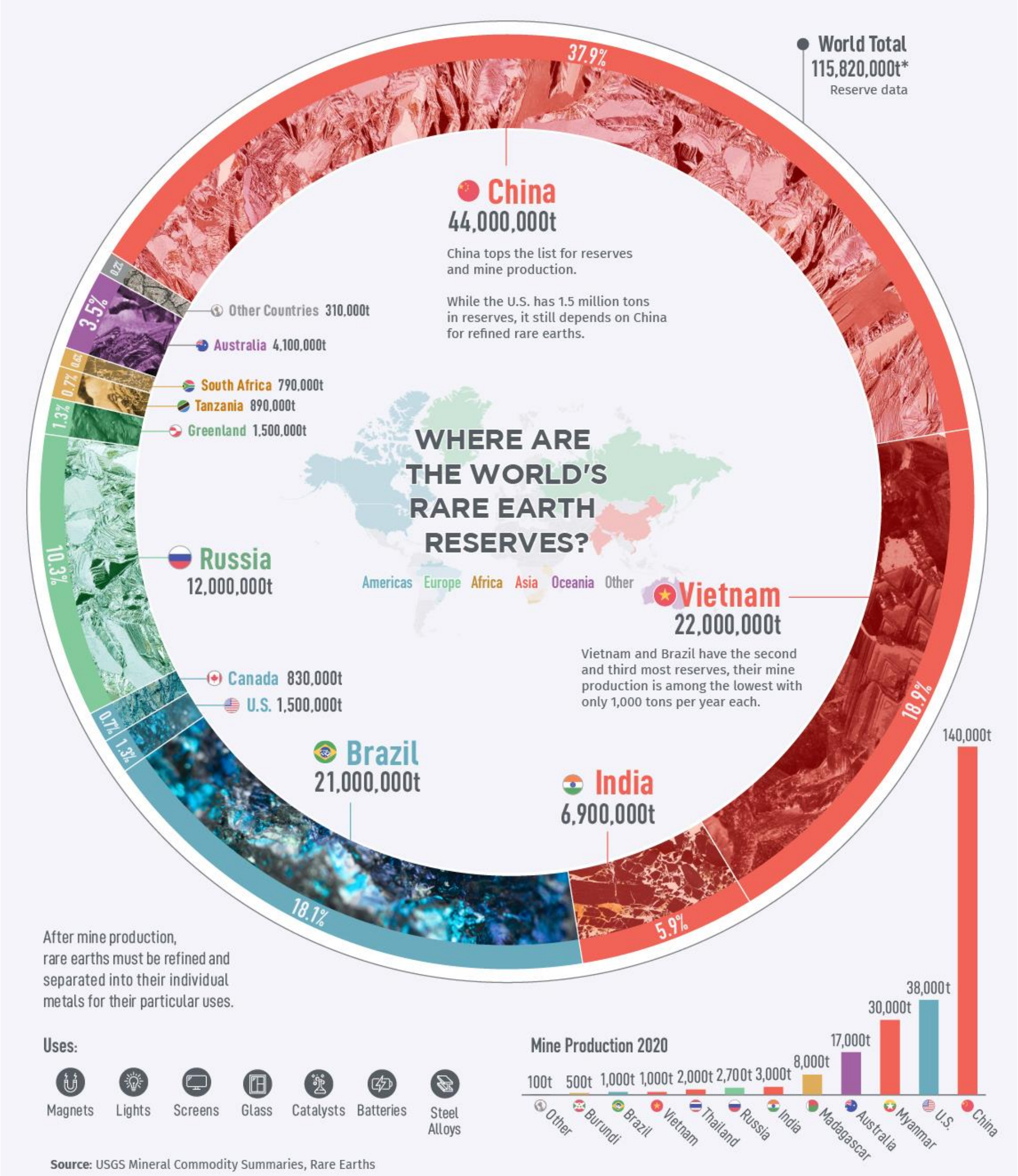


**Figure 61: Global REE deposits (BGS 2019)**



Source: USGS Mineral Commodity Summaries, Rare Earths

Figure 33. World reserves of rare earth (Mining.com 2021)[2]

## GLOBAL RESOURCES AND RESERVES3

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[2] Rare earth elements: Where in the world are they? - MINING.COM

[3] There is no single source of comprehensive evaluations for resources and reserves that apply the same criteria to deposits of REEs 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.[3], 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.

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 reserve estimates according to USGS and new studies, are presented in Tables 19 and 20. The 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.

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 global REE reserves are 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 light REE (Machacek and Kalvig 2017: EURARE).

**Table 19: Estimates of the global REO reserves in tonnes in 2021 (LePan, 2021; IRENA, 2022).**

| Country | Mine Production 2020 | Reserves | % of Total Reserves |
|---|---|---|---|
| China | 140,000 | 44,000,000 | 38.0% |
| Vietnam | 1,000 | 22,000,000 | 19.0% |
| Brazil | 1,000 | 21,000,000 | 18.1% |
| Russia | 2,700 | 12,000,000 | 10.4% |
| India | 3,000 | 6,900,000 | 6.0% |
| Australia | 17,000 | 4,100,000 | 3.5% |
| United States | 38,000 | 1,500,000 | 1.3% |
| Greenland | - | 1,500,000 | 1.3% |
| Tanzania | - | 890,000 | 0.8% |
| Canada | - | 830,000 | 0.7% |
| South Africa | - | 790,000 | 0.7% |
| Other Countries | 100 | 310,000 | 0.3% |
| Burma | 30,000 | N/A | N/A |
| Madagascar | 8,000 | N/A | N/A |
| Thailand | 2,000 | N/A | N/A |
| Burundi | 500 | N/A | N/A |
| **World Total** | **243,300** | **115,820,000** | **100%** |

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 REEs. Alternatively, REEs 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 heavy REEs. The REEs 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 REEs and crystalline REE carbonates and REE fluorocarbonates (e.g. bastnäsite) as well as REE phosphates (monazite and xenotime). The carbonatite-associated deposits are dominated by light REE-enriched REE minerals. Mountain Pass (USA), Mt. Weld (Australia), and Bayan Obo (China) constitute examples of carbonatites currently 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 REEs 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 REEs 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 for the production of REEs as a by-product. The REE-bearing apatite is currently treated as waste during iron-ore processing; there is however, an on-going pilot-project to start small-scale REE 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 rutile, ilmenite and/or zircon, 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 REEs 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. They have also been recently identified in Chile,  Brazil and Australia. 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. In general, however, exploitation of this type of deposit has a negative environmental impact.

## EU RESOURCES AND RESERVES[4]:

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-earth reserves (respectively 1,528,000 tonnes and 140,000 tonnes of REO) have been performed using international reporting code and can be qualified as reliable at the present date.

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[4] 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.

