IRENA
International Renewable Energy Agency

# CRITICAL MATERIALS FOR THE ENERGY TRANSITION:

# RARE EARTH ELEMENTS

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BY DOLF GIELEN AND MARTINA LYONS

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For further information or to provide feedback: **publications@irena.org**

## Disclaimer

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# BOXES

# ABBREVIATIONS

| | |
|---|---|
| **EV** | electric vehicle |
| **GW** | gigawatt |
| **HCl** | hydrochloric acid |
| **IRENA** | International Renewable Energy Agency |
| **kg** | kilogramme |
| **kt** | kilotonne |
| **LED** | light-emitting diode |
| **Mt** | megatonne |
| **NaOH** | sodium hydroxide |
| **NdFeB** | neodymium-iron-boron |
| **PVC** | polyvinylchloride |
| **REE** | rare earth element |
| **wt%** | weight percent |

# EXECUTIVE SUMMARY

The rare earths are of a group of 17 chemical elements, several of which are critical for the energy transition. Neodymium, praseodymium, dysprosium and terbium are key to the production of the permanent magnets used in electric vehicles (EVs) and wind turbines. Neodymium is the most important in volume terms. Yttrium and scandium are used for certain types of hydrogen electrolysers, while europium, terbium and yttrium are used in energy-efficient fluorescent lighting. Conventional energy also relies on rare earth elements (REEs), for example to produce car exhaust catalysts. But the mix of energy-relevant REEs that are needed going forward differs from that of the past.

## DEMAND AND MARKET GROWTH PROJECTIONS

Rare earth production amounted to 240 kt in 2020. It is especially the need for permanent magnets that is expected to grow substantially in the coming years. Some 29-35% of all rare earth materials were used for permanent magnets, less than 15% of which went into EVs. Around 6-9 kilotonnes (kt) of neodymium were used for EVs in 2020, 15-20% of all permanent magnet use in 2020. Around 10% of permanent magnets (4 kt neodymium) were used for wind turbines, notably offshore turbines and Chinese onshore turbines. EV and wind turbines together accounted for around one third of the permanent magnet use in 2020. Whereas wind turbine production is projected to double this decade, EV manufacturing is projected to grow by an order of magnitude.

Dysprosium and to a lesser extent terbium, are added in small quantities to permanent magnets to improve thermal stability. Although the quantity of dysprosium is small compared to that of neodymium dysprosium is much scarcer than neodymium. Dysprosium supply is therefore a critical factor in terms of REE supply.

The supply of permanent magnet materials will need to increase substantially to meet the demand of a growing EV industry. Under an ambitious energy transition scenario EV and wind total demand for permanent magnets and the REE they contain may more than double between now and 2030. Some sources even suggest a quadrupling. Demand projections vary widely due to growth uncertainties for key demand categories.

## SUPPLY OUTLOOK

The natural REE resources dwarf current consumption. Although there are sufficient known rare earth resources to supply all the needs of the energy transition, the main challenge is to expand mining and processing activities across the entire value chain in line with demand growth.

Natural rare earth deposits usually contain a mixture of REEs. Neodymium makes up around 20% of those deposits, on average. But the supply of each type of REE needs to be assessed separately; data for the whole group are of limited value and do not reflect actual scarcity levels. Many deposits also contain radioactive uranium or thorium, which complicates the management of mine tailings. The fact that different REE are co-produced while the markets for them are diverging means that some are scare while others are oversupplied. This divergence will grow in the coming years. As the composition of deposits varies, some are more valuable than others. It is critical to understand individual REE, instead of dealing with them as a group.

REE deposits are widely distributed. It is economically viable to expand mining in many places, but processing capacity is less readily expandable, depending on a variety of factors, including know-how, that are concentrated in certain countries. Increased mining needs to be also combined with circular economy concepts such as recycling and reuse, as well as innovations to mitigate demand growth.

Comparatively high concentrations of dysprosium occur in ionic clay deposits in South China and also Myanmar. Other countries in the region such as Viet Nam hold similar type resources that are yet to be exploited.

Apart from natural resources, certain residue streams such as red mud (from aluminium production), fly ash from coal combustion and gypsum (from coal power generation) contain significant amounts of REEs that can be recovered. Also, new offshore deposits have been discovered recently. However, these options are not yet economically viable and so may not meet demand as needed.

Rare earth metallurgy, including separation, metal making, casting and magnet making, are technologically challenging. This poses limits to the entry of new suppliers.

## DE-RISKING THE SUPPLY CHAIN

The majority of REE mining (58% in 2020) and purification (90%), as well as most permanent magnet production (90%), are concentrated in China. This concentration poses a supply concern. Processing costs and environmental concerns outside China have limited capacity development or even resulted in closures. In recent years, also the Chinese government has tried to limit the growth of the rare earth mining for environmental reasons. China's large REE deposits, enabling policy frameworks and long-standing efforts to master relevant separation and processing technologies have fostered growth, while other countries have not invested in this value chain over the past 30 years. The emergence of the EV industry has focused attention on the need to diversify the supply and many initiatives are ongoing to diversify the supply and de-risk supply chains. In recent years recognition has grown that a focus on mining alone is not enough, the full supply chain must be considered.

China's market dominance has resulted in a very competitive national supply chain. An exception is the market segment of sintered high-performance permanent magnets that are presently used in cars. Whereas a Japanese company held some of the key original technology patents, China and the United States have stepped up patenting for bonded and sintered magnets in recent years and more than 500 new patents have been filed for sintered patents in the last decade. This is an indicator of the importance of this future market.

At the same time, countries with EV expansion plans are looking to reduce dependence on Chinese exports. It will be difficult to do so anytime soon, however. Today only 11 major mines and 7 major processing plants are found worldwide; 6 of the latter are in China and 1 in Malaysia, as well as a smaller plant in Estonia. New mines and processing facilities are under development in Australia, Canada, Norway, South Africa, the United States and several African countries. But these projects are controversial due to environmental concerns and the long time frames for their development. For example, Greenland's parliament recently prohibited the development of one of the largest undeveloped rare earth deposits in the world.

Strategic investments are necessary to build capacity outside China; advance commitments from equipment manufacturers and end users usually must be secured before investments become viable. Governments, too, have a role in de-risking the necessary investments.

A multistage strategy will be needed to reduce the supply risk across the entire supply chain. China will remain the main supply of REE based products in the foreseeable future. At the same time China depends increasingly on REE raw material imports. While supply diversity is beneficial, purely national supply approaches will be economically and trade-wise challenging. Therefore, the international dialogue among suppliers and users of REEs should be intensified. More dialogue is also needed between technology developers, suppliers and policy makers. Strategic investments are necessary where parties co-operate more closely along the supply chain.

## INNOVATIONS TO REDUCE REE DEPENDENCY

Car makers have recognised the industry's dependency on rare earth elements (REEs) and developed alternative motor designs that avoid permanent magnets. However, these designs are lower in performance, notably a reduction in driving range, a critical factor. Research continues to find new permanent magnet materials that offer adequate performance for certain applications where weight is less critical.

Research also continues to find new permanent magnet materials that reduce the dependency on REE. The includes alternatives for certain electronics applications where weight is less critical. Also in wind turbine design alternatives exist.

Ways of limiting the use of dysprosium in permanent magnets, or to eliminate it altogether, is a subject of current research and development efforts.

New magnet processing technologies are being developed that can reduce the dependency on sintered permanent magnets and that can reduce the need for critical REEs. The ability to produce certain shapes limits today's processing choices, which in turn limits the materials composition.

## POLICY IMPLICATIONS

In the coming years, it is vital to expand the supply for critical materials for permanent magnets. As the volume of material that is needed is comparatively small, the environmental footprint of such effort can be limited: even a few new mining and processing developments can grow the global supply substantially. In order to develop an effective REE strategy it is critical to recognize the different steps in the supply chain and their characteristics. While the mining step is well documented, the processing and the permanent magnet production is less well understood. It is recommended to enhance the public data availability to foster the global market transparency.

There is a need to understand better the bottlenecks in the development of new supply capacity. Also the twin objectives of greater supply volumes and de-risked supply chains should not be confused as they require different approaches.

Innovation to reduce critical materials dependency should be given due consideration. Energy technology designs offer opportunities to reduce or even eliminate the use of critical REE. The design opportunities need to be understood better.

Europe has established the European Raw Materials Alliance (ERMA), which has initially focused on REE. A European list of 30 critical raw materials exists. In the United States administration has directed a whole-of-government approach to assessing vulnerabilities in, and strengthening the resilience of, critical supply chains including minerals, and initial efforts are focused on REE. Also other major consumers such as China and Japan have also put policies in place.

Meanwhile the countries that hold the natural resources see an economic opportunity. International co-operation will be needed and fair long-term prices and demand certainty will be needed to convince suppliers to invest in long term mining. The environmental and social concerns have to be addressed in parallel. Also focus should not be on mining alone: processing seems a higher priority.

The 12th IRENA Assembly in January 2022 and subsequent discussions have resulted in a strong mandate for the Agency to deepen its engagement on this topic. Following the consultations with member countries, IRENA launched the Collaborative Framework on Critical Materials for the Energy Transition to expand its observatory for critical materials and facilitate dialogue among its 167 members including the European Union to foster the nexus between critical materials and the energy transition (IRENA, 2022).

# INTRODUCTION

An accelerated energy transition to mitigate climate change requires a growing supply of critical materials (Gielen, 2021; Gielen and Lyons, 2022). The International Renewable Energy Agency's (IRENA's) World Energy Transition Outlook emphasises the importance of electric vehicles (EVs) and wind turbines for that transition (IRENA, 2021). To accomplish it, electromobility must become the dominant form of road transportation and wind turbine capacity additions must double between 2020 and 2050, while the installed capacity of offshore wind must grow from 35 gigawatts (GW) to 2 000 GW.

These technologies depend on rare earth elements (REEs). To expand their supply sufficiently, mining and materials processing industries need to expand an accelerated pace, though in a way that is both environmentally and socially sound (IRENA, 2020). Increased mining needs to be combined with circular economy concepts such as recycling and reuse, as well as innovations to mitigate demand growth.

Sometimes referred to as rare earth metals and rare earth oxides, REEs are moderately abundant in the Earth's crust and possess unique properties of particular value in catalysts, optical materials, magnets, batteries and lighting applications, amongst others.

Of the 17 chemical elements commonly considered to be REEs, 15 are in the lanthanide group of elements, together with period III yttrium and scandium, the latter two being included because of their similarity in chemical nature. REEs are often categorised as either light or heavy rare earth elements depending on their atomic number. The light elements are lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium and gadolinium. The heavy are terbium, dysprosium, holmium, erbium, thulium, ytterbium and lutetium (USCRS, 2020).

The 40 largest ore exploration projects contain over 3 000 megatonnes (Mt) of inferred resources at various grades in over 15 countries, with 11 mines in operation in 2017 (USCRS, 2020). REE production was on the rise again in 2020 following a decline in the previous year, jumping to 240 kilotonnes (kt) worldwide. The principal sources of REE production today are hard rock deposits and clays. These resources contain various types of REEs, which are co-produced (or mined together). The neodymium essential for EVs and wind turbines is typically 10-18% of the rare earth content of the light rare earth minerals bastnaesite and monazite. Although the largest mines are in China, others are found in Australia, Brazil, India, Sri Lanka and the United States of America.

While REEs are often discussed as a group, their various properties and applications differ markedly. From the perspective of the energy transition, neodymium, praseodymium, dysprosium and, to a lesser extent, terbium are critical elements due to their application in the permanent magnets needed for certain clean technologies. Europium, terbium and yttrium are mostly used in fluorescent lighting, and new phosphors have reduced their need in recent years. Cerium, europium, gadolinium, lanthanum, terbium and yttrium are important minerals used in semiconductor technology based on light-emitting diodes (LEDs). (Jaroni, Friedrich and Letmathe, 2019). Solid oxide electrolysers require yttrium oxide (Minke *et al.*, 2021; SBH4, 2021). Yet the total amount of REEs used in these applications is comparatively small, and so the main focus of the following discussion is on magnets.

REEs, notably neodymium and dysprosium and other rare earths are an essential component of the permanent magnets used in wind turbines' generators and in the motors that power EVs. A megawatt of direct drive wind turbine capacity may require around 500 kilogrammes (kg) of permanent magnets,[1] a third of which is REEs (notably, for direct drive offshore turbines). A typical EV requires around 2-5 kg of magnets, depending on type and design. Together, these applications could require around 150 kt of permanent magnet production annually by 2030 and generate demand for 50 kt of REEs.[2]

Neodymium-iron-boron (NdFeB) magnets, because of their high-energy properties, lend themselves to compact designs that result in innovative applications and lower manufacturing costs. In commercial sintered NdFeB magnets, part of the neodymium is usually replaced by other REEs, including praseodymium, dysprosium and terbium (Advanced Magnets, 2021). Neodymium and praseodymium usually co-exist in ore, as they have similar physical and chemical properties and are hard to separate. Therefore it is more economical to produce praseodymium-neodymium alloy instead of pure neodymium metal and to use it as the raw material for a magnet. In general, such a magnet's total REE content is around 30 weight percent (wt %) and accounts for at least 70% of its total cost (Advanced Magnets, 2021). NdFeB account for around two-thirds of all permanent magnets; the remainder is dominated by ferrite (Ma and Henderson, 2021).

