

RARE EARTH INDUSTRY OVERVIEW

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*Any use of trade, firm, or product names is for descriptive purposes only
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Abstract

The rare earth elements (REEs) are a group of moderately abundant elements comprising the 15 lanthanides, scandium (Sc), and yttrium (Y). Most REE production has been from deposits where specific minerals (usually bastnaesite, loparite, monazite, and xenotime) or ores such as ion-adsorption clays are amenable to known industrial-scale physical and chemical separation techniques. The rare earth industry is complex and evolving with changing geographic sources of supply and shifting demand for specific REEs. Global mine production tripled from 2010 to 2022. New sources of supply have changed trade patterns for mineral concentrates, metals, and compounds. While China has remained the largest global producer, its imports have increased from 12 thousand metric tons (KMt) in 2010 to over 126 KMt in 2021. A few mine producers have emerged as established sources of supply, and interests in developing new alternative sources of

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supply are ongoing. Several factors have contributed to price volatility for rare earth materials including political tensions, shifts in demand patterns, and supply disruptions. Prices for rare earth materials peaked in 2011 following changes in China's export quotas and political tensions between China and Japan. In subsequent years, prices for most rare earths decreased significantly but were influenced by rising or falling demand for specific applications such as permanent magnets and phosphors.

1.1. Introduction

Despite their name, the rare earth elements (REEs) are a group of moderately abundant elements comprising the 15 lanthanides, scandium (Sc), and yttrium (Y). The lanthanides are the elements with atomic numbers 57 through 71, in the following order: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu).

Excluding scandium, REEs can be classified as either light rare earth elements (LREEs) or heavy rare earth elements (HREEs). The LREEs include the lanthanide elements from atomic number 57 (La) through atomic number 64 (Gd), and the HREEs include the lanthanide elements from atomic number 65 (Tb) through atomic number 71 (Lu). The division is based on the LREEs having unpaired electrons in the 4f electron shell and HREEs having paired electrons in the 4f electron shell. Yttrium is chemically similar to the HREE lanthanides and commonly occurs in the same minerals as a result of its similar ionic radius. Consequently, yttrium is considered an HREE even though it is not part of the lanthanide series (Rare Earth Industry Association, n.d.).

In rock-forming minerals, rare earths typically occur in compounds as trivalent cations in carbonates, oxides, phosphates, and silicates (Mason and Moore, 1982, p. 46). Because REEs often share a divalent or trivalent charge and similar ionic radii, they are found together in a complex and diverse suite of minerals. Hundreds of REE-bearing minerals have been identified in a variety of depositional environments (Van Gosen, et al., 2017).

1.2. Production

Most REE production has been from deposits where specific minerals (usually bastnaesite, loparite, monazite, xenotime) or ores such as ion-adsorption clays are amenable to known industrial-scale physical and chemical separation techniques.

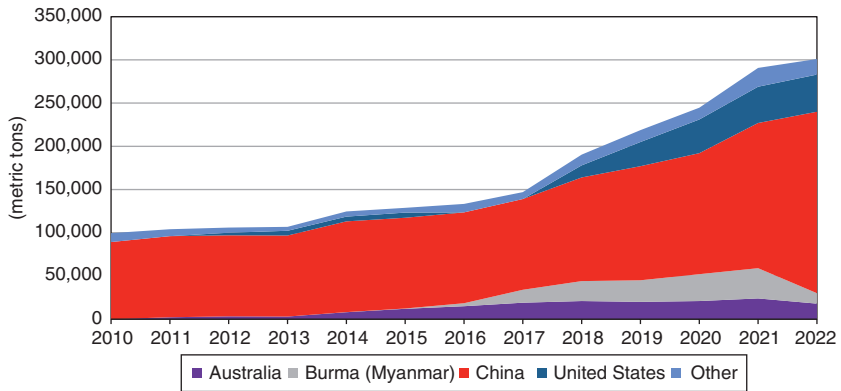


Figure 1.1 Global estimated rare earth mine production (metric tons (Mt) of rare-earth-oxide equivalent). Source: U.S. Geological Survey National Minerals Information Center, [https://www.usgs.gov/centers/national-minerals-information-center/rare-earths-statistics-and-information./United States Global Change /Public Domain](https://www.usgs.gov/centers/national-minerals-information-center/rare-earths-statistics-and-information./United%20States%20Global%20Change%20/Public%20Domain).

LREEs have been produced predominantly from bastnaesite and monazite found in carbonatite and placer deposits, while production of HREEs has largely been from ion-adsorption clays in Southern China and Burma (Myanmar). Sources of rare earths are evolving with changes in end uses, mining and processing technologies, and environmental concerns. Extensive research is ongoing to recycle REEs and recover REEs as byproducts of mine tailings and intermediate process streams.

Global production tripled during the period from 2010 to 2022 exceeding 300 thousand metric tons (Kt) of rare-earth-oxide (REO) equivalent in 2022. Since the 1980s, China has consistently led global production. Owing to increased production from Australia, Burma (Myanmar), and the United States, China's contribution to the total has fallen from 90% in 2010 to about 70% in 2022. Concurrent with increased production outside of China, China increased its mine production quota to 210 Kt in 2022 from 89 Kt in 2010 (Figure 1.1).

1.2.1. Australia

Australia has significant production, reserves, and resources of REEs. Prior to the commissioning of the Mount Weld mining operations in 2011 by Lynas Corp., Australia's REE mine production was as monazite-xenotime mineral concentrates, a byproduct of heavy-mineral sands (HMS) mining and processing. HMS operations typically produce titanium, zirconium, and a variety of other mineral concentrates. In 2022, Australia's REE production was based primarily on production of concentrates from the Mount Weld

mining operations. Mount Weld is a carbonatite deposit with ore reserves of 18.6 million metric tons (MMt) containing 8.2% (1.53 MMt) REO equivalent. Total resources at Mount Weld were 54.7 MMt containing 5.3% (2.88 MMt) REO equivalent (Lynas Rare Earths Ltd., 2023). Mining at Mount Weld has been on a campaign basis in support of downstream crack, leach, and separation operations in Kuantan, Malaysia. The Mount Weld operations were initially designed to produce up to 66 thousand metric tons per year (KMT/year) of mineral concentrate containing about 26.5 KMT/year of REO equivalent (Lynas Rare Earths Ltd., n.d.). Lynas has plans to expand mine capacity and move its initial hydrometallurgical processing operations that produce mixed chemical concentrates from Malaysia to Australia.

