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TECHNICAL ASSISTANCE ON BRAZIL MINERAL RESOURCES

Rare Earth Elements – Market Analysis and Competitiveness Report

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Prepared by:
Deloitte Financial Advisory Services, LLP
1919 N. Lynn Street
Arlington, VA 22209

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Acronyms

ANM	Brazil's National Mining Agency
BMI	Benchmark Minerals Intelligence
BPA	Blanket Purchase Agreement
BOF	Basic Oxygen Furnace
CAGR	Compound Annual Growth Rate
CAPEX	Capital Expenditure
CBMM	Brazilian Metallurgy and Mining Company
CPRM	Geological Survey of Brazil
DERA	German Mineral Resources Agency
DOS	Department of State
EMGP	Energy and Mineral Governance Program
ENR	Bureau of Energy Resources
ESG	Environment, Social, and Governance
ECGA	The European Carbon and REE Association
EVs	Electric Vehicles
FOB	Free on Board
GHG	Greenhouse Gas
HREE	Heavy Rare Earth Elements
INB	Nuclear Industries of Brazil
IPT	Institute for Technological Research
IRR	Internal Rate of Return
LOM	Life of Mine
LREE	Light Rare Earth Elements
M&A	Mergers and Acquisitions
MME	Ministry of Mines and Energy
MoU	Memorandum of Understanding
NPV	Net Present Value
OEM	Original Equipment Manufacturer
PM	Permanent Magnet
PNM	National Plan for the Brazilian Mineral Sector
PPM	Parts per Million
R&D	Research and Development
RE	Rare Earth
REE	Rare Earth Elements
REO	Rare Earth Oxides
REPMs	Rare Earth Permanent Magnets
SASAC	State-owned Assets Supervision and Administration Commission

USGS	U.S. Geological Survey
VAT	Value-Added Tax
VFAC	Variable Frequency Air Conditioner
WTO	World Trade Organization

EXECUTIVE SUMMARY

Deloitte is implementing the *Government of Brazil Mining Sector Technical Support and Cooperation* Task Order (the Project) under Deloitte's Blanket Purchase Agreement (BPA) with the U.S. Department of State (DOS) in support of the Bureau of Energy Resources (ENR), Energy and Minerals Governance Program (EMGP). The Deloitte team is providing technical assistance to support the Government of Brazil's Ministry of Mines and Energy (MME) and the Geological Survey of Brazil (CPRM) as they seek to improve their ability to:

- Develop safe, sustainable, and effective mine closure procedures and use of tailings, including methods of tailings sampling and characterization, based on international leading practices, to protect and improve the legacy of ongoing and future projects, thereby realizing sustainable benefits from the extractives industry;
- Manage a growing mineral sector and compete effectively in the global market, given a growing market and accelerated demand for critical minerals that are essential to the development of innovative technologies to advance the global clean energy transition (electric vehicles [EVs], batteries, and battery storage systems, etc.); and
- Streamline the structure of Brazil's Ni-Co data inventory, so Brazil can improve its understanding and maximize development of critical minerals.

Under *Task 2A: Economic Viability and Global Market Competitiveness of Specific Minerals*, the Deloitte team will develop a series of Reports focused on (i) a high-level analysis of nine minerals including, graphite, lithium, nickel, cobalt, rare earth elements (REEs), titanium, vanadium, tantalum, and copper; and (ii) a deep-dive analysis of four minerals identified by MME and CPRM that includes graphite, lithium, nickel, and REEs. The purpose of these Reports is to provide recommendations to the Government of Brazil for where and how Brazil could compete most effectively and inform their long-term strategic planning for mineral commercialization based on global market trends and challenges to mineral resource development that may inhibit Brazil's overall market competitiveness. Deloitte's recommendations will also inform the National Plan for the Brazilian Mineral Sector (PNM 2050) and future policy actions for the Government of Brazil. This Report is focused on REEs, one of the four minerals selected by the Government of Brazil for a deep-dive market analysis.

Key Findings

- **Brazil's existing REE production is low, but the country has significant potential to expand production.** Existing production of REEs in Brazil is limited, and production currently only comes from the Buena Industrial Unit, which is a monazite operation. The mine is currently in the decommissioning phase and monazite is only recovered from tailings reprocessing. The limited scale of current production notwithstanding, according to the U.S. Geological Survey (USGS), Brazil has the third largest reserve base (21 Mt – approximately 17 percent) of REEs in the world, and Brazil's National Mining Agency (ANM) reports REE resources (measured, indicated, and inferred) at 25.0 Mt. Approximately 88 percent of these resources are in Araxá in Minas Gerais, where there is potential to extract REE from new and existing niobium mining operations. At present, Brazil has two advanced REE projects in development – Serra Verde (expected to commence production in 2022) and Morro do Ferro (at the pre-feasibility stage). There is also one earlier-stage exploration project (Bahia) which has the potential to produce the rare earth oxides (REO) from monazite contained in marine placers. This project is being acquired by U.S.-based Energy Fuels.[1]

[1] Energy Fuels Secures Major Rare Earth Land Position in Brazil - May 19, 2022

Global REE Demand and Potential for Development in Brazil

- ***Green Uses of REE:*** *Required for clean energy technologies, including neodymium and dysprosium for wind turbine development, lasers, computer hard-drives and specialty steels.*
- ***Market Demand for REE:*** *Forecasts suggest long-term market demand and tight supply through 2030. The market consensus is also that neodymium and praseodymium are expected to experience market shortfalls toward the end of this decade, and prices are expected to rise. Increased demand for REE in renewable technology (wind turbines and EV batteries) will result in near-term REE supply constraint, that could continue mid- and long-term depending on global policy trends.*
- ***Opportunities in Brazil:*** *REEs are considered strategic minerals under Brazil's Pro-Strategic Minerals Policy[2], which is designed to streamline environmental approvals and permitting procedures to accelerate production. Brazil has the third largest reserve base of REE in the world according to USGS. Although Brazil is currently not a significant global producer of REE, production is expected to increase as two advanced REE projects come on stream – the Serra Verde project (expected to commence production in 2022) and the Morro do Ferro project (currently in the pre-feasibility stage and could come on stream over the next few years). The Bahia earlier-stage exploration project also has the potential to produce REO from monazite contained in marine placers. On May 19, 2022, U.S.-based Energy Fuels [NYSE: UUUU] announced an agreement to acquire the Bahia project. In addition, Brazil has the potential to produce REE as a by-product from an existing niobium mine in Araxá in Minas Gerais. This region has approximately 88 percent of Brazil's REE resources.*

- **Brazil has limited data available on its potential REE projects.** Deloitte evaluated potential REE operations worldwide, including in Brazil. Deloitte aggregated the production and economic details of 27 other projects (Figure 19); however, a full comparative analysis was not possible because most project details were unavailable. Accurate data on the REE market is difficult to find, given the industry's relatively small size. Much of the REE mining, and most downstream processing and consumption takes place in China, which does not make industry data readily available. Consistent availability of geological data will be crucial to generating sustainable investor interest in REE in the mid-term to long-term.
- **China dominates the REE value chain.** China currently controls 61 percent of global REE mining capacity, 86 percent of the REO processing facilities, 93 percent of the rare earth metals processing operations, and 67 percent of rare earth permanent magnet (REPM) production. The future REE market outlook is very sensitive to the level of REE mine production in China. The lack of transparent Chinese supply figures therefore creates investor uncertainty, which slows the development of new mines in locations such as Brazil and, in turn, serves to solidify the competitive position of China.

[2] Through the Pro-Strategic Minerals policy, the Government of Brazil has issued a list of specific critical minerals it aims to boost production of, and that are deemed of special interest to the country. Resolution No. 2 of June 18, 2021, defines the list of strategic minerals for the country. https://www.in.gov.br/web/dou/-/resolucao-n-2-de-18-de-junho-de-2021-327352416. Through the Pro-Strategic Minerals policy, the Government of Brazil is focusing on easing the environmental licensing process by facilitating, for example, the dialogue between the environmental agency responsible for conducting the environmental licensing process and authorities such as the managing bodies of Conservation Units, the National Indian Foundation (Funai), the National Institute for Colonization and Agrarian Reform (Incra) and the National Institute of Historic and Artistic Heritage (Iphan).

- **REE demand is expected to expand dramatically over the next decade due to the increased use of REPMs.** The REPMs are critical inputs for EVs and wind turbines, among other low-emissions energy technologies. As a result, the rate of demand growth for REPMs out to 2030 is expected to be 6 to 8 percent annually. Brazil should be able to capture upstream (mine production) market share in the extraction of REE, but the country is unlikely to capture downstream growth in REPMs without significant investment and industrial development. As such, Brazil may need to purchase REO from China, unless it develops its own REO processing industry. Figure 11 provides a simplified overview of this REO process, from the mining of REO concentrate to the production of final components.
- **The current market supply-demand balance looks to remain tight until 2030, given that few new mines are likely to come on stream (see Section 9)**. Market consensus is that neodymium and praseodymium (which are used in REPMs) will experience supply shortfalls toward the end of the decade, and prices will likely increase. Deloitte's analysis of the REE market (see Section 9) shows that from a supply perspective, few new mines will likely come on stream before 2030, and demand will likely outpace supply. Capacity expansions from the two currently operating mines in the U.S. (Mountain Pass operated by MP Minerals) and Australia (Mt. Weld operated by Lynas Rare Earths), along with prospective expansion projects elsewhere in the world, will be needed to meet demand and balance the market by 2030. If the market moves into a deficit and REO prices remain strong, as forecasters project out to 2030, this higher price environment should help to encourage further REE exploration and development, including in Brazil.

Key Recommendations

Brazil has a window of opportunity to ramp up its REE output over the next few years. The REE market is expected to be in deficit over the next decade, and if prices rise as a result (as is currently the case), the REE market could offer attractive returns for investors. The Government of Brazil should therefore look to further develop its resources and encourage investment in the longer term by:

- **Increasing access to, and circulation of, up to date REE resource data to domestic and international exploration companies to promote REE development in Brazil.** Increasing access to data may require gathering and distributing more extensive information from those regions that are considered to have significant REE potential. Legacy CPRM geological data, reports, and studies should be made more broadly available online in a range of languages. Brazil should also undertake appropriate marketing of these documents to expand their circulation and increase their impact.
- **Pursuing a faster and larger expansion of its existing REE production.** Brazil should accelerate discussions with the country's two REE proposed projects, bring forward the timing, and expand the scale of their planned operations.[3] Any expansion should satisfy economic return requirements, but the Government of Brazil could help expedite the projects by providing streamlined approvals, infrastructure support, workforce capacity building support, credit guarantees, higher capital allowances, and tax reductions, if required and appropriate.

[3] Brazil has two advanced REE projects – Serra Verde (expected to begin production in 2022) and Morro do Ferro (at the pre-feasibility stage).

- **Expediting the assessment of the potential of the Araxá region.** Brazil has the potential to produce REE as a by-product from an existing niobium mine in Araxá in Minas Gerais. The Brazilian Metallurgy and Mining Company (CBMM), a private entity, has been exploring the feasibility of producing REE from an existing niobium mine in Araxá in Minas Gerais for several years.[4] The status of this project is currently unknown, but Brazil should verify whether it can become a significant source of future REE production. Again, the project should satisfy economic return requirements, but the Government of Brazil could assist by providing credit guarantees, higher capital allowances, and tax reductions.
- **Developing downstream processing facilities to capture more of the REE value chain.** Downstream REE processing is currently concentrated in China, but Brazil could process REO concentrates as part of a strategy to develop a downstream REPM industry. Processing REO concentrates would capture more of the REE value chain, provide skilled employment, and allow Brazil to produce REPMs. These are a key input into electric motors for EVs and wind turbines, and could be part of a strategy to also develop these industries further. Brazil could begin to achieve this by building a facility to process REO concentrate to produce REE. CBMM has also been working with the Institute for Technological Research (IPT) to assess the possibility of processing REO into REPM powders.
- **Undertaking a comparative review of Brazil's exploration and mining policies versus those of other countries with REE projects.** This review should analyze whether the Government of Brazil can encourage REE exploration and mine development through legal, regulatory, and environmental, social, and governance (ESG) improvements. Such improvements may include simpler licensing and permitting processes, lower royalties, preferential tax rates, and more robust environmental policy.[5] The ultimate objective of such policy improvements should be to encourage development and stability for investors looking to develop Brazil's mineral sector as a whole, and REE specifically. The Pro-Strategic Minerals policy which focuses on simplifying the environmental licensing process by facilitating a dialogue between different environmental agencies in the country, is a right step in this direction.

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[4] CBMM is a private company and has not disclosed their expansion plans. As such access to additional information on their expansion plans is limited.

[5] Effectively mitigating and managing the environmental impact of REE projects is challenging. It is a complicated process to isolate individual REEs into nearly-pure metal oxides due to their complex physio-chemical properties. Techniques, such as dry processing (dry processing techniques include gravity methods for separation of REEs and pilot techniques such as separation from coal ash and tailings) cause less harm to the environment; though the potential to create radioactive particles (e.g., uranium and thorium) as a by-product would require strict dust control measures to mitigate exposure risks to workers and surrounding communities.

1. INTRODUCTION

1.1. Purpose of this Report

The purpose of this Report is to provide a detailed analysis of the global REE market and give an informed understanding of the current and future dynamics of the industry, potential opportunities, and possible risks associated with REE development. The Report analyzes global REE resources, supply and demand dynamics, technological and industrial drivers, current and future mineral producers and processors, and the economics of the REE market. The Report also examines Brazil's position in the context of the current REE market and its potential for the future. The analysis and recommendations in this Report can help MME and CPRM make informed decisions about future policy actions regarding Brazil's REE industry and resources.

1.2. Organization of this Report

This Report is organized into 11 main sections and five annexes:

- **Section 1: Introduction** – Presents the purpose of this Report, background on REE, and a summary of market trends and outlook for REE.
- **Section 2: Rare Earth Physical Characteristics** – Provides information on different REE types and REE uses and applications.
- **Section 3: Rare Earth Resources** – Provides information on global REE resources and reserves, as well as more country-specific data.
- **Section 4: Rare Earth Supply** – Gives an overview of the global production of REE concentrates and recent supply trends.
- **Section 5: Rare Earth Demand** – Explains global REE demand trends based on end-user markets.
- **Section 6: Rare Earth Trade and Prices** – Provides information on main features of global REE trade and presents historical pricing data for REE products.
- **Section 7: Outlook for Rare Earth Demand** – Outlines how global REE demand is expected to change in the future, given growing consumption trends in relevant end-use industries, particularly rare earth permanent magnets (REPMs).
- **Section 8: Outlook for Rare Earth Supply** – Presents how the global supply of REE must increase to meet rising demand trends. This section also examines potential production increases from existing producers and other mining projects that could potentially come on stream by 2030.
- **Section 9: Market Balance and Price Outlook** – Explains how the REE market balance is expected to remain tight out to 2030 and provides insights on how certain factors, like demand for certain REPMs and mine production, may impact this balance.
- **Section 10: Economic Competitiveness** – Summarizes production, cost, and other economic measures of 27 mining projects to benchmark and assess the economic competitiveness of the sector and exploration projects in Brazil.
- **Section 11: Conclusions and Key Recommendations** – Summarizes Deloitte's analysis of the REE market, including project financing and potential global opportunities. This section also presents key recommendations for the Government of Brazil to inform future policy actions with respect to the REE industry.
- **Annex 1** – Provides a description of typical REE deposit types.
- **Annex 2** – Provides a description of mining and beneficiation of REE.

- **Annex 3** – Provides a description of REE uses.
- **Annex 4** – Provides further information on REPMs.
- **Annex 5** – Provides a list of REE pre-feasibility projects.

1.3. Background and Context

Energy decarbonization will play a key role in meeting future global climate goals and shifting away from high-emissions fossil fuels to low-emissions energy sources. REE and other specific technologies are crucial inputs for these low-carbon energy sources. For example, REPMs are critical components in EV motors and wind turbine generators, along with other industrial uses.