The world's dysprosium supply is even more constrained than the neodymium supply, and this may pose a problem for the energy transition. For neodymium magnets to perform at elevated temperatures and improve their temperature resistance, significant amounts of dysprosium and terbium are added (up to 12 wt%). In addition, dysprosium when further optimised can provide thermal stability to the magnet (Ormerod and Trout, 2021). However, in terms of relative abundance in the Earth's crust, dysprosium is less than 1% of all REEs (Constantinides and De Leon, 2011). Thus, its supply cannot expand fast enough to meet the growing demand for high-temperature neodymium magnets for EVs; alternative additives or new supply sources will have to be found.

Prices of REEs vary widely, from less than USD 2 to nearly USD 2 000 per kg (Table 1). The prices of those used for magnets have risen substantially in recent years, while cerium and lanthanum are oversupplied; their prices have held steady or declined.

**Table 1:** Rare earth oxide prices

| PRODUCT (OXIDE) | (% PURITY) | USD/KG | | |
|---|---|---|---|---|
| | | 2017 | 2018 | 24 DECEMBER 2021 |
| **Scandium** | 99.990 | 4 600 | 4 600 | 836 |
| **Yttrium** | 99.999 | 3 | 3 | 11.9 |
| **Lanthanum** | 99.500 | 2 | 2 | 2 |
| **Cerium** | 99.500 | 2 | 2 | 1.5 |
| **Praseodymium** | 99.500 | 65 | 63 | 140 |
| **Neodymium** | 99.500 | 50 | 50 | 143 |
| **Samarium** | 99.500 | 2 | 2 | 4.5 |
| **Europium** | 99.990 | 77 | 53 | 32 |
| **Gadolinium** | 99.999 | 37 | 44 | 76.2 |
| **Terbium** | 99.990 | 501 | 455 | 1 720 |
| **Dysprosium** | 99.500 | 187 | 179 | 452 |

**Note:** Products are listed in order of atomic number. Prices depend on purity; data on similar purities from different sources have been combined. The source for the data on scandium is Stanford Metals Corporation. The source for all other elements is Argus Media Group – Argus Metals International. The source of the December 2021 data is ISE (2021).

1 Some high-speed wind turbines do not use a permanent magnet generator; medium-speed wind turbines use only one-tenth of the permanent magnets needed in direct-drive turbines.

2 Assuming 35 million EVs and 3 kg of permanent magnets per EV, plus 100 GW wind turbines with permanent magnets (50% market share) at 0.5 kt magnets/GW, with 30% rare earth content in the magnets (IRENA, 2021).

# DEMAND

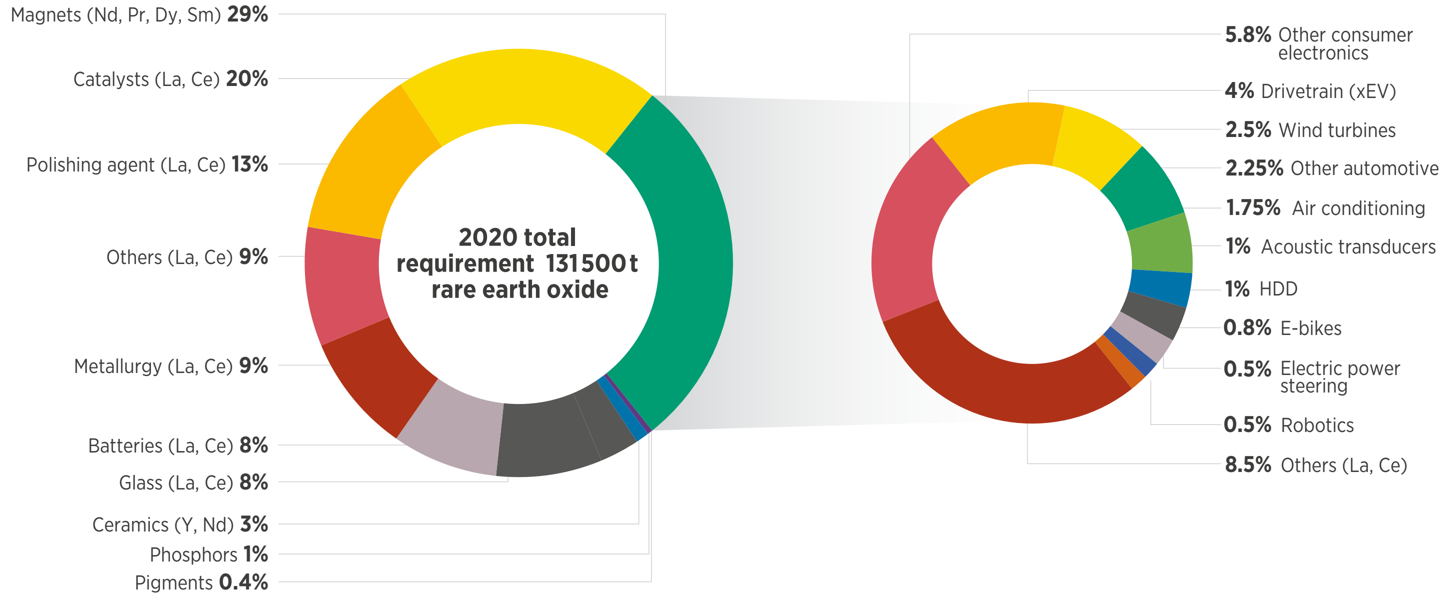
The sudden REE boom reflects these elements' unique optical and magnetic properties (Adler and Müller, 2014). Magnets accounted for 34% of the demand for REEs in 2019, according to IHS Markit. Roskill (2021) reports that rare earth permanent magnets, the largest single end use, accounted for 29% of total demand in 2020. By 2030, magnets are predicted to constitute approximately 40% of total demand. If that forecast proves accurate, demand for key magnetic REEs may far exceed supply by the end of this decade (Alves Dias *et al.*, 2020; Barrera, 2021).

REEs are also widely used for conventional and clean energy applications. Batteries and catalysts accounted for 8% and 20%, respectively, of REE demand in 2020 (Figure 1). For both demand types, there is a link with energy. The consumption of REEs in the battery industry is due solely to the application of REEs in nickel-metal hybrid batteries (NiMH), which contain between 18 and 28 wt% lanthanum depending on their anode chemistry. This battery type is not projected to grow significantly in coming years. Cerium is widely used as a catalyst in motor vehicles' catalytic converters. Cerium oxide is also used as a petroleum cracking catalyst in petroleum refining. Lanthanum oxide is used as a catalyst in polyvinylchloride (PVC) production.

The effect of the energy transition on total REE use is the sum of positive and negative changes in demand. However, its effect on specific elements can be very different, as discussed below.

Roskill (2021) indicates that total REE demand and demand for permanent magnets will continue to grow. The survey projects that overall demand for REEs is projected to increase by 41% through 2030, while the share of permanent magnets is projected to increase from 29% to 36% – slightly lower than the projections cited in the paragraphs above. The share of battery and catalyst applications is projected to decline as demand for oil products and refining shrinks. Here, too, the projections of total demand hide significant shifts at the level of individual elements.

**Figure 1:** Rare earth demand by end use sectors and breakdown of magnet demand by mass, 2020




**Source:** Roskill, 2021; BGR, 2021.

**Note:** Ce = Cerium; Dy = Dysprosium; HDD = hard disk drives; La = lanthanum; Nd = neodymium; Pr = praseodymium; Sm = samarium.

REE production amounted to 240 kt rare earth oxide equivalent in 2020, according to the U.S. Geological Survey (USGS, 2021a). Of that, 50 kt is neodymium oxide. The fact that 70 kt of the 240 kt total goes into magnets suggests that most neodymium is used for this purpose.[3] Transportation applications account for about one-quarter of magnet use, half of which is for drivetrains (EV motors). This translates into a demand of 6-9 kt neodymium oxide for vehicle motors, or 2-4% of total REE demand. Around 10% of all permanent magnets were used for wind turbines (Figure 1), mainly offshore turbines and onshore turbines in China.

It is also possible to estimate demand from the bottom up. In 2020, 3.2 million EVs were sold; this includes battery EVs and plug-in EVs, including light commercial vehicles (EV volumes, 2021). But EV sales in 2021 are a better measure for magnet demand in 2020, when the market volume doubled. At 3 kg of magnets per car, the demand would total 13 kt. With 30% of each magnet being neodymium, the result would be 4.5 kt neodymium or 5.5 kt neodymium oxide.

In total, less than 20 kt of neodymium was used for key energy transition technology applications in 2021. This equals less than half of the total production of neodymium oxide. The total for wind turbines and EVs together equals less than 8% of total REE production.

Demand projections vary by source, with the demand growth estimates more than double the low. By 2028, Adamas Intelligence projects that global demand for mined neodymium and praseodymium oxide will reach approximately 7 kt per year (Barrera, 2021). These demand projections are twice those of BGR (2021), which sees magnet demand for REEs grow from 38 kt to 68 kt between 2020 and 2030 at a rate of 3 kt per year. It should be noted that the absolute amounts involved are relatively small compared with the megatonne-scale production and consumption of other mineral and metal commodities.

By 2030, the demand for permanent magnets could grow from 50 kt to 225 kt per year, with 180 kt coming from EVs and 50 kt from wind turbines (Ma and Henderson, 2021). If this proves true, the supply deficit for NdFeB magnets could reach 135 kt by 2030, driven largely by the growth of the EV and wind turbine industries (Ma and Henderson, 2021). EVs and wind demand together may double the demand for the REEs used in permanent magnets between now and 2030. Because the REEs used in permanent magnets are co-produced with other types of REEs (because they occur together in the mined ores), total REE production would have to rise accordingly. Wind turbines and EVs will be discussed in more detail below, together with the options for product innovation to reduce demand growth. The discussion emphasises that supply will have to expand significantly in coming years.

3 While permanent magnets for industrial motors are not discussed in detail in this report, developments in this market segment have the potential to affect overall demand for and supply of permanent magnets.

## WIND TURBINES

Permanent magnets make possible small, light, space-saving designs for the gearboxes of wind turbines. They also enhance low-voltage ride-through capability, thus improving a turbine's capacity to remain connected to the grid.

The global expansion of wind power raises the prospects of growing imbalances in supply and demand for some REEs, chiefly neodymium, praseodymium and dysprosium. It will not be possible to meet the substantial increase in demand driven by the 2050 global wind power targets unless REE production rises 11 to 26 times over present levels (Li *et al*., 2020). Ren *et al*. (2021) foresee demand for REEs in China rising 18 times over 2020 levels by 2050. By that year, annual demand for neodymium may equal 1.6-3.3% of the country's reserves. The same range for dysprosium is 1.4-2.8%. After 2050 recycled metals will play a growing role in supplying Chinese wind farms.

The materials used in wind turbines, and substitutes for those materials, have been the focus of multiple studies (*e.g*. Lacal-Arántegui, 2015; Marx, 2018; Pavel *et al*., 2017).

Carrara *et al*. (2020) point out the differences between the material content of the direct-drive and gearbox-driven wind turbines used in onshore and offshore installations. As a result of major differences in generator design, drive-train systems, and provisions for grid connection, the two designs differ greatly in their material content, just as they do in their speed and mass.

Some gearbox drives are assisted by a permanent magnet; others employ electromagnet generators (high-speed induction generators with multistage gearboxes). Gearboxes with a permanent magnet generator come in medium- and high-speed variants, with the latter being less dependent on the permanent magnet. The medium-speed gearbox design with a permanent magnet generator has gained popularity in both onshore and offshore farms in recent years. But gearbox designs in general are less competitive in large plants and offshore installations because of their weight and need for periodic maintenance.

The generators in direct-drive turbines, by contrast, can be based either on permanent magnets (the Goldwind, Siemens and General Electric models are examples) or an electric generator (*e.g*. Enercon direct-drive models). A key advantage of the direct-drive configuration is that it makes possible smaller and lighter turbines (by eliminating the gearbox), making it more competitive in offshore applications.