In Western Australia, Northern Minerals Ltd. commissioned its pilot production at the Browns Range project in 2018. Hard rock ore containing xenotime was used to produce a mixed REE carbonate. In the Australian financial year 2022 (1st July 2021 to 30th June 2022), the pilot plant processed 8.5 KMT of ore and produced 70 Mt of carbonate. Indicated resources for the Browns Range project were estimated to be 4.54 MMt containing about 0.7% (31.7 KMT) REO equivalent. Probable reserves were 3.29 MMt containing about 0.7% (22.3 KMT) REO equivalent (Northern Minerals Ltd., 2022).

In 2020, heavy-mineral sands producer, Iluka Resources Ltd., began processing a stockpile of mine tailings to produce monazite-rich mineral concentrates at its Eneabba operations in Western Australia. The first phase of the project commenced in 2021, and the company produced 44 KMT of concentrate in 2020 and 58 KMT in 2021. In 2022, a second phase was completed to produce a 90% monazite concentrate from stockpiled tailings supplemented with ongoing process tailings. In the third phase of the project, the company planned to use monazite concentrates from potentially multiple sources to produce mixed and separated REE compounds. Reserves of the stockpile were estimated to be close to 1 MMt grading 84% heavy minerals. Monazite and xenotime comprised about 19% of the heavy minerals fraction (Iluka Resources Ltd., 2023a, p. 39; 2023b, p. 14).

Australia has been an active region for mineral exploration and development. Publicly listed companies developing projects with Joint Ore Reserve Committee (JORC)-compliant rare earth reserves in Australia included Alkane Resources Ltd. (Dubbo Zirconia), Arafura Resources Ltd. (Nolans Bore), Australian Mines Ltd. (Sconi), Clean TeQ Holdings Ltd. (Sunrise), Hastings Technology Metals Ltd. (Yangibana), Lynas (Mount Weld), Northern Minerals Ltd. (Browns Range), Platina Resources Ltd. (Owendale), and Scandium International Mining Corp. (Nyngan). According to Geoscience Australia, economic demonstrated resources in Australia in 2021 were 4.26 MMt of REO equivalent (Hughes et al., 2023, p. 12).

1.2.2. Brazil

Brazil was an early producer of monazite mineral concentrates from heavy mineral sands deposits. In addition to mining, some chemical processing of monazite took place from 1949 to 1992 until environmental concerns closed the operations. In 2021, Brazil exported about 833 Mt of mineral concentrates that were produced from existing stockpiles of mixed heavy-mineral concentrates. According to the Agência Nacional de Mineração, Brazil's prior exports were derived from Indústrias Nucleares do Brasil inventories in Sao Francisco do Itabapoana (Andrade, 2019, p. 168).

In 2018, Companhia Brasileira de Metalurgia e Mineração (CBMM) conducted trial processing of monazite-bearing tailings from its Araxá mine and processing operations in the State of Minas Gerais. CBMM Araxá operations produced niobium metal, ferroniobium, and compounds from pyrochlore ore containing about 2.3% niobium oxide. The plant capacity was 1 KMt/year of REO in the form of mixed compounds and pilot capacity for separated compounds was less than 20 Mt/year of REO equivalent. No production has been reported since 2018 (Ferreira Neto, 2021).

1.2.3. Burma (Myanmar)

Mine production in Burma (Myanmar) is estimated based on China's reported imports of REE compounds from the country. Mining of ion-adsorption clays has been reported in Kachin State, which borders China's Yunnan Province (Htoi Awng, 2022). Although much of the production is undocumented, exports of REE compounds from Burma (Myanmar) to China were first reported in 2014 and peaked at an estimated 35 KMt of REO equivalent in 2021 (Zen Innovations AG, 2023).

1.2.4. Burundi

Rainbow Rare Earths Ltd. began trial mine production at its Gakara project in 2017. Although the company was targeting 100 Mt/month of concentrate production, the project was placed on care and maintenance in June 2021 at the request of the Government of Burundi. Measured resources are yet to be defined. The Gakara project includes numerous occurrences where REEs are hosted in bastnaesite-rich veins and breccia pipes (Rainbow Rare Earths Ltd., 2022, p.56).

1.2.5. Canada

Canada has significant REE reserves and resources. According to Natural Resources Canada, Canada's measured and indicated resources were over 15.1 MMt of REO in 2022. Numerous other projects in British Columbia, Saskatchewan, Ontario, Quebec, Newfoundland and Labrador, and Northwest Territories were reported to be active in 2021. Active REE mineral projects included Alces Lake, Crater Lake, Eldor (Ashram), Falcon Point, Port Hope Simpson (Foxtrot), Kipawa (Zeus), Kwyjibo, Montviel, Nechalacho, Red Wine, and Strange Lake. The Kipawa (Zeus) and Nechalacho–Basal Zone were at the feasibility stage of development. Active processing facilities included the Nechalacho–T Zone and Tardif Zone, SRC Processing Facility, Vital Metals Processing Facility, and the St-Bruno Recycling Demonstration Plant (Natural Resources Canada, 2023).

In 2021, Vital Metals was conducting a mining demonstration project at the Nechalacho project in the Northwest Territories. Mineral concentrates were shipped to Saskatchewan, for further processing. In the North T deposit where the company was sourcing ore for the demonstration, total resources were 94 KMt containing about 9.1% REO. Using a 0.1% Nd oxide cutoff, total resources for the Tardiff Upper Zone were 95 MMt containing about 1.5% REO (Vital Metals, 2022, p. 18).

1.2.6. China

China has dominated the supply of mine production and downstream products for decades. The Government of China sets production quotas for the mining and separation of REEs. However, actual Chinese production is estimated to have exceeded the quotas, as illegal production has been a concern since 2010. The illegal production has been difficult to quantify; however, it was estimated by one news source to have been 60 KMt in 2017 and was expected to fall to 8 KMt in 2021 (Argus Media Group, 2020).