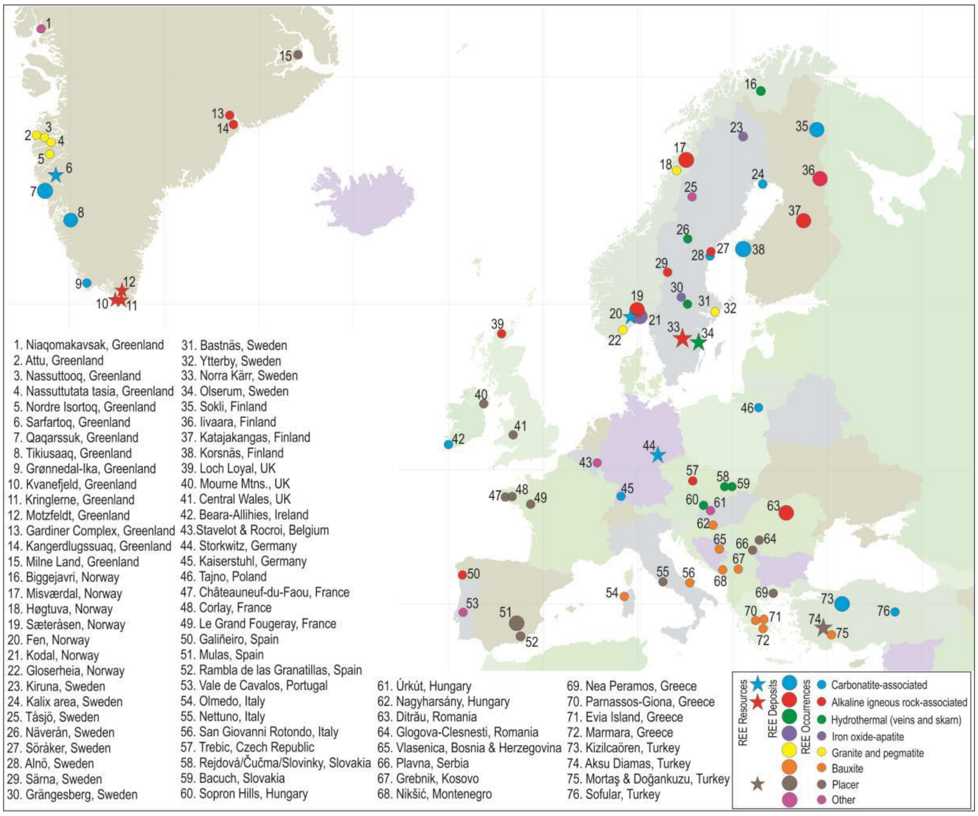

Figure 34: REE deposits in the EU according to the EURare project. (BGS NERC 2019: SCRREEN)

Table 20: 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 | | | 12461 | | |
| | Kontioaho | | | 27336 | | |
| | Korsnas | | | | | 7740 |
| | Kovela | | 1160 | | | |
| Germany | Storkwitz | | 9900 | 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 | |
| | Kiruna | | | | >1000000 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Olserum | | 47790 | | | |
| | Tasjo | | 82500 | | | |

## IMPORTANCE OF REE MINERALOGY

REEs can be found in 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 projects targeted the alkaline igneous deposits that contain less conventional REE silicate ore minerals such as eudialyte, gadolinite, and steenstrupine. These minerals can be of interest because of their more balanced ratio of heavy to light REEs which makes them potentially highly valuable resources, 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 REEs compared with typical values of <100 ppm to ~500 ppm REEs in bauxites. (Deady et al. 2014)

Similarly, phosphate rocks are a perspective source of REE, for example the EU project SecREEts aimed to unlock REE potential in 650,000 tonnes of phosphate rock mined annually in Norway, containing about 0.3 - 1.0% of REE.

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

Each of the REE minerals has a characteristic average REE ratio (Kanazawa and Kamitani, 2006), e.g., bastnäsite and monazite are dominated by light REEs, whereas xenotime is relatively rich in heavy REEs. 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.

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

**Table 21: 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<br>Cheralite | $Ca_5(PO_4)_3(F,Cl,OH)$<br>$CaTh(PO_4)_2$ | -<br>Variable | -<br>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) | $(Y,Na,Ca,U)_{1\text{-}2}Nb_2(O,OH)$ | 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; 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 the development of tailor-made beneficiation and cracking flowsheets. REE distribution is key to market acceptability and, consequently, to the 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 for further development. 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 economically mineable part of the rock hosting REE minerals.
- Composition of the REE mineral: the mismatch between the ratio of the REEs 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 REE 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 REE / total REE (%), reflecting the relative 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 light REEs may reach a lower GMV than a low-grade ore dominated by heavy REE. Further, high GMV does not guarantee a market for the products.
- Basket price (EUR/kg), reflecting the potential price if one kilogram of the REOs present are extracted from the ore – not accounting for the ore grade or the total recovery rates. From this it follows that low-grade ore containing a relatively high distribution of more valuable REEs may well result in a higher basket price than a high-grade ore with a relatively low distribution of such REEs.
- Mineralogy of the ore: To date there have only been 4 minerals (bastnästite, monazite, xenotime and ion-adorbed clays in China) that have been successfully processed commercially. It has taken Australian Strategic Materials 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 bastnäsite and eudialyte-like minerals 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: most REE 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 REEs, 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 saleability 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 (REE oxide, REE carbonate; REE 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 for 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.

## WORLD AND EU MINE PRODUCTION

### GLOBAL MINE PRODUCTION

According to WMS (WMD, since 1984) the global mine production of REO equivalent in 2020 reached 225,000 tonnes. China contributes over 62% of global production, compared to 66% and 67% in 2018 and 2019. USA, Myanmar and Australia are the only notable producers of REEs outside China, which contributed 17.3%, 9.3% and 8.6% respectively, to global production in 2020 (WMD, since 1984) (Figure 22). USGS data present a differentiation for the same year. The global REO equivalent is estimated at 245,700 tonnes, while the production share of China, US, Myanmar and Australia is: 53.7%, 15.8%, 12.6% and 8.1%, respectively (USGS, since 2000) (Figure 64). Early data for 2021 show an increase of the global production reaching 277,600 tonnes and an increase of China's share to about 60%.