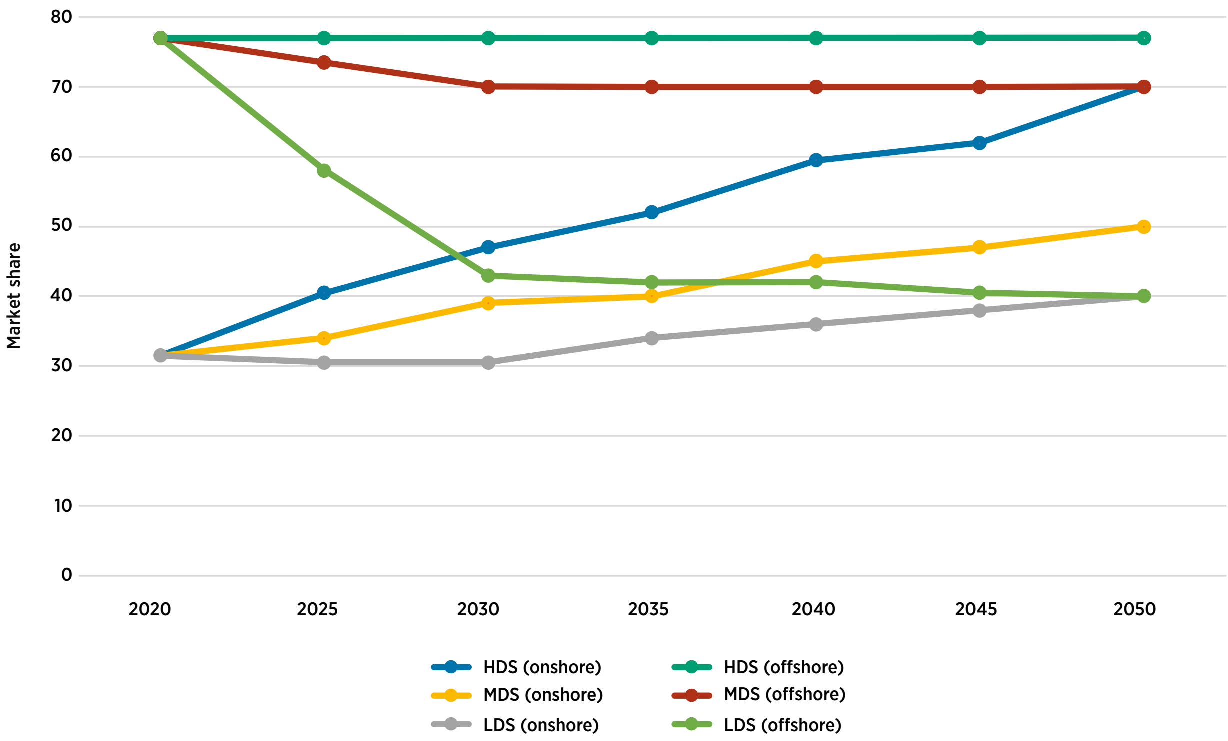
Hybrid drives are also produced. Their smaller permanent magnets require less rare earth material than direct drives having the same power specifications.

In the future, as rare earth elements become scarcer, high-temperature superconductors could come to be used in direct-drive turbines. In addition to cutting consumption neodymium and dysprosium, gains would include better performance owing to a decrease in weight. But further cost reductions and technological progress will be necessary before this design becomes viable, even in the offshore settings where it would yield the greatest benefits.

The share of permanent magnet drives has been rising worldwide. Permanent magnet turbines drove three-quarters of the world's offshore installations in 2018, while gearbox induction generator turbines dominated the onshore market with a 52% share. Turbines using permanent magnet drives made up most of the remainder (GWEC, 2019; Carrara *et al*., 2018).

Permanent magnets in wind turbines follow one of three scenarios, according to Carrara *et al.* (2020). All assume a convergence for onshore and offshore by 2050 (Figure 2), but the range between the low- and high-demand scenarios is wide. In the latter, the market share of permanent magnet drives in onshore settings could be as high as 70% in 2050, which would impose a great strain on REE supplies (Carrara *et al.*, 2020). That possibility indicates the importance of product innovation in shaping future REE demand, which deserves more attention in decision-making and policy design.[4]

**Figure 2:** Scenarios for the use of permanent magnets in wind turbines




**Source:** Adapted from Carrara *et al.*, 2020.

**Note:** HDS = high-demand scenario; LDS = low-demand scenario; MDS = mid-demand scenario.

## ELECTRIC VEHICLES

Rare earth magnets figure in various automobile components (Fears, 2021), but motors account for the bulk of their use. In fact, one in four permanent magnets produced worldwide in 2020 was used in transport, mostly for electric motors, but also for micromotors, sensors and speakers (Roskill, 2021; Kane, 2020) (see Figure 1). That share is expected to grow as the use of EVs expands (Figure 4). EVs alone are expected to account for around 25% of NdFeB consumption in 2030 (Adamas Intelligence, 2021). Traction motors for vehicles (including electric bikes, scooters and motorcycles) will capture 23% of the market.

The average hybrid or EV uses between 2 kg and 5 kg of permanent magnets, depending on its design (Onstad, 2021).[5] The permanent magnets in the motors cost more than USD 300 per vehicle, or up to half the cost of the entire motor (Onstad, 2021).

4 See also the section below entitled “Slowing growth in demand for rare earths in magnets”.

5 The European Raw Materials Alliance (ERMA 2021) assumes 1.5 kg of rare earth magnets per vehicle but states that the magnet mass in EVs using this motor technology will most likely increase.

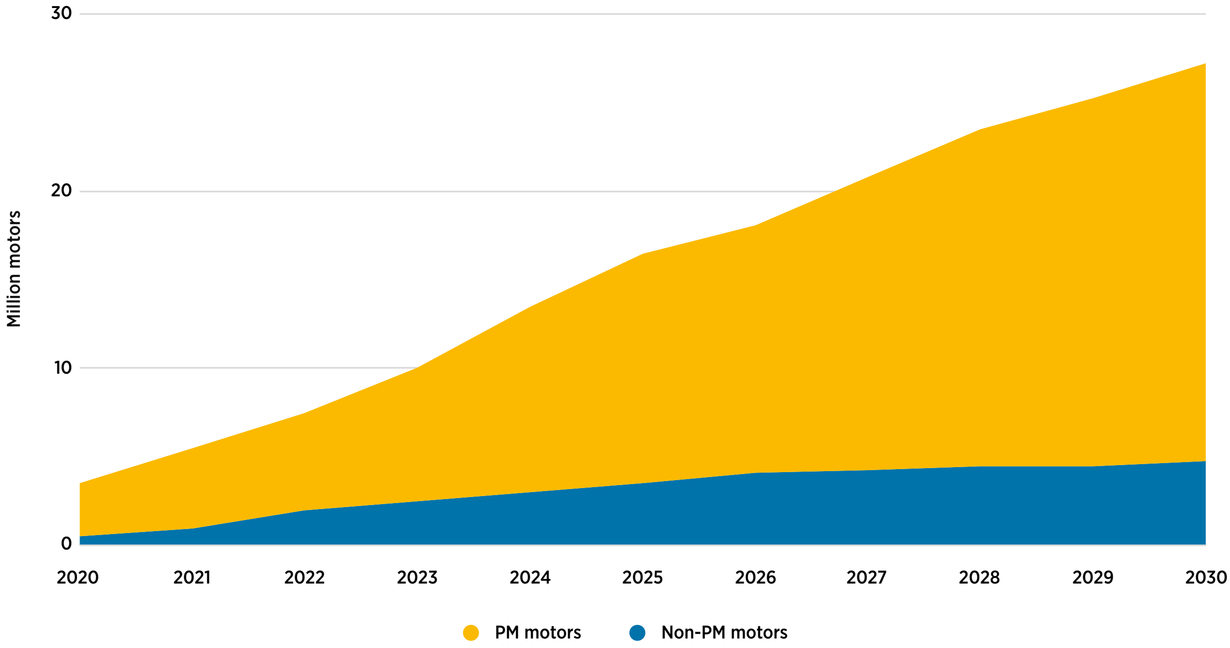
The rate at which production of permanent magnets based on REEs will have to grow to meet demand in 2030 depends on several factors. The most important of these is the level of EV production, which will be between 20 and 40 million. Other factors are the share of EVs using permanent magnet motors, the weight of the magnet used and the impact of technological innovation. Most EVs are expected to still be using permanent magnets in 2030. Taking EV sales projections together with predictions about the continued use of permanent magnets yields a forecast of up to 225 kt in possible demand for NdFeB magnets in 2030 (Ma and Henderson, 2021).

Taking these considerations into account, the most significant bottleneck to meeting higher demand for generators and traction motors using permanent magnets is likely to be upper-limit temperature performance, availability of dysprosium and associated costs, which affects demand for dysprosium. It is here that technological breakthroughs will be most keenly felt (Onstad, 2021).

Product innovation can affect REE demand in other ways as well. The use of reluctance motors, for example, already allows low-cost ferrite-based magnets to be substituted for the rare earth variety. These innovations may one day be adapted for use in higher-performance traction motors. Improvements in energy density (kilowatts per kg) could lower motors' REE requirement. BMW's i3 EV motor achieves 2.5 kilowatt/kg, substantially higher than the 1-1.5 kilowatt/kg density in a typical hybrid (Onstad, 2021).

Currently, NdFeB magnets are essential for optimising the power-to-weight ratio in motors and generators, but automobile manufacturers are seeking ways to reduce their dependency on REEs. Manufacturers accounting for 46% of total 2020 light-vehicle sales, including the world's two largest automakers, Toyota and Volkswagen, have announced moves to scale down or eliminate the use of rare earth magnets in their EVs (Onstad, 2021). Nissan has removed such magnets from its new Ariya model; in 2021, BMW did the same for its iX3 electric SUV (Onstad, 2021). Renault and Tesla have eliminated them from some of their models by applying wound rotor and induction motor technologies; Tesla is combining permanent magnet motors with induction motors.

**Figure 3:** Projections for rare earth permanent magnet use in electric vehicles, 2020-2030




**Source:** Adapted from Onstad, 2021.

**Note:** Estimates of motors used in battery and fuel cell electric vehicles. Permanent magnet (PM) motors are axial flux permanent magnets and surface-mounted permanent magnets. Non-PM motors are of the current-excited wound synchronous and induction types.

## EFFICIENCY OF RARE EARTH ELEMENTS' USE

Dependence on REEs can be reduced through the development of permanent magnets that minimise their use or eliminate it entirely (Northeastern, 2018). Promising advances have been made since 1982, when Japanese and U.S. groups independently discovered how to produce NdFeB magnets having a very high maximum energy product.

The trick is to reduce heavy REE consumption in NdFeB magnets without a significant loss in coercivity (resistance to demagnetisation). Adding dysprosium, terbium or another heavy REE is the most common way to improve coercivity.[6] Although heavy REEs are scarce and sourced from limited areas, production of neodymium is expected to keep pace with growing demand, even under ambitious scenarios for growth in electric machines using permanent magnets. Where technological advances will be essential, however, is in finding substitutes for dysprosium, which is used to improve the upper-limit temperature performance of generators and traction motors using permanent magnets. Standards and specifications will be critical in this respect. If a design specifies lower temperature stability, critical materials can be saved.

High-performance sintered NdFeB magnets dominate the market today.[7] They are used in wind turbines and EV motors because of their high magnetic properties and productivity. The amount of dysprosium they contain can be greatly reduced by employing "grain boundary diffusion processing". Using current production technology and applications, the amount of added dysprosium can on average be halved. In the best scenario, it can be brought down to about 2% without reducing coercivity.

Although sintered magnets dominate, hot-deformed and bonded magnets are attracting interest. These types are very different in terms of their raw materials, manufacturing technologies and product applications. Sintered and hot-deformed NdFeB magnets have similar magnetic properties but differ in their microstructures. Hot-deformed anisotropic NdFeB magnets may eventually reach high coercivity owing to their fine crystal grained microstructure, which is one order of magnitude finer than their sintered cousins. They are considered a promising way to produce high-performance NdFeB magnets completely free of heavy REEs. However, coercivity is still only about a quarter of the full potential of the anisotropy field (Hioki, 2021).

Wang *et al*. (2021) found that doping single-layer graphene at 0.1 wt% could raise the coercivity of hot-deformed NdFeB magnets without a significant effect on remanence (the magnetism left in a material after the magnetising field has been removed). This opens a pathway to using grain growth control to prepare high coercivity and high remanence permanent magnets and ultra-strong magnetic materials.

Lambard *et al*. (2022) have devised a process using machine learning, as well as Bayesian optimisation, to predict magnetic properties from process parameters, making it possible to determine optimum conditions for high coercivity and remanence in NdFeB anisotropic magnets fabricated by direct hot extrusion. Their method underpins a process for manufacturing magnets with high coercivity and remanence yet free of heavy REEs. The magnets have an excellent maximum energy product of (BH) max –380 kilojoules per cubic metre ($kJ/m^3$).

6 Magnetic coercivity is more often referred to as the resistance of a material to demagnetisation because that gives us more insight into the magnetic properties of the material than its resistance to magnetisation. Magnetic coercivity is measured as the strength of the applied magnetic field needed to bring the material's magnetic field to zero. It is measured in Oersteds (Oe), with 1 Oe being equivalent to 79.57747 A/m. https://matmatch.com/learn/property/magnetic-coercivity

7 In 2019, 94% of all NdFeB magnets were sintered.

At present, hot-deformed magnets can be moulded only in circular formats. Because of this, they are used mainly in EVs and cannot yet be used in wind turbines. Some challenges remain that constrain the upscaling of production and keep costs high. Therefore the market share of hot-deformed magnets is still very small.

Bonded magnets can be formed more easily into irregular and sophisticated shapes, but, owing to the higher technical requirements and precision required in processing, their deployment is relatively small at present. However, the technology is progressing fast, and longer-term prospects appear promising. Although, like hot-deformed magnets, bonded magnets cannot yet be used for wind turbines, they are suitable for use in small or micromotors (not primary motors) in EVs and in electronics. In recent years, cerium magnets have been widely used, reducing the demand for scarce didymium (a mixture of praseodymium and neodymium elements). In this context, cerium magnets deserve mention. They cannot be classified as high-performance magnets but can be used in products not requiring high performance.

Alternatives to REE-based alloys already exist, but they lack the energy density needed to replace neodymium-based magnets. Although the physics of magnetism are such that alternative magnets will never be more than 60% as powerful as their rare earth counterparts, with samarium-iron-nitrides (Sm-Fe-N) as the best option (Harris, 2021), some of the potential replacements exceed the performance of the neodymium-based alloys at temperatures above 200°C. Many of these compounds have been known for decades, but serious interest in their optimisation waned after the REE-based compounds were discovered (Kramer *et al*., 2012).