Owing in part to illegal mining activities and environmental concerns, China has been consolidating its rare earth industry and enforcing more restrictive environmental policies. In 2022, China's Ministry of Land and Resources (MLR) allotted most of the mining production quota to four entities (China Rare Earth Group Co., Northern Rare Earth, Xiamen Tungsten Co., and Guangdong Rare Earth Industry Co.) In 2021, the China Rare Earth Group was established to consolidate production from Chinalco, Minerals Rare Earth, and Southern Rare Earth. The mining quota for 2022 was set at a record high of 210 KMt, a 25% increase from 168 KMt in 2021 and more than triple the 89 KMt set in 2010. China's

reserves were estimated to be 44 MMt of REO and the identified resources were estimated to be 1,400 MMt of REO (Argus Media Group, 2022a).

1.2.7. India

India is one of the earliest sources of monazite concentrates with production beginning in the early 1900s. Monazite concentrates containing REEs are produced in India as a byproduct of heavy mineral sands mining operations that also produce titanium and zirconium concentrates. Production capacity of monazite concentrates is reported to be 6 KMt/year at the Manavalakurichi operations and 240 Mt/year at the Chavara operations. A processing plant was commissioned in 2015 with more than 11 KMt/year of capacity to produce mixed rare earth compounds from monazite concentrates.

India's monazite resources in heavy mineral sands deposits were estimated to be 12.5 MMt of monazite. The distribution by state was Andhra Pradesh (3.69 MMt); Tamil Nadu (2.46 MMt); Odisha (3.06 MMt); Kerala (1.84 MMt); West Bengal (1.2 MMt); and Jharkhand (21 KMt) (Indian Bureau of Mines, 2020).

1.2.8. Madagascar

In Madagascar, monazite concentrates are a byproduct of heavy mineral sands mining operations near Fort-Dauphin that produce titanium and zirconium mineral concentrates (Rio Tinto plc, 2022). In 2018, initial shipments of mixed heavy mineral concentrates containing monazite were produced from mine tailings and exported to China. Based on the unit value of China's imports of these concentrates from Madagascar, the monazite content was estimated to be significantly less than those from other sources (Zen Innovations AG, 2023). Resource estimates for heavy mineral sands were not available at a national level. At the Tantalus ionic clay project in northern Madagascar, measured and indicated resources were 198 MMt containing 897 parts per million (177 KMt) of REO equivalent. In 2019, China Nonferrous agreed to provide engineering procurement and construction services to the project, purchase up to 3 KMt of output within 3 years of commissioning, and make future investments into the project (ISR Capital, 2019; Tantalus Rare Earths, 2014).

1.2.9. Malaysia

Historically, Malaysia produced monazite and xenotime concentrates that were recovered as a byproduct of tin and titanium–zirconium heavy mineral sands operations. In 2021, Malaysia produced and exported less

than 100 Mt of REO equivalent in mineral concentrates. In downstream processing, an additional 15.6 KMt of REO equivalent in compounds was produced from Australian mineral concentrates (Lynas Rare Earths Corp., 2022b, p. 8).

1.2.10. Russia

Russia's Lovozersky GOK produces loparite concentrates from its Karnasurt Mine in Murmansk. Loparite concentrates are further processed into mixed rare earth compounds by Solikamsk Magnesium Works. Russia's mine production of REO was estimated to have been 2.6 KMt in 2021 (U.S. Geological Survey, 2023). Russia's exports of REE compounds totaled 5.6 KMt (gross weight) in 2021 and Estonia (80%) and China (16%) were the leading destinations (Zen Innovations AG, 2023).

1.2.11. South Africa

Although South Africa has no reported mine production of rare earths, monazite concentrates are a potential byproduct from heavy-mineral sands production at the Richards Bay and Exxaro Resources mining operations. In addition to recovery from byproduct sources, feasibility studies have been completed on the Steenkampskraal project in the Western Cape province where reserves were estimated to be 605 KMt containing 14.4% (87 KMt) of REO equivalent (Liedtke, 2019). Prefeasibility studies were also started at the Phalaborwa, Glenover, and Zandkopsdrift REE projects (Frontier Rare Earths Ltd., n.d.; Galileo Resources Plc, n.d.; Rainbow Rare Earths Ltd., 2022).

1.2.12. Tanzania

No production of REE mineral concentrates have been reported for Tanzania; however, feasibility studies have been completed on the Ngualla project in southwest Tanzania. Reserves were reported to be 18.5 MMt containing 4.8% (887 KMt) REO equivalent using a 1%-REO cutoff grade. Resources were reported to be 210 MMt containing 2.15% (4.62 MMt) REO equivalent, and 93% of the resources were classified as measured and indicated (Peak Resources Ltd., 2022, p. 8, 92, 94).

1.2.13. Thailand

Thailand is known to be an intermediate processor of tin tailings and mixed HMS concentrates and produces monazite-xenotime concentrates that are then exported to China. During the period from 2010 to 2022,

production fluctuated between a low of less than 1 KMt REO equivalent in 2012, 2013, and 2015, and a high of 8.1 KMt REO equivalent in 2022. Estimates of Thailand's reserves and resources were not available (U.S. Geological Survey, 2023).

1.2.14. Vietnam

Despite limited commercial-scale mine production, Vietnam has significant reserves and resources of rare earths. Ore reserves have been estimated to be 22 MMt of REO equivalent. Notable REE deposits include Dong Pao (Lai Chau Province), Nam Xe (Lai Chau Province), and Yen Phu (Yen Bai Province). Historically, mine production from Vietnam was largely based on monazite–xenotime concentrates recovered from HMS. More recently, REEs have been recovered from ion-adsorption clay deposits. Vietnam has commercial-scale downstream capacity to produce REE metals and compounds. In 2022, Vietnam's exports of REE compounds and metals were 2.5 KMt and 4.3 KMt, respectively (Zen Innovations AG, 2023).

1.2.15. United States

Mine production of rare earths in the United States was almost entirely from bastnaesite mineral concentrates produced at Mountain Pass, CA, where mining operations were most recently recommissioned in 2018. Monazite concentrates were also produced as a separated concentrate or included as an accessory mineral in mixed HMS produced in the southeastern United States. In 2022, mine production at Mountain Pass was reported to be 42.5 KMt of REO. Reconfigured separation operations were scheduled to be recommissioned in 2023 (MP Materials Corp., 2023).