Brazil has some of the largest and most diverse mineral deposits in the world, yet most of its mining sector activities are focused on traditional core commodities such as iron-ore, gold, copper, bauxite, niobium, and dimensional stones. While the production of these resources will remain valuable to global industries and markets, there is growing demand and new opportunities for REE and other critical minerals that can be found in Brazil.

Brazil is not currently a significant global producer of REE, although it holds approximately 17 percent of the world's reserves as defined by the USGS. Nevertheless, production is expected to increase going forward as two advanced REE projects come on stream – the Serra Verde project (expected to commence production in 2022) and the Morro do Ferro project (currently in the pre-feasibility stage and could come on stream over the next few years).

In addition, Brazil has the potential to produce REE as a by-product from an existing niobium mine in Araxá in Minas Gerais. This region holds 88 percent of Brazilian REE reserves and, if economically viable, could become a major source of production. REEs are considered strategic minerals under Brazil's Pro-Strategic Minerals Policy, which is designed to streamline approvals and permitting procedures to accelerate production and could allow Brazil to become a significant producer of REE in the future.

1.4. Summary of Market Trends and Outlook for REE

Given the industry's relatively small size, accurate data on the REE market is difficult to find. Much of the REE mining, and most of the processing, and consumption takes place in China, which does not make industry data readily available. Even when REE data is reported, it can vary significantly among sources because types of REE products (mixed rare earth carbonates, oxides, or metals) are often misidentified in trade data or aggregated by product groups.

1.4.1 REE Resources

China has the world's largest REE reserves[6] (35 percent), followed by Vietnam (18 percent), Brazil (17 percent), and Russia (17 percent), according to the USGS. REE reserves and resources are usually reported as REO which is the commonly used form of refined REE.

The grade of an REE deposit, however, may not always be a useful indicator of its economic viability. Some higher-grade deposits may have characteristics that require expensive means of extraction or are technologically unfeasible to produce. Alternatively, some lower-grade deposits (such as some Chinese clay deposits) may have characteristics that facilitate REE extraction, resulting in an economically viable deposit.

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[6] Reserves refer to the amount of REE that could be economically extracted or produced at the time of determination, defined by a high level of mineral exploration and confidence. Resources are the amount of REE that could *potentially* be economically extracted based on geological evidence, but have a lower level of exploration and confidence.

China also has the largest REE resources, possessing hard rock, placer, and ion adsorption clay deposits. The deposits in Inner Mongolia Autonomous Region of China and the Sichuan province mostly contain light rare earth elements (LREE) from bastnäsite ores. The REE-bearing ion-adsorption clays located in various Chinese southeastern provinces mainly contain heavy rare earth elements (HREE). The Bayan Obo mine in Inner Mongolia is reported to be the largest single resource of REO in the world.

1.4.2 REE Supply and Demand

According to the USGS, global REO production was approximately 277 kt in 2021. REE production is dominated by China. Chinese REE production, which accounted for 61 percent of mine output, is the largest, followed by the U.S. (16 percent), Burma (9 percent), Australia (eight percent), and Thailand (three percent). As noted in the background section of this Report, Brazil currently only produces minor amounts of REE from processing tailings.

REEs are used in a wide range of consumer products and are indispensable in electronic, optical, magnetic, and catalytic applications. They play a vital role in environmental protection, improving energy efficiency and enabling digital technology. The REE end-use supply chain is complex, with processes depending on the end products desired by consumers as well as the type of metals, alloys, or chemicals.

The REPMs are the most important use for REEs and are found in electrical motors and generators. In descending order, neodymium (Nd), praseodymium (Pr), dysprosium (Dy), terbium (Tb), and samarium (Sm) are the REE most important for REPMs. From 2015 to 2020, global production of REPMs increased from approximately 149.9 kt to some 217.4 kt, a compound annual growth rate (CAGR) of 7.7 percent. China is not only the largest producer of REPMs, but also the largest consumer, and net exporter. In 2020, China produced 90 percent of global supply, approximately 196.2 kt of REPMs.

China has long recognized REE as a strategic asset and has developed processing and downstream activities to manufacture REE products since the early 1990s. Since 2016, China's REE mine production and processing have been largely controlled by six enterprises, which are currently being restructured into two companies.[7] More recently, China has been reducing waste discharges, improving environmental standards, cleaning up historical environmental damage caused by REE mining and processing, and combatting illegal REE production[8].

Outside of China, there are only two significant REE mines – Mt. Weld in Australia (operated by Lynas Rare Earths) and Mountain Pass in the United States (operated by MP Minerals). There are also many smaller mines operating in Russia, Vietnam, and Burma. However, most of the operations in Vietnam and Burma are very small scale and/or artisanal and remain largely undocumented.

1.4.3 REE Trade and Prices

The REE pricing is somewhat opaque due to the industry's structure and the relatively small production volumes. The REE market is a specialty market, characterized by business-to-business trade rather than exchanges on metal markets. The REEs are produced to precise chemical and physical specifications. The REE markets have remained largely in balance and prices have been broadly stable, apart from the spike in 2011 and a strengthening in 2021.

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[7] One of the companies is China Rare Earth Group, the second company has not been formed yet.

[8] China's public policies toward rare earths, 1975-2018. Yuzhou Shen & Ruthann Moomy & Roderick G. Eggert

1.4.4 Future Market Outlook

Long-term secular demand for REPMs is the most significant driver of future REO demand, which will be strongly influenced by the rate of growth of EVs, wind turbines, and other areas of technology. Future demand growth of REEs is supported by existing technological and governmental policies, initiatives, and environmental standards. Global consumption of REPMs is forecasted to grow between 6 and 8 percent per annum out to 2030. This market will increase demand for neodymium, praseodymium, and other magnetic REO; however, since REE mining is not selective and all REEs are mined, other REOs will remain in oversupply.

From an REE supply perspective, there are few new mines likely to come on stream and most of these projects will be required to satisfy demand. Capacity increases from the two developed markets' mining operations and expansions of projects in Russia will also be important for market balance. Nevertheless, the ultimate deciding factor in achieving a balanced market could be the rate of continued growth in REE mine production in China. The future REE market outlook is very sensitive to the level of REE mine production in China. The lack of transparent Chinese supply figures therefore creates investor uncertainty, which slows the development of new mines in locations such as Brazil and, in turn, serves to solidify the competitive position of China

Research and development (R&D) efforts continue to assess ways of reducing REE consumption and improving recycling recovery. Most of the substitution possibilities have already been achieved, but recycling progress has been slow due to technological and economic issues. Deloitte does not expect any changes in these factors to be significant to the market balance out to 2030.

Although accurate data regarding the REE market is difficult to find, available information suggests that the current supply-demand balance will remain tight until 2030. The market consensus is also that neodymium and praseodymium are expected to experience market shortfalls toward the end of the decade, and prices are expected to rise.

1.4.5 Economic Competitiveness

Deloitte has collected data and analyzed information from 22 companies that have produced feasibility, pre-feasibility, and scoping study reports for the market (which is typically part of the process of developing projects). The key measures for economic competitiveness are shown in a series of charts for comparison, analysis, and discussion, where data is available (see Section 10 for more information).

Project details are not available for Serra Verde or Morro do Ferro, the most advanced REE projects in Brazil, as they are operated by private companies. As a result, Deloitte could not conduct a comparative analysis of the competitiveness of these projects. In addition, existing REE mining operations are principally located in China, where production costs are not reported. Mt. Weld (in Australia) and Mountain Pass (in the United States) are the two largest operations outside of China, but detailed cost data is not reported by either company.

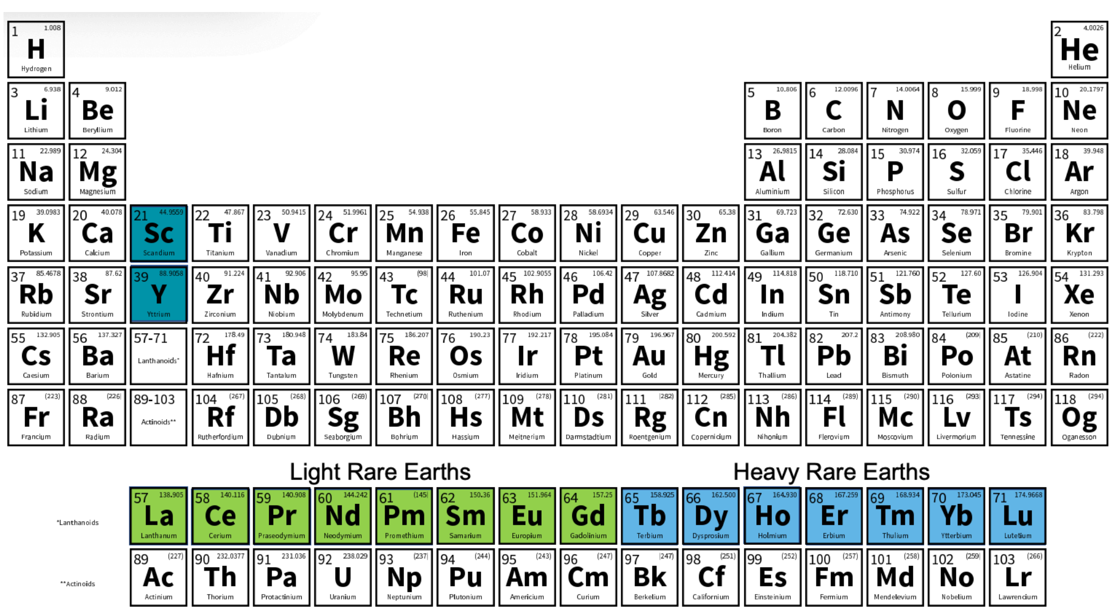
2. RARE EARTH PHYSICAL CHARACTERISTICS

The REEs are a group of metals with unique physical and chemical properties. The REE are a group of 17 chemically similar metallic elements that include 15 Lanthanides, scandium, and yttrium. The 15 Lanthanides are commonly divided into groups – lower atomic weight elements or LREE (lanthanum through to gadolinium), and the heavy rare earth elements or HREE (terbium through to lutetium and yttrium). In Figure 1, REE are highlighted in different colors on the periodic table of elements.

As refined metals, rare earths are lustrous, iron grey to silvery in appearance. While neither rare nor earth-like, REE are characteristically soft, malleable, ductile, and typically reactive. The electron structure of rare earths gives them some unusual magnetic and optical properties. The REEs have a diverse range of specific applications – they are used in the widest range of consumer products of any element group and are indispensable in electronic, optical, magnetic, and catalytic applications. In these applications, REEs play a vital role in improving energy efficiency, enabling digital technology, and limiting emissions. Many components and products containing REEs are also used for defense applications. *Annex 3 provides a full description of each REE and its uses.*

The REEs do not occur naturally as metallic elements but occur in a range of mineral types including halides, carbonates, phosphates, and silicates. Rare earths-bearing minerals generally contain most of the rare earths in varying concentrations, but individual deposits tend to be weighted towards either the LREE or HREE. The most commercially important REE deposits are associated with magmatic processes and are found in, or related to, alkaline igneous rocks and carbonates.

Figure 1: Periodic Table and the Rare Earths Elements



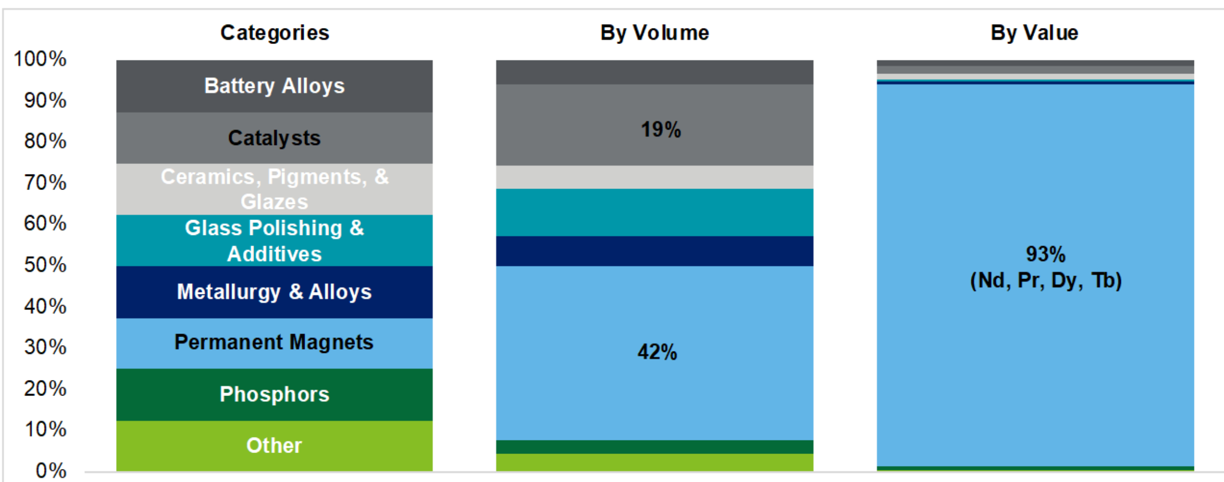
Source: Science Notes.

The REE markets are more complicated than that of other metals because they include many elements with a broad range of applications for which demand has changed over time, largely because of technological developments. Furthermore, REEs are not present in equal amounts in REE ores, due to the difference in the natural abundance of these elements. They also occur in low concentrations (grade) measured in parts per million (ppm).

However, mining can rarely select for specific elements, and all rare earths are recovered at the same time because REEs are chemically similar. The REEs are very difficult to produce economically. Their physical separation can be difficult, time consuming, costly, and environmentally challenging because the REE in a deposit may be equally distributed among silicate, carbonate, and phosphate minerals. This means that a pure 'neodymium mine' (or other REE) does not exist. Consequently, this wholesale extraction results in shortages of some rare earths and surpluses of others, depending on the demand profile of each REE. The balance between the demands of the market and the proportions of each rare earths that is mined is a concern for manufacturers and consumers of these commodities.

One of the most important areas of REE demand is to produce REPMs. The REPMs are the strongest permanent magnets available. They allow the miniaturization of products, such as motors and generators, and are used wherever space and weight are at a premium. Generally, these permanent magnets contain neodymium, praseodymium, dysprosium, and terbium. Permanent magnets containing REEs are used extensively in low-emissions technologies like wind turbines and EVs. Around 95 percent of EVs use permanent magnet traction motors because they provide the highest energy efficiency. *Annex 4 provides further information on permanent magnets.*

Figure 2: REE Categories by Volume & Value 2020



Source: Adamas Intelligence. NB A 42 percent by volume for PMs is likely to also include some cerium production.