One line of current research focuses on creating more powerful magnets by altering the crystal structure of iron, nickel and other common metals (Northeastern, 2018). But such transition metal systems are not yet within reach. Even though theoretical models have shown promise, it is not yet clear whether they can be synthesised, of, if they can, whether they will have the thermodynamic stability required for use in electric devices using permanent magnets (Kramer *et al*., 2012).

Another alternative magnet strategy is based on re-engineering products so that they can operate with a weaker magnet. Some product redesign options and trends were discussed in the demand section above.

## PATENT ACTIVITY IN MAGNETS

As of 2020, Japan controlled more than half of NdFeB patents, and its preponderance may explain why China has not expanded its role in the manufacture of high-performance magnets, even though China also owns a large number of patents in sintered magnet technologies (Box 1). Hitachi licensed its advanced sintered magnet technology to just eight large Chinese manufacturers (several of them in Zhejiang province) among the 200 or so NdFeB producers in China (Ma and Henderson, 2021). Hitachi's decision created a fragmented domestic industry in China. Most of the 200 players are small, with annual production under 1 500 tonnes. Moreover, of the nearly 160 000 tonnes of NdFeB magnets that China produced in 2018, only about 15% (23 000 tonnes) are high-performance types. Worldwide, about a dozen companies – including the eight Chinese companies that benefitted from Hitachi's license – have the capacity and quality to supply Tesla, Siemens and other high-end users. The Chinese producers largely supply the domestic markets for both EVs and wind turbines.

Although Japan and Germany still account for around half of the world's output of high-performance magnets, their production levels have remained relatively constant. The United States has no large-scale NdFeB manufacturing operations (Ma and Henderson, 2021).

Finally, savings in permanent magnets for phones and hard disks may free up REEs for the EV market (Ormerod and Trout, 2021). And superconducting magnets that do not depend on critical REEs are suitable for use in the very large offshore wind turbines (>14 MW) planned for deployment in the near future.

### **Box 1:** Patent activity in bonded and sintered magnets

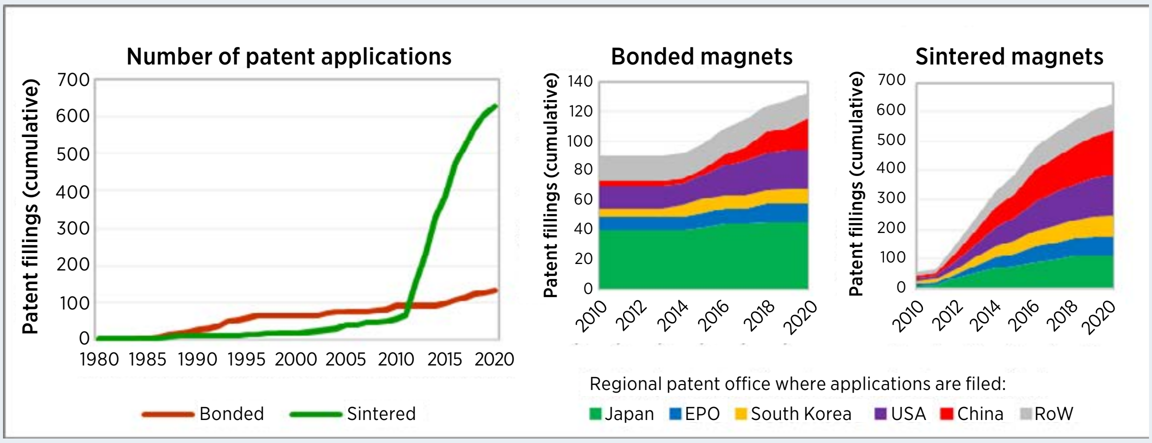
Patenting in bonded and sintered magnets containing REEs shows different trends.[a] Patenting activity related to bonded magnets initiated in the 1990s, rapidly reaching a level that has remained almost constant over the decades up to 2015, when the trend surged. (In cumulative values, 2020 showed a +36% of patents compared to 2015). Filings for sintered magnets began in the early 2000s, though the basic patent for the manufacturing technology behind them was granted in 1983. In 2012 they registered unprecedented growth (up 123% in 2012 over 2011) that has continued. Through 2020, about five times more patents were registered sintered than bonded processes (see line chart on the left in Figure 4).

Patents related to bonded and sintered magnets also differ in where they are filed.[b] Bonded magnet patents are concentrated in Japan, but Japan's share has shrunk over time. In 2010, 44% of all bonded patents were protected in Japan; by 2020 that share had dropped to 34%. This is the consequence of a rising relevance of China and the United States, that moved from 3% to 16% and from 17% to 20%, respectively, between 2010 and 2020.

Patents related to sintered magnets since 2012 are much more uniformly distributed across regions: 22% in China (on average between 2012 and 2020), 20% in both Japan and the United States, and 11% in Europe (European Patent Office) and South Korea (stacked area charts on the right in Figure 4).

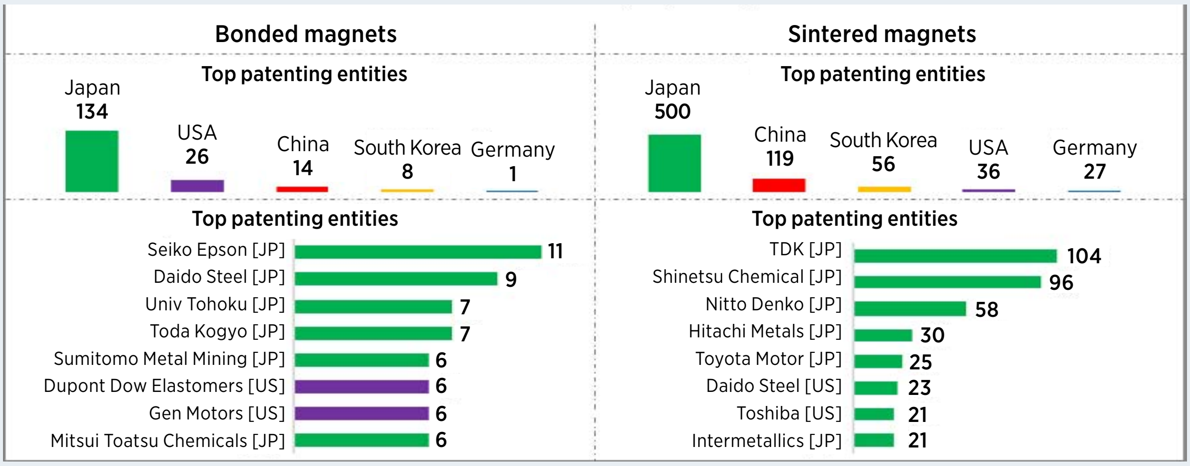
In both bonded and sintered patent activity, Japan is the leading country. Between 1980 and 2020, Japan was the country of residence of the applicants for 73% of all patent applications related to bonded magnets, followed by the United States with 14%.[c] The corresponding figures for sintered-related patents were Japan at 66% followed by China with 16% (vertical bar charts on the bottom in Figure 5). Six of the top eight patenting entities on bonded magnets are Japanese, five of them companies and one a university. The remaining two are US companies. All the top eight patenting entities on sintered magnets are Japanese companies (horizontal bar charts on the bottom in Figure 5).

**Figure 4:** Trend in patent applications




**Note:** The line chart on the left shows the cumulative number of patent applications filed, from 1980 to 2020, and related to both bonded and sintered magnets. The two stacked area charts on the right (about bonded and sintered magnets) show the cumulative number of patent applications (from 2010 to 2020) detailed by regional patent offices, that is where patent applications are filed. EPO = European Patent Office.

**Figure 5:** Total number of patent applications based on country of residence of applicant, 1980-2020




**Note:** Total number of patent applications is based on the country of residence of patent applicants. Vertical bar charts on the top show the top five countries patenting on bonded (left) and sintered (right) magnets. Horizontal bar charts on the bottom show the top eight entities patenting on bonded (left) and sintered (right) magnets.

a. Two codes of the Cooperative Patent Classification are used for this analysis: H01F1/0533 (bonded) and H01F1/0536 (sintered). These codes refer to magnets with inorganic materials, characterised by coercivity of hard-magnetic materials (metals or alloys) and containing rare earth metals.

b. Filing a patent application in a region (*e.g.* to a specific national or regional patent office) indicates foreseen market opportunities in that region.

c. Patent applications filed by multiple applicants from different countries are double counted.

# SUPPLY

There are around 245 types of known rare earth deposits. Economically relevant production is currently limited to three types: bastnaesite (a carbonate mineral), monazite and xenotime (both phosphate minerals). REEs are typically associated with radioactive uranium and thorium. The deposits contain a mixture of REEs that are co-produced from a single deposit (Table 2). Apart from mineral rock deposits, some ion absorption clays contain significant amounts of REEs. Deposits of this type are currently exploited in South China and Myanmar and occur across Southeast Asia. Peralkaline deposits also contain significant quantities of REEs, but these cannot be exploited economically at present, except those from a mine in Russia.

As demand for REEs is focused on a few elements (such as neodymium and dysprosium), surpluses are produced of other elements such as cerium and lanthanum.

In 2020, 240 kt of rare earth oxides were produced. Nearly 60% of production took place in China, followed by the United States, Myanmar, and Australia. These four countries accounted for more than 90% of global production in 2018 (Table 2). The strong mining position of the United States is not supported by an equally strong resource endowment (Table 3) or processing capacity, and the country's mined minerals are mainly shipped to China for processing. Therefore in the longer term, other countries must pick up the mining and processing role to ensure diversity of supply. USGS (2021b) describes 799 deposits around the world, a measure for the widespread distribution of REEs.

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. China North also owns 73 500 tonnes of processing capacity (Rockstone, 2016). In China, REEs are also mined in Jiangxi, Fujian and Sichuan provinces.

Ion absorption clays in South China and Myanmar accounted for 17% of the world's production in 2020 (around 35 kt). These clays are important because they are enriched with heavy REEs including dysprosium. In Myanmar, production is concentrated in the politically unstable Kachin and Shan states, and production reports are unreliable. Ion absorption clays are processed through leaching with ammonium sulphate.

The world's known REE reserves are equivalent to 500 years of current demand, assuming continued annual production of 240 kt and 116 Mt of reserves. Aside from China, countries with major resources, such as Viet Nam, Brazil and Russia, have no significant production. According to the USGS (2021a), Greenland holds the largest reserves of undeveloped rare earth deposits, particularly neodymium. Amid environmental concerns, many projects struggle to get approval, as was the case with a large mining project recently terminated by legislators in Greenland.

But only a few REEs are relevant to the energy transition. Neodymium is one of them. Global reserves of this element are estimated at 8 Mt, making it the second-most-abundant REE after cerium. Although reserves are adequate, ramping up supply in the short and medium term may be difficult. The key to scarcity is therefore not reserve levels, but the development of new mining capacity.

**Table 2:** Rare earth content of selected source minerals (% of rare earth oxide)

| PRIMARY SOURCE | COUNTRY | LOCATION | LANTHANUM (LA) | CERIUM (CE) | PRASEODYMIUM (PR) | NEODYMIUM (ND) | SAMARIUM (SM) | EUROPIUM (EU) | GADOLINIUM (GD) | TERBIUM (TB) | DYSPROSIUM (DY) | HOLMIUM (HO) | ERBIUM (ER) | THULIUM (TM) | YTTERBIUM (YB) | LUTETIUM (LU) | YTTRIUM (Y) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Bastnaesite** | **China** | Bayan Obo, Nei Mongol Autonomous Region[a] | 23.00 | 50.00 | 6.20 | 18.50 | 0.80 | 0.20 | 0.70 | 0.10 | 0.10 | NA | NA | NA | NA | NA | NA |
| | | Dechang, Sichuan Province[b] | 35.60 | 43.80 | 4.73 | 13.10 | 1.22 | 0.23 | 0.52 | 0.06 | 0.09 | 0.05 | 0.04 | 0.01 | 0.06 | NA | 0.40 |
| | | Maoniuping, Sichuan Province[b] | 29.50 | 47.60 | 4.42 | 15.20 | 1.24 | 0.23 | 0.65 | 0.12 | 0.21 | 0.05 | 0.06 | 0.04 | 0.05 | 0.01 | 0.70 |
| | | Weishan, Shandong Province[b] | 35.50 | 47.80 | 3.95 | 10.90 | 0.79 | 0.13 | 0.53 | 0.14 | NA | NA | NA | NA | 0.03 | NA | 0.76 |
| | **United States** | Mountain Pass, CA[c] | 34.00 | 48.80 | 4.20 | 11.70 | 0.79 | 0.13 | 0.21 | NA | NA | NA | NA | NA | NA | NA | 0.12 |
| **Loparite** | **Russia** | Revda, Murmansk Oblast[d] | 25.00 | 50.50 | 5.00 | 15.00 | 0.70 | 0.09 | 0.60 | NA | 0.06 | 0.70 | 0.80 | 0.10 | 0.20 | 0.15 | 1.30 |
| **Monazite** | **Australia** | Mount Weld Central Lanthanide, Western Australia[e] | 23.90 | 47.60 | 5.16 | 18.10 | 2.44 | 0.53 | 1.09 | 0.09 | 0.25 | 0.03 | 0.06 | 0.01 | 0.03 | NA | 0.76 |
| | **China** | Nangang, Guangdong Province[b] | 23.00 | 42.70 | 4.10 | 17.00 | 3.00 | 0.10 | 2.00 | 0.70 | 0.80 | 0.12 | 0.30 | NA | 2.40 | 0.14 | 2.40 |
| | **India** | Manavalakurichi, Tamil Nadu[f] | 22.00 | 46.00 | 5.50 | 20.00 | 2.50 | 0.02 | 1.20 | 0.06 | 0.18 | 0.02 | 0.01 | 0 | 0 | 0 | 0.45 |
| **Rare-earth laterite** | **China** | Xunwu, Jiangxi Province[b] | 38.00 | 3.50 | 7.41 | 30.20 | 5.32 | 0.51 | 4.21 | 0.46 | 1.77 | 0.27 | 0.88 | 0.13 | 0.62 | 0.13 | 10.10 |
| | | Xinfeng, Jiangxi Province[b] | 27.30 | 3.23 | 5.62 | 17.60 | 4.54 | 0.93 | 5.96 | 0.68 | 3.71 | 0.74 | 2.48 | 0.27 | 1.13 | 0.21 | 24.30 |
| | | Longnan, Jiangxi Province[b] | 2.18 | <1.09 | 1.08 | 3.47 | 2.34 | <0.37 | 5.96 | 1.13 | 7.48 | 1.60 | 4.26 | 0.06 | 3.34 | 0.47 | 64.90 |
| **Xenotime** | **China** | Southeast Guangdong Province[g] | 1.20 | 3.00 | 0.60 | 3.50 | 2.20 | 0.20 | 5.00 | 1.20 | 9.10 | 2.60 | 5.60 | 1.30 | 6.00 | 1.80 | 59.30 |