Government agencies in the United States have been partnering with industry and academia to foster domestic production and identify new byproduct recovery sources of rare earths such as coal fly ash. In 2020 and 2021, respectively, Lynas announced plans to establish light and heavy separation operations in the United States with support from the U.S. Department of Defense (Lynas Rare Earths Ltd., 2021, 2022a).

1.3. Trade

Rare earths are traded on a global basis and are contained in mineral concentrates, compounds, and metals. Global trade flows of rare earths are usually reported on a gross weight basis under selected harmonized

system (HS) and country-specific trade codes. The HS codes are common between countries to the 6-digit level. Country specific codes like the U.S. Harmonized Tariff Schedule may have up to 10 digits and add specificity for categorizing either imports or exports or both. Rare earths are also contained in numerous downstream products such as catalysts, batteries, and magnets. Downstream codes are often not specific to rare earths and it is difficult to estimate their rare earth content.

1.3.1. Mineral Concentrates

For mineral concentrates, there is not a 6-digit HS code dedicated to rare earths. However, monazite and xenotime concentrates are usually traded under the HS code 2612.20 (defined as thorium ore and concentrates). At the 8-digit code level, China Customs has a dedicated code (2530.90.20) for rare earths (defined as ores of rare earth metals).

China is the largest and one of only a few countries that has the capability to process rare earth mineral concentrates at an industrial scale. In addition to being the largest mine producer, China is the largest importer of mineral concentrates. The volume of concentrates imported into China has increased significantly in recent years rising from 12 KMt in 2010 to over 126 KMt in 2021. The unit value of concentrate imports into China has varied significantly by country reflecting the differences in grade and quality of source materials. In 2010, China imported 12 KMt of concentrates, and import levels remained below 10 KMt/year until 2018 when imports from the United States and Madagascar increased the volume significantly. In the 5-year period between 2018 and 2022, the United States was the leading supplier of rare earth mineral concentrates to China, accounting for more than 60% of China's imports. Madagascar supplied 23% of imports during this period and China's total volume of imports peaked in 2021 at 127 KMt (Figure 1.2).

Malaysia is the second largest importer of rare earth mineral concentrates. Malaysia's production of REO compounds in Kuantan is sourced entirely from imports of mineral concentrates from Australia. The Mount Weld mineral concentrate operations were commissioned in 2011 and exports to Malaysia began in 2012. Although these exports are mineral concentrates, they have been included under the HS code for rare earth metals (2805.30). Imports from Australia to Malaysia of 50 KMt in 2014 may include misclassified material, as this import level does not align well with the 7.2 KMt of REO production of REO compounds in Malaysia (Figure 1.3).

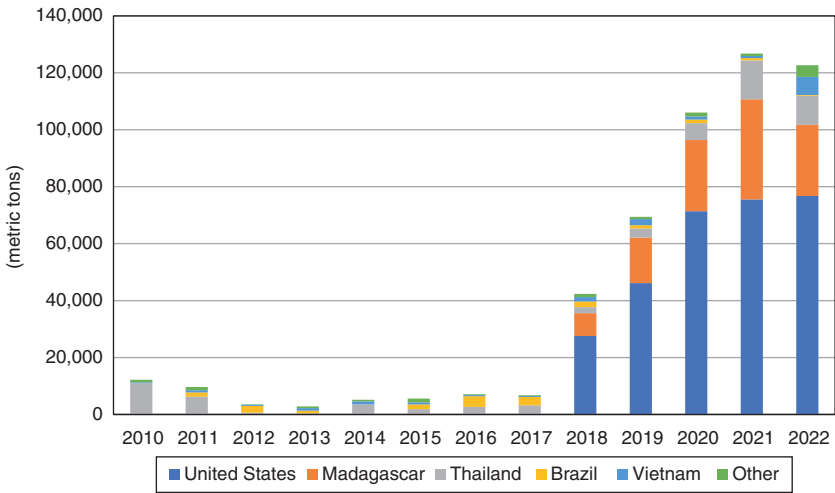


Figure 1.2 China’s imports of rare earth mineral concentrates by country of origin (metric tons, gross weight). Source: Global Trade Tracker, <https://www.globaltradetracker.com/>.

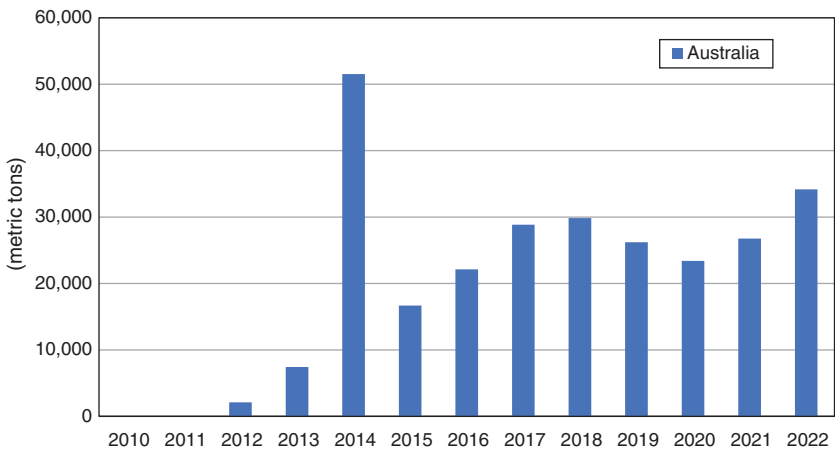


Figure 1.3 Malaysia’s imports of rare earth metals from Australia (metric tons, gross weight). Source: Global Trade Tracker, <https://www.globaltradetracker.com/>.

1.3.2. Compounds

Trades of rare earth compounds are reported on a gross weight basis under the HS code heading 2846 (defined as compounds, inorganic or organic, of rare earth metals, of yttrium or of scandium, or of mixtures of these metals). During the period from 2010 to 2021, the leading global importers of REE compounds, in descending order of gross weight, include China, Japan, United States, Germany, and Estonia. In 2016, Burma (Myanmar) emerged as a significant source of rare earth compounds supporting China's downstream processing into separated compounds and metals. Satellite imagery shows significant growth in the mining of ion-adsorption clays in Kachin State, Burma (Myanmar), similar to mining operations in China's Jiangxi Province. Coinciding with increased imports of compounds, several operations in the Jiangxi Province were idled over environmental concerns in 2017 (Argus Media Group, 2020). With limited ability to separate mixed compounds, Japan, United States, and Germany imported mixed and separated compounds (primarily from China) for downstream processing into catalysts, polishing compounds, etc. Estonia imported mixed compounds primarily from Russia and the United States to support its separation and metallurgical operations in Sillamäe (Figure 1.4).