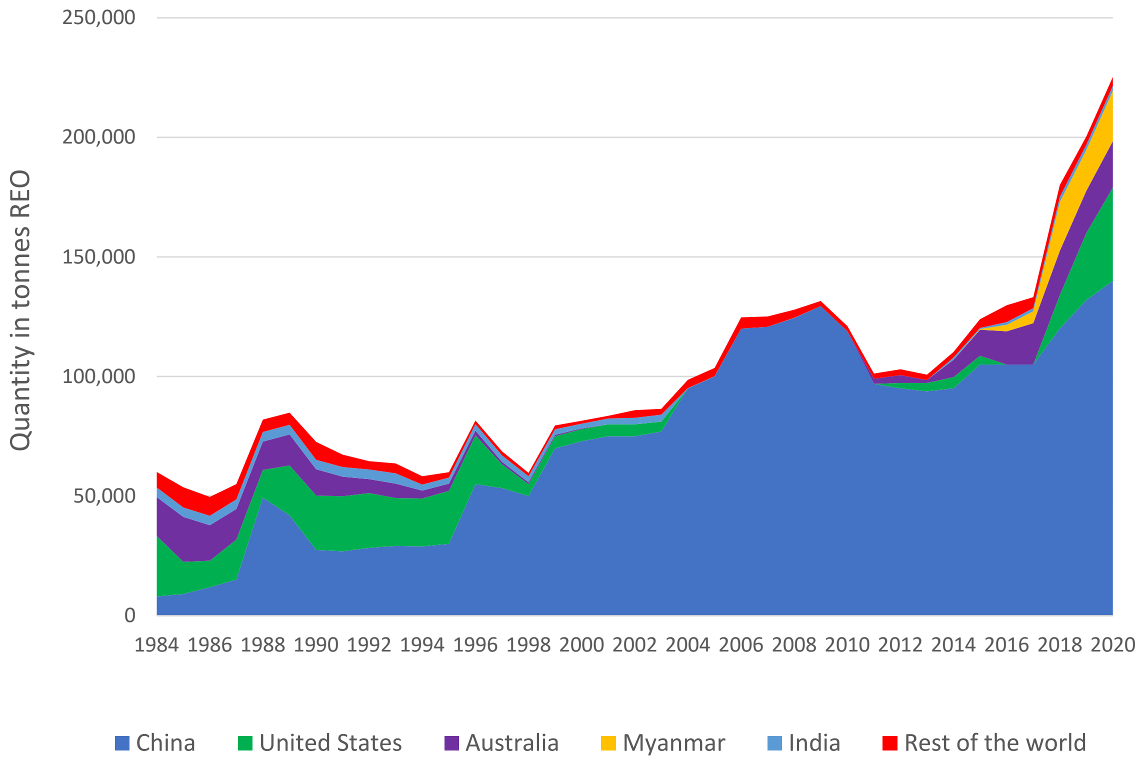

**Figure 35: Rare earth elements primary production in terms of REO content since 1984 (WMD, since 1984).**

An additional undocumented annual production in China is reported. For example, its amount estimated at 60,000-80,000 tonnes in 2018 (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.

Around 70% of global production originates from carbonate clay. The Bayan Obo carbonate clay deposit mined in Inner Mongolia alone accounts for 32% of the world's production. Here, the REEs are a by-product of iron ore mining. Bayan Obo contains more than 40 Mt of rare earth reserves. The China North Rare Earth Group, centred on the Bayan Obo mine, is the largest producer of REEs worldwide. Ion absorption clays in South China and Myanmar accounted for 17% of the world's production in 2020. These clays are important because they are enriched with heavy REEs including dysprosium. Greenland holds the largest reserves of undeveloped rare earth deposits, particularly neodymium, however the productions is impeded due to environmental concerns (IRENE, 2022).

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 table 23, 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).

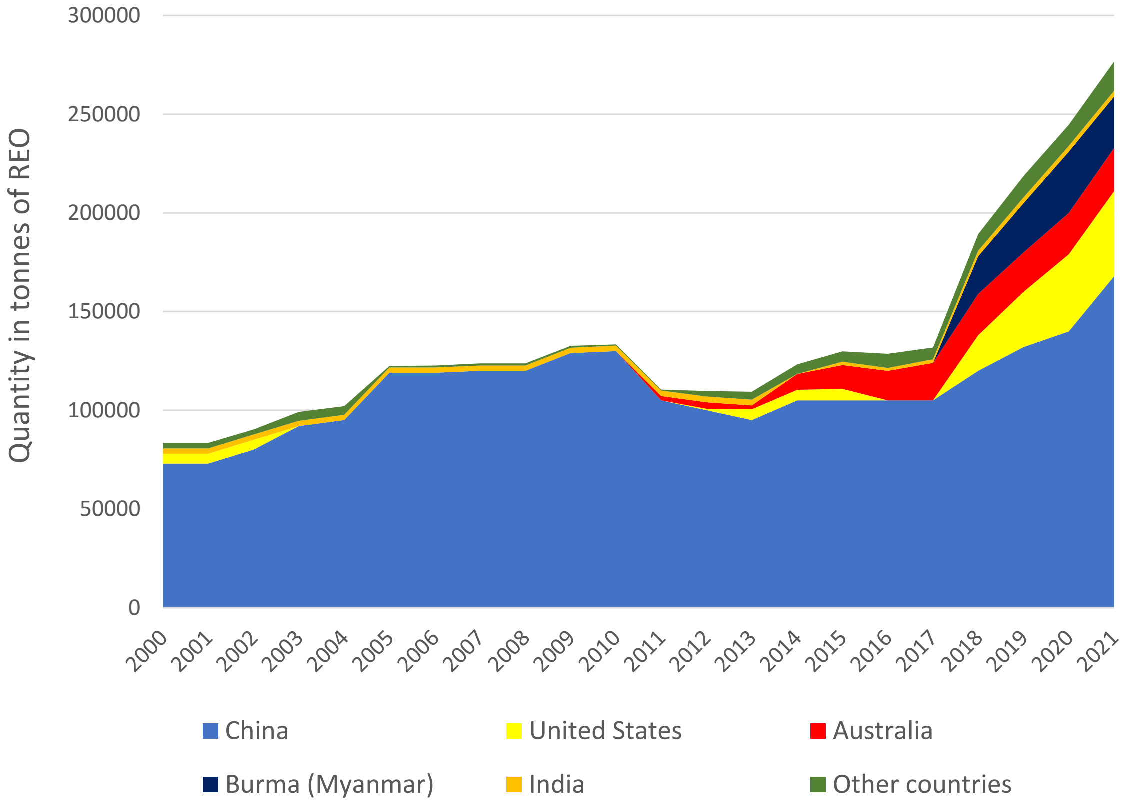

Figure 36: Rare earth elements primary production in terms of REO content since 2000 (WMD, since 2000).

**Table 22: 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 Adamas 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 producers of primary REE started operation in the last 5 years: Lynas* [Rare Earths] *at Mount Weld, Australia, and MP Materials at Mountain Pass, USA.*

Since acquiring the Mountain Pass mine in 2017, MP Materials has revitalized the site's production of rare earth elements and produces a mixture of rare earth concentrate that contributes around 15 percent of the rare earth minerals consumed each year, according to the United States Geological Survey.

**Table 23: 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[5] | Bayan Obo | Carbonatite | 59,500 | LREO | Mixed and separated REO |
| **China** | Jiangzi Copper Rare Earth | Maoniuping | Carbonatite | 2,500 | LREO | Mixed and separated REO |

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[5] 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.

| | | | | | | |
|---|---|---|---|---|---|---|
| **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** | MP Materials *(operation restarted in 2018)* | Mountain Pass | Carbonatite | 26,000 | LREO | Mixed and separated REO |
| **Vietnam** | Lavreco/Sojitz/Toyota | Dong Pao | Placer | 220 | LREO | Minex and separated REO |