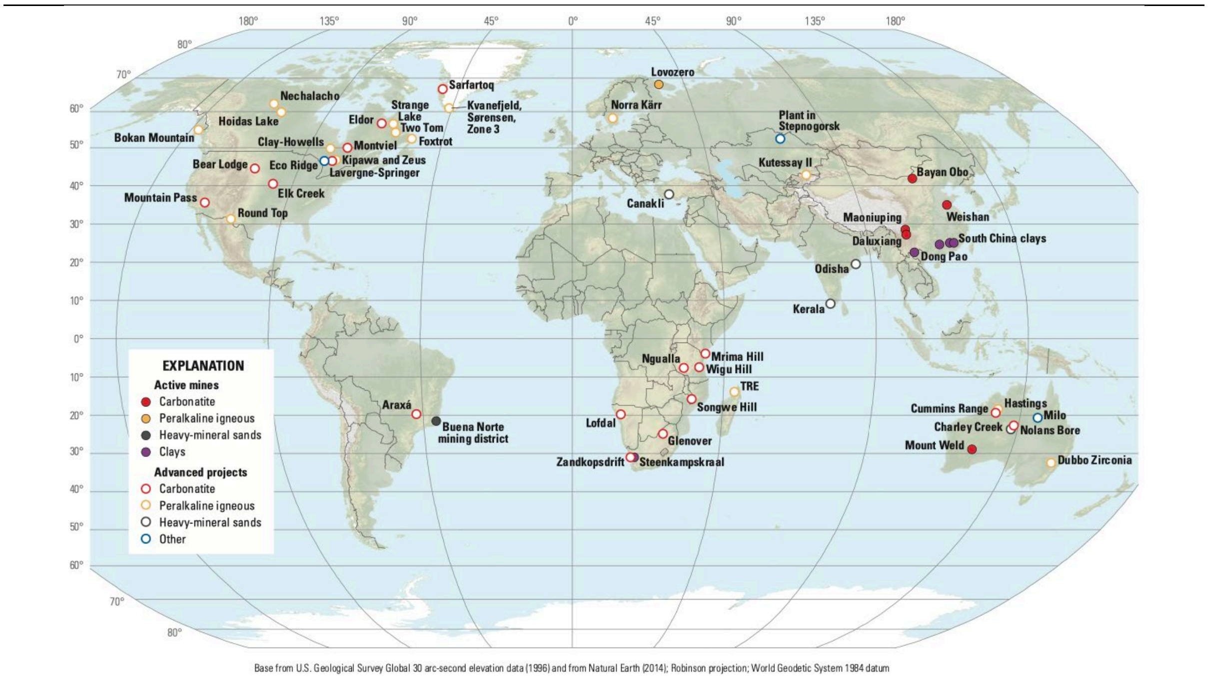
As a result, approximately 23 to 42 percent of REEs consumed are used in permanent magnets (depending on which REEs are included), which accounts for 93 percent of the industry's value (see Figure 2 above). The REE substitutes are available in some applications, but they tend to be less effective. The main 'magnet' REEs are also not easily substituted.

REEs are essential materials for the world's economy and for advancing climate policy. Given China's dominance at the mined and processing stage of production, REE are considered critical minerals by Europe, Japan, the United States, and other countries. In China, the REE value chain is viewed as a highly strategic asset to secure a growing market share in major downstream industrial ecosystems. The largest REE mining and processing companies are state-owned and are sustained by various direct and indirect state subsidies. This means that there is limited supply-chain diversification and resilience against supply shocks.

3. RARE EARTH RESOURCES

REEs are relatively abundant in the Earth's crust, but minable concentrations are less common than other mineral commodities and found in specific geographic areas (see Figure 3). The REE-bearing mineral deposits occur in a diverse range of igneous, sedimentary, and metamorphic rock types. At least 245 individual REE-bearing minerals are recognized; they are mainly carbonates (fluorocarbonates and hydroxylcarbonates), oxides, silicates, and phosphates. However, the majority of economic REE resources are associated with just three minerals – bastnäsite (fluorocarbonate), monazite (phosphate), and xenotime (phosphate). The distribution of REE in mineral deposits is controlled by rock-forming and/or hydrothermal processes, which include enrichment in magmatic or hydrothermal fluids, separation into mineral phases, and precipitation (Figure 4 shows the breakdown of REE orebody types). The REE ores may be radioactive due to concentrations of thorium and uranium. If the ores are highly radioactive, mining companies must treat radioactivity.

Figure 3: Global REE Deposits 2017



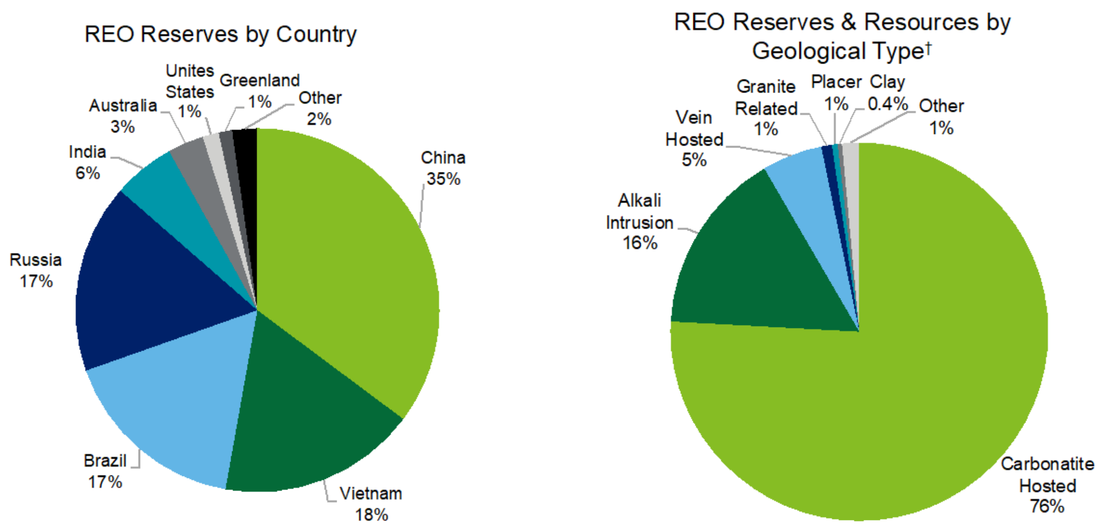
Source: USGS.

Subsequent weathering, and other surface processes, can cause a redistribution and concentration of REE deposits. However, the environments in which the REE become economically concentrated can be broadly divided into two categories: (i) primary deposits associated with igneous and hydrothermal processes (for example, those associated with carbonatites and alkaline igneous rocks); and (ii) secondary deposits formed by sedimentary processes and weathering (such as ion-adsorption clays and placers). *Annex 1 provides more detail on the principal types of deposits.*

Figure 4 shows the breakdown of REE orebody types based on S&P Global Intelligence and company reports for 62 mines and projects where reserves and resources are publicly available. Carbonatite intrusions account for 76 percent of those reserves and resources, with the Bayan Obo mine in China accounting for 48 percent (the REE enrichment mechanism and genesis of this deposit remain intensely debated), while alkali intrusions account for 16 percent of the total.

The sections that follow will provide more information on the REE reserves and resources available worldwide, with special focus given to China, Brazil, Russia, and Vietnam.

Figure 4: Global Reserves & Resources of REO



Source: USGS 2022. †S&P Global Intelligence reserves & resources.

3.1. Global REE Resources

China has the world's largest REE reserves (35 percent), followed by Vietnam (18 percent), Brazil (17 percent) and Russia (17 percent). Figure 4 shows this breakdown, based on data from the USGS.[9] However, an accurate figure for global rare earths resources is difficult to establish due to the quality and availability of data.

Table 1 shows both REE reserves (i.e., the amount of REE that could be economically extracted or produced at the time of determination, defined by a high level of mineral exploration) and resources (i.e., the amount of REE in or on the earth's crust that could *potentially* be economically extracted based on geological evidence, but have a lower level of exploration). The resources of REE are usually reported as REO, a commonly used form of refined REE. The S&P Global Intelligence data comprises REO reserves and resources from mines and projects where data is publicly available.

The grade of an REE deposit may not always be a useful indicator of economic viability. Some higher-grade deposits have characteristics that require expensive means of extraction or are technologically unfeasible to produce. Alternatively, lower-grade deposits (such as some Chinese clay deposits) may have characteristics that facilitate REE extraction, resulting in an economically viable deposit.

[9] The USGS derives national information on reserves from a variety of sources. These sources include comprehensive evaluations, as well as national reserves estimates compiled by countries, academic articles, company reports, presentations by company representatives, and trade journal articles.

Table 1: Global REE Reserves and Resources Based on Reported Data

Country	USGS Reserves Mt cont. REO	S&P Global Reserves Mt cont. REE	S&P Global Reserve Grade % REE*	S&P Global Resources Mt cont. REE
China	44.00	58.74	2.56	0.14
Vietnam	22.00	10.80	5.36	0.02
Brazil	21.00	0.15	N/A	1.19
Russia	21.00	1.66	14.56	4.64
India	6.90	N/A	N/A	N/A
Australia	4.00	2.82	3.76	3.75
Unites States	1.80	1.75	5.24	2.34
Greenland	1.50	1.53	1.41	10.67
Tanzania	0.89	0.89	4.79	3.73
Canada	0.83	0.33	0.96	35.54
South Africa	0.79	0.07	8.68	0.17
Angola	N/A	N/A	N/A	4.47
Kenya	N/A	N/A	N/A	6.14
Gabon	N/A	N/A	N/A	1.47
Other	0.28	N/A	N/A	2.48
Total	**124.99**	**78.73**	**2.83**	**76.61**

Source: USGS 2022, S&P Global Intelligence. * S&P Global grades only for primary lanthanides.

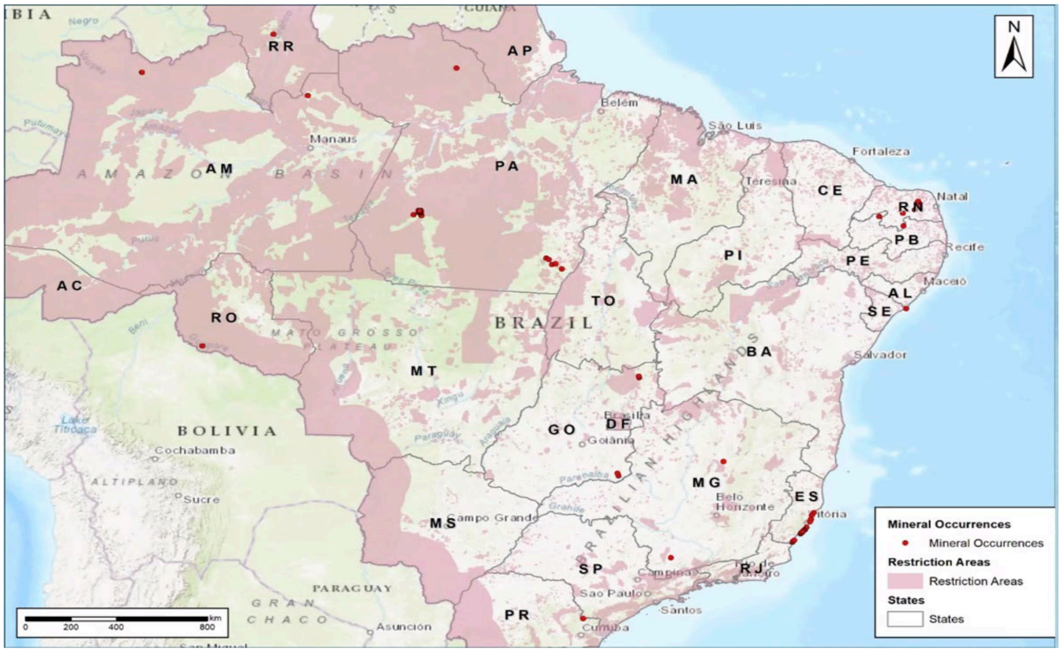
3.2. Brazilian REE Resources

In Deloitte's review of REE resources in Brazil, we found that there is limited company-reported reserve data for mines and projects. Nevertheless, the USGS and ANM in Brazil both publish data. The USGS reported REO reserves in Brazil of 21.0 Mt. The ANM reported REO resources (measured, indicated, and inferred) of 25.0 Mt in June 2021, with an average grade of 1.32 percent.

Araxá in Minas Gerais is the site of most of Brazil's REO resources – the ANM reported that 88 percent of the country's REO resources come from Araxá. Approximately 1.0 Mt of REO resource is reported at the Araxá REE project owned by Itafos [TSXV:IFOS]. This is an advanced-stage exploration project where niobium-rich laterites are being evaluated for the recovery of REE as a by-product of niobium production. Brazil is already a major niobium producer, and sources niobium from these laterite deposits in Araxá at a nearby mine operated by CBMM. These deposits are found in carbonatite intrusions hosted primarily in the mineral pyrochlore, which are several hundred meters thick and overlie the Barreiro carbonatite complex.

In 2015, CPRM published the "Avaliação Do Potencial De Terras Raras No Brasil," an evaluation report on REE potential in Brazil with the aim to improve the information and understanding of rare earth deposits in the country. The report states that there are REE mineralized alkaline complexes outside of Araxá; however, these deposits have logistical problems and legal issues while other deposits are small.

Figure 5: REE Mineral Occurrences in Brazil



Source: CPRM.

Until the early 2000s, Brazil was a producer of REE monazites from marine placers located on the Brazilian coast to the north of Rio de Janeiro in Espírito Santo state, and in the south of Bahia state (see Figure 5). In the 2015 report on REE by CPRM it stated that this marine placer type of mineralization was no longer economic because the resources are generally small and widely dispersed, have a low yield, and have a high thorium content. The extraction and processing of monazite for the recovery of REE is under state control through Indústrias Nucleares do Brasil (INB) due to uranium and thorium content. Nevertheless, in May 2022, U.S.-based Energy Fuels [NYSE:UUUU] announced an agreement to acquire the Bahia project which comprises marine placers containing heavy mineral sands (HMS - ilmenite, rutile, and zircon) and REO in the form of monazite with the aim of bringing the project to production (see 8.5 The Rare Earth Projects in Brazil).

CPRM reports that there is some potential in Brazil to recover REE from reprocessing of historical tailings and waste dumps of other former mines.

3.3. Other Significant Resources

China, Russia, and Vietnam are the other three countries with significant REE resources. China has the largest resources of REE globally, which are found in hard rock, placer, and ion-adsorption clay deposits[10]. Additionally, the Bayan Obo mine in the Inner Mongolia Autonomous Region of China is reported to be the largest single resource of REO in the world. The deposits in Inner Mongolia and the Sichuan province mostly contain LREE from bastnäsite ores. The REE-bearing ion-adsorption clays located in various southeastern provinces mainly contain HREE.

Russia has significant resources in the Kola Peninsula (Khibina and Lovozerskoye complexes) as well as extensive deposits in Sakha, Siberia. These locations share difficult terrain and weather conditions, which have historically made rare earths production challenging.

[10] USGS

Vietnam has significant REE reserves in both carbonatites and mineral sands. Vietnam's rare earths are largely concentrated in the northwestern provinces of Lào Cai and Lai Châu, bordering southern China (Table 1). The largest deposits, Mau Xe North, Mau Xe South, and Dong Pao, contain cerium, lanthanum, neodymium, praseodymium, yttrium, gadolinium, and europium. The Dong Pao deposit is the most significant, although the ore is a multi-metallic complex mineralization that is difficult to beneficiate.

4. RARE EARTH SUPPLY

According to the USGS, the global mine production of REOs was approximately 277 kt in 2021. China currently dominates the production of REEs and accounts for 61 percent of mine output, followed by the United States (16 percent), Burma (9 percent), Australia (8 percent), and Thailand (3 percent). Table 2 shows REO production by country.

Global production shares of individual REE are generally unavailable but estimated based on each mine's production and relative distribution of in-situ REO. From the 1960s until 1985, the United States was the world's largest producer of REE, with all production coming from the Mountain Pass mine in California. In the mid-1980s, China began its REE mining and extraction operations. The country subsequently became the largest contributor to global REE production and the supplier of 90 percent of processed REE metals.

The REE used in the production of permanent magnets (neodymium, praseodymium, terbium, and dysprosium) makes up approximately one quarter of the global REE production. The main producers are China (67 percent), Burma (12 percent), Australia (10 percent), and the United States (9 percent). For specific elements, market diversification can be even poorer; this is the case for dysprosium and terbium, which are sourced almost exclusively from China and Burma.