**Source:** USGS, 2021a.

a Zang, Zhang Bao, Lu, Ke Yi, King, Kue Chu, Wei, Wei Cheng, and Wang, Wen Cheng, 1982, Rare-earth industry in China: Hydrometallurgy, v. 9, no. 2, p. 205–210.

b Yang, Xiaosheng and Zhi Li, Ling, 2014, China's rare earth ore deposits and beneficitation techniques: ERES 2014—1st European Rare Earth Resources Conference, Milos. Greece, April 4-7, 11 p.

c Molycorp, Inc., 2015, Form 10–K—2014: Greenwood Village, CO, Molycorp, Inc., 145 p. (Accessed June 30, 2016, at http://www.molycorp.com/investors.)

d Hedrick, J.B., Sinha, S.P., and Kosynkin, V.D., 1997, Loparite, a rare-earth ore: Journal of Alloys and Compounds, v. 250, p. 467–470.

e Lynas Corp., Ltd., 2012, Increase in Mt Weld resource estimate for the Central Lanthanide deposit and Duncan deposit, January 18.

f Patra, R.N., 2014, Latest scenario in rare earth and atomic minerals in India: PDAC Convention 2014, Toronto, Ontario, Canada, March 2-4, 42 p.

g Nakamura, Shigeo, 1988, China and rare metals—Rare earth: Industrial Rare Metals, no. 94, May, p. 23–28.

**Table 3:** Rare earth world production by country

| COUNTRY OR LOCALITY | 2016 | | 2017 | | 2018 | | 2019 | | 2020 |
|---|---|---|---|---|---|---|---|---|---|
| Australia[est] | 15 000 | | 19 000 | | 21 000 | | 20 000 | | 17 000 |
| Brazil | 2 700 | rev, est | 1 700 | est | 1 200 | | 710 | | 1 000 |
| Burundi[est] | - | | 40 | | 620 | | 200 | | 500 |
| China[a] | 105 000 | | 105 000 | | 120 000 | | 132 000 | | 140 000 |
| India[est, b] | 1 500 | | 1 800 | | 2 900 | | 2 900 | | 3 000 |
| Madagascar | - | | - | | 2 000 | | 4 000 | | 8 000 |
| Malaysia[est] | 1 100 | | 180 | | 990 | | pm | | pm |
| Myanmmar[est] | 3 500 | | 15 000 | | 23 000 | | pm | | pm |
| Russia | 2 700 | rev | 2 700 | rev | 2 700 | | 2 700 | | 2 700 |
| Thailand[est,c] | 1 600 | | 1 300 | | 1 000 | | 1 900 | | 2 000 |
| United States[est] | - | | - | | 14 000 | | 28 000 | | 38 000 |
| Viet Nam[est, c] | 240 | rev | 220 | rev | 920 | | 1 300 | | 1 000 |
| Total | 133 000 | rev | 147 000 | rev | 190 000 | | 220 000 | | 240 000 |

**Source:** USGS, 2021a.

**Note:** Metric tonnes, rare-earth oxide equivalent. Table includes data available through 26 January 2021. All data are reported unless otherwise noted. Totals and estimated data are rounded to no more than three significant digits, except US data which are rounded to two significant digits; may not add to totals shown.

est = estimated; rev = revised; — = zero; pm = pro memoriam.

[a] Official production quota. Illegal production could not be quantified.

[b] India's Department of Atomic Energy did not disclose monazite production data.

[c] Rare-earth-oxide content of exports.

**Table 4:** Rare earth production and reserves by country

| COUNTRY | MINE PRODUCTION, 2020 [TONNES/YEAR] | RESERVES [TONNES] | % OF TOTAL WORLD RESERVES |
|---|---|---|---|
| China | 140 000 | 44 000 000 | 38.0 |
| Viet Nam | 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 |
| Myanmar | 30 000 | NA | NA |
| Madagascar | 8 000 | NA | NA |
| Thailand | 2 000 | NA | NA |
| Burundi | 500 | NA | NA |
| **World Total** | **243 300** | **115 820 000** | **100** |

**Source:** LePan, 2021.

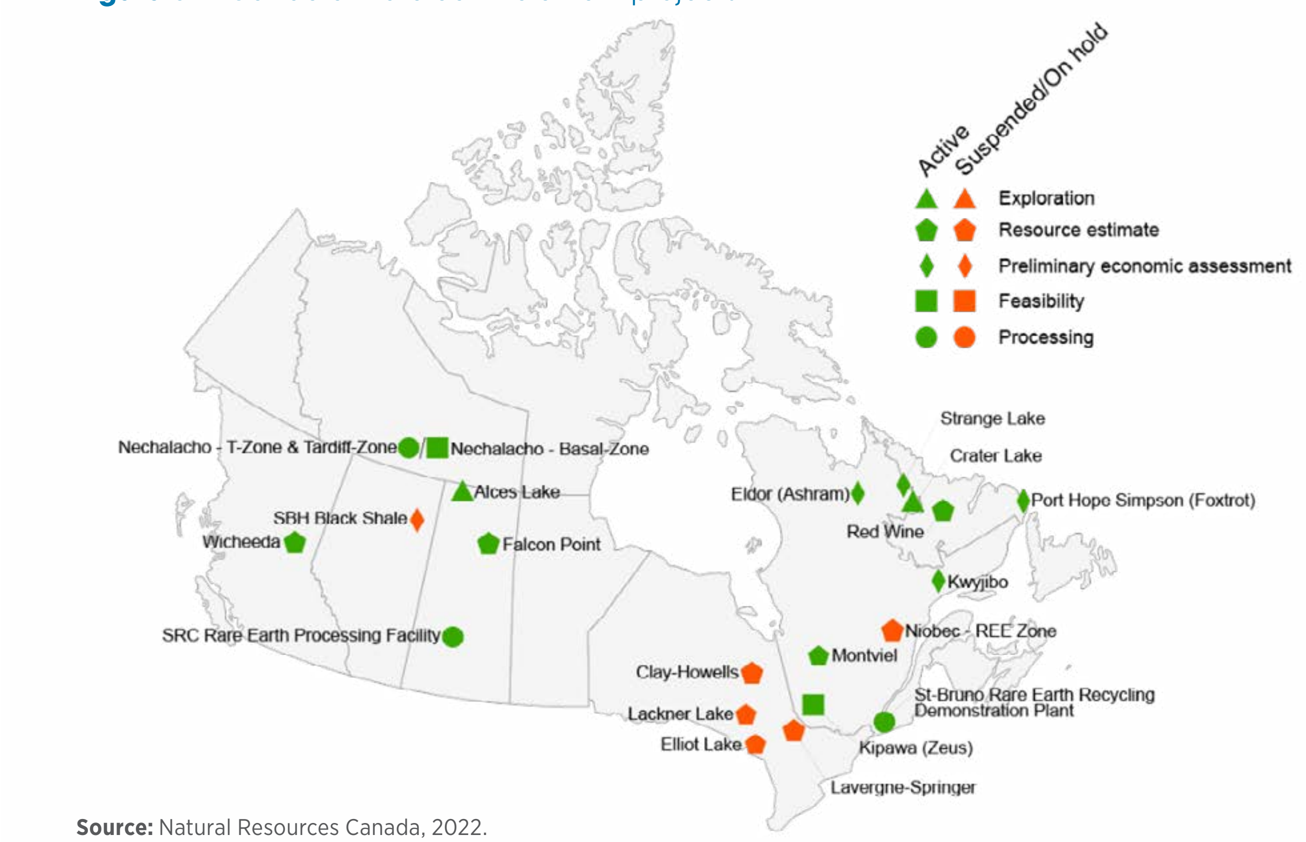
China's role is even more dominant in REE processing and magnet manufacturing than it is in REE production. As of 2020, the country accounted for 55% of global REE production capacity and 85% of refining output (Roskill, 2021). Yet China's demand for REEs is so high that it has consistently exceeded domestic supply for the past five years, leading to a surge in imports.

China has traditionally co-located refinement factories 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 on the global market.

The monazite fraction of rare earth deposits is drawing growing interest. Monazite typically offers greater contents by weight of neodymium, praseodymium and heavy REEs such as dysprosium and terbium, than do bastnaesite deposits. Monazite's natural radioactivity has historically made it too expensive to handle, but as REE prices rise, the cost calculation has changed. Reinforcing the trend is progress in separating radioactive thorium from the titanium mining residues that contain abundant supplies of monazites.

The development of REEs continues unabated. Several advanced exploration projects are underway in Canada, which is not yet a commercial producer of REEs, though it holds some of the largest reserves. The country's resources of rare earth oxides are thought to exceed 14 Mt while reserves are currently at 830 kt (Natural Resources Canada, 2022). The Nechalacho Rare Earth Mine project in Thor Lake, Canada's Northwest Territories enjoys favourable geological conditions. The deposit features near-surface mineralisation of neodymium and praseodymium (T-Zone, Lake Zones), as well as zirconium and lithium, while radioactive material content is low. Avalon acquired title to the property in 2005. In 2019, the near-surface mineralisation at Nechalacho was purchased by Cheetah Resources (a subsidiary of Vital Metals). The Nechalacho Rare Earth Mine began production in June 2021, becoming Canada's first REE mine as a three-year smaller-scale demonstration mining project. Material is crushed and sorted on-site and will be transported to Saskatoon Saskatchewan for further processing. The company plans to produce a minimum of 5 000 tonnes of rare earth oxides by 2025 (Tester, 2011; Avalon, 2021).

**Figure 6:** Canadian rare earth element projects




**Source:** Natural Resources Canada, 2022.

**Disclaimer:** This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Greenland's parliament recently passed legislation to prohibit prospecting, exploration and exploitation of uranium. (The government may issue provisions to apply the restriction to other radioactive elements, such as tritium.) The new law will block the development of the Kuannersuit mine, which is one of the world's largest undeveloped rare earth deposits containing terbium and dysprosium (Reuters, 2021b). The law does not apply to prospecting, exploration and exploitation directly of non-uranium resources if the average uranium content is less than 100 parts per million. However, Greenland has a plenitude of REEs not associated with uranium. Another expected REE project, the Sarfartoq carbonite complex, is under development by a Canadian-based mining and exploration company (Mining, 2021).

Kenya, Malawi, Namibia, Madagascar and Tanzania host carbonite and peralkaline projects that could come on stream in coming years. Several critical REEs, including praseodymium, are found in Tanzania, making it especially noteworthy (Earth.org, 2020).

Japan could also become an important source of REEs, with substantial deposits in its far eastern territorial waters. Seabed mining is difficult, however, and environmental concerns loom large, so these deposits may not be tapped for years to come. The deposit near Minamitori Island reportedly contains 16 million tonnes of valuable metals (Takaya *et al.*, 2018).

The recycling of REEs from mine tailings, end-of-life scrap and other secondary sources offers other major opportunities to secure additional supplies, though they are not yet economically viable. While REE concentrations in waste and by-products are generally much lower than in harvested ores, the quantities of REEs contained in secondary sources could meet current global demand even at low yields. Phosphogypsum, coal ash and red mud from aluminium production are promising candidates for recovery because of their high concentrations of valuable REEs and ample quantities. Moreover, some secondary sources are actually richer than ores in scandium and certain other high-value elements. It is not yet known which of the processes for extracting REEs from secondary sources can be made profitable at large scale and under strict environmental constraints (Gaustad, Williams and Leader, 2021).

Two primary extraction methods exist for primary ores. The first involves removing the topsoil, transporting the ore to a leaching pond and adding chemicals (such as ammonium sulphate and ammonium chloride) to separate out the metals. The chemicals used in this separation process can create air pollution, cause erosion and leach into groundwater. The second processing method involves drilling holes in the ground, inserting PVC pipes and rubber hoses, and pumping in chemicals to flush out the earth. The resulting slurry is then pumped into leaching ponds to separate out the rare-earth metal.