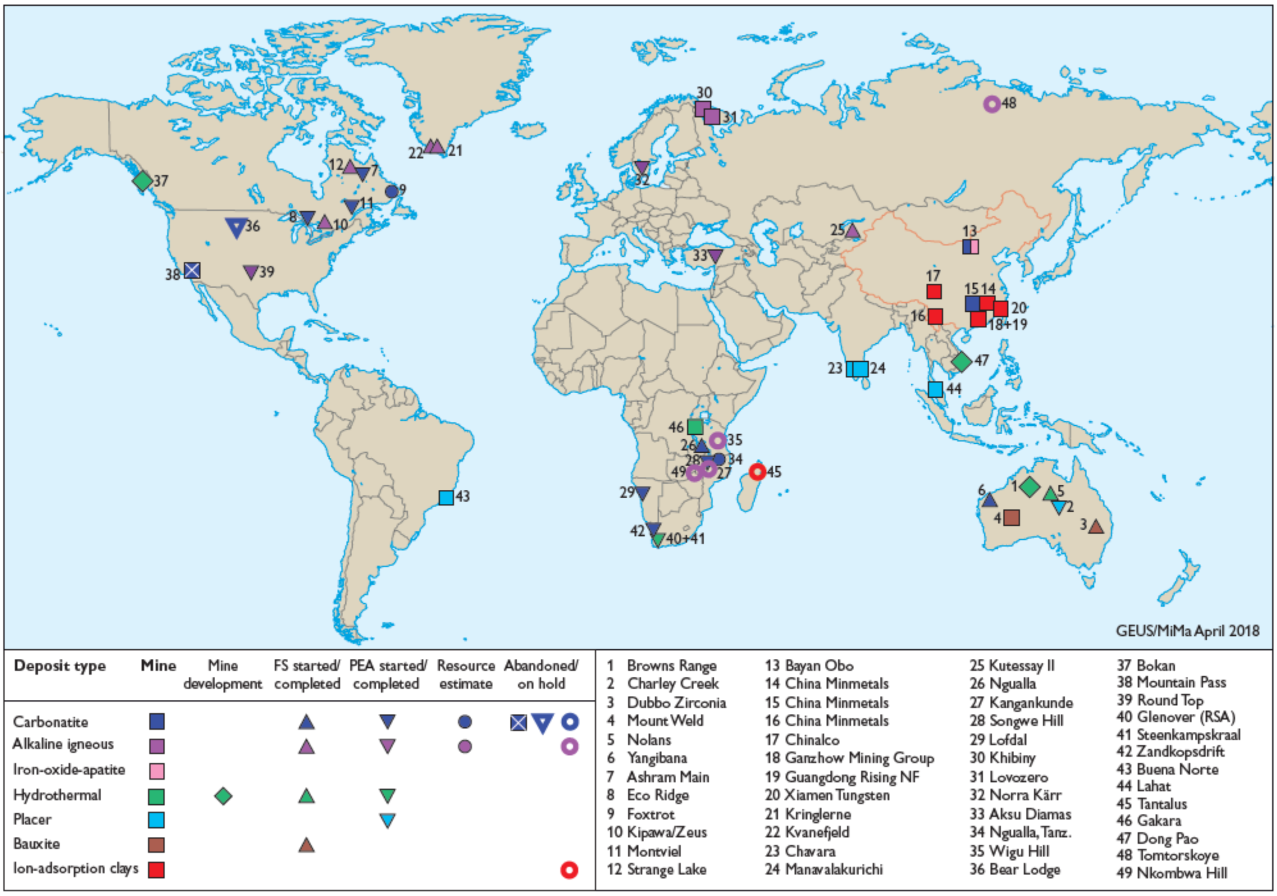

**Figure 37: Major global rare earth element mines and advanced exploration projects (GEUS/MiMa, 2018) (Machacek and Kalvig 2017: EURARE).**

Kingsnorth (2013, 2018) reported on undocumented extraction of REEs 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 24: 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 REEs, individual figures of REE production were obtained by 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 Mt Weld, are open-cast operations, involving conventional blast, load and haul techniques. No underground mines have ever been developed 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 and Myanmar but many are small-scale operations, with much of the mining undertaken by manual labour. The clay deposits are excavated and leached to extract REE, mostly using in-situ leaching techniques, sometimes over large areas.

All REE ores must be beneficiated to produce REE concentrates. Each deposit will need a specific flowsheet for the physical and chemical techniques and technology tailored to the particular operation, aimed at producing either REE-mineral concentrates or mixed REE concentrates. 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 crushed and then ground to fine particles, in order to liberate 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, 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 ($(Ce,La,Y,Th)PO_4$), for which routine cracking procedures exist are considered commercial products.

This is currently not the case for less conventional REE minerals (e.g62forementite, synchisite, gadolinite, fergusonite, loparite and steenstrupine) for which no standard cracking procedures are available. However, in particular eudialyte 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 undertaken on the plant site, producing a mixed REE carbonate as the commercial product. Subsequently, the individual REEs will need to be separated from this mixed product (see below).

For both route 1 and 2, the discharge composed of the gangue minerals forms the tailings. Mining REEs 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 assessed these environmental risks, with respect to radiogenic contents.

Ion-adsorption clays are typically leached with sodium chloride or ammonium sulphate 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 tonne of REEs. 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 REE mining operations, but imports ores and concentrates for refining. An iron-–ore producer - LKAB in Sweden, and phosphates fertili–ers producer - Yara in Norway, are currently developing processes to start modest REE production from their mining wastes. Potential exists also in coal- and aluminium-ore mining wastes.

### New developments concerning the exploitation of REEs outside China

**USA:** The US government is looking to modify the legislative framework concerning the mining and processing of raw materials containing hazardous elements including uranium and thorium. It is supposed that these changes will support REE mine- and extraction-plant developments in the USA, especially at Mountain Pass, Bokan Mountain, Bear Lodge, Round Top and Elk Creek (**Ilankoon et al. 2022**). In 2021, Lynas Rare Earths was awarded US$30.4 million in US government funding to design and build a LREE separation plant in Texas. In 2022 the same company was awarded US$120 million in US government funding to build a HREE separation plant, also in Texas (**Ilankoon et al. 2022; Gross, 2020**). In 2022, MP Materials was also awarded US$35 million in US government funding to build a HREE separation facility, in California (**Ilankoon et al. 2022**). Energy Fuels, a uranium processing company in Utah, is now processing REE feedstocks produced by the Chemours Company on the East Coast, derived from heavy-mineral-sands operations.

**Canada:** Saskatchewan Research Council (SRC) is developing a REE processing and separation plant in Saskatoon. It will comprise two stages of REE processing: production of a REE carbonate concentrate using deposits in Saskatchewan and other provinces, and subsequent separation and purification of the concentrate (**Drivas, 2020**).

**Australia:** Lynas Rare Earths is planning to develop a REE carbonate production facility in Kalgoorlie, Western Australia. The facility will produce high-quality REE carbonates for the company's separation and purification plant in Mala63forementioned aforeentioned future constructed facility in the USA (**Ilankoon et al. 2022**).

**Europe**: The mining of REEs in Greenland is uncertain as the 2021 change in government could delay the development of the Kvanefjeld mining project, which could hamper the development of independent REE supply chains in Europe (Jacob, 2021). The new government's concerns about the environmental impact of mining in Kvanefjeld are to the presence of radionuclides.

**India:** A plant (**OSCOM Odisha**) to produce mixed REE chlorides was established with 112,00 tonnes per annum of capacity. Individual REE compounds will be produced at Aluva Kerala, as a unit or IREL (**IREL, 2020**).

**Russia:** Russia developed "*the development strategy of the rare and rare earth metal industry of the Russian Federation for the period up to 2035*", aimed at the exploration and exploitation of REEs mainly in the Arctic region. Several deposits were identified in Russia, however no detailed data are given concerning their supply opportunities (**Solovyova et al., 2020**).

**Rest of the world:** Efforts for the exploitation of REEs are taking places in numerous countries around the world including: Norra Kärr, Sweden, Fens field, Norway, Kola peninsula and Yakutia, Russia, Longonjo, Angola, Songwe Hill, Malawi and many others. The exploitation situation in most of the cases is at a preliminary stage (i.e. feasibility study or earlier) (**Ilankoon et al. 2022**).

## OUTLOOK FOR SUPPLY

The demand for REEs is focused on a few elements (such as neodymium and dysprosium) which are relevant to the energy transition. Although reserves of these elements are adequate, ramping up supply in the short and medium term may be difficult. On the other hand, surpluses are produced of other elements such as cerium and lanthanum. In the near future, neodymium, samarium, dysprosium and praseodymium will remain the most critical REEs due to their essential need and function in permanent magnets. Industries such as those focused on EVs and wind energy are continually expanding and becoming increasingly dependent on permanent magnets, due to their superior performance over electromagnets. The key to scarcity of REEs for magnets is not reserve levels, but the development of new mining capacity (**Kleinmanenergy, 2021**).