Table 2: Global REO Mine Production by Country

Country	2015 REO t	2016 REO t	2017 REO t	2018 REO t	2019 REO t	2020 REO t	2021 REO t
China*	105,000	105,000	105,000	120,000	132,000	140,000	168,000
United States	5,900	0	0	18,000	28,000	39,000	43,000
Burma	0	0	0	19,000	25,000	30,000	26,000
Australia	12,000	15,000	19,000	21,000	20,000	21,000	22,000
Thailand	760	1,600	1,300	1,000	1,900	3,600	8,000
Madagascar	0	0	0	2,000	4,000	2,800	3,200
India	1,700	1,500	1,800	2,900	2,900	2,900	2,900
Russia	2,800	2,800	2,600	2,700	2,700	2,700	2,700
Brazil	880	2,200	1,700	1,100	710	600	500
Vietnam	250	220	200	920	1,300	700	400
Others	500	300	180	690	266	400	400
Total	**129,790**	**128,620**	**131,780**	**189,310**	**218,776**	**243,700**	**277,100**

Source: USGS 2022. *Production quota only.

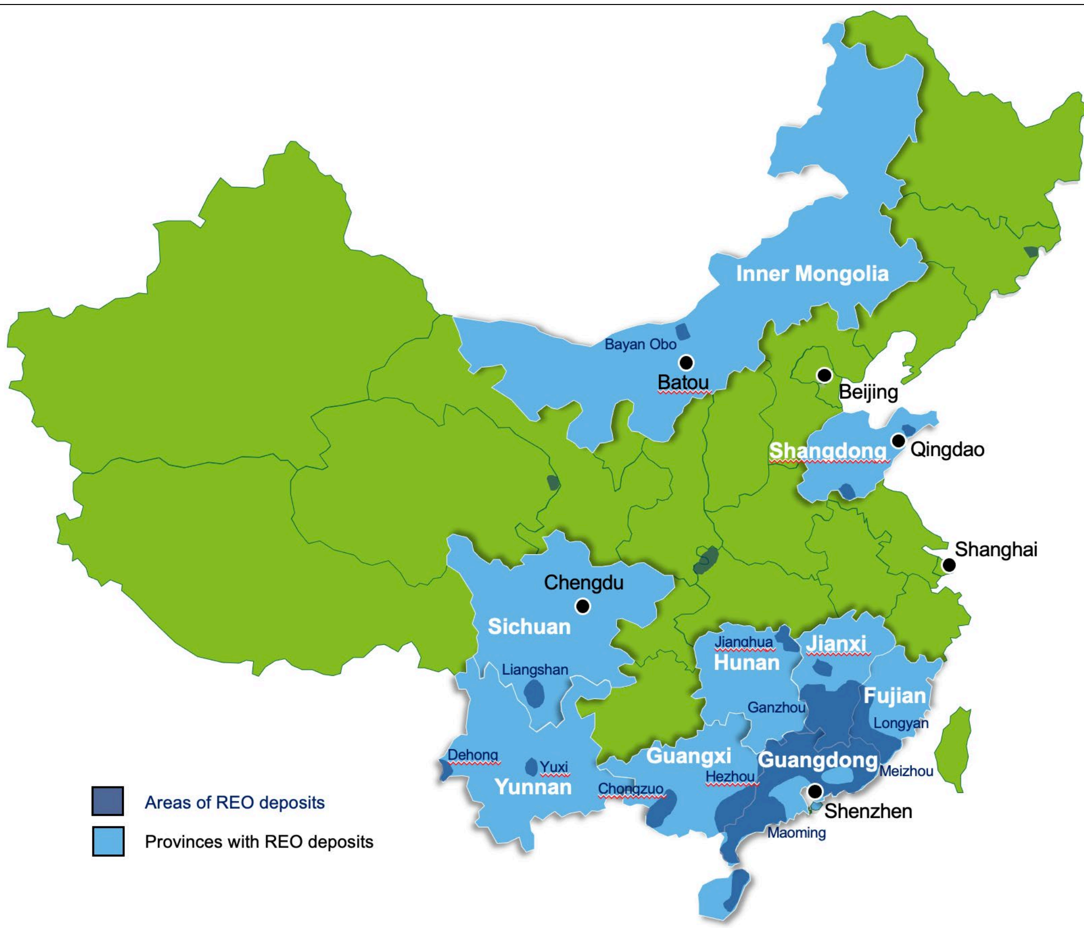
The sections that follow provide more detailed information about REE mining worldwide, with a particular focus on REE supply in China and Brazil. The sections also highlight REO processing and advances in REE recycling, which is still at an early stage of development, but could have an impact on supply, assuming favorable economic and technological advances.

4.1. REE Mining in China

In 2018, China had mining capacity of 170 kt/y and smelting capacity of 276 kt/y REO.[11] Most of China's REE deposits are in the provinces of Inner Mongolia, Sichuan, and Shandong, and within seven provinces that share borders in southern China (Jiangxi, Fujian, Guangdong, Guangxi, Hunan, and Yunnan). The deposits in the Inner Mongolia Autonomous Region of China and Sichuan contain mainly LREE from bastnäsite ores. Conversely, the deposits in the southeastern provinces are REE-bearing ion-adsorption clays which are valued for their HREE content.

China has long recognized REE as a strategic asset and has developed processing and downstream activities to manufacture REE products since the early 1990s. In 2010, China imposed export restrictions on REE and set annual quotas, which impacted production and increased prices outside of China. As a result, several countries, including Japan and the U.S., filed a dispute with the World Trade Organization (WTO) alleging the restrictions breached trade regulations. In 2015, the WTO ruled against China and mandated the removal of export quotas. China followed the ruling; however, it has since implemented several other measures to control global REE supply, including restricting mining licenses and imposing separation quotas, value-added taxes (VAT) on REE concentrate, and resource taxes. These measures allow China to control domestic production, exports, and the industry profitability.

Figure 6: Chinese REO Deposits

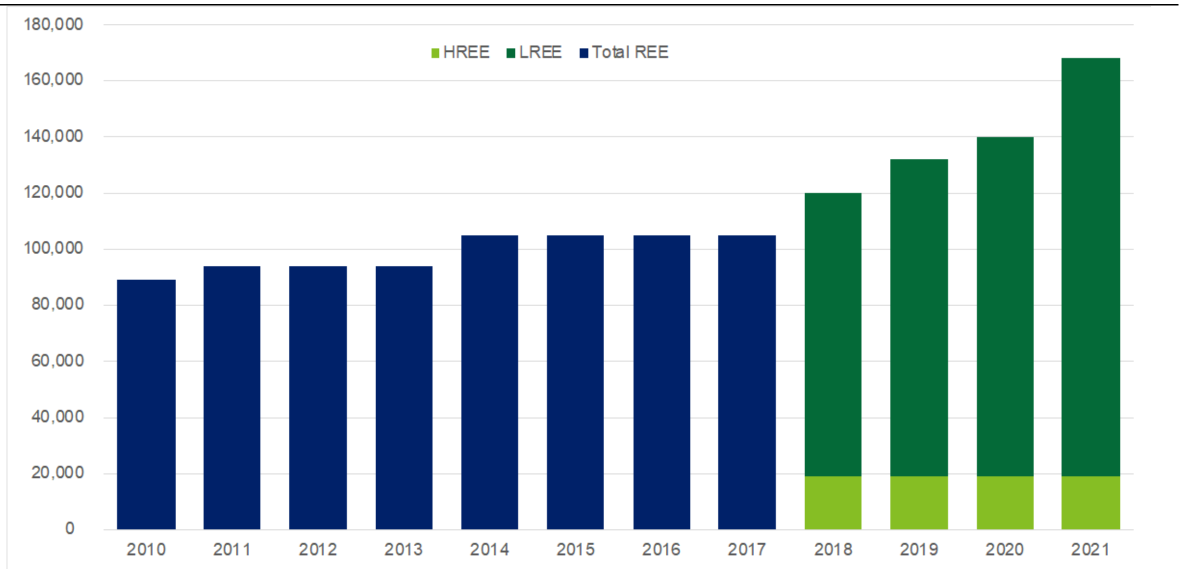


Source: Deloitte, Jost Wübbeke Berlin University.

[11] USGS Mineral Yearbook China 2018.

In response to higher demand from downstream sectors, China's separation quotas have generally risen over time. In 2021, China also raised its annual production quotas for legally produced REEs to 168 kt of REO equivalent from 140 kt the previous year (Figure 7). The domestic increase was intended to compensate for reduced production in Burma, one of the biggest REE exporters to Chinese refiners, where production and exports were restricted, amid political turmoil, following the military coup in February 2021.

Figure 7: China REO Mine Production Quotas



Source: China Ministry of Industry and Information Technology.

In 2016, China released its Rare Earth Industry Development Plan (2016–2020) and consolidated the industry into six REE conglomerates. China continued its objectives of establishing industrial order, treating environmental problems, and encouraging the downstream use of REE. China's REE mine production and processing have since been largely controlled by these six conglomerates:

- China Northern Rare Earths Group (listed - Baosteel Group 39 percent – state owned);
- Aluminum Corporation of China (Chinalco – state-owned);
- China Minmetals Rare Earth (owned by China Minmetals Corp. – state-owned);
- China Southern Rare Earth Group (owned by Ganzhou Rare Earth Group);
- Guangdong Rare Earth Industry Group; and
- Xiamen Tungsten.

These six conglomerates are state-owned and have nearly all the mining and separation quotas. The central government, through the State-owned Assets Supervision and Administration Commission (SASAC), controls three conglomerates (first three groups listed in Table 3). The dominant stockholders of the remaining three groups are either provincial or city governments. Each of the groups covers various parts of the REE supply chain but principally the upstream and midstream sectors. However, in addition to the state-owned REE groups, there are hundreds of small REE firms that are run and owned by private entities. Figure 8 shows how the six conglomerates accounted for 62 percent of REO production in China in 2021.

China now plans to consolidate these six conglomerates into just two REE producers – one in the north responsible for LREE, and one in the south responsible for HREE. In December 2021, the Chinese government announced the merger of the REE units from Chinalco, China Minmetals, Ganzhou Rare Earth Group, and two rare earth technology developers, to form the China Rare Earth Group. With this merger, the SASAC will control approximately 37 percent of China's rare earths mining and ore separation and processing capacity.

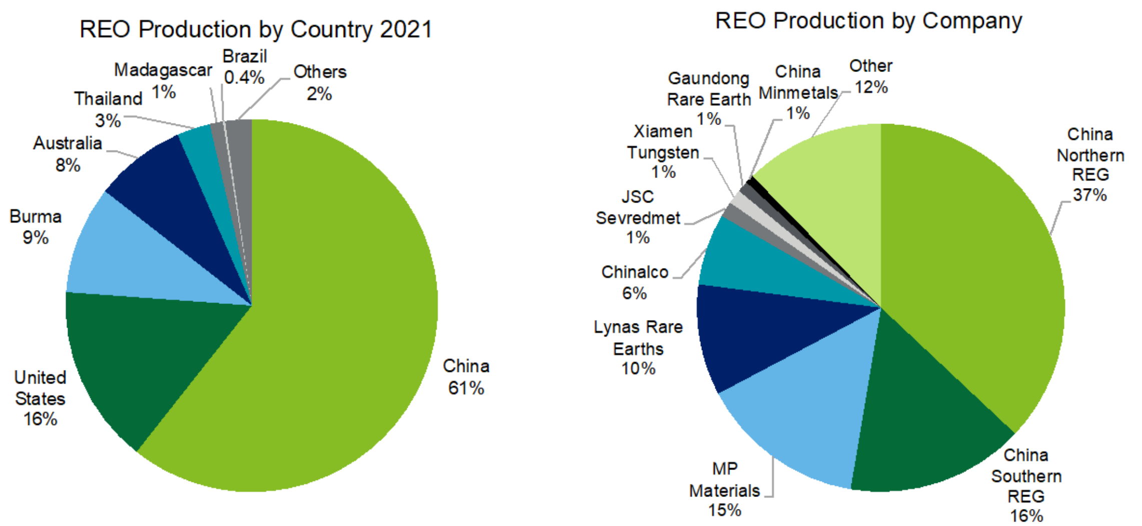
Table 3: China REO Mine & Smelter Capacity and Production Quotas 2021 (t REO)

		Capacity		Production Quota		
Company	**Headquarters**	**Mine REO**	**Smelter REO**	**Mine LREO**	**Mine HREO**	**Smelter REO**
China Northern REG	Inner Mongolia	100,000	140,000	100,350		89,634
Chinalco	Beijing	20,000	45,000	14,550	2,500	23,879
China Minmetals RE	Beijing	3,500	14,000		2,010	5,658
China Southern REG	Jianxi	40,000	42,000	33,950	8,500	28,262
Guangdong Rare Earth	Guangdong	3,000	28,000		2,700	10,604
Xiamen Tungsten	Fujian	3,000	7,000		3,440	3,963
Total		**169,500**	**276,000**	**148,500**	**19,150**	**162,000**

Source: USGS, China Ministry of Industry and Information Technology.

China has several significant rare earth mines, the most prominent of which is the Bayan Obo mine in the Inner Mongolia Autonomous Region of China. The China Northern Rare Earth Group is the operator of the processing facilities and the mine is operated by Baotou Iron & Steel. This mine has 84 percent of China's total REO reserves and produces iron ore, niobium, and bastnäsite and monazite as the main REO minerals. Recent news reports from Argus Media suggest that the Inner Mongolia Autonomous Region of China aims to raise its capacity for REE magnetic materials to 100,000 t/y by 2025, from around 45,000 t/y currently. Other significant rare earth mines in China include Daluxiang and Maoniuping in the Sichuan province.

Figure 8: Global Mine Production of REE 2021



Source: USGS 2022, China Ministry of Industry and Information Technology, company data.

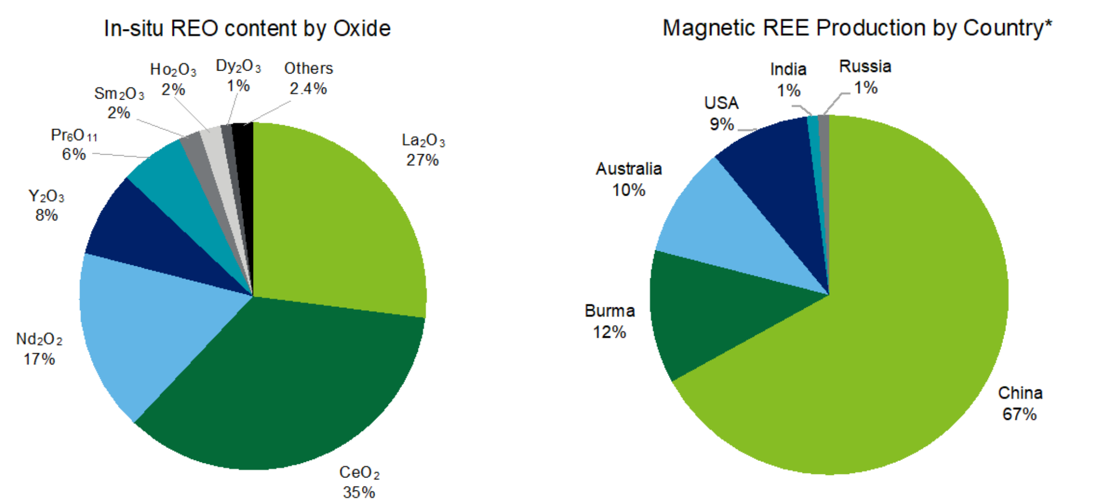
China consumes most of the REO that it mines in domestic downstream facilities. Although China has extensive REO production, it is increasingly reliant on imports from Burma (as mentioned previously), Madagascar, Australia, and the United States. However, as China borders Burma and other REE-producing countries, some miners unofficially import illegal production to China, evading environmental and social regulations as well as mining quotas.

In addition to the official Chinese production quotas shown in Table 3 it is estimated that some 30 to 50 kt/y REE has been produced from mines operating without an official license, especially in southern China. As part of its REE policy[12], the Chinese government has been trying to control the illegal mining of REE, and production from illegal mining has registered a notable decline since 2015. China has also been reducing waste discharges, improving environmental standards, and cleaning up the historical environmental damage caused by REE mining and processing (this has been particularly applicable to the ionic adsorption clay mining operations in southern China).