1.3.3. Metals

Imports and exports of rare earth metals are reported on a gross weight basis primarily under the HS code heading 2805.30 (defined as

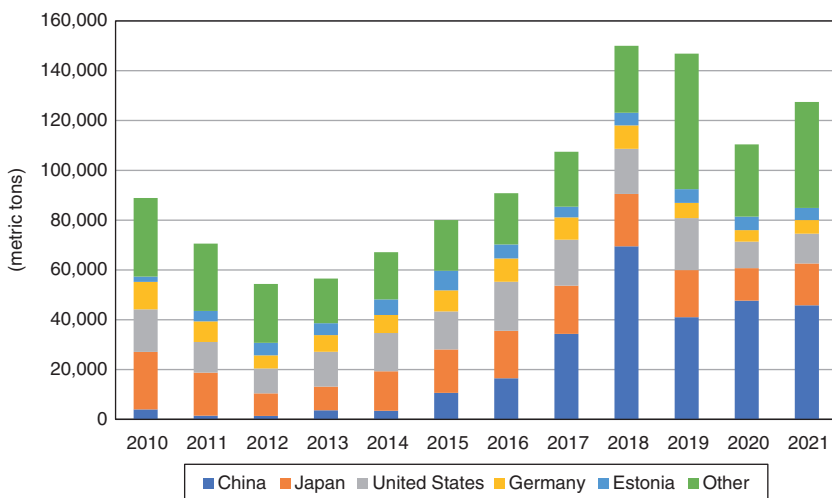


Figure 1.4 Global importers of rare earth compounds (metric tons, gross weight). Source: Global Trade Tracker, <https://www.globaltradetracker.com/>.

rare earth metals, scandium and yttrium, whether or not intermixed or interalloyed). On a gross weight basis, global trade in metals is significantly less compared with trade in compounds or concentrates. Japan was the leading importer of REE metals with about 60% of global imports. The next three countries (Norway, India, and the United States) sum to about 15% of global imports during the period from 2010 to 2021. Global trade in metals reached a high of 14.2 KMt in 2021 compared with 10.7 KMt in 2020.

In addition to trade under 2805.30, significant volumes of REE metals are contained in other ferrous and nonferrous alloys and are traded under different base metal trade codes. Tracking these can be problematic. For example, ferrocerium is traded under the HS code 3606.90 (defined as ferrocerium and other pyrophoric alloys in all forms). The REE content within this HS code varies significantly and other pyrophoric materials that do not contain REEs are included within the data. Another significant volume of rare earths is contained in finished and semifinished materials like permanent magnets (HS 8505.11 defined as permanent magnets and articles intended to become permanent magnets after magnetization). Specific HS trade codes for rare earth permanent magnets (NdFeB and SmCo) are not defined at the 6-digit level but are available with certain country-specific codes like the HTS codes for NdFeB-sintered magnets (8505.11.0070) and SmCo-sintered magnets (8505.11.0050) (Figure 1.5).

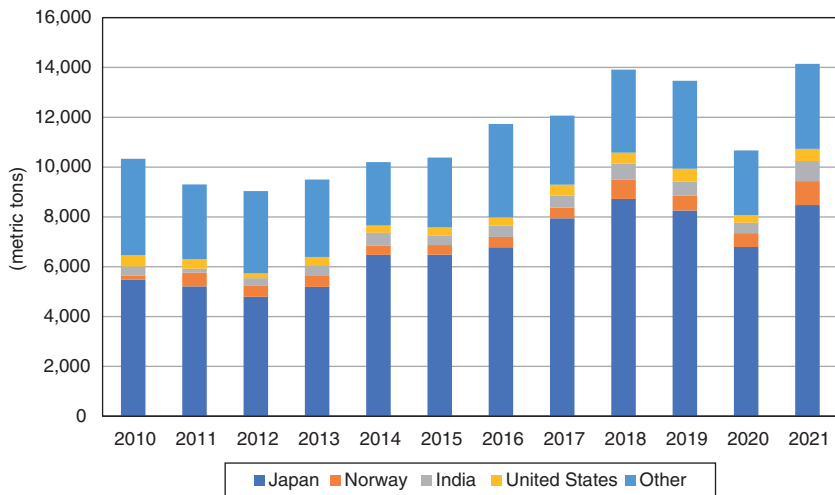


Figure 1.5 Global importers of rare earth metals. Source: Global Trade Tracker, <https://www.globaltradetracker.com/>.

1.4. Prices

Unlike base metals, rare earths are not traded on the Commodity Exchange (COMEX) or the London Metal Exchange (LME), but price data for rare earths are available from a variety of sources. For LREEs, the data are available; however, for certain HREEs that are used in niche markets, the data are unavailable or have a limited price history. For purposes of discussion, it is useful to group certain elements that are relatively close on the periodic table, are treated together during the separation processing steps, or have overlapping uses. For this review, prices are reviewed for the period 2010–2022. Thulium prices were not available and only partial data for this time period were available for gadolinium, holmium, and erbium oxides.

Several factors have contributed to price volatility for rare earth materials including political tensions, shifts in demand patterns, and supply disruptions. Concerns for the availability of rare earths rose to global attention in 2010. In July 2010, China's Ministry of Commerce announced that China would cut its exports of rare earth minerals by about 72% for 2010. Consequently, most of the 2010 quota had already been met. In September 2010, China's rare earth exports to Japan decreased dramatically following a territorial waters incident between the two countries (Grasso, 2013). By 2011, prices for rare earth materials had increased to record highs and there were widespread reports of illegal mining, processing, and exports of China's rare earths. Since 2010, prices of some REEs have experienced significant price volatility owing to shifting demand and limited availability for certain HREEs.

Growing demand for rare earth magnets have reshaped the market over the last decade. Since REEs are mined and extracted together, the supply of specific REEs related to magnet materials has outpaced demand for certain elements while being in deficit for other elements. Subsequently, prices of some materials have declined significantly over the 2010–2022 period (Argus Media Group, 2023).