Mining and refining of REEs within the USA, aside from Mountain Pass, are still largely in the pilot phase, and Australia / Malaysia remain the only major producers of REEs besides China. Hence, the Chinese REE monopoly will continue in the short term, and gradually abate as both the USA and other countries develop their own REE supply chains, likely by pooling data and best practices. Kenya, Malawi, Namibia, Madagascar and Tanzania host carbonite and peralkaline projects that could come on stream in coming years (**IRENE, 2022**). Several critical REEs are found in Tanzania, making it especially noteworthy. However, Greenland has a plenitude of REEs deposits not associated with elevated levels of uranium. For example, the Sarfartoq carbonite complex project, previously under development by a Canadian-based mining and exploration company (**Earth.org, 2020; Mining, 2021**), is now being developed by Neo Performance Materials, a leading produce of REE-based magnetic materials.

China is expected to continue to dominate the REE-ores processing sector in the short term. Currently, approximately 85% of refined REEs are produced in China, which has traditionally co-located refining plants close to mines so that raw material can be quickly reduced to production-ready metals and metal oxides. This practice increases production efficiency and lowers transportation costs, making it difficult for other countries to compete with China. The strong mining position of the USA is not supported by commensurate processing capacity, and the country's mined minerals are mainly shipped to China following initial mineral concentration. Therefore in the longer term, other countries must take on the mining and processing role to ensure diversity of supply (**IRENE, 2022**).

It has been asserted that the USA and other countries, through stockpiling of key REEs at both governmental and corporate levels, should ensure that domestic industries are relatively unimpacted by future fluctuations in the REE market for a reasonable period of a year or more (**Kleinmanenergy, 2021**).

The development of REE projects outside China and, therefore the potential supply by alternative sources/producer countries, comprises a complex issue dependent on various constrains. Ilankoon et al. identified the following 13 factors that could impede the development of new projects:

- Complexity in the establishment of REE separation and purification plants
- High operational costs of REE separation and purification plants
- Lack of large-scale R&D to develop niche REE separation and purification techniques
- Lack of REE recycling and challenges associated with REE recycling
- Challenges associated with REE substitution technologies
- Variability of ore geology compared to the Chinese REE resources
- Waste management challenges
- Uncertainty in business due to REE price volatility
- High capital costs and lack of government support and subsidies
- Lack of interest from investors
- Supply chain pressures on global REE companies
- Chinese REE interests outside China

Lengthy legislative processes in countries outside China to commission REE projects

## SUPPLY FROM SECONDARY MATERIALS/RECYCLING

Recycling R&D on new processes were accelerated in 2011 in the 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 the recycling of REEs, such as neodymium, dysprosium, praseodymium, samarium, gadolinium, europium, terbium, but also cerium and lanthanum.

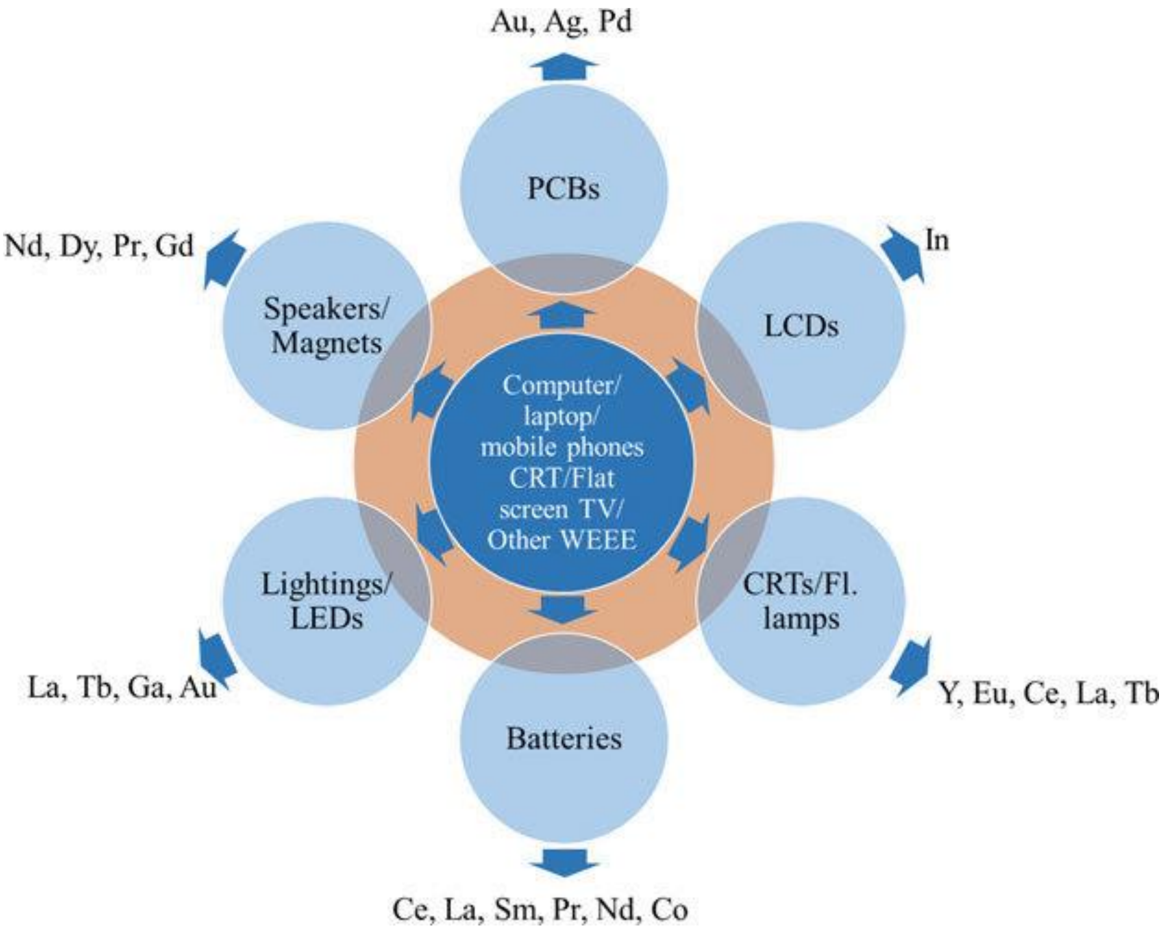

**Figure 38: Example of different types of WEEE and potential for recycling raw materials, including rare earths. (Sethurajan et al., 2019)**

Today, recycling input rates are 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 reported only thanks to the 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 number of research projects are on-going to identify the best targets and processes (ERECON, 2014). In 2022 Solvay announced plans to expand its operations, with a view to servicing the permanent magnet supply chain (Solvay 2022). In 2023 it announced plans with Canada-based Cyclic Materials to process recycled REE feedstocks (Solvay 2023).

Recycling is often difficult because of the way that REEs are incorporated as small components in complex items, or are part of complex materials. The processes required can be energy intensive and complex (Schüler et al., 2011); however, the energy requirements are still generally lower than processing primary or virgin materials (Zakotnik et al, 2016).

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 (EoL) recycling input rate of individual REEs are summarized in 26.