4.2. REE Mining Outside of China

Outside of China, there are only two significant REE mines: Mt Weld in Australia, operated by Lynas Rare Earths [ASX: LYC]; and Mountain Pass in the United States, operated by MP Minerals [NYSE:MP]. There are also many smaller mines operating in Russia, Vietnam, and Burma; however, most of the mining operations in Vietnam and Burma are very small-scale and/or artisanal and largely undocumented. Figure 8 shows REO production by country, while Figure 9 shows this breakdown by magnetic REO production.

Figure 9: REO Production by Oxide and Magnetic REO Production by Country



Source: European Commission Joint Research Centre. *Neodymium, praseodymium, dysprosium, and terbium.

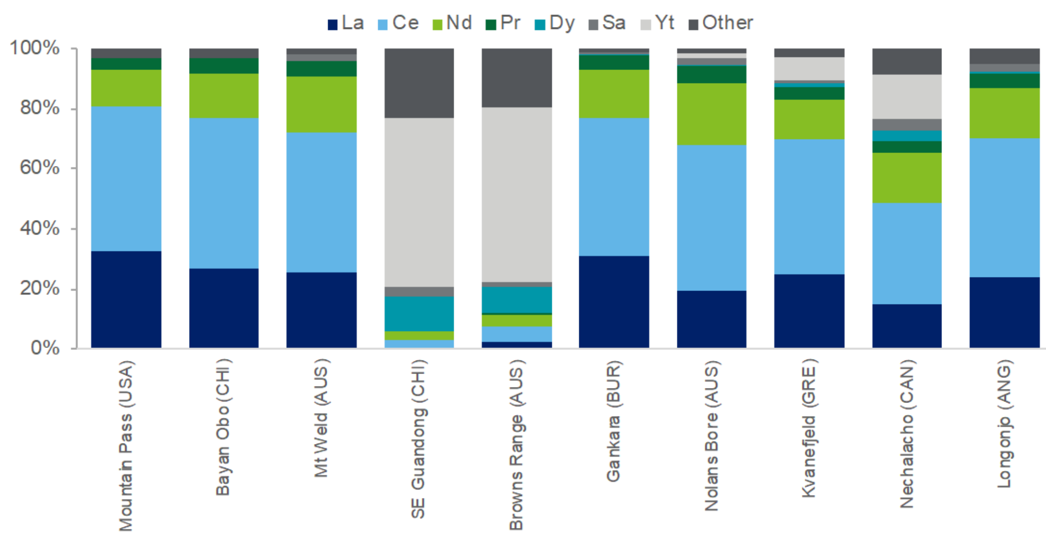
Lynas Rare Earths began production at the Mt Weld mine in Western Australia in 2011. Lynas can produce up to 26,500 t/y of REO at Mt Weld but produced 15,761 t of total REO and 5,461 t of neodymium-praseodymium (NdPr) oxide in the financial year ending in June 2021 (NdPr oxide is a primary ingredient in REPMs).

[12] China's public policies toward rare earths, 1975–2018 - Yuzhou Shen & Ruthann Moomy & Roderick G. Eggert.

At the Mt Weld mine in Australia, REEs are found in carbonatite deposits, predominantly LREE enriched. The REOs are hosted in secondary phosphate minerals, which can contain up to 60 to 70 percent REO. The REOs are also finely disseminated within various iron oxides, including cerium (47 percent), lanthanum (26 percent), neodymium (19 percent), and praseodymium (5 percent). Figure 10 provides more information on the REE content of the Mt Weld mine, as well as others.

Lynas is the largest non-Chinese supplier of refined REE products. The company operates the world's single largest REO processing plant, which is located in Malaysia. At its processing plant, Lynas produces rare earth materials to export to manufacturing markets in Asia, Europe, and the United States. The company is also the leading supplier of NdPr products to the Japanese market and the only producer of separated REO outside of China.

Figure 10: REE Content of Selected Mines and Selected Projects Globally



Source: Deloitte, company data.

The MP Materials operates the Mountain Pass REE mine and processing facility in California, which has a capacity of approximately 39,700 t/y, consisting of cerium (49 percent), lanthanum (33 percent), neodymium (12 percent), and praseodymium (4 percent). The MP Materials consortium (JHL Capital Group, QVT Financial, and Leshan Shenghe Rare Earths) purchased the mine in July 2017 from MolyCorp, which had declared bankruptcy. Operations restarted in the first quarter of 2018 after being put on care-and-maintenance status in the fourth quarter of 2015. The mine has an off-take agreement with Shenghe, which funded its restart. Mountain Pass currently produces a rare earth concentrate that is sold to Shenghe and accounts for more than 90 percent of product sales. MP Materials is currently installing a roasting circuit at the mine that will allow the company to become a low-cost producer of separated NdPr oxide (which represents most of the value contained in the ore). MP Materials expects to achieve its targeted production rates in 2023.

Aside from these two major REE mines, there are also smaller mining operators in Russia, Vietnam, and Burma. In Russia, the main REE producer is JSC Sevredmet, which operates the Lovozerskoye mine on the Kola Peninsula in Murmanskaya Oblast. The mine produces loparite mineral concentrates containing tantalum, niobium, and REE, and has the capacity to produce an estimated 3,700 t/y of REO contained in mineral concentrates. The company ships the concentrates to the Solikamsk Magnesium Plant in Permskiy Kray, from which it exports REE-bearing residues for REE recovery.

In Burma, much of the HREE mining occurs in the Kachin State, in the northern part of the country. This area is near the border with China and controlled by the Kachin Border Guard Force (BGF), a local militia group. Most of the REE concentrate produced here, which can include significant illegal mining product, is typically exported by truck to China. However, following the military coup in February 2021, friction between the local militia and government military has impeded exports to China and disrupted the supply of REE ores, concentrates, and semi-processed products between Burma and China. The conflict appeared to ease toward the end of 2021.

In Vietnam, REE mining is mostly small-scale and artisanal. In addition, producers use processing technology that is outdated, resulting in low recoveries. Dong Pao is the largest REE open pit mine and it produces 20 to 30 t/y of bastnäsite ores. Central coastal placer mines produce some 2,000 to 3,000 t/y of monazite ores for limited sale by quota. *Detailed information on general REE mining and processing can be found in Annex 2.*

In recent years, limited REE production has also come from a few prospective projects. The Browns Range pilot plant in Australia, for instance, produces heavy rare earth carbonate. Northern Minerals [ASX: NTU] has operated the plant since 2018. The Gakara project in Burundi, operated by Rainbow Rare Earths [LON: RBW], has been trial mining and processing since 2017, although operations are currently suspended.

More recently, the uranium producer Energy Fuels [TSX: EFR] has started commercially producing an REE carbonate (approximately 1,300 REO) from purchased monazite sand at its White Messa Mill in the United States. Neo Performance Materials [TSX: NEO] then processes this REE carbonate in Europe. In addition, Vital Metals [ASX: VML] is constructing an REE-extraction facility in Saskatchewan, Canada at the Nechalacho project. The company expects the first product out of the plant will occur in the first half of 2022. The REE production capacity will initially be 1,000 t/y excluding cerium.

4.3. Brazilian REE Production

Brazil has produced REO since 1946 from a variety of sources. However, REO production has been gradually declining since 2016 to a level that accounts for less than 0.5 percent of global production.

The REO production is currently concentrated in operations at the Buena mine in São Francisco do Itabapoana (Rio de Janeiro state), which is owned by the government-owned Nuclear Industries of Brazil (INB). The Buena mine has stopped all mining extraction work – since 2012, operations have focused on recovering monazite from tailings. INB oversees this operation because the ore being processed contains both uranium and thorium.

ANM reports that monazite production in Brazil totaled 600 t in 2019, 700 t in 2020, and 800 t in 2021. Based on an REO comprising 50 to 60 percent of the monazite mass, this equates to REO production of approximately 350 t in 2016, 400 t in 2020, and 450 t in 2021 (which was entirely destined for export). The USGS reports production levels for Brazil that are higher than reported by the ANM; however, small volumes of REE production are also reported from Barra do Itapirapuã in Sao Paulo, and there is also some undocumented informal production taking place in the country.

4.4. REO Processing

Processing REO into a refined product is complex. China dominates this downstream production, as well as the manufacture of most rare earth alloys and metals, and the production of high-end permanent magnets. The remaining global high-end permanent alloy (NdPr) and magnet production is conducted primarily in Japan or Japanese-owned facilities in Asia (e.g., Vietnam, Philippines, and Thailand). Figure 11 provides a simplified overview of this REO process, from the mining of REO concentrate to the production of final components.

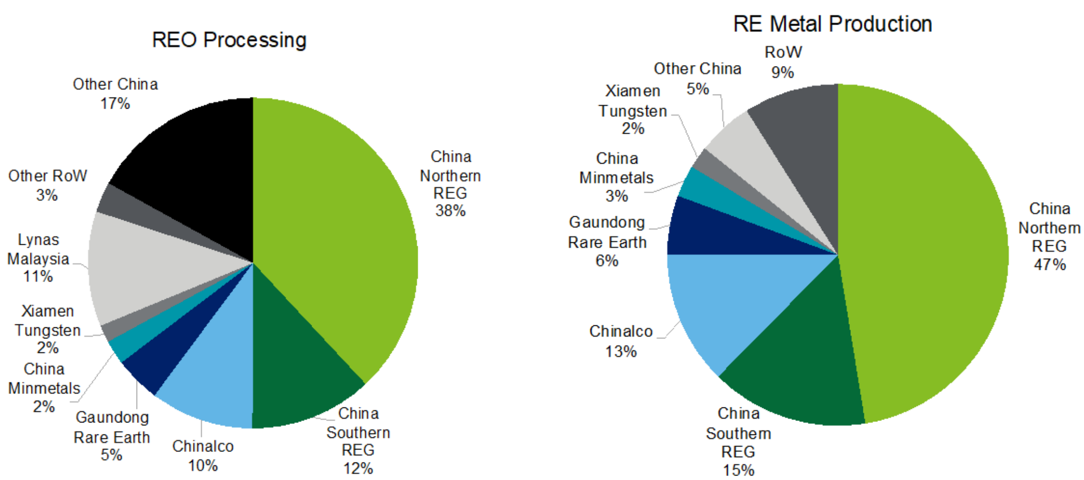
Figure 11: Steps in REO Processing

Source: Deloitte.

REO concentrates produced from the mines are transported to processing facilities that separate the different REO. From this, producers refine REO into REE metal at smelters. As with REE mining data, the information about REO processing is opaque and often unavailable. However, China is responsible for the production of 86 percent of REOs and 90 percent of rare earth metals globally. Figure 12 provides more information on REO processing and REE metal production by major companies, the majority of which are in China.

The leading export markets for China's REE are Japan, the United States, and France. However, as mentioned in Section 4.1, China uses production quotas. The supply of REE available to consumers outside of China is thereby determined by China's Ministry of Commerce (MOFCOM) and the Ministry of Industry and Information Technology.

Figure 12: Global REO Processing and REE Metal Production



Source: Rare Earth Magnets & Motors: A European Call for Action, China Ministry of Industry and Information Technology smelter quotas 2021, Deloitte estimates, company data.

A handful of companies produce rare earth metals and alloys outside of China. These companies are mostly located in Europe and the United States and include Solvay in France, Silmet in Estonia, Treibacher in Austria, Less Common Metals in the UK, and the Magnetic Materials and Alloys facility in the United States. A few Japanese firms are also involved, such as Hitachi Metals, Santoku Corp., Showa Denku, Shin-Etsu Chemical, and Nippon Yttrium.

Chinese companies are also becoming increasingly active in developing overseas REE mine production. Shenghe Resources, for instance, is a vertically integrated rare earth company based in Chengdu and listed on the Shanghai stock exchange[13] is involved in REE mining and processing as well as manufacturing rare earth alloys and other products for industrial consumers, but it has REE interests around the world. In 2013, the company signed a memorandum of understanding (MoU) with Arafura [ASX:ARU] to develop the Nolans project in Australia.

[13] Shenghe that is partially owned by China Geological Survey (19.9 percent stake) and Chinalco (2 percent stake).

In 2015, Shenghe acquired a 12 percent stake in Greenland Minerals and Energy [ASX:GGG], the owner of Greenland's Kvanefjeld project. In 2017, Shenghe became a non-voting minority shareholder in a consortium that acquired the Mountain Pass mine in California from a bankrupt Molycorp. Finally, in February 2022, Shenghe acquired a 19.9 percent interest in Peak Resources, which operates the Ngualla REE project in Tanzania. China has been very successful in concluding deals despite heightened concerns about Chinese control of REE production since 2010.

4.5. REE Recycling

The REE recycling is at an early stage of development. As a result, the market supply from recycling rare-earth magnet elements was minor in 2020 (less than 1 percent). Although recycling is set to grow by 2030, it is not projected to be a significant source of supply by 2030 and will not yet provide a substitute for raw material inputs. These low recycling rates are largely due to technological challenges, inefficient collection, and a lack of incentives. The commercialization of REE recycling will ultimately depend on REE demand and price levels, favorable economics, and technological advances.

The presence of adhesives, plastics, corrosion, and metals such as nickel, zinc, and cobalt prevent the use of pyrometallurgical routes for recycling end of life magnets. Therefore, hydrometallurgical based REE recycling is being pursued for recycling magnets. Hydrometallurgical processing is also the method commonly used to extract REEs from ores and requires a variety of chemicals.

Some firms, like Apple [NASDAQ: AAPL], have recently started to incorporate REE recycling into their supply chains. This allows the companies to create a closed-loop process and reduce industry sensitivity to supply disruption and pricing pressure from increased demand. Some wind turbine manufacturers (e.g., Goldwind and Siemens) are exploring similar actions.

5. RARE EARTH DEMAND

REEs are used in a wide range of consumer products. As previously mentioned, the characteristics of REE mean that they are important across electronic, optical, magnetic, and catalytic applications. Collectively, REEs fall into one of eight main end-use categories:

- Permanent magnets;
- Catalysts;
- Glass polishing powders and additives;
- Metallurgy and alloys;
- Battery alloys;
- Ceramics;
- Pigments and glazes;
- Phosphors; and
- Other end-uses and applications.

REPMs are the most important use for REE and are found in electrical motors and generators. Neodymium (Nd), praseodymium (Pr), dysprosium (Dy) terbium (Tb), and samarium (Sm) are the most crucial REE used to produce REPMs. The dominance of REPMs is expected to increase further with the growth of EV and renewable energy markets.

The sections that follow provide more information on key applications on REE, as well as market demand and the REE substitutions that are available in some areas. *Annex 3 provides a full list of REE and their applicable uses.*

5.1. Key Applications of REE

The REEs have several applications, ranging from EV development to steelmaking and battery production. The list below provides more information on their most common uses:

- **Permanent magnets** – Auto manufacturers use REPMs in a variety of electric motors, including drive motors for EVs as well as micro motors and sensors in vehicles. Drive motors featuring REPMs provide the benefit of lower weight, higher torque density, and improved efficiency when compared to induction motors, making them ideal for hybrid electric vehicles and plug-in EVs. Over 90 percent of EVs use REPMs, which contain neodymium, praseodymium, dysprosium, and terbium. Companies also use REPMs in consumer electronics, such as mobile phones and laptops, energy efficient appliances, and hundreds of other applications.
- **Catalysts** – Companies use cerium and lanthanum in catalytic converters of gasoline- and diesel-powered vehicles. Oil refiners also use cerium and lanthanum as fuel-cracking catalysts and additives to break down crude oil into lighter distillates, such as gasoline, diesel, and kerosene.
- **Glass polishing powders and additives** – Companies use cerium to polish optical glass, hard disk drive platters, LCD display screens, and gemstones. Cerium is also used as an additive in UV-filtering glass and container glass. Lanthanum, yttrium, and gadolinium are used to produce high-quality optical glass used in camera lenses, microscopes, and telescopes.