This method creates the same problems as do open-pit mines, with the additional problem of the PVC pipes, rubber hoses and other equipment used by mining crews left strewn about the mines (Earth.org, 2020). Abandoned mines pose ongoing environmental hazards while residual chemicals continue to leach into local groundwater.

Mine closures for environmental and social reasons will no doubt increase in years to come, constricting supplies. The supply of heavy REEs, in particular, is expected to tighten, following suspensions of activity at multiple mines in southern China for environmental and social reasons.

## RARE EARTH PROCESSING: COMPANIES AND METHODS

REE processing is much more concentrated than REE mining. Whereas China accounted for around 58% of mining, it accounted for 85% of processing in 2020. Apart from Chinese operations, around 24 kt of ore from Australia was processed in Malaysia in 2020 (about 10% of world production), while the remainder is processed in Estonia.

The spike in rare earth prices a decade ago provoked the opening of hundreds of new rare earth mining projects. However, no more than five reached production. Only one managed to move from mining ore to large-scale processing and separation (Argus, 2020). Australia's Lynas is the only large producer of light rare earth oxides. And Lynas's operation was able to reach commercial scale only with support from the Japanese government.

China remains the least costly source of the REEs used in magnets (Xie, 2021). But new efforts are underway to develop processing refining capacity outside China. Those efforts are described briefly below.

In August 2020, the government of Saskatchewan announced USD 31 million in funding for a rare earth processing facility to be owned and operated by the Canadian province (SRC, 2020). The facility's commercial processing plant with a capacity of 3 kt per year will concentrate, separate and treat the monazite sands that are a good source of light REEs (notably cerium, lanthanum, praseodymium and neodymium). An intermediate concentrate of mixed rare earth carbonates will be processed into separated rare earth oxides, as the market requires (SRC, 2020).

Canadian developer Medallion Resources has completed an assessment for a facility to extract REEs from monazite sands. The proposed facility will have a capacity of 7 kt per year, producing 870 tonnes of neodymium and praseodymium oxide from a cerium-depleted mixed rare earth carbonate product. The project has a capital cost estimated at USD 34 million and an operating cost of USD 12/kg of cerium-depleted mixed rare earth oxides, which does not include monazite supply costs (Embleton, 2021).

Iluka Resources is planning a new REE processing facility at the company's existing mineral sand facility in Eneabba, Western Australia. The Australian government declared its backing for the project in May 2021 (Fastmarkets, 2021). Iluka is the world's largest producer of zircon and rutile, both derived from titanium dioxide. The company intends to process large monazite stockpiles at Eneabba and to mine feedstock from a site to be developed at Wimmera, Victoria. Goldman Sachs estimates that Iluka will have to spend USD 1.2 billion to build a cracking and leaching plant, create a refinery to produce 20 000 tonnes of rare earth oxides annually, and develop the Wimmera mine, tentatively scheduled to begin production in 2025 (Cholteeva, 2021).

Uranium refiner Energy Fuels has entered the REE sector by buying monazite for processing at its uranium facilities in the United States (Fastmarkets, 2021). The company envisions an annual processing volume of more than 15 000 tonnes of monazite and other ores to recover REEs and uranium (Cholteeva, 2021).

Australia's Lynas has reached an agreement with the U.S. government to build a new plant in Texas to separate light REEs. Annual production is estimated at 5 000 tonnes (Cholteeva, 2021).

Australian Strategic Materials produces specialty metals and oxides for advanced technologies. The company owns the Dubbo Project, which processes zirconium, praseodymium, neodymium, niobium and hafnium from a deposit in New South Wales, Australia. In a joint venture partnership with South Korea's Ziron Tech, the company is developing oxide separation and metallisation technologies to produce materials from the outputs of the Dubbo Project (Cholteeva, 2021).

Mountain Pass owner MP Materials operates large REE mining and processing facilities in the United States and supplies rare earth concentrate to Shenghe Resources in Singapore (Stocklight, 2021). The company's Stage II optimisation plan is designed to expand the Mountain Pass facility where concentrates are produced to include separation of individual rare earth oxides (Stocklight, 2021).

Energy Fuels and Neo Performance Materials produce mixed rare earth carbonate at the Energy Fuels White Mesa Mill in Utah, United States. Neo separates and processes these carbonates in Estonia into earth oxides and other rare earth compounds. The Energy Fuels/Neo production initiative represents the only supply chain outside China supplying separated heavy rare earth oxides (Embleton, 2021). In December 2021, Energy Fuels announced the development, in partnership with Nanoscale Powders LLC, of environmentally friendly technology for manufacturing rare earth metals. The innovative technology uses a process that makes REE metals from oxides through molten sodium reduction of anhydrous REE chlorides. The process promises to reduce production costs, energy consumption and greenhouse gas emissions (Energy Fuels, 2021).

USA Rare Earth's Round Top site in Sierra Blanca, Texas, is expected to come on stream in 2023. Round Top's enriched polymetallic deposit contains 16 of the 17 REEs, as well as lithium, gallium and other valuable minerals. Resources sufficient to feed production at the announced rate for more than 100 years have been identified. The preliminary economic assessment projects a net present value of USD 1.56 billion over 20 years. The preliminary economic assessment estimates an internal rate of return of 70% and average annual net revenues of USD 395 million after royalties of USD 26 million. If these projections and estimates prove accurate, Round Top will be one of the lowest-cost REE producers and one of the world's lowest-cost lithium producers. The company opened a rare earth and critical minerals processing facility in Wheat Ridge, Colorado, in 2020; in April 2020 it acquired an NdFeB permanent magnet manufacturing system in North Carolina that had been owned by Hitachi Metals America, Ltd. (US Rare Earth, 2021).

Ucore Rare Metals is developing the Bokan Mountain Project southwest of Ketchikan, Alaska, to produce rare earth oxide concentrates. The preliminary economic assessment estimates a pre-tax net present value of USD 577 million based on a 10% discount rate, an 11-year operating life and a pre-tax internal rate of return of 43%. Ucore conducted field mapping to identify the two bulk sample areas and co-ordinate activities for feasibility studies (Ucore, 2021b). It plans to construct the separation and purification facility (Alaska Strategic Metals Complex) for both heavy and light REEs (Ucore, n.d.). Ucore signed a memorandum of understanding with Vital Metals for a long-term supply of mixed rare earth chemical concentrate from Vital Metal's Nechalacho project starting in 2024 (Ucore, 2021a).

One important reason why processing centres are concentrated largely in China is that the chemical characteristics of REEs make separation challenging. As a consequence, special know-how is needed, processing plants are costly and operating costs are high.

REE are difficult to separate from one another as they have very similar chemical natures. To extract the REEs present in mineral concentrates, the REE-bearing mineral must be decomposed using hydrometallurgical and pyrometallurgical techniques that use acids and alkalis (often interactively) to leach the REEs from the mineral into a pregnant leach solution. The concentrate is dried and roasted with sulphuric acid and subsequently leached again with sulphuric acid. This leachate is treated with ammonium hydrocarbonate to extract the REEs. These are treated with hydrogen chloride and again extracted.

Well-known approaches include:

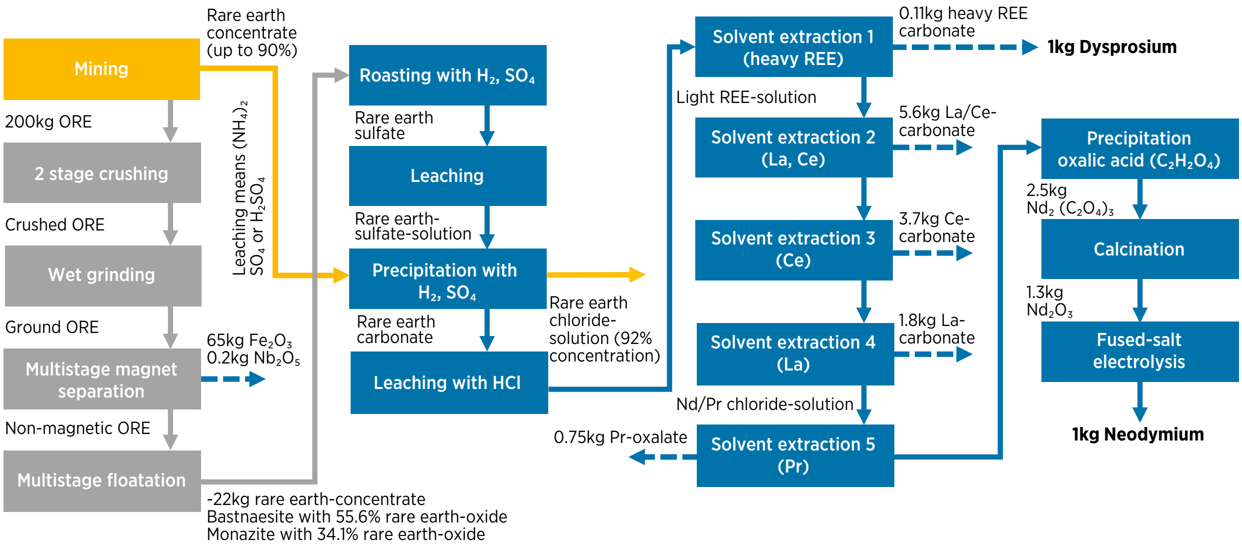
- Acid baking with sulphuric acid ($H_2SO_4$) followed by water leaching. These are used at Bayan Obo (bastnaesite and monazite) and Mt Weld (monazite, apatite).

- Agitated acid leaching of flotation concentrates with hydrochloric acid (HCl), followed by caustic sodium hydroxide (NaOH) treatment of leach residue and subsequent HCl leaching. This process is used at Mountain Pass (bastnaesite).

Typically, the concentrate will be a mixed-REEs carbonate, oxalate, chloride, hydroxide or oxide, with a purity greater than 90%. This compares with the starting mineral concentrate, which may have an REE concentration of 20-40%. The chemical concentrate will then be sent to a facility for separation into individual REEs of high-purity (99%+) (Anderson and Hatch, 2017). The separation of individual elements is complex, and some steps must be repeated many times to achieve a necessary purity. This separation is the most demanding step in the supply of REEs. Physical properties, notably solubility and magnetic properties are used to separate different elements (Adler and Müller, 2014). This is followed by organic solvent separation in steps to obtain individual REEs. The process used to obtain neodymium is illustrated in Figure 7.

The separation process is expensive and labour intensive, as the raw material is dissolved and funnelled through hundreds of liquid-containing chambers. This refining is concentrated in China, which has built up special technical expertise, but there is also some activity by Japanese companies, both in Japan and in parts of Southeast Asia. For the production of metals, the individual oxides are electrolysed. This fused-salt electrolysis step is today almost entirely concentrated in China.

**Figure 7:** Processing scheme for the production of neodymium




**Source:** BGR, 2021.

**Note:** Ce = Cerium; $Fe_2O_3$ = ferric oxide; HCl = hydrochloric acid; $H_2SO_4$ = sulphuric acid; kg = kilogramme; La = lanthanum; Nd = neodymium; $Nb_2O_5$ = niobium pentoxide; NdCl3 = neodymium(III) chloride; $Nd_2O_3$ = neodymium oxide; $Nd_2(C_2O_4)_3$ = neodymium oxalate; $(NH_4)_2SO_4$ = ammonium sulphate; Pr = praseodymium.

The separation of radioactive elements is a particular challenge. In the case of monazite, disposal of mine tailings containing thorium has led to radioactive pollution, for example, around Bayan Obo. Thorium, which can be used as a fuel for nuclear reactors, can be extracted from wastes, concentrated and subsequently disposed of through hydroxycarbonate precipitation at a specific alpha activity of less than 1·10-3 curie/kg. If necessary, thorium hydroxycarbonate can be calcinated into thorium dioxide (Anufrievaa *et al.*, 2014). China hopes to complete the world's first commercial thorium reactor by 2030 (Mallapaty, 2021).

In recent years various leaching technologies have been developed for primary REE minerals and secondary resources (Table 5). All of the processes involve multiple steps; some use acids and alkalis interactively.