**Table 25. EOL-RIR of individual REEs (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% |

The recycling rates of REEs contained in alloys in several applications were identified in a recent study (Graedel and Miatto, 2022) (Table 10). It can be seen that the recycling rate of alloyed REEs is negligible. The lack of available recyclable material and/or their small concentration in various applications (e.g., electronics) are the most important reasons for this.

**Table 26**: Recycling rate of REEs used as alloys in various applications (Graedel and Miatto, 2022).

| REE | Alloy applications | Recycling rate |
|---|---|---|
| Cerium | Metal alloys, batteries | 0% |
| Lanthanum | Batteries, metal alloys | 0% |
| Terbium | Magnets | 1% |
| Dysprosium | Magnets | 0% |
| Praseodymium | Magnets, metal | 1% |
| Neodymium | Magnets, metal alloys, | 1% |
| Erbium | Vanadium alloys | 3% |
| Samarium | Batteries | 1% |

## MAGNETS

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

Swarf coming from the shaping and cutting of final magnet components 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.

Magnet 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 companies 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). The University of Birmingham and European partners have also successfully piloted such technologies.

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

The first, called short-loop or direct-recycling processing, targets a "magnet to magnet' approach, following scrap demagnetization, thermal treatment and re-alloying by the addition of additional REE compounds in the EoL material. The low environmental impact comprises the main advantage of the short-loop or direct-recycling process. Researchers at the University of Birmingham optimised the direct recycling of NdFeB magnets via hydrogen-decrepitation technology. Such processed materials could also be sent for re-melting with primary alloy materials.

The second recycling methodology concerns the elemental recovery of Nd, Pr, Dy and Sm through classic hydro- and pyrometallurgical techniques. Delft University developed a metallurgical route which is based on scrap leaching and REE extraction through selective precipitation. Various entities including Geomega and Cyclic Materials in Canada have also developed hydrometallurgical flowsheets for this purpose. Several technological barriers should be overcome prior to the commercialisation of REE extraction from EoL magnets. The most significant are: (a) automation of magnet dismantling, (a) reducing the environmental impact of leaching and (c) the effective separation/purification of REE within 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-sized magnets, which are difficult to be recovered
- The wide variety in magnets composition complicates the set-up of generic recycling schemes
- The reduction in REE prices after 2011 to more historical levels slowed research into magnets recycling.

An important boost to magnet recycling could come from the expansion of the market associated with large-sized NdFeB magnets for wind turbines and EVs: although the major size of such kinds of magnets makes their collection easier, their long life span (10-20 years or more) significantly impacts on the time in which these materials will become available as EoL feedstocks (Roskill, 2016).

### BATTERIES

Several processing technologies have been developed by Japanese (e.g. Toyota, Honda) and European companies (e.g. Umicore, Rhodia-Solvay) aiming at the recycling of REEs contained in 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 REEs 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 end permanent magnets via numerous novel processes is described in literature. These processes have been successfully tested at laboratory or pilot scale, using shredded 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)

## CATALYSTS

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

It is an open question whether the recovery of REEs (mostly La) from FCCs could be interesting from an economic point of view in the near future. This mainly depends 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 becomes more abundant (c.f. the 'balance’ problem of REE separation).

Currently, recycling activities on catalysts from the automotive sector are based only on the recovery of platinum-group metals (PGMs) 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).

## 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).

## 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.

## PHOSPHORS

Phosphors originating from EoL LCDs, computers, X-ray tubes, light bulbs and TV sets are 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).

As previously stated, europium, terbium and yttrium from EoL lamps have previously been recycled at the Rhodia-Solvay plant in La Rochelle, France 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). In 2010-2011, primary europium oxide, terbium oxide and yttrium oxide were particularly expensive (peaking at US$5,900/kg for europium oxide, and US$5,000/kg for terbium oxides) (BRGM, 2015) and there was a demand for cheaper, recycled REOs. However, by 2015 prices of prices of primary terbium oxide had dropped to below US$500/kg until the present day, and primary europium oxide had dropped significantly first to US$445 $/kg in 2015, and to $30/kg by 2019, thus rendering the recycling process far less competitive than during the REE pricing crisis (2011-2014). Solvay announced in early 2016 the closure of the plant by the end of the same year. Solvay however still offers yttrium oxide among its 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 recent years, several European projects were carried out to improve and to develop novel strategies for recycling REEs. 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 cerium-containing LEDs has been attempted at pilot scale. The developed process comprises a combination of manual and mechanical processing steps aimed at the removal of non-metallic components and the enrichment of the recycling stream. The results of this research constitute a useful tool for the further development of the dismantling and pre-treatment processes for other electronic wastes. However today, the market price of cerium is very low (US$6/kg for the pure metal, US$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 sustainable secondary production of cerium (Samouhos et al. 2019: SCRREEN).

### 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).

## PROCESSING AND SEPARATION

The processing and extraction of REEs by primary and secondary resources through pyrometallurgical and hydrometallurgical processes is summarized in the simplified flowsheet in Figure 26 (**Jyothi et al. 2020**). Pyrometallurgical techniques are applied, as a preliminary beneficiation step, for the processing of secondary resources. Hydrometallurgy is mainly applied for the processing of primary resources. REEs are obtained from the leachates of (mineral concentrates of) REE ores via various separation methods including: precipitation; solvent extraction (liquid-liquid extraction); solid-liquid extraction, adsorption, supported liquid membrane, ion-exchange, super-critical extraction methods, etc. Electro-refining and electrowinning are final steps to obtain REEs under elemental form.

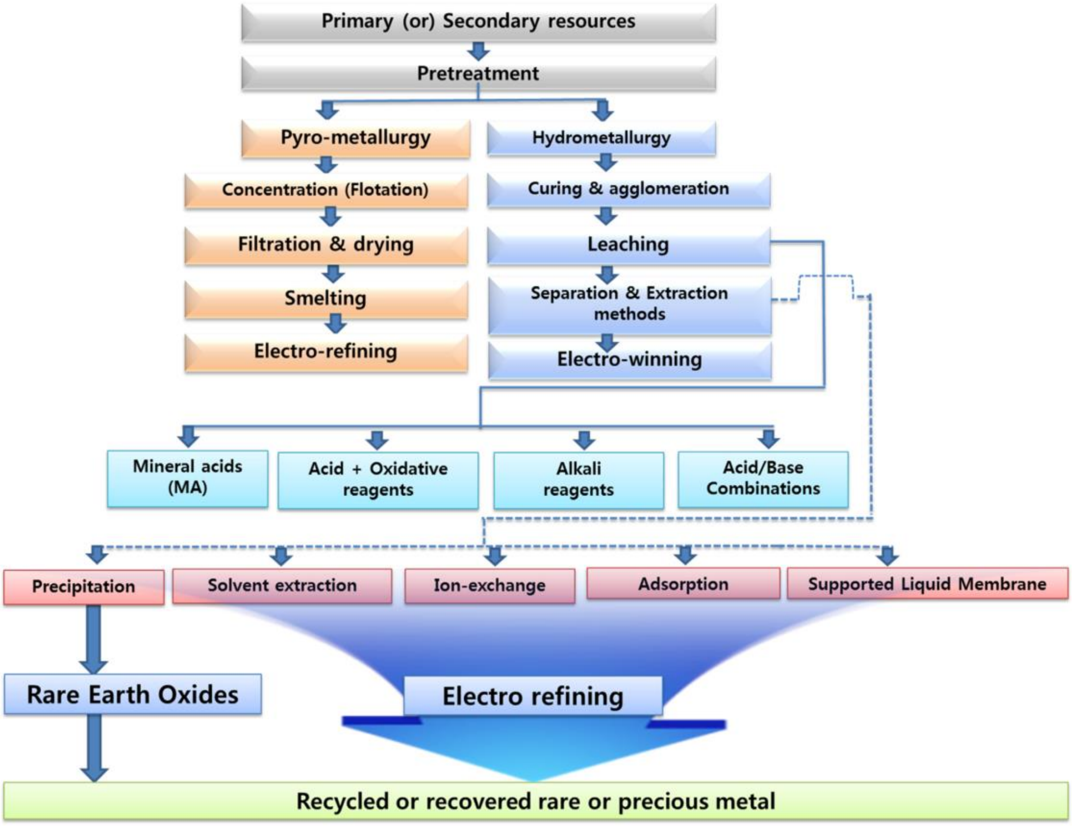

**Figure 39: Simplified flowsheet describing the extraction of REEs by primary and secondary resource (Jyothi et al. 2020).**