1.4.1. Cerium and Lanthanum

Cerium and lanthanum are the most abundant REEs and are often used together in various applications. The applications that require the most cerium and lanthanum, by volume, include catalysts, glass additives, polishing, and metallurgical applications. These two elements also serve other diverse markets and are used in a variety of other applications such as magnets, lasers, and ceramics.

Prices for cerium and lanthanum oxides have followed very similar trends. Prior to 2007, average prices for both oxides were less than \$2/kg. China's restrictions in exports combined with other factors caused a spike in prices that peaked in 2011 at over \$100/kg for both oxides. In the following year, average prices decreased by about 77%. Excluding moderate increases in 2017 and 2018, prices have continued to decline post 2011. In 2022, the average annual prices for cerium and lanthanum oxides were about \$1.50/kg (Figure 1.6).

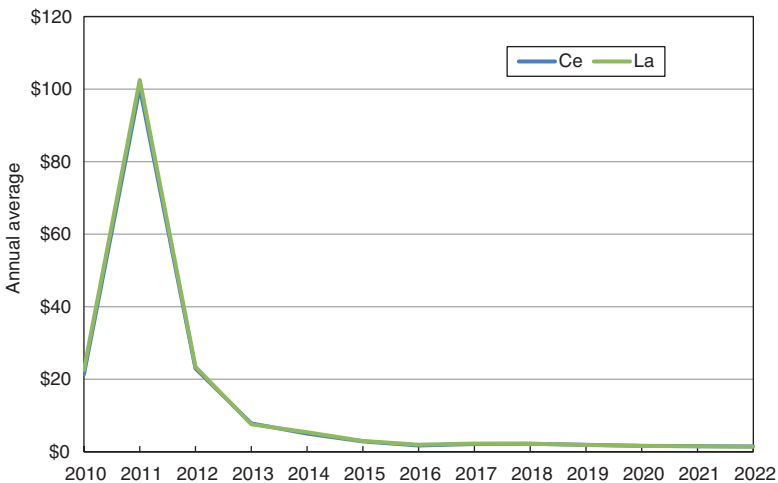


Figure 1.6 Cerium and lanthanum oxide prices in U.S. dollars per kilogram (FOB China). Source: Argus Media group (Argus Metals International), <https://metals.argusmedia.com/>.

1.4.2. Neodymium and Praseodymium

Neodymium–iron–boron (NdFeB) permanent magnets are the leading end use for both neodymium and praseodymium. Other end uses include catalysts, pigments, and other metallurgical uses typically as alloying elements. NdFeB magnets typically contain greater than 30% REE elements by weight with the majority of the REE content as neodymium and praseodymium.

Average prices for neodymium and praseodymium oxide peaked in 2011 at about \$233/kg and \$196/kg, respectively. Since 2011, fluctuations in prices have been mixed with numerous double-digit year-on-year increases and decreases. In 2022, the average prices for neodymium and praseodymium oxides significantly increased to \$134/kg and \$128/kg, respectively, from \$49/kg and \$47/kg in 2020 (Figure 1.7).

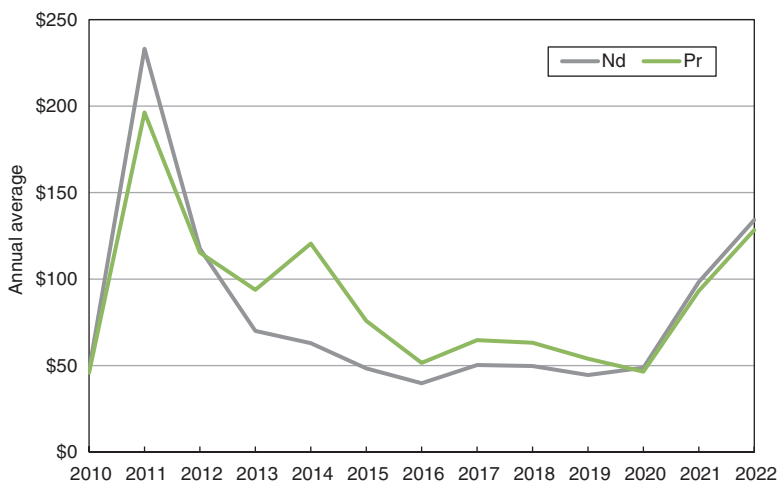


Figure 1.7 Neodymium and praseodymium oxide prices in U.S. dollars per kilogram (FOB China). Source: Argus Media group (Argus Metals International), <https://metals.argusmedia.com/>.

1.4.3. Samarium and Gadolinium

Samarium and gadolinium are used predominantly in magnetic applications. Samarium is used in samarium–cobalt (Sm–Co) permanent magnets, which have a lower energy product than neodymium magnets. Although they have a lower magnetic strength, the advantage of Sm–Co magnets over NdFeB magnets is that they are capable of being used at higher operating temperatures before they lose magnetism. In 2011, the annual average price for samarium oxide increased sixfold, compared with 2010. By 2013, the average price was less than that in 2010. Subsequently, oxide prices reached a low of less than \$2/kg in 2016 and have risen above \$3/kg in 2022.

For some grades of Sm–Co magnets, samarium is substituted with gadolinium for improved temperature stability. Gadolinium is also known for its use as a contrast agent in magnetic resonance imaging. Gadolinium oxide prices were not available prior to 2015. In 2015 the average price was about \$21/kg, and in 2022, the price had increased to \$79/kg (Figure 1.8).

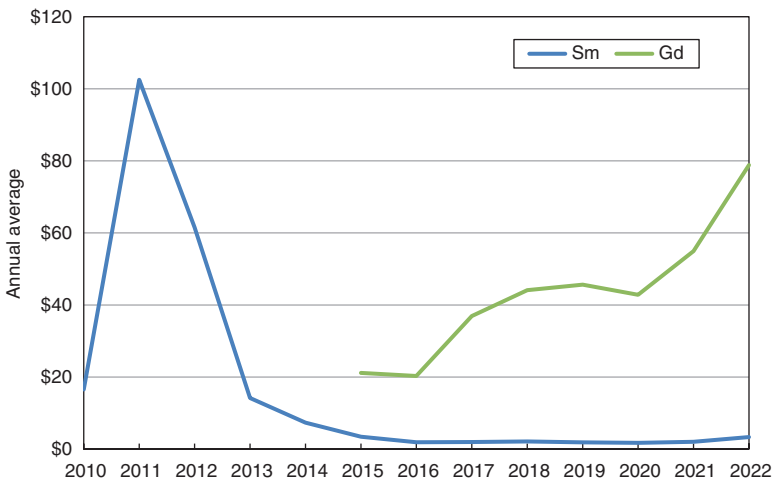


Figure 1.8 Samarium and gadolinium oxide prices in U.S. dollars per kilogram (FOB China). Source: Argus Media group (Argus Metals International), <https://metals.argusmedia.com/>.