**Table 5:** Summary of leaching technologies in primary rare earth elements production

| MINERAL | PROCESS/STEPS | REE YEILD | REMARKS | STATUS |
|---|---|---|---|---|
| BASTNAESITE | I. Hydrochlorid acid (HCl) leaching to remove non REE carbonate<br>II. Calcination of esidue to form rare earth oxide | 85-90% | • The oldest way to producte bastnaesite concentrates. | Outdated |
| | I. Digestion with nitric acid ($HNO_3$) or sulphiric acid ($H_2SO_4$) | 98% | • Acid choice depends on further processing: solvent extraction to nitric acid ($HNO_3$) precipitation to sulphiric acid ($H_2SO_4$) | Outdated |
| | I. Roast at 620°C to drive of carbon dioxide ($CO_2$)<br>II. 30% HCl leach | - | • Cerium+III oxidises to cerium+IV during roasting ⟶ will not leach REE fluorides<br>• Residue is marketable | Outdated |
| | I. Alkine conversion rare-earth metal-fluoride $REF_3$ to rare-earth hydroxide $RE(OH)_3$<br>II. 30% HCL leach | - | • Process can be preceded with hydrochlorid acid leach to extract REE carbonates before alkaline conversion. | In use |
| | I. Sulphiric acid roast<br>II. Sodium chloride solution leach<br>III. Precipitation as sodium double sulphates | - | • Precipitates are converted to chlorides for further purification with solvent extraction. | In use |
| MONAZITE | I. Digestion in hot sulphiric acid ($H_2SO_4$) | - | • Process conditions determine what is leached: only light REE or light + heavy REE + thorium | Outdated |
| | I. Digestion in hot 60-70% sodium hydroxide<br>II. Washing residue with hot water<br>III. Leach with mineral acid of choice | 98% | • Cerium cannot be leached if manganese is present<br>• Thorium is leached together with REE<br>• Trisodium phosphate ($Na_3PO_4$) is marketable by-product | In use |
| | I. Heat under reducing and sulphidising atmosphere with calcium chloride ($CaCl_2$) and calcium carbonate ($CaCO_3$)<br>II. Leach with 3% HCl | 89% | • Requires no fine grinding<br>• Thorium does not leach, remains in residue as thorium dioxide ($ThO_2$)<br>• No manganese problem | In use |
| IRON CLAY | I. Salt leach with ammonium sulphate $(NH_4)_2SO_4$ | 80-90% | • Targets physisorbed REE through cation exchange | In use |
| | I. Leach with saltwater | 40% | • Inefficient but cheap process | Research & development |
| | I. Acid leach with strong acid (pH<1) | 100% | • Dissolves entire clay<br>• Incurs significant additional costs | Not used |

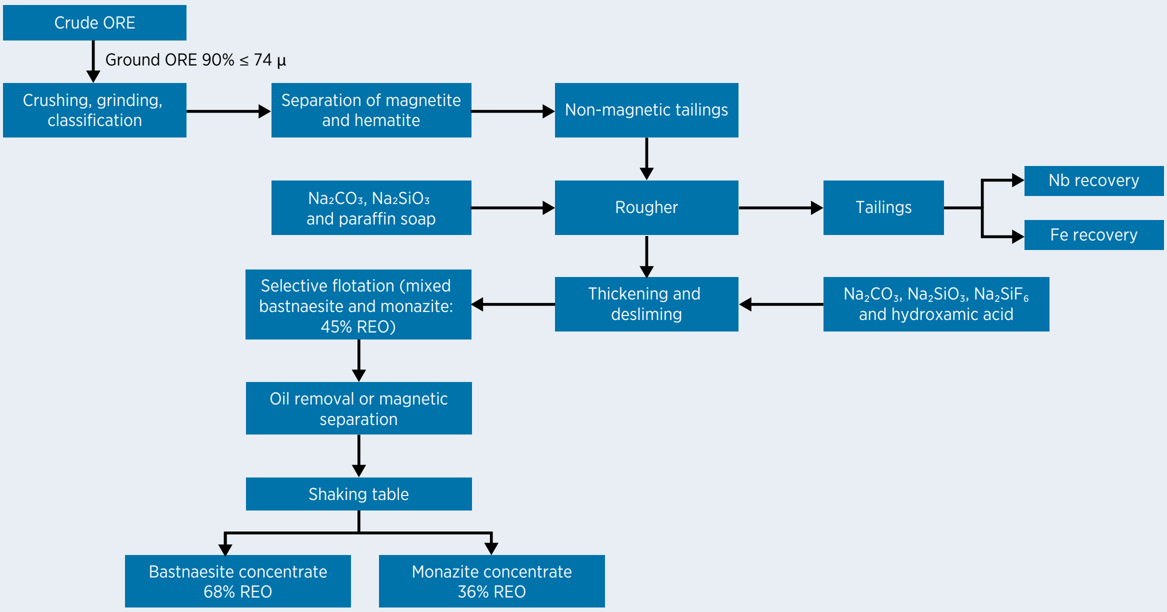
**Source:** Peelman *et al.*, 2014.

New methods of treating bastnaesite and monazite are described in Box 2. In the case of ion-absorbed clays, REE ions are weakly bonded at the surface of clay particles. Aggressive leaching systems are therefore not required (Box 3). Brine or ammonium sulphate is used to leach the REE ions. Heap leaching or in-situ methods have been used (Anderson and Hatch, 2017). Treatment often also involves HCl.

## **Box 2:** New methods for bastnaesite and monazite treatment

Bastnaesite is the source of 70% of the world's rare earth elements (REEs). Bayan Obo, the world's largest REE production site, contains a unique mixed deposit of bastnaesite and monazite, a refractory rare earth phosphate. To separate them, the mixed elements are first concentrated and then separated by a process illustrated in Figure 8.

### **Figure 8:** Bayan Obo rare earth processing flowsheet




**Source:** Peelman *et al.*, 2014.

**Note:** Fe = iron; $Na_2CO_3$ = sodium carbonate; $Na_2SiF_6$ = sodium hexafluorosilicate; $Na_2SiO_3$ = sodium silicate; Nb = Niobium; REO = rare earth oxide.

At Bayan Obo, the mixed concentrates are heated with concentrated sulphuric acid (98%) at a temperature exceeding 300°C, after which the rare earth minerals are converted to water-soluble sulphates. A rare earth sulphate solution obtained through water leaching and purification is then used to prepare a mixed carbonate (by adding ammonium bicarbonate) or to produce single rare earth products by solvent extraction.

The traditional process used a two-stage leaching system involving a high-temperature HCl leach followed by a caustic crack stage. Colligan, O'Kelley and Anderson (2021) found that the recovery rate could be raised from 70% using the two-stage leach process to 95% using a single-stage, high-temperature, high-concentration HCl leaching process that produces a slurry of low density. To better understand what accounts for the higher recovery rate in the single-stage process, further work is being done to determine how the fluorine interacts with the system. To bring this novel process to industrial scale, the system needs to be optimised for acid use, solid-liquid separation after leaching and post-leach separation of the individual REEs.

Owing to its capacity for processing large amounts of pregnant liquors, solvent extraction is now widely acknowledged as the most commercially suitable technique for REE separation (Cen *et al.*, 2021). Deep eutectic solvents have attracted growing attention in the past decade as "green" solvents capable of replacing traditional solvents in hydrometallurgical processes applied to rare earths. At low vapor pressure, these highly biodegradable and low-toxic solvents are usually liquid and non-volatile at room temperature. Their properties depend largely on the hydrogen bonding donors. The wide range of donors means that the solvents are particularly adaptable and can be customised for specific applications. (Cen *et al.*, 2021).

### **Box 3:** Treatment of ion absorption clays

Ion absorption–type rare earth ores are low in radioactivity and rich in medium and heavy rare earth elements (REEs). They range from 0.05 to 0.3 wt%, with over 80 wt% of their total REEs in ion-exchangeable state. When ion-exchangeable rare earths are brought into contact with chemically active cations (*e.g.* $Na^{+}$, $NH4^{+}$, $Mg^{2+}$, $Ca^{2+}$, $Al^{3+}$, etc.), the REEs can be exchanged and desorbed. A series of leaching agents, such as ammonium sulphate, magnesium sulphate and aluminium sulphate, have been developed for extracting REEs in-situ.

Once the leaching liquor is collected, aluminium usually must be removed to purify the rare earth–containing dilute solution. Ammonium bicarbonate is commonly used for this task, followed by roasting to obtain mixed rare earth oxides with a purity of more than 92 wt% and aluminium content of less than 1.5 wt% (in the form of aluminium oxide).

Three to six tonnes of ammonium bicarbonate are consumed to obtain 1 tonne of mixed rare earth oxides. As a result, ammonia nitrogen eutrophication in the water system of the mining area poses a serious environmental problem.

Using alkaline calcium/magnesium compounds as alternative precipitating agents holds the promise of simplicity, low cost and wide applicability, while also solving the ammonia nitrogen problem. However, further process development is needed. Other new extraction technologies are also worthy of study. These include improved centrifugal extraction and a cheap, green form of synthesis using new extractants (He *et al*., 2021).

## RARE EARTH SUPPLY COSTS

Most REE deposits contain a preponderance of either heavy or light REEs, with some being much more abundant, such as cerium and lanthanum. The more abundant minerals cost less than those in short supply.

REE prices are difficult to track in real time because, unlike gold and silver, they are not commodities traded on global public exchanges. However, regular price assessments are published by commercial firms such as Argus, based on surveys of market participants that monitor trends in REEs and the products in which they are used. Analyst firms and pricing forums such as Adamas Intelligence, ISE, Stormcrow Capital, Technology Metals Research and Asian Metal also include price forecasts in their reports (Pistilli, 2021).

Prices for neodymium, praseodymium, terbium and dysprosium have risen the fastest of the 17 rare earth metals recently (see Table 1). All are used in magnets. For example, the average price of neodymium-praseodymium oxide, the main rare earth component of magnets produced in China, rose from USD 40.80/kg in the second quarter of 2020 to USD 69.90/kg in the same period in 2021 (Lynas Rare Earths, 2021.

Economic analysis suggests that a USD 10/kg increase in the price of neodymium-praseodymium oxide (an increase of 15%) and a USD 100/kg increase for dysprosium oxide (an increase of one-third) would be enough to create the economic incentive to raise REE supply. Such a price increase would raise the cost of magnets by around USD 7/kg, or around USD 15/kg per electric car, assuming 2 kg of magnets per car (Makichuk, 2021). However, the rate at which supply can expand is often limited by factors other than profitability.

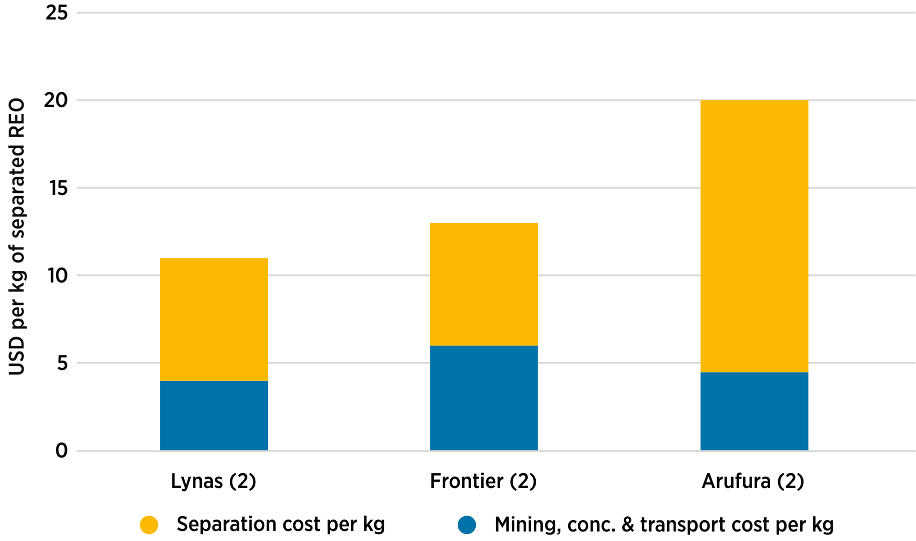
Because prices by weight of specific REEs vary by more than three orders of magnitude and the composition of deposits varies considerably, the average value of a weight unit of mixed product varies widely from mine to mine (Sykes, 2013). The Bayan Obo and Mountain Pass mines are at the lower end in terms of the value of their product mix, while Dubbo and Nechalacho are at the upper end of the range.

"The problem of projected inequality of supply and demand in the REE market is a major concern", according to MIT (2016). "Although total REE demand and total supply are approximately equal (and are expected to remain so for some time), supply for individual elements such as neodymium and dysprosium will soon fall behind global demands. This will result in large price instabilities for many sectors of the economy and will have negative effects on the integration and development of new technologies."

Processing cost can be split into operating expenditure and capital expenditure. No recent data are available on the cost breakdown. The data provided by Sykes (2013) are nearly a decade old.

Figure 9 shows operating expenditure, typically USD 10-15/kg, in which the cost of separation is predominant.

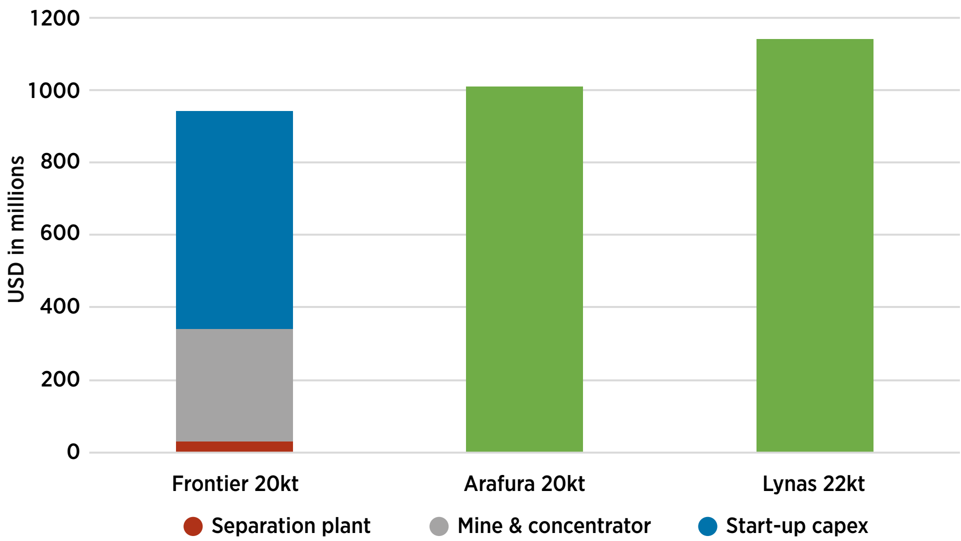
**Figure 9:** Operating expenditure of projects producing separated rare earth oxides




**Source:** Sykes, 2013.
**Note:** kg = kilogramme; REO = rare earth oxide

Figure 10 shows capital expenditure. This amounts typically to USD 1 billion for 20-40 kt annual capacity of separated rare earth oxides. Assuming a 10% annuity, this translates into USD 5/kg (Sykes, 2013). A recently announced rare earth separation plant in the UK with a capacity of 12.5 kt/year is projected to cost USD 190 million (Mineralprices, 2021).