## WORLD

There is no data on the 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 has one of the largest REE separation plants in the world, treating mixed REE concentrate produced from mineral concentrates derived from the Mt Weld deposit in Australia. The plant produces separated LREE 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 REE 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, for concentrates derived from the Round Top deposit in El Paso, Texas, containing LREE and HREE, lithium, uranium, beryllium, gallium, hafnium and zirconium.

In 2020, USA Rare Earth announced the purchase of mothballed NdFeB permanent-magnet manufacturing equipment, with a reported 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. (now part of Proterial). In late 2011, Hitachi announced the phased construction of a state-of-the-art sintered REE magnet manufacturing facility, planning to spend up to $60 million over four years. However, following settlement / resolution of a number of patent-infringement issues brought by Hitachi, Hitachi closed the plant in 2015 after less than two years of operation.

### EU

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

At the mining stage, REE are assessed as mixed 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.

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

At the refining stage, one considers mixtures of high-purity single REEs (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 Chinese industrial scale separation plants (Barakos, 2018). Estonia and United Kingdom produced 500 tonnes in the same period.

REEs 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 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 leads to REE compounds such as REE 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 REE compounds to a degree of purity of 99.9% (3N) to 99.9999% (6N) depending on the application. The majority of production is in the oxide form, but individual REE 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 La-Ce, La-Ce-Pr or La-Ce-Pr-Nd, and didymium (Pr-Nd). These products are combinations of individual REEs and can be supplied directly to downstream metallic-product producers. The heavier fractions (Sm-Eu-Gd and beyond) 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 HREEs from initially purified REE solutions, to 6N purity (BRGM, 2015).

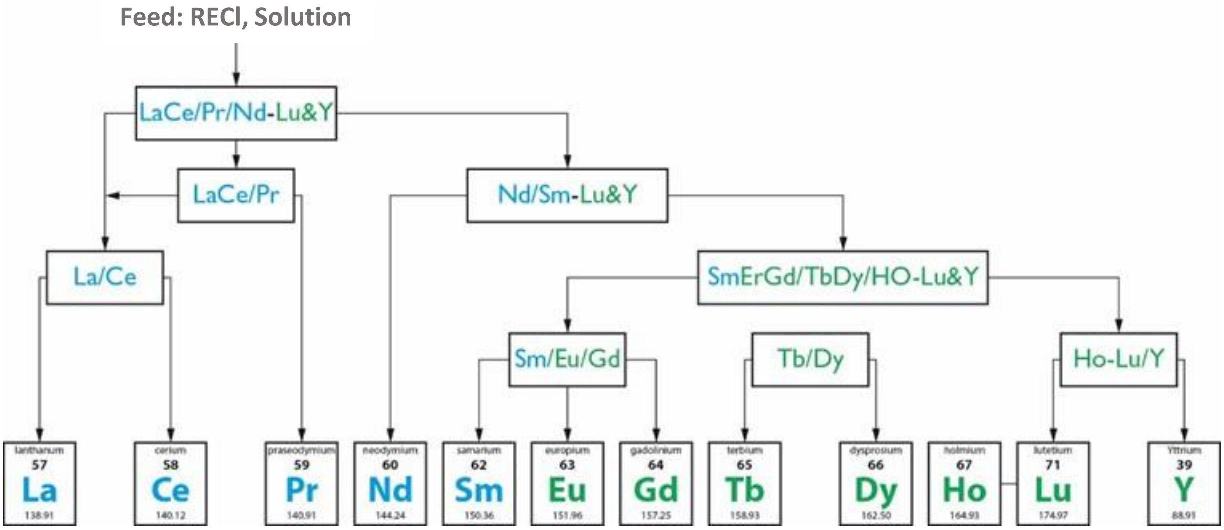

**Figure 40: Example of a schematic REE solvent extraction (SX) separation process (Machacek and Kalvig 2017: EURARE adapted from Zhang and Zhao, 2016)**

Further refining is needed for the production of REE metals and alloys. It is also a very costly and complicated step. Molten-salt electrolysis or metallothermic reduction is used for preparation, followed by alloying, where for example, boron, iron or cobalt can be added to form desired magnets alloys. Pure REE metals (99.999% or more) are the most expensive products and are usually purchased only for very specific applications and in small quantities.

## 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). (Izatt et al., 2016). SX (with some IX) constitutes the processing technology applied on an industrial scale, close to 80% of which occurs in China, with most of the rest in Malaysia.

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

Ion-exchange (IX) method: originally developed to remove REEs from U and Th, it was later used to separate the REEs. A single operation enabled the separation of multiple REEs 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.

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 centred primarily on establishing toll-process capabilities. 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 concentrates 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$^{TM}$ and (ii) Molecular Recognition Technology (MRT). The technology applied is briefly described below:

RapidSX$^{TM}$: in 2016, Innovation Metals Corp (IMC) released details of a more-efficient SX-technology, called RapidSX$^{TM}$. This had been developed with the aim of accelerating chemical processing, reducing both CAPEX and OPEX, and reaching product purities greater than 99%. The process has been tested on a variety of feedstocks including materials from the Serra Verde deposit in Goias State, Brazil. A RapidSX pilot plant is presently being commissioned in Ontario, Canada.

Molecular Recognition Technology (MRT): in 2016 Ucore Rare Metals (Ucore) and IBC Advanced Technologies Inc. (IBC), released a white paper on a highly metal-selective green-chemistry procedure, not based on the use of organic solvents. It has been applied to the separation of individual REEs 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) argued that significant savings in CAPEX and OPEX can be achieved by use of MRT. Ucore and IBC terminated their association following litigation between the two companies, and the current status of MRT for REE separation is unknown.

Generally, the separation of the LREEs La, Ce, Pr and Nd, is easier than that for HREEs, which pose more separation challenges (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 SX methods, 30-100 stages are needed for each separation cut between adjacent REE, to reach purity for individual REEs of 99% up to 99.999% (5Ns) (Leveque, 2014).