- **Steelmaking and alloy production** – Companies use rare-earth mischmetal (a mixture of LREE metals) for some types of steelmaking as well as ductile ironmaking. Companies also use REE to produce a variety of alloys, such as ferro-cerium, ferro-holmium, ferro-gadolinium, ferro-dysprosium, and others.
- **Batteries** – Battery makers use REE to produce anode materials for nickel-metal hydride (NiMH) batteries. The NiMH batteries are used in hybrid electric vehicles, consumer electronics, cordless power tools, and other applications of rechargeable batteries.

5.2. REE Market Demand

Finding data about REE demand is difficult – if not impossible[14] – because the REE industry is relatively small. Much of the mining, processing, and consumption also takes place in China, which does not make industry data readily available. This is further complicated by illegal production and the stockpiling of REO products and manufactured items by companies and governments. Even when REE data is reported, it can vary significantly among sources because types of REE products (mixed rare earth carbonates, oxides, or metals) are often misidentified in trade data or aggregated by product groups. For instance, Curtin-IMCOA (one source that publishes REO demand data), reports numbers qualified by a +/-25 percent accuracy.

The sections that follow present the data that was available across various sources on global REO consumption, with a special focus on REPMs and corresponding demand trends.

5.2.1 Total REO Consumption

Deloitte estimates that total REO consumption was approximately 190-210 kt in 2020 and 230-250 kt in 2021. These estimates are based on the USGS' data on REO production numbers and average REO recoveries[15], assuming no stocking. However, estimates vary. Roskill reported slightly lower total REO consumption – 148 kt in 2020.[16] Conversely, Adamas Intelligence reported higher REO production of approximately 245 kt in 2020, while CRU estimated production at approximately 207 kt. Deloitte estimates that the total REO commodity market was worth approximately $6.1 billion in 2021 using average prices for that year.

Despite the lack of precision in consumption data, market information indicates that REE consumption is increasing. In the five years prior to 2020, REE consumption grew by an estimated 3.9 percent per year. Annual growth accelerated to 5.0 percent in 2020, despite the impacts of the COVID-19 pandemic.[17]

China produces approximately 86 percent of the world's refined REO products. China also consumes approximately 70 percent of global REE products and exports around 15 percent of global output to Japan, Europe, and the United States. Outside of China, Lynas Rare Earths is the largest Chinese supplier of refined REE products. However, capacity for further refining is being developed in the United States, Australia, and Russia.

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[14] Rare Earths and the Balance Problem: How to Deal with Changing Markets? Feb 2018.

[15] Alkane Resources presentation Oct. 2017.

[16] Roskill (2021) from Australian Department of Industry, Science, Energy and Resources (2021).

[17] Outlook for Selected Critical Minerals: Australia 2021.

5.2.2 REO Consumption in REPMs

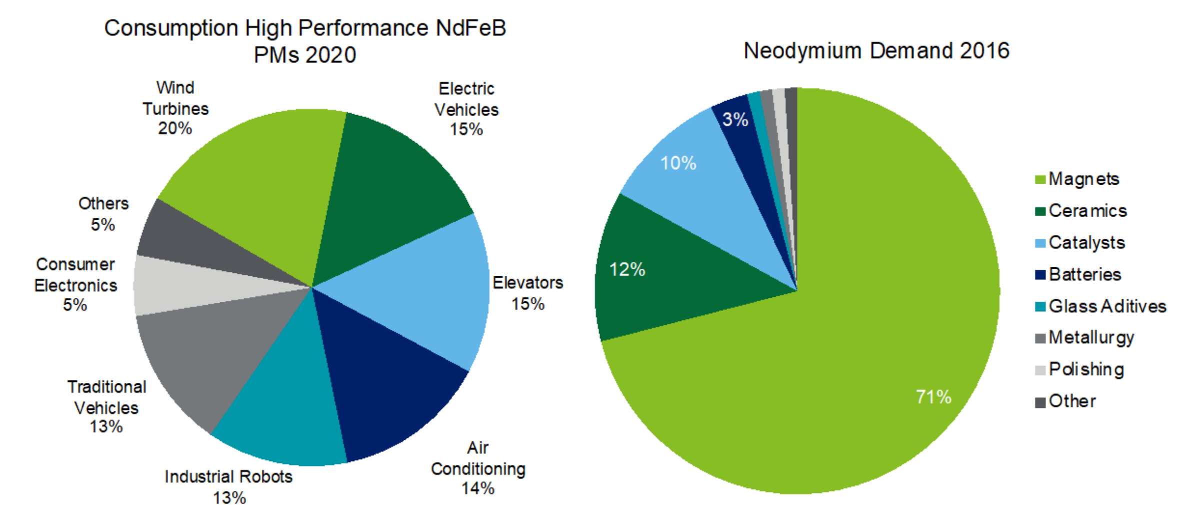
Most data sources focus on the REO consumed in REPMs because most of the value in the REE market is concentrated in magnetic REO. Magnetic REO are primarily neodymium and praseodymium oxides (usually expressed as NdPr), although some sources also include dysprosium and terbium. On average, NdPr accounts for approximately 23 percent of total REO consumption[18], with dysprosium and terbium adding a further 1.5 percent (this is both in-situ and after considering recoveries).

These numbers are significantly lower than the 42 percent reported by Adamas Intelligence for the four magnetic REE (as shown in Figure 2). This discrepancy could be due to the inclusion of some cerium production by Adamas Intelligence. When processing neodymium-iron-boron magnets (NdFeB), the main type of REPM, producers sometimes use praseodymium, gadolinium, and cerium in place of neodymium, although they generally produce weaker magnets. REO comprise 30-33 percent by weight of the main elements with NdFeB magnets.[19] *Annex 4 provides more detail on the different types of REPMs*.

The NdPr oxide tends to receive the most market focus as a magnetic REO. CRU reports NdPr oxide consumption as 47.7 kt in 2020, while Roskill data estimates 45.5 kt. Adamas Intelligence does not report consumption by type of magnetic REO and instead lists consumption of the four magnetic REO at 56.5 kt. Adamas data includes assumptions about illegal production of REO.

REPMs do not consume all the magnetic REO. For example, neodymium is also consumed in ceramics, catalysts, and batteries, as shown in Figure 13. Based on data from 2016 (current data is unavailable), Deloitte estimates that REPMs accounted for over 90 percent of neodymium consumption in 2020. Deloitte calculated this percentage by factoring in the growth for each sector for 2016 to 2020.

Figure 13: Neodymium Demand by Sector and Finished Products in the EU (2016)



Source: JL Mag Rare Earth, Frost & Sullivan – Left. Resources, Conservation, and Recycling 142 (2019) – Right.

[18] Mining and exploration company reports.

[19] Bunting Magnetics. https://e-magnetsuk.com/introduction-to-neodymium-magnets/how-neodymium-magnets-are-made/

Most countries consume REEs mainly to produce magnets. For instance, China consumes REEs primarily to produce magnets, although it also uses REE for polishing powder and catalysts, followed by battery alloys. Other countries, like Japan, also consume REE for magnet production, as well as for other applications. Due to the strategic nature of magnet metals supply, stockpiling plays an important part in planning for longer-term consumption. Japan, and more recently Germany, have sought to secure key metal supply through long-term relationships with producers outside China and have secured offtake from potential producers. Japan Oil, Gas and Metals National Corporation (JOGMEC) has a 50 percent interest in the Lofdal REE project in Namibia and has made loans to Lynas in return for secured supply of REO concentrates. Thyssenkrupp Materials Trading of Germany has secured marketing rights for Northern Minerals' Browns Range REE project.

5.2.3 Demand for REPMs

From 2015 to 2020, REPM production volume increased from approximately 149.9 kt to 217.4 kt worldwide, indicating a CAGR of 7.7 percent. China is the largest producer of REPMs as well as the largest consumer and a net exporter. In 2020, China produced 196.2 kt of REPMs, which was equal to 90 percent of global production.[20] Consumption over this period was slightly lower than supply, which indicates strategic stockpiling.

REPMs have different strengths, depending on the type and quantity of REO used. The best performing REPMs are called high-performance REPMs. In 2020, high-performance REPMs accounted for 31 percent of global REPMs. Figure 13 shows the main areas of consumption for high-performance REPMs in 2020. Moving forward, high-performance REPMs are expected to be the fastest-growing industry segment, with a CAGR of 14.7 percent expected out to 2025[21], based on demand from EVs and wind turbines. In addition, REPM producers are strongly promoting REPM technology in steel, cement, and machinery markets as it provides 20 to 40 percent energy savings. *Annex 4 provides additional information on REPM types and their technology uses.*

5.3. REE Substitution

REE substitutes are available in some applications, but they tend to be less effective. REE users have responded to supply issues and price spikes by reducing their use in non-essential applications (for instance, REE gadolinium is sometimes substituted for terbium). However, the three main REEs are not easily substituted in the production of REPMs. For applications where substitutes have been identified, the substitutes are generally other types of critical raw materials or more expensive. These include magnesium which can substitute for cerium and lanthanum in some foundry steel applications.

The EV manufacturers' high dependence on REE raises concerns given the geographical concentration of raw material and processing in China, the lack of recycling pathways, and large price fluctuations. Manufacturers use upwards of 1.0 kg of REE neodymium, praseodymium, dysprosium, and terbium per EV motor.

As a result, government agencies and firms have been looking at technologies that can reduce REE demand for several decades. In Europe, several programs have been initiated to reduce REE use across sectors. GreenSpur Renewables in the UK has developed a permanent-magnet synchronous generator that uses ferrite instead of REE. Enercon in Germany has developed a gearless design for wind turbines that does not require REE. Additionally, the EU-funded EcoSwing project seeks to replace the REPMs used in machinery with superconductors that reduce REE use by more than 95 percent.

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[20] JL Mag Rare Earth Prospectus Jan 2022, Frost & Sullivan.

[21] JL Mag Rare Earth Prospectus Jan 2022, Frost & Sullivan.

In the U.S., the National Energy Technology Laboratory is also researching the use of unconventional REE resources.[22] These include:

- Acid mine drainage and mineral mine drainage;
- Legacy impoundment materials;
- Refuse and tailings from coal preparation facilities;
- Coal-seam over- and under-burden clay and shale materials;
- Power-generation ash;
- Waters produced from carbon capture and storage and from oil and natural gas produced in brines; and
- Associated chemical wastes or waste streams.

Other institutions in the United States are also exploring potential REE substitutes. For example, the Critical Materials Institute (a U.S. DOE Energy Innovation Hub) is seeking to accelerate innovative solutions to develop resilient and secure supply chains for RE metals and other materials.[23] The University of Houston and Brookhaven National Lab are also working together to explore the capacity to produce high-temperature superconductor (HTS) magnets to replace permanent magnets used in wind turbines. At Northeastern University, researchers are also developing iron-nickel alloys that could potentially replace neodymium and dysprosium demand.[24]

The automotive industry has been a leader in finding alternatives to REPMs. The electric-induction motor developed by Tesla, as well as the wound motor crated by Renault, do not require rare earths. Additionally, the vehicle and motorcycle manufacturer, BMW, uses fewer REE in its hybrid motors by limiting REE use to certain parts of the motor.

Despite the industry's interest in developing alternative products, there are significant challenges at this early stage of research and development. These challenges include technological obstacles, higher costs, and reduced efficiency and efficacy. At present, alternatives to some products do not appear to exist within current technological capabilities.

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[22] https://netl.doe.gov

[23] https://www.ameslab.gov/cmi

[24] Rare Earths and the U.S. Electronics Sector: Supply Chain Developments and Trends, U.S. International Trade Commission June 2021.

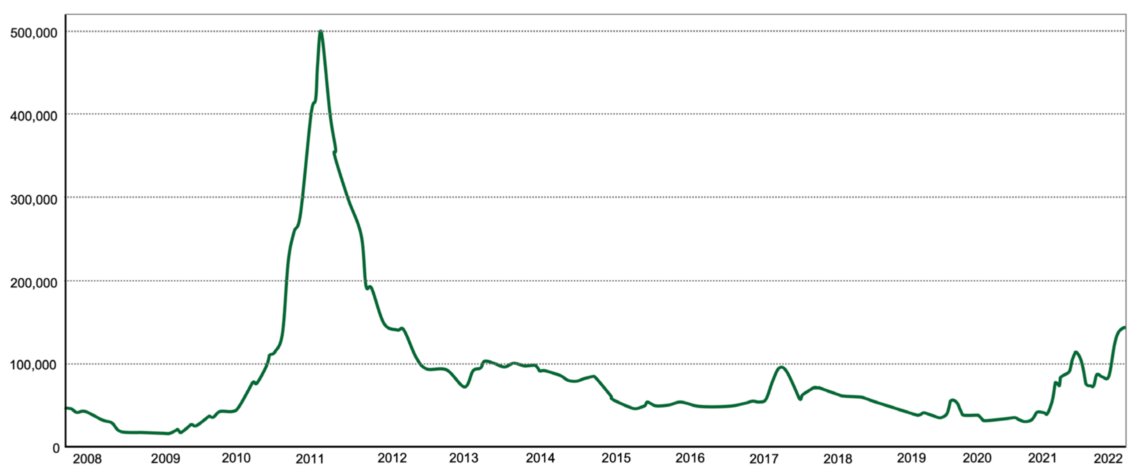
6. RARE EARTH TRADE AND PRICES

China dominates the upstream and downstream industries associated with the REE market. The country oversees about 67 percent of mined REE production and controls approximately 86 percent of REE processing. Domestically, China also carefully controls REE supply and REE separation through quotas and regulatory policies. It balances supply based on the demand for manufactured REE products, which is driven largely by the significant REPMs market.

The industry structure for REEs, combined with the relatively small volumes of production, makes REE pricing somewhat opaque. The REE market is a specialty market, and REE are produced to precise chemical and physical specifications, characterized by business-to-business trade rather than trade on metal market exchanges. However, some indicative REE prices are published by Asian Metal. Nevertheless, the use of stockpiles makes analyzing supply and demand balances difficult. Apart from the main magnetic REE, most individual REE market supply and demand balances are not closely evaluated, but most analysts believe REEs such as lanthanum and cerium are generally in constant oversupply.

Price fluctuations have historically been linked to supply shortages from major producers. For example, there was a major price spike in REEs in 2010 following a dispute between China and Japan, during which China halted its REE exports to Japan and reduced global export quotas by 40 percent. This resulted in extremely sharp price increases for REO in 2011, although demand cutbacks and some substitution resulted in REE prices returning to lower levels (see Figure 14). Several countries, including the United States and Japan, subsequently filed a dispute with the WTO alleging that China's export quotas breached trade regulations. The WTO panel ruled in favor of these countries in 2015 and China eventually relaxed the quotas the following year.

Figure 14: Long-term Price Chart for Neodymium Oxide ($/t)

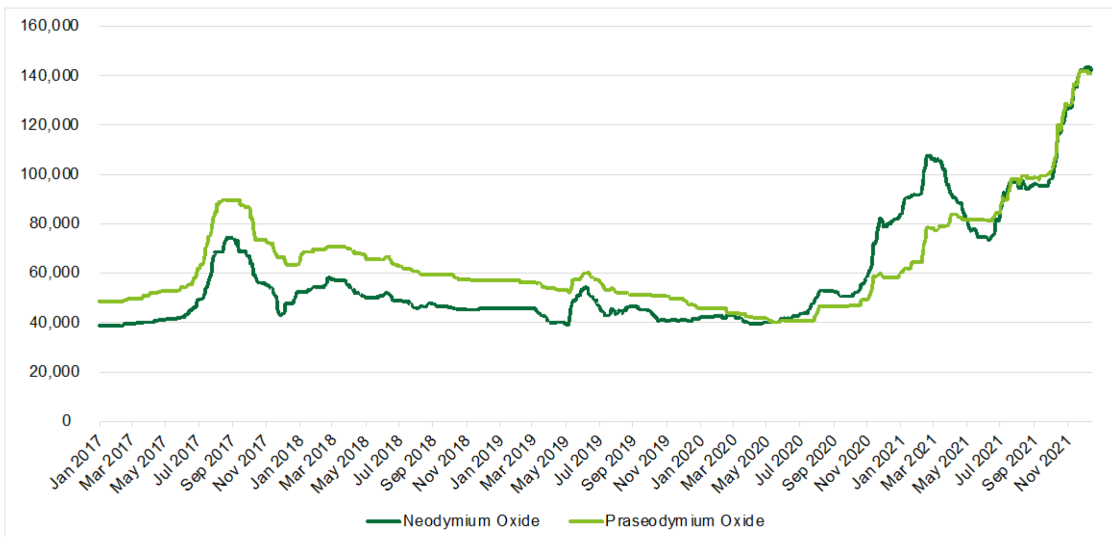


Source: Datastream, S&P Global Intelligence.