1.4.4. Europium

Europium is known for its use in phosphor compounds used to produce red light. During the 1960s, much of production and demand for rare earths was related to REE europium and yttrium phosphor compounds used in color televisions. The transition from fluorescent lighting to solid state lighting has significantly reduced demand for these phosphors and depressed prices for europium relative to other REEs.

The annual average price for europium oxide peaked in 2011 at about \$2,900/kg and in subsequent years decreased significantly. By 2013, the average price had decreased to \$1,100/kg and had dropped to less than \$100/kg by 2016. In 2022, the price was about \$30/kg (Figure 1.9).

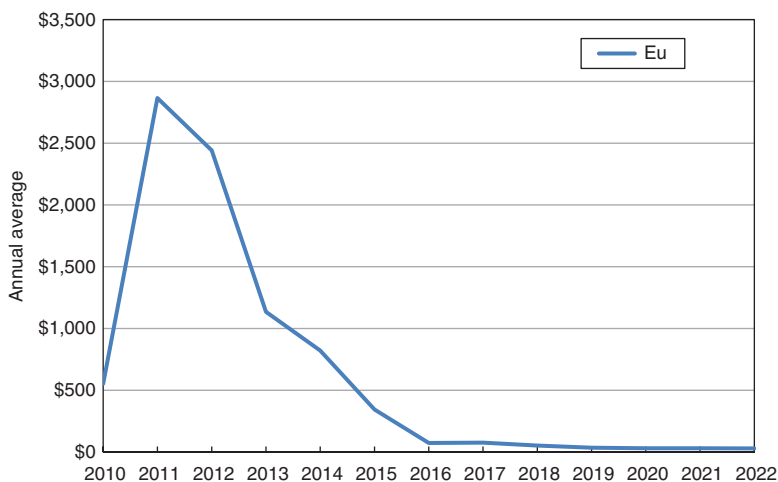


Figure 1.9 Europium oxide prices in U.S. dollars per kilogram (FOB China). Source: Argus Media group (Argus Metals International), <https://metals.argusmedia.com/>.

1.4.5. Dysprosium and Terbium

Dysprosium and terbium are HREEs that are used in NdFeB magnets to expand their thermal operating range. Terbium is also used in phosphors and in specialty alloys like Terfenol-D. Terfenol-D has the highest known magnetostriction of any alloy.

Prices for Dy and Tb peaked in 2011 at \$1,450/kg and \$2,350/kg, respectively. Prices for these materials decreased significantly following the spike in 2011. The terbium price increased significantly between 2020 and 2022 owing to limited supply of mineral concentrates high in HREEs and increased demand for magnets in transportation (Figure 1.10).

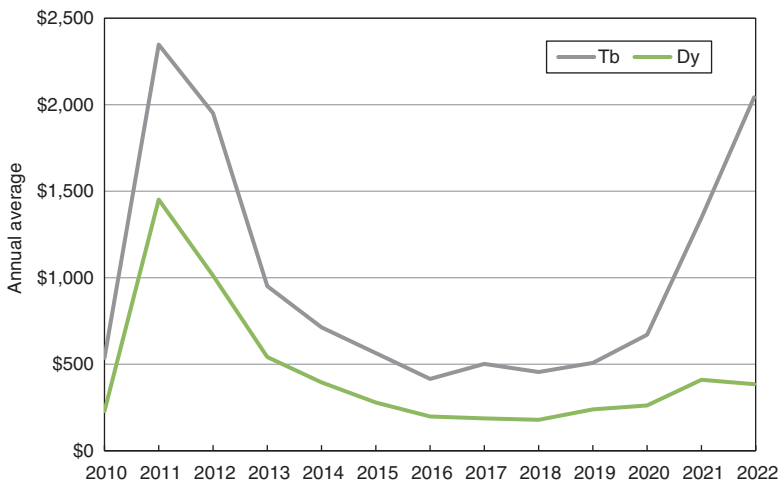


Figure 1.10 Dysprosium and terbium oxide prices in U.S. dollars per kilogram (FOB China). Source: Argus Media group (Argus Metals International), <https://metals.argusmedia.com/>.

1.4.6. Holmium and Erbium

Holmium is used in some NdFeB magnets to improve coercivity properties. Holmium is also used in phosphors and as a dopant in lasers. In the nuclear industry, holmium is used in the reactor control rods. Availability of price data for holmium began in 2020. The annual average price increased to \$179/kg in 2022 from \$66/kg in 2020.

Erbium is used for fiber optic signal amplification and as a dopant in lasers. Available price data for erbium began in 2015 at \$37/kg. Prices reached a low of \$23/kg in 2019 and a high of \$58/kg in 2022 (Figure 1.11).

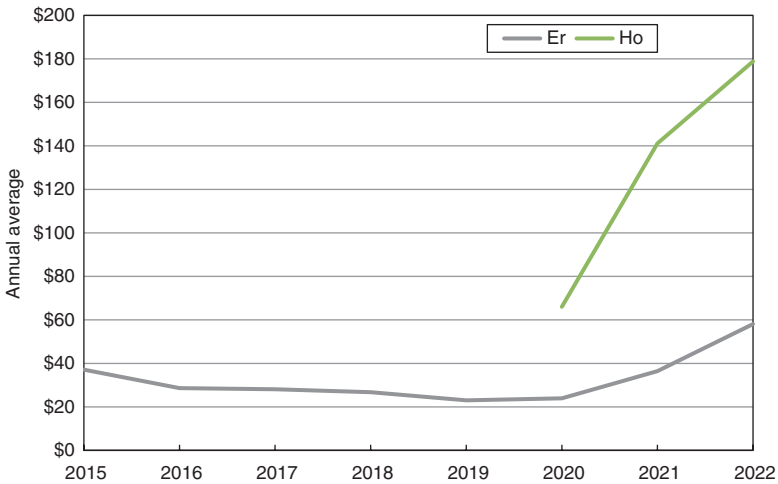


Figure 1.11 Holmium and erbium oxide prices in U.S. dollars per kilogram (FOB China). Source: Argus Media group (Argus Metals International), <https://metals.argusmedia.com/>.