Before its suspension, the proposed Kvanefjeld project planned to utilise solvent extraction to remove La and Ce from the REE chloride to produce $La_2O_3$, $Ce_2O_3$, mixed La-Ce-oxide, all at 99% purity, and a mixed 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 a few minutes. Considerable selectivity was observed, favouring retention of HREEs (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 the external use of magnets. The principles of the EURARE technology are shown in Figure 41. Application of this technology in processing REE from both ore leachate and from dissolved components in recycling processes could offer efficient uptake and controlled release under precisely defined pH conditions. (Machacek and Kalvig 2017: EURARE)

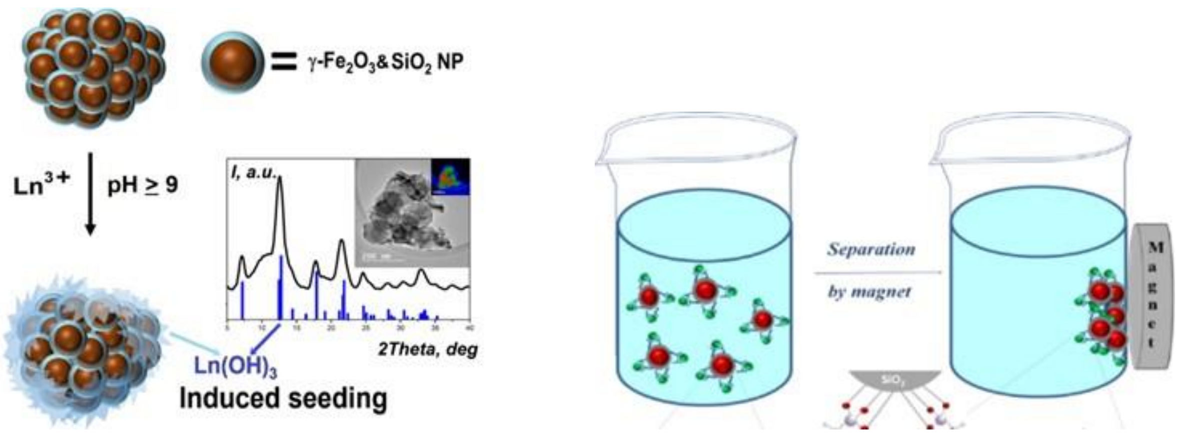

**Figure 41: Principles in the magnetic nanoparticle separation technology (Machacek and Kalvig 2017: EURARE)**

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 aimed to both decrease the CAPEX and OPEX, and to separate the HREEs from aqueous chloride feed solutions using a neutral extractant (Larsson and Binnemans, 2015). Until recently, neutral extractants could not efficiently extract REE from chloride solutions. The EURARE-technology involved an ionic liquid that effectively transported the REE from the chloride aqueous phase into the water-immiscible ionic liquid. This ionic-liquid extraction technology has the potential to reduce CAPEX for the separation plant (less equipment and fewer extraction stages), and OPEX due to the exclusion of acidic extractants, and easier wastewater treatment. Moreover, the replacement of organic solvents by non-fluorinated water-saturated ionic liquids, would be an improvement on current technology, regarding health, safety and environmental standards.

A REE-separation plant was established by REEtec AS in Norway, with a new process for the manufacture of high-purity REEs. The plan is for REEtec's first factory, in Herøya, Norway, to be ready by the second half of 2024, and for a second factory, planned for 2026, that can process material from LKAB that will be available as of 2027. LKAB has invested MNOK 400 in this new issue and is the principal shareholder. In addition, Norwegian state-owned Nysnø Klimainvesteringer, Mercuria and TechMet are also new shareholders. The first factory for separation rare earth elements in Herøya will produce some 720 tonnes of the rare earth elements neodymium and praseodymium, corresponding to 5 percent of Europe's demand. Production start is planned for 2024. Raw material to supply the first factory will come from Vital Metals in Canada and there is an agreement with Vital Metals that will allow for a tripling in volumes. REEtec has sold 80 percent of the planned production via, among other agreements, a five-year contract with a global supplier to the vehicle industry, Schaeffler Group.

### Optimization of bastnäsite and monazite processing

Bastnaesite is the source of 70% of the world's REEs. Bayan Obo, the world's largest REE production site, contains a unique mixed deposit of bastnäsite and monazite. The procedure for the extraction of REEs from Bayan Obo ore is displayed in Figure 29. A number of improvements have recently been described in the literature that could increase the recovery yield of REEs and decrease the operating cost, including (IRENE, 2022): (a) the replacement of two-step leaching using high-temperature HCl leach, followed by a caustic-crack stage by a single-stage, high-temperature, high-concentration HCl leaching process that produces low-density slurry; (b) the use of deep-eutectic environmentally friendly solvents through the solvent-extraction process and, (c) the use of alkaline calcium/magnesium compounds as alternative to ammonium bicarbonate precipitating agents.

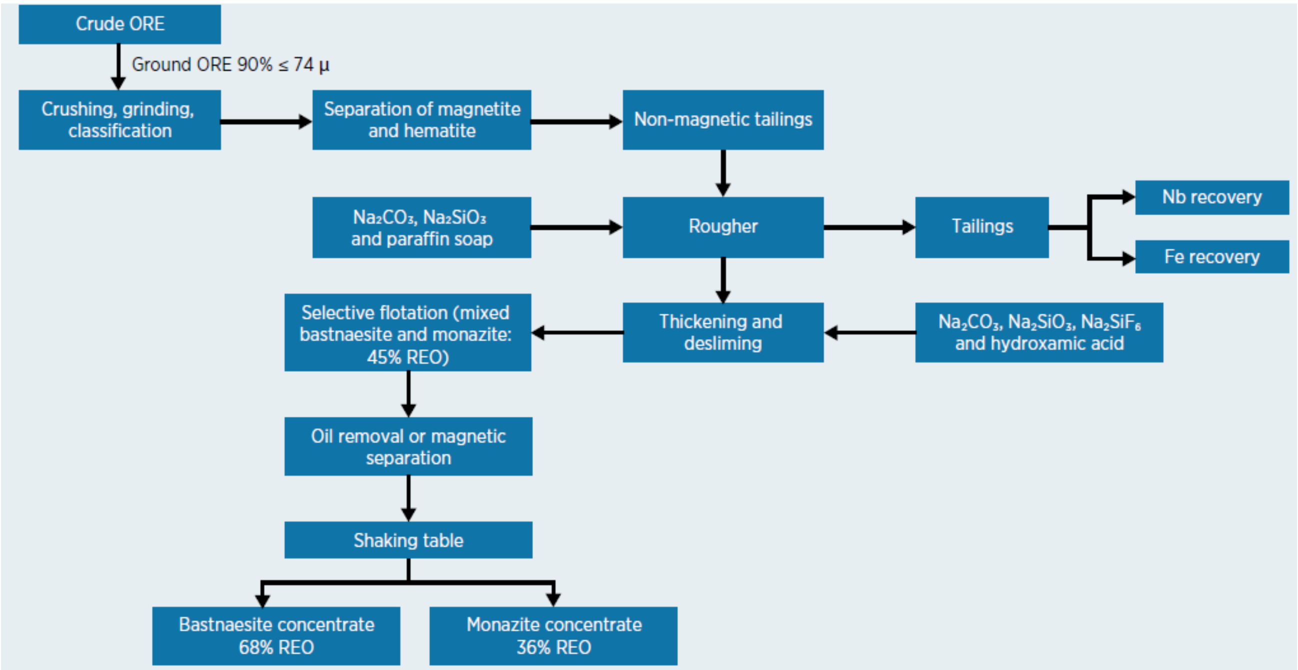

**Figure 42: Flowsheet of the processing of Bayan Obo bastnaesite/monazite ore (Peelman et al., 2014; IRENE, 2022).**

## OTHER CONSIDERATIONS

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