The high prices experienced in 2010-2012 prompted an investment boom in REE exploration. The Mt Weld and Mountain Pass REE mines started operations during this period; however, only a small number of new mine projects have emerged or progressed toward development since then. Table 6 provides a list of nine greenfield REE mining projects under construction or close to a final investment decision (FID).

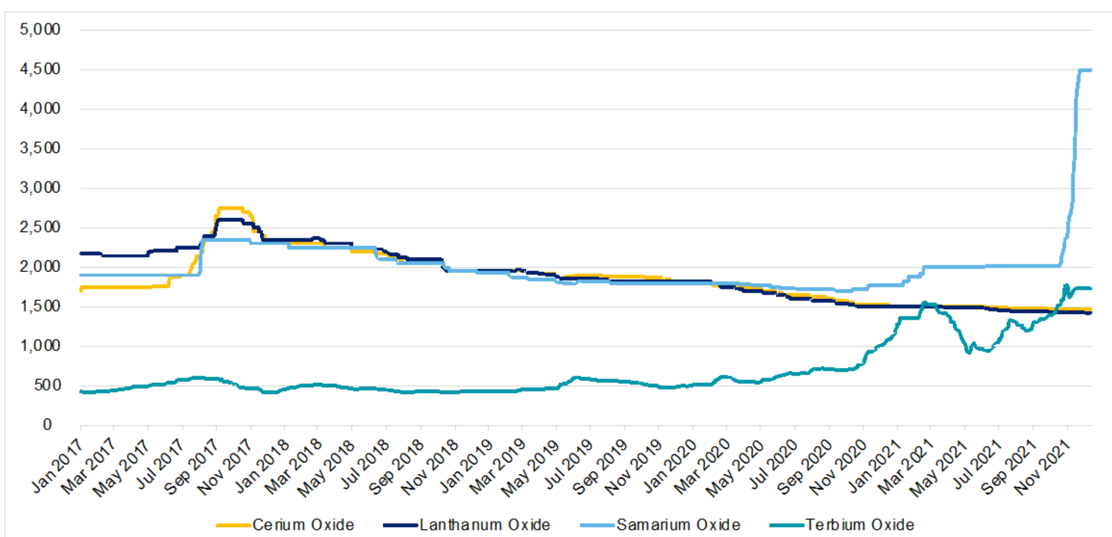
From 2015 to 2020, the REE market was in slight oversupply and prices declined. Beginning in 2021, the market started moving into deficit and prices have subsequently risen (see Figure 15 and Figure 16). Price increases are attributed to supply disruptions in Burma, supply shortages in southern China, COVID-19 supply chain disruptions, and the growing demand for REPMs.[25] The cost of inputs is also beginning to impact supply – REE production is energy-intensive, and power prices in China have risen, increasing production costs.

Figure 15: Recent Prices of Oxides of Neodymium and Praseodymium ($/t)



Source: S&P Global Intelligence. NB. FOB China.

Figure 16: Recent Prices of Oxides of Lanthanum, Cerium, Samarium and Terbium ($/t)

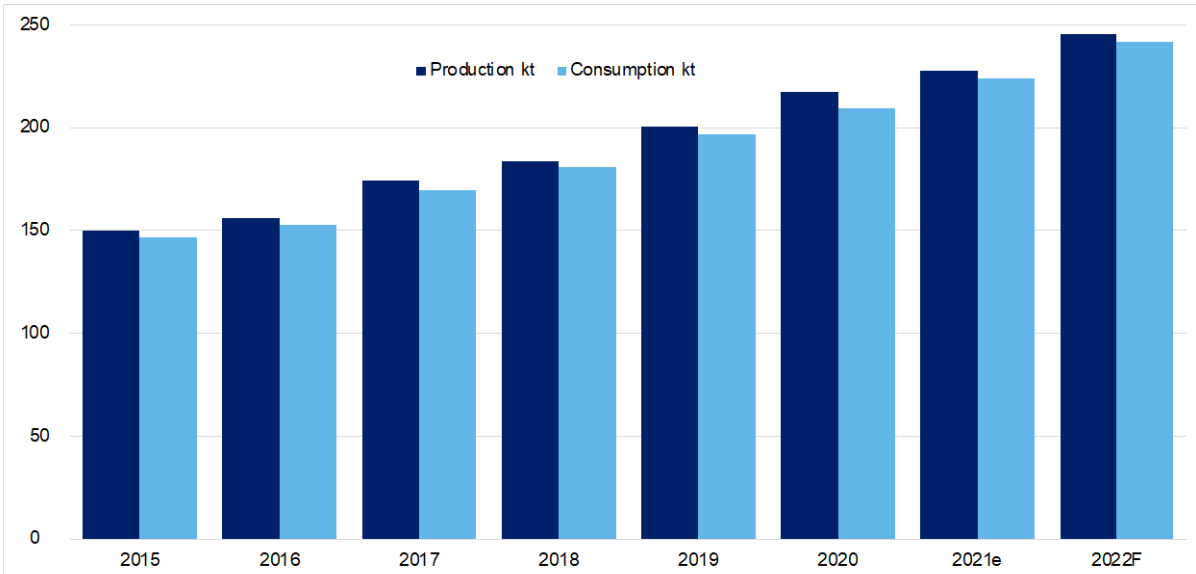


Source: S&P Global Intelligence. NB. FOB China.

[25] Lynas Rare Earths Quarterly Report Jan 2022.

Figure 15 shows how the market price for neodymium reached $140/kg at the end of 2021, marking the first time since 2011 that it reached this level. Dysprosium, terbium, and samarium prices have also been particularly strong (see Figure 16), due in part to the fact that China produces 50 percent of these REE from imported ore from Burma. In January 2022, the Chinese government increased REE mining and smelting quotas by 20 percent to reduce price levels.

Figure 17: Production and Consumption Volumes of Global REPMs (2015-2022)



Source: JL Mag Rare Earth Prospectus (Jan 2022).

Figure 17 shows how REPM global production has grown over time, based on data from JL Mag Rare Earth [300748.SZ], one of China's largest REPMs producers. The figure also shows that the global REPMs industry has been in market surplus from at least 2015 through 2021. This indicates that a degree of stockpiling has taken place in China.

7. OUTLOOK FOR RARE EARTH DEMAND

The REE demand is expected to grow strongly over the next decade and beyond. Future demand growth of REOs will be strongly influenced by the growth rate of EVs, wind turbines, and other areas of technology (see Figure 13). This will drive secular demand for REPMs. Global consumption of REPMs is forecasted to grow at 7.8 percent per annum until 2025 according to Frost and Sullivan[26], while Roskill forecasts a growth of 6.2 percent per annum until 2030, and CRU forecasts seven percent per annum growth until 2030.

Growth forecasts for NdPr oxide are relatively high, but also vary out to 2030, with some reaching up to 10.0 percent per year. Roskill data suggests an annual growth rate of approximately 6.1 percent, based on the rise in REE consumption for REPMs out to 2030 (as well as other uses).[27] CRU data indicates an annual growth rate of 8.7 percent, while Adamas Intelligence forecasts 9.5 percent. However, data sources have revised these numbers upward over the past year due to strengthening demand in the REPM market. In November 2021, Lynas Rare Earths updated its annual growth rate forecast for NdPr consumption from 7.5 percent to an average 10 percent for this reason.[28]

Table 4: NdPr Oxide Global Consumption Forecasts out to 2030

Consultant	2020E consumption tonnes	Annual growth rate	2030F consumption tonnes	NdPr Increase %	NdPr Increase tonnes
Roskill	45,500	6.1%	82,000	80%	36,500
CRU	47,700	8.7%	109,800	130%	62,100
Adamas Intelligence	56,500	9.5%	140,000	148%	83,500

Source: Roskill 2021, CRU 2021, Adamas Intelligence 2021.

As shown in Table 4, forecasts suggest that producers will have to increase output of NdPr oxide by 36.5 to 83.5 kt/y to meet demand from 2020 to 2030. Since NdPr oxide accounts for approximately 23 percent of REO total production, approximately 159 to 363 kt/y of additional REO are required by 2030. Growth rates beyond 2030 are expected to be strong but end-of-life magnet recycling is expected to begin slowing this demand growth for newly mined REE.

The sections that follow provide more information on rising demand trends for REPMs, particularly for the EV and wind turbine markets.

7.1. Future Demand Outlook for REPMs

There is a wide range of future demand scenarios for REPMs because of the underlying factors that affect the EV and wind turbine markets. Technological advancements and material optimization, as well as the political ambitions underlying their development, will impact future REE demand for EVs and wind turbines. Demand in other sectors, including for electronics and specialized equipment, will mainly be influenced by market dynamics. The following text provides a brief outlook for the two main areas of consumption for REPMs.

Annex 4 provides additional details on REPM. In addition, Deloitte will provide more information in the forthcoming report on renewable energy, EVs, and lithium-ion batteries.

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[26] Frost & Sullivan, JL Mag Rare Earth Prospectus Jan 2022

[27] Roskill (2021), Australian Department of Industry, Science, Energy, and Resources (2021)

[28] Lynas Rare Earths AGM presentation November 2021

7.1.1 Electric Vehicles

The largest use of REPMs is in electric motors. This includes drive motors in EVs as well as micro motors and sensors in vehicles. Drive motors featuring REPMs provide benefits of lower weight, higher torque density, and improved efficiency compared to induction motors, making them ideal for hybrid electric vehicles and full EVs. This means they provide faster acceleration and reduced vehicle weight. It is therefore expected that REPM motors will become the dominant EV technology.

Global EV demand has surged over the past decade, owing to the increased availability and affordability of EVs, improved brand development and recognition, and increased global attention on climate change and emissions. However, government policies remain the key driving force for global electric car markets. In November 2021, the U.S. Government announced a target of 50 percent electrification for new automobiles by 2030. In Europe, the EU Commission proposed to bring the CO_2 emission standard for new cars to zero by 2035.

As a result of these market forces, EV sales reached $6.6 million in 2021, more than tripling their market share from two years earlier and representing close to 9 percent of the global automotive market.[29] BloombergNEF forecasts passenger EV sales will increase to $14 million in 2025, reflecting a CAGR of 35 percent.[30] Electrification is also making inroads into heavier vehicles.

The strong market observed in 2021 reflects a very active year for the automotive industry, which aligned with significant commitments for expanding EV production and phasing out traditional vehicles with internal combustion engines (ICE). At least 12 automakers have declared EV fleet conversion targets for 2050 or earlier. Seven of those automakers have also committed to either stopping all ICE investment by 2030 or completely phasing out ICE vehicles by 2040.[31] This has helped strengthen consumer opinion that the future of automobiles is electric.

7.1.2 Wind Turbines

Wind power capacity has grown significantly in recent years, although this increase is expected to slow a bit due to changing market conditions in China. In 2020, 93 GW of additional wind power capacity were installed globally (of which, close to 87 GW were installed onshore), taking the cumulative wind power capacity up to 743 GW. This was a 93 percent increase in capacity growth from the previous year. For 2021, rising cost pressures started to impact the roll-out of wind projects, and the expiry of key subsidies in China meant that capacity additions fell from the 2020 record level, according to GWEC Market Intelligence. China and the United States remained the world's largest markets for new onshore additions.

GWEC Market Intelligence expects that developers will add over 469 GW of new onshore and offshore wind capacity from 2020 out to 2025, reflecting a CAGR of 10.3 percent. The CAGR for offshore wind from 2020 to 2025 is expected to be even higher at 31.5 percent. The level of annual installations for offshore wind is also expected to quadruple from 6.1 GW in 2020 to over 76 GW in 2025.

Wind power generation depends on wind-turbine technology. There are two turbine designs – direct-drive turbines and geared turbines. Direct-drive turbines have a higher reliability and are usually installed in offshore locations with higher wind and in areas with more difficult access. Geared turbines, on the other hand, are typically installed in onshore locations with lower wind speeds and easier access.

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[29] IEA commentary — 30 January 2022

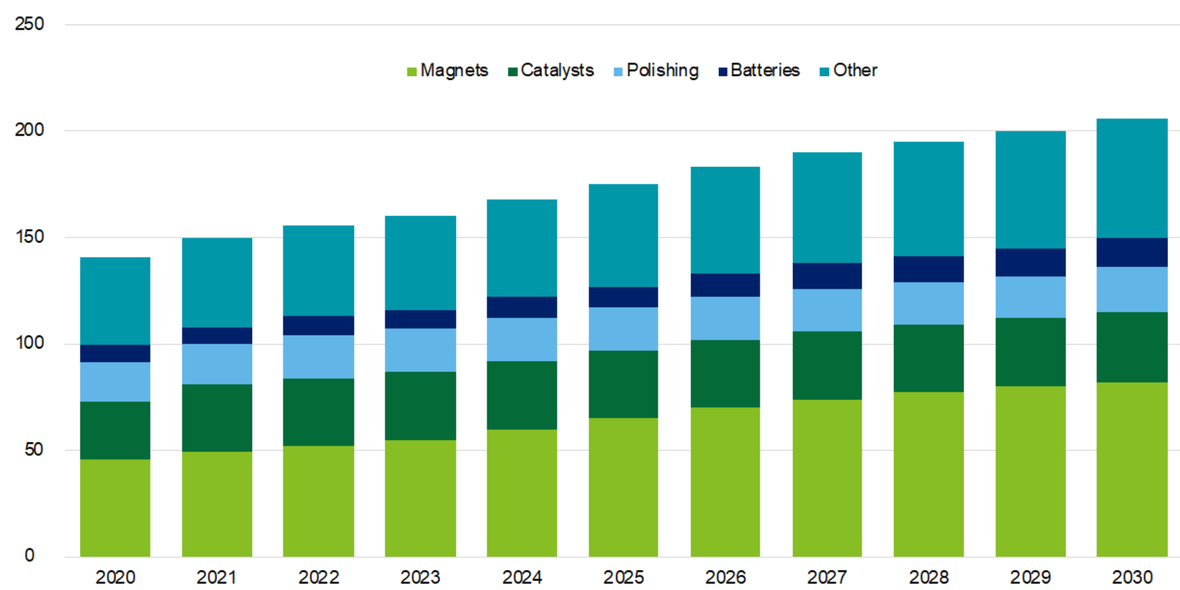
[30] Electric Vehicle Outlook 2021, BloombergNEF

[31] Electric Vehicle Outlook 2021, BloombergNEF

Many direct-drive wind turbines, along with some geared turbines, use permanent magnet generators that contain REPMs. In 2018, generators containing permanent magnets were used in approximately 76 percent of offshore wind turbines worldwide. They were used less frequently for onshore applications, where the need for powerful generators with a reduced size and weight is not as strict. Overall, about 23 percent of all installed wind turbines currently use REPMs; however, this is expected to grow to 72 percent by 2030.[32]

For wind turbines, the average permanent magnet weighs up to 4.0 tonnes and contains 28.5 percent neodymium, 4.4 percent dysprosium, 1 percent boron, and 66 percent iron. Every MW of direct-drive wind power installed therefore creates approximately 650 kg of incremental NdPr demand. The wind turbine market is expected to account for 28.8 percent of global growth in the use of NdPr in REPMs from 2020 to 2030, according to CRU. Figure 18 shows the projected REO consumption by end use, out to 2030, as forecast by Roskill.