1.4.7. Ytterbium

Ytterbium is similar to other HREEs in that it is used in niche technology applications such as optical fiber amplifiers, fiber optic technologies, thermal barrier coatings, and as a dopant in laser applications. Other uses include stainless steels and dental amalgams.

Prices for ytterbium oxide were not available prior to 2020. Annual average ytterbium oxide prices started at about \$15/kg in 2020 and decreased to about \$14/kg in 2022 (Figure 1.12).

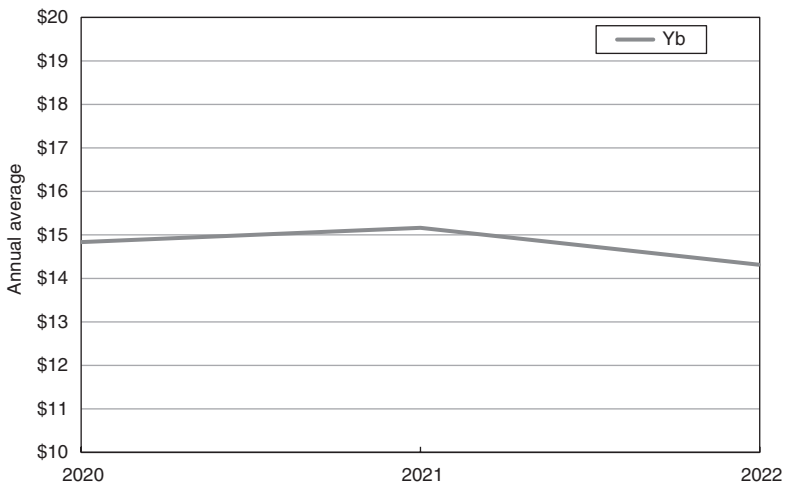


Figure 1.12 Ytterbium oxide prices in U.S. dollars per kilogram (FOB China). Source: Argus Media group (Argus Metals International), <https://metals.argusmedia.com/>.

1.4.8. Lutetium

Lutetium is the least abundant REE in the crust, with an average crustal abundance of less than 1 ppm. It is important for use in specialized applications including scintillators for medical imaging, certain electronics, and some cancer therapies.

Prices for lutetium oxide were not available prior to 2020. Annual average lutetium oxide prices started at about \$750/kg in 2020 and increased to about \$810/kg in 2021 and 2022 (Figure 1.13).

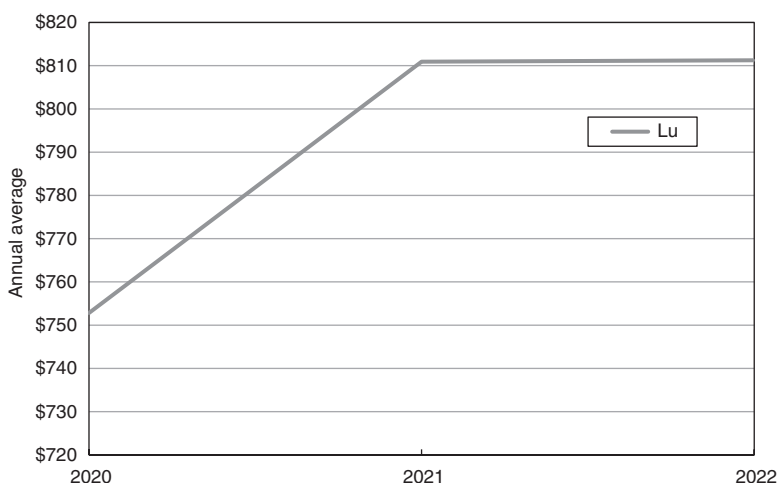


Figure 1.13 Lutetium oxide prices in U.S. dollars per kilogram (FOB China). Source: Argus Media group (Argus Metals International), <https://metals.argusmedia.com/>.

1.4.9. Yttrium

On a volume basis, yttrium is among the primary REEs used in ceramics and phosphors and has important uses in metallurgical applications such as superalloys. Yttrium oxide has been estimated to account for 87% of all the TREO in ceramics (Roskill Information Services Ltd., 2019). Similar to all REE prices, the average price of yttrium oxide peaked in 2011. In the years following 2011, the price declined precipitously reaching a low of about \$2.80/kg in 2019. In 2021, the price was about \$6.40/kg, more than double the price compared with the prior year (Figure 1.14). The rise in price in 2021 has been attributed in part to the scarcity of rare earth ores rich in yttrium (Argus Media Group, 2022b).

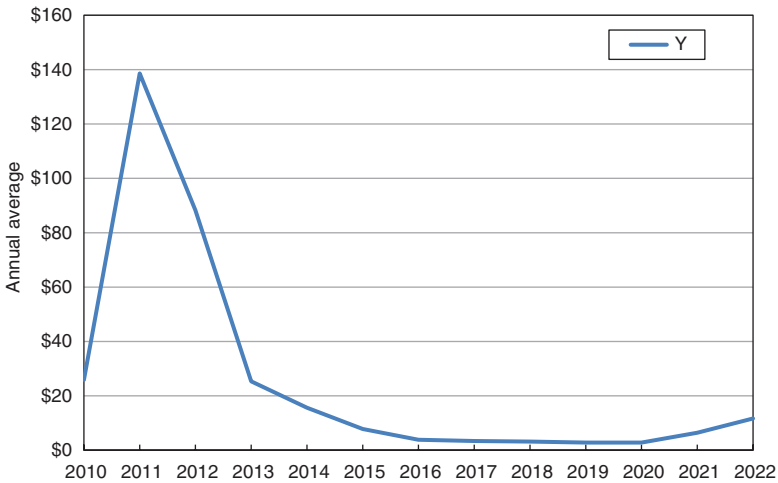


Figure 1.14 Yttrium oxide prices in U.S. dollars per kilogram (FOB China). Source: Argus Media group (Argus Metals International), <https://metals.argusmedia.com/>.

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