**Figure 10:** Actual and forecasted capital expenditure of projects to produce separated rare earths




**Source:** Sykes, 2013.
**Note:** kg = kilogramme; REO = rare earth oxide

Total capital expenditure for the Zandkopsdrift project (developed by Frontier in South Africa) is comparable with similar scale projects worldwide. Two-thirds of the capital expenditure relates to the South Africa's Saldanha separation plant; published data from peers – *i.e.* Lynas and the proposed Arafura separation plants – indicate comparable capital split requirements.

In summary, total average production cost amounts to USD 15/kg (2010-2013 values). This compares favourably with today's product prices, providing an economic incentive to start new mining projects.

# ENHANCING THE SECURITY OF RARE EARTH ELEMENTS SUPPLY

As noted elsewhere in this report, critical minerals for the digital and post-carbon economy are highly concentrated geographically, while rising global trade uncertainties have triggered a rush to secure them.

The fact that mining and processing of REEs are so heavily concentrated in China worries importing countries. Deposits of REEs are present on all continents, but efforts to develop capacity outside China have been hampered by economics, environmental concerns, and the presence of radioactive uranium and thorium by-products in many deposits.

China mined 58% of all REEs in 2020 (Table 5); it refines 85%. As noted above, the manufacture of permanent magnets also came to be concentrated in China, as the country gained expertise in the technologies involved in processing REEs (Hurst, 2010). Through infrastructure development, resource allocations, and industrial policies, the Chinese government is promoting resource exploitation at scale and the development of industrial clusters. Moreover, China has strived for years to globalise the extraction of REEs under its Belt and Road Initiative, in the knowledge that governments in the countries where many critical resources are located will often be willing to accept exclusive deals in return for China's one-stop-shop financing schemes and other forms of assistance (Kalantzakos, 2020a).

Now China is striving to move further up the value chain (Chu and Serpell, 2021). The country began to regulate the industry intensively in the early 1990s after realising the strategic value of products made with REEs. Its 2016-2020 National Mineral Resource Plan calls for close attention to the "strategic" REE industry through the creation of a monitoring, evaluation and advisory system to be activated in the event of international conflict or another form of serious disturbance. At the same time, China's Mineral Resource Plan indicates that the country intends to designate strategic areas vital to national security. The six companies listed below contain more than 80% of the country's REE capacity and China imposes production quotas on them (Shen, Moomy and Eggert, 2020).

- China Minmetals Rare Earth
- Chinalco Rare Earth & Metals
- Guangdong Rising Nonferrous
- China Northern Rare Earth Group
- China Southern Rare Earth Group
- Xiamen Tungsten

The Chinese government is now merging assets from several state-owned firms to create the China Rare Earth Group (Durden, 2021). State-owned China Minmetals has received approval from the State Council to merge with two other giants, Chinalco Rare Earth and Metals and Ganzhou Rare Earth Group.[8] The new entity will control 70% of China's output of REEs and have the power to set prices (Yu and Mitchell, 2021).

8 Ganzhou Rare Earth has suspended production for more than six years to meet environmental requirements.

Because China's production gives rise to substantial pollution, the government has established strict limits on REE production and processing (Schüler-Zhou, 2018). In the past, China had significant informal mining on top of legal production. However, that source of supply has been reduced significantly, falling from 120 kt in 2011 to 10 kt in 2020 (BGR, 2021). The World Trade Organization ruled against Chinese REE export quotas in 2014, leading China to remove its industry caps. The country also eliminated its export tariffs in May 2015, causing prices to drop.

That China has the ability to control production – and thus the global availability – of metals of ever-increasing economic importance due to years of research and industrial policy in a worsening geopolitical context has led the governments of major consuming states to search for alternative supplies. The development of mining operations in other countries pushed China's share of global production down from 92% in 2010 to 58% in 2020. Jaroni, Friedrich and Letmathe (2019) assessed 14 rare earth mining projects outside China. Under positive assumptions (*i.e.* high product price), 12 of the 14 projects can be made economically feasible. However, less optimistic assumptions reduce the number of economically feasible projects to 4. This wide range is a measure of the economic risk involved with REE mining projects. This risk is one factor that explains why developing mining projects is difficult.

However, with its continued dominance in the production of refined REEs (85%), China retains strong control over the supply chain (LePan, 2021), though opinions differ on the magnitude of that risk (Hsu, 2019; Kalantzakos, 2020a).[9]

In any event, the economic importance of REEs and the lopsided nature of the supply market make diversification a vital and unavoidable goal. In practical terms, this means building up supply capabilities outside China. But repeated calls by governments to develop supply chains outside China have achieved little (Kalantzakos, 2020a).

Accordingly, governments, mining companies, manufacturers of products using REEs and countries where key strategic resources are concentrated should increase co-operative efforts to develop new supply chains. New forms of inter-governmental co-operation with developing countries should figure prominently in any such effort. Sustainable mining that creates local benefits and aids the producing country will be critical. The location of the future processing plant also deserves careful attention. REE-dependent companies outside China will be able to ensure the reliability of alternative supply only through long-term contracts and commitments, which, to the extent those commitments reach up the supply chain to mining and processing companies, would be an effective way to de-risk projects. Furthermore, if REE-processing companies were to invest jointly in deposits outside China, the stability of the investment would be enhanced. Presently, given the volatility of the market and China's ability to control supplies (and thus prices), investing in a new mine without horizontal co-operation and vertical commitments is a fool's errand. Finally, because competence in rare earth metallurgy and mining are in short supply outside China, the other countries should also invest in process know-how, possibly in co-operation with China (Jaroni, Friedrich and Letmathe, 2019).

One possible vehicle for the necessary co-operation is the European Commission's Global Gateway. Unveiled in December 2021, the Global Gateway is a plan to invest EUR 300 billion (USD 340 billion) globally by 2027 in infrastructure, digital and climate projects (EC, 2021). The frameworks are not aimed specifically at securing critical materials, but they could be adapted for that purpose.

9 Patent activity is another aspect of China's dominant power over global production of REEs. As of October 2019, China had applied for 25 911 patents on all the rare earth elements since 1950, compared with 13 920 for Japan, 9 810 for the United States and 7 280 for the European Union (Ng, 2019).

To secure access to sustainably produced rare earth magnets from both primary and secondary sources, the European Raw Materials Alliance brought together almost 200 stakeholders from industry, governmental organisations, non-governmental organisations and universities in September 2021 and developed an action plan entitled "Rare Earth Magnets and Motors: A European Call for Action". Estimating current and projected demand for REEs in Europe, the plan describes detailed actions that the European Union, member states, industry and communities should implement to secure supply chains. The recommended actions are based on a two-fold approach that focuses on needed investments and on regulatory issues that hinder the sector's growth. It calls on European policy makers to create a level playing field and asks European producers of components using REEs to consider making commitments to source a significant share of their supplies from European producers. It also exhorts European policy makers and industry to ensure reprocessing and recycling of end-of-life products and waste materials. Finally, it focuses on innovative financial instruments to trigger investments in the emerging European REE value chain (ERMA, 2021).

A bill extending tax credits to companies that domestically produce rare earth magnets was introduced in the U.S. House of Representatives in 2021. The bill would set up a USD 20/kg credit for NdFeB magnets produced in the United States, with the credit growing to USD 30/kg for magnets made with REEs supplied from American mines (Reuters, 2021a).

In January 2022, the U.S. Senate unveiled a bill to promote domestic production of REEs to reduce dependence on China by establishing a strategic reserve of REEs by 2025 (Edwards, 2022). Countries maintain various types of strategic stockpiles, including some metals (Siripurapu, 2020). Opinions differ if strategic stockpiles constitute an effective response. Whereas stocks of REEs can help in case of short-term emergencies, they do not pose an alternative for a supply shock similar to that employed by oil stock reserves, as the level of concentration in REE supply is currently much higher and response time to develop new supply is much longer. Contrary to fossil fuels the issue is consumer competition, not supplier behaviour. At the same time, China as the world's largest processor of REEs is also the world's largest consumer. However, Japan maintains a stockpile of minerals that qualifies as rare/critical, and new stockpiles are being discussed in the United States.

In summary, governments have several options to enhance supply security for REEs:

- Increase market transparency
  - » Track current supply in more detail.
  - » Develop scenarios for future demand.
  - » Assess mining developments and their likely commissioning date and supply contribution.
  - » Track public prices and future prices of key REE products.
  - » Ensure international quality standards and certification to facilitate the market formation.
- Deepen the international dialogue on critical materials
  - » End the piecemeal approach to strategies for securing critical minerals by forming co-ordinated partnerships.
  - » Address the geographic concentration of both extractive and processing activities.
  - » Build new avenues of trust and co-operation with developing countries.
  - » Search for practical solutions such as state investment in exploration, recycling, substitution, diversification of supply chains, legislative responses, compilation of critical materials lists, and further research and innovation (Kalantzakos, 2020b).

- Invest in mining, processing, infrastructure and human capital
    - » Streamline the permitting process for new mines and processing plants while adhering to stringent compliance measures in the areas of environment, society and transparency/anti-corruption regulations, regardless of whether they are operating domestically or internationally (Wood *et al.*, 2021).
    - » Help the private sector lower the risk for investors in the mining and processing of REEs by promoting long-term, fixed-price contracts to guarantee supply, invest in new technologies and invest in human capital (Wood *et al.*, 2021).
- Act to diversify supply by promoting the development of mines in different parts of the world and diversifying ownership to create competitive deep markets.
- Build stocks of critical materials.
- Provide incentives to the private sector to induce them to tackle REEs-related business.

# CONCLUSIONS AND RECOMMENDATIONS

Rare earth elements constitute a group 17 chemical elements. But treating them as a group provides limited insights. Only certain REE are critical materials that are becoming the subject of increasing global political attention because of their role in magnets, which is reflected in rising prices. Attention should focus on the supply of such elements that play a critical role in the energy transition.

The rise of electromobility and, to a lesser extent, growing deployments of wind turbines in the coming years will combine to boost demand for some REEs, notably those used in the manufacture of permanent magnets: neodymium, praseodymium, dysprosium and terbium. Their supply needs to double or even quadruple between now and 2030. Especially the growth of dysprosium supply poses a challenge. The amounts of material deployed are small compared with commodity materials, and the number of mining and processing companies is correspondingly limited. However, the industry will have to grow rapidly through 2030 to meet rapidly rising demand for the materials that go into permanent magnets. The problem of meeting demand would appear less serious in the long term (through 2050), as planned new mines will have come on stream. Also the role of recycling can increase in decades to come while certain waste streams can be mined to recover REE. As mineral deposits contain a mix of REE that varies, those that contain magnet materials are of special economic and strategic interest.

Efforts are ongoing to reduce dysprosium use in magnets and develop high performance magnets that do not need critical REE. However such innovative product designs generally reduce the performance. Scientific efforts to find new solutions are ongoing, but the outcome is uncertain and significant uptake of even the most successful solutions will take time. In combination with high but uncertain growth expectations for electromobility, REE demand projections are uncertain, and further analysis of this specific aspect is warranted.

In terms of supply growth the main challenge is not in the mining, as resources are widely distributed. The stumbling block is in processing, which is complex and requires special knowledge to separate individual REEs and convert them into high-quality permanent magnets. China plays a key role throughout the REE supply chain. However China faces environmental problems caused by mining and processing and has been trying to regulate and contain the growth of this industry. Therefore China's share in the mining of REEs has been declining in recent years, but processing and magnet production remain highly concentrated in China. Such general statements must be nuanced: the Chinese position is less dominant in high-end sintered permanent magnets for EVs.

In order to reduce supply risks, efforts have been ongoing for some years to diversify the supply. As progress has been limited to date and the economic relevance of the REE supply is growing rapidly, the efforts have been intensified. Countries such as China, the United States, Japan and the EU have historically mapped their dependencies on REEs and developed REE supply strategies, with more countries now following their lead. As the interests of all countries converge on the need to increase supply, more dialogue and co-operation are warranted. The recently established IRENA Collaborative Framework critical materials can be used for such dialogue.

Governments and the private sector should co-operate to develop new, sustainable supply chains. The mining sector would benefit from consolidation – or at least substantially increased co-operation. A typical 10-40 kt separation plant may cost USD 200-1 000 million. Many of the companies that hold the resources are start-ups that lack the financial means that are needed to develop these resources. Therefore, mining companies, consumers (notably car and wind turbine manufacturers) and governments should co-operate to de-risk projects. An environmental label attesting to sustainable supply should be considered.

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