Figure 18: Projected REO Consumption by End Use (2020-2030)



Source: Roskill (2021), Australian Department of Industry, Science, Energy, and Resources (2021).

[32] EU Joint Research Centre 2015.

8. OUTLOOK FOR RARE EARTH SUPPLY

The robust demand outlook for REPMs is expected to drive the expansion of REE mine capacity as well as the construction of new processing facilities. The market expects most of the focus to be on magnetic REO production, particularly neodymium and praseodymium (NdPr). In this section, Deloitte examines the potential supply growth in more detail.

8.1. REE Mine Supply

The United States, Canada, Australia, Europe, and other developed markets have been acutely aware of the potential supply shortage of REE for many decades. Emerging low-emissions technologies are dependent on REPMs (and hence on magnetic REE). This has led to some governments reclassifying these minerals as 'critical' and taking measures to support the market in the long term.

There are a multitude of studies and technical papers covering this subject that focus on developing traditional and non-traditional (such as coal fly ash) sources of REE. There has also been research into REE recycling and the better utilization of REE or replacement minerals and technologies in areas for which REE are used. These appear to have had very modest success in reducing the supply deficit. While Mineral Pass mine in the United States and Mt Weld mine in Australia are now contributing to global REE output, much of the growth in mine production has continued to come from China.

Many REE projects have struggled to make significant and/or timely progress. This is partly because of the complex nature of REE orebodies and the potential difficulty in processing and recovering REE, but also because REO prices have remained at low levels since 2015 (following the price spike of 2011-12). Prices have, however, seen some recovery in 2021 and into 2022. Price levels that are high enough to make acceptable returns are, and will continue to be, an important factor to enable ongoing REE exploration and the development, financing, and construction of new REE mines.

8.2. Expansion of Existing Producers

Several key producers are expected to expand operations in the coming years and contribute to REE production growth. Deloitte expects that rising Chinese mine quotas, along with increased mining production from Lynas Rare Earth and Russian operators, will drive production growth for existing operators. From now until 2030, Deloitte expects an increase of 35.4 kt/y of NdPr from these sources.

Table 5 provides more information on these potential expansions, which are partially based on Deloitte estimates. Although the expansions in Russia and China are somewhat opaque and they may not fully achieve the plans reported, these estimates present a plausible case for the expansion of NdPr mine production. The sections that follow present more information on these existing producers.

Table 5: Existing Producers Mine Capacity Expansions of NdPr

Company/Region	Production Capacity t/y NdPr			Increase
	2020	2025F	2030F	t/y NdPr
Chinese mine quotas*	25,000	40,700	47,700	22,700
Lynas Rare Earths	4,656	10,500	10,500	5,844
Russian mines & projects	850	2,460	7,750	6,900
Total	**30,506**	**53,660**	**65,950**	**35,444**

Source: Company data, news reports, Deloitte estimates. *Chinese data assumes a 3 percent REO growth rate.

8.2.1 Chinese REE Mine Production

China's reported production is assumed to match the level of quotas and excludes illegal production. China has regularly raised annual production quotas for REE in the last couple of years to meet demand. China produced 140 kt of REO in 2020 and 168 kt in 2021. China's total REO production has risen at a CAGR of 5.9 percent from 2010 to 2020. Most of this rise is driven by strong growth since 2018 (CAGR 11.9 percent).

LREE production growth has been even stronger (CAGR 13.9 percent), while HREE production has remained flat since 2018 (HREE and LREE data before this year is unavailable). Based on the REE-grade distributions across the main regions of China, Deloitte estimates NdPr production of approximately 25 kt in 2020 using this data. Figure 7 in Section 4 shows how REO production has grown in China over the past decade.

In January 2022, the Chinese government increased REE mining and smelting quotas for the first half of 2022 by 20 percent. If this is repeated in the second half of 2022, data indicates that China's full year production will be just over 200 kt.

Deloitte expects continued production growth out to 2030 given China's significant REE reserves and resources and its historical growth rate of REE production. If total production grows at just 3 percent from 2022 onwards (with HREE production remaining flat), total REO mine output would rise to approximately 255 kt by 2030, with 47.8 kt of NdPr produced. A 5 percent growth rate would result in REO mine output rising to approximately 300 kt by 2030, with 56.3 kt of NdPr produced. These increases could be driven by the reported planned expansion in Inner Mongolia.

8.2.2 Lynas Rare Earths

As mentioned in Section 4, Lynas is the largest non-Chinese supplier of refined REO (mixed oxide products), which it processes at its plant in Malaysia. In fiscal year 2020, Lynas produced 4.7 kt of NdPr and NdPr production is forecasted to increase to 10.5 kt/y by 2025 with higher mine throughput.

Lynas' refined REE production is forecasted to increase further with the development of the planned Kalgoorlie cracking and leaching plant near the Mt Weld mine, and other possible U.S. separation facilities. The first stage cracking and leaching is expected to take place in Western Australia by mid-2023. Lynas is looking at additional extraction of dysprosium and terbium and testing a pilot plant in Texas, United States. Additionally, Lynas is looking to produce REE metals via toll treatment in Vietnam.

8.2.3 Russia REE Mine Production

In March 2021, the Russian government announced an initiative to increase its domestic REE capacity. The new program, which foresees approximately $4 billion in funding, is jointly led by the Russian Ministry of Industry and Trade and Rosatom, a state-owned nuclear corporation. The program plans to fund the construction of 10 new plants to produce REE. In addition to expected REE production of 7 kt/y by 2024 and 30 kt/y by 2030, this initiative would also support the production of lithium, niobium, and tantalum.[33] The REE mine projects under development include Tomtorskoye in the north of the Sakha Republic and the Zashikhinskoye deposit in Irkutsk Oblast. How far these projects have progressed is currently unknown.

[33] Kommersant, Russian business news outlet

8.2.4 MP Materials

MP Materials is considering opportunities to integrate further downstream; however, the company has not announced any capacity expansions. MP Materials is exploring the business of upgrading NdPr into metal alloys and magnets, which would allow MP Materials to ultimately expand its presence as a global source for REPMs. MP Materials' CEO has mentioned the company is considering future capacity expansions during company webcasts, but no output increases from MP Materials are included in the calculations of this report.

8.3. Potential New REE Mines

New mine capacity could also contribute significantly to future REE production supply. Nevertheless, new developments that could potentially come on stream are low, partly due to the low prices experienced by the market from 2015 through the beginning of 2021. Deloitte analyzed 19 projects near to construction and at feasibility stage and found that approximately 33.2 kt/y of NdPr could come on stream by 2030.

8.3.1 Mines Under Construction

Deloitte has identified nine greenfield REE mining projects under construction or close to a final investment decision (FID), as shown in Table 6. If all these projects came on stream before 2030, they would add approximately 17.9 kt/y of additional NdPr mine production.

Browns Range has been operating a pilot plant since late 2018, but some other projects remain in doubt. For instance, the last feasibility study on some of the projects occurred years ago. Bokan Mountain's last feasibility study was in 2013, Brown Range's was in 2015, and Kvanefjeld's was in 2016. Kvanefjeld also looks to be in doubt after facing political opposition. Greenland's parliament passed new legislation in November 2021 banning the mining of mineral resources that have a uranium content greater than 100 ppm (the REE orebody in Kvanefjeld contains 0.036 percent U_3O_8 or 360 ppm).

Table 6: Greenfield REE Projects Under Construction or Near FID

Mine	Country	Owner	Prodn REO t/y	Prodn NdPr t/y	Expected Startup
Nolans Bore	Australia	Arafura Resources	13,343	4,357	Late 2024
Kvanefjeld	Greenland	Greenland Minerals	22,162	3,911	N/A
Yangibana	Australia	Hastings Tech. Metals	8,500	3,400	2024
Eneabba	Australia	Iluka Resources	12,000	2,640	1H 2022
Dubbo	Australia	Aus. Strategic Min.	1,875	1,875	2H 2022
Serra Verde	Brazil	Miner. Serra Verde	5,000	875	2022
Nechalacho Surface	Canada	Vital Metals	1,000	447	June 2022
Bokan Mountain	USA	Ucore Rare Metals	1,828	336	N/A
Browns Range	Australia	Northern Minerals	3,098	84	N/A
Total			**68,806**	**17,925**	

Source: S&P Global Intelligence, Company data, Deloitte estimates.

Two projects that produce REE as by-products and are expected to start up in 2022 are Eneabba and Dubbo. Iluka Resources [ASX: ILU], an Australian mineral sands producer, is developing the Eneabba tailings operation to produce monazite residues. Phase 1 is in production, which involves the extraction of old tailings through a screening plant.

In Phase 2, Iluka Resources will construct a plant to produce 90 percent monazite concentrate that is expected to be commissioned in the first half of 2022. In Phase 3, the company will build a fully integrated refinery (currently undergoing a feasibility study that is expected to be finalized in early 2022). The project is expected to produce 16 to 20 kt/y of 90 percent monazite concentrate over its 10-year life, equivalent to approximately 10 to 13 kt/y REO.

Australian Strategic Minerals [ASX: ASM] is advancing the Dubbo titanium project, which produces neodymium as a by-product. The project is expected to produce 2.5 kt/y of NdFeB powder in 2022, which will increase to 6.25 kt/y by 2026 (30 percent Nd content assumed).

8.3.2 Feasibility Stage Projects

In addition to the projects near to construction, Deloitte identified 10 projects where a feasibility has been completed or is currently underway (indicating that these REE exploration projects are at an advanced stage and have the potential to come on stream by 2030, if not sooner). Table 7 lists these projects, which have a combined production potential of 15.2 kt/y NdPr of mine supply. However, some of these projects may have long permitting times, further exploration and/or REE extraction testing requirements, high capital expenditures and operating costs, or complex mineralogy, and so it is possible that they may not reach production.

Table 7: REE Projects at Feasibility Stage

Mine	Country	Owner	Prodn REO t/y	Prodn NdPr t/y	Expected Startup
Longonjo	Angola	Pensana Rare Earths	20,700	4,592	Unknown
Ngualla	Tanzania	Peak Rare Earths	14,905	3,110	Unknown
Nechalacho Basal	Canada	Avalon Advanced Mat.	6,810	1,502	Unknown
Goschen	Australia	VMH Ltd	6,300	1,400	Unknown
Steenkampskraal	South Africa	Steenkampskraal Thor.	1,512	1,109	Unknown
Gakara	Burundi	Rainbow Rare Earths	5,000	1,050	Unknown
Songwe Hill	Malawi	Mkango Resources	2,841	983	Unknown
Makuutu	Uganda	Ionic Rare Earths	2,673	766	Unknown
Kipawa	Canada	Quebec Precious Metals	3,651	619	Unknown
Aclara	Chile	Aclara Resources	742	114	Unknown
Total			**65,134**	**15,245**	Unknown

Source: S&P Global Intelligence, Company data, Deloitte.

In Burundi, Rainbow Rare Earths [LON: RBW] has been undertaking trial mining operations at its Gakara mine and producing high-grade REE concentrates; however, this is still a feasibility-stage project. The company plans to implement a modular, commercial-scale operation of 5,000 t/y REO concentrate, that can scale up to 10,000 to 20,000 t/y. Operations are currently suspended at the request of the Burundi government because of the price of mineral concentrate.

The Goschen project in Australia is another mineral sand project, owned by private company VHM Ltd, where REE are a by-product. The mine is expected to produce zircon and titanium products and 10 kt/y of REO concentrate is expected to be processed at VHM's proposed REE refinery. The refinery will produce refined NdPr oxide and mixed HREE carbonate (terbium and dysprosium).

8.3.3 Total Supply Potential from Existing Producers and New Projects

The combined capacity of the 19 projects near to construction and at feasibility stage is approximately 33.2 kt/y of NdPr. According to Deloitte estimates, a further 35.4 kt/y NdPr is possible from expansions from existing producers/countries. Together, this is equal to an additional 68.6 kt/y NdPr of mine concentrate supply by 2030, equivalent to approximately 61.7 kt/y of recovered NdPr oxide.

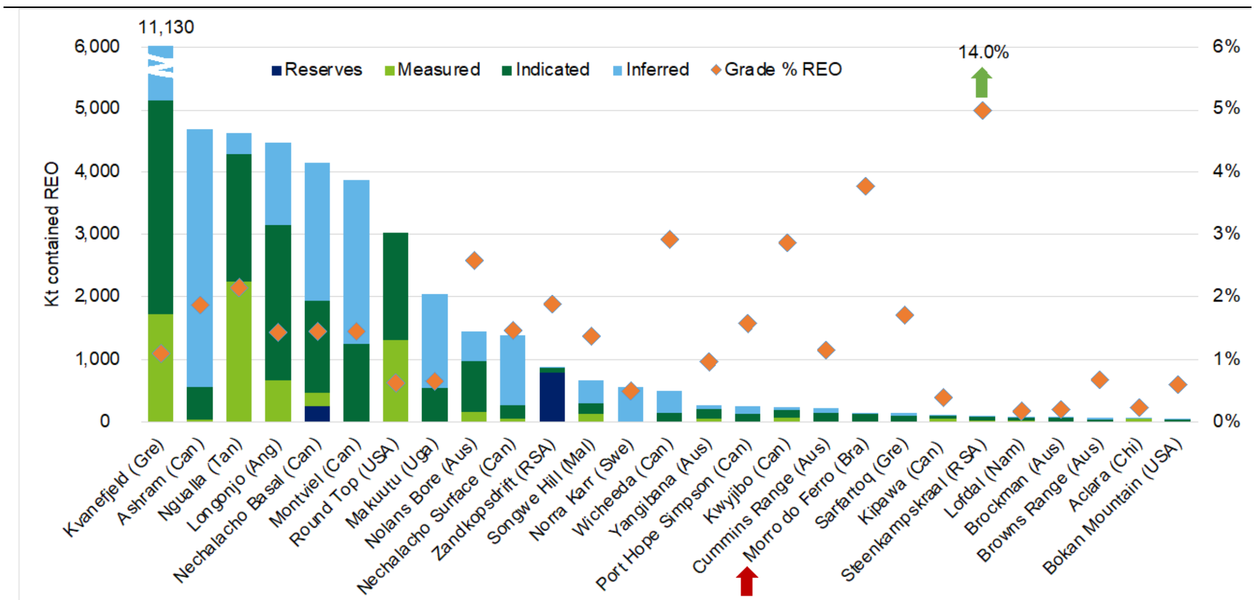
This figure assumes that every project makes it to production and does not account for the timing of capacity build-up. However, this figure does not reflect potential production from other projects, not yet identified, where only small amounts of REE might be extracted as a by-product of other commodities (for instance, in mineral sands, niobium, and tantalum operations).

8.4. Other Exploration Projects

In addition to the more advanced projects mentioned, Deloitte has identified 13 active REE projects of interest. These projects include those in early-stage exploration and development and those where a resource has been identified. Most of these are at the pre-feasibility stage. While these are earlier stage exploration projects, it is possible that one or more of these could be in production before 2030. However, it is likely these projects would begin production post-2030 if they are economic and progress satisfactorily. Table 12 in Annex 5 lists these 13 projects. This is not an exhaustive list, but other projects with ongoing exploration have limited resources.

Figure 19 shows data related to the reserves and resources and average REO grade for 27 of the 32 REE projects at pre-production, feasibility, and pre-feasibility stages. The figure shows the significance of the Kvanefjeld project, which is in doubt after new legislation was passed in Greenland, banning the mining of mineral resources with uranium content above 100ppm. It has the largest REE resources of the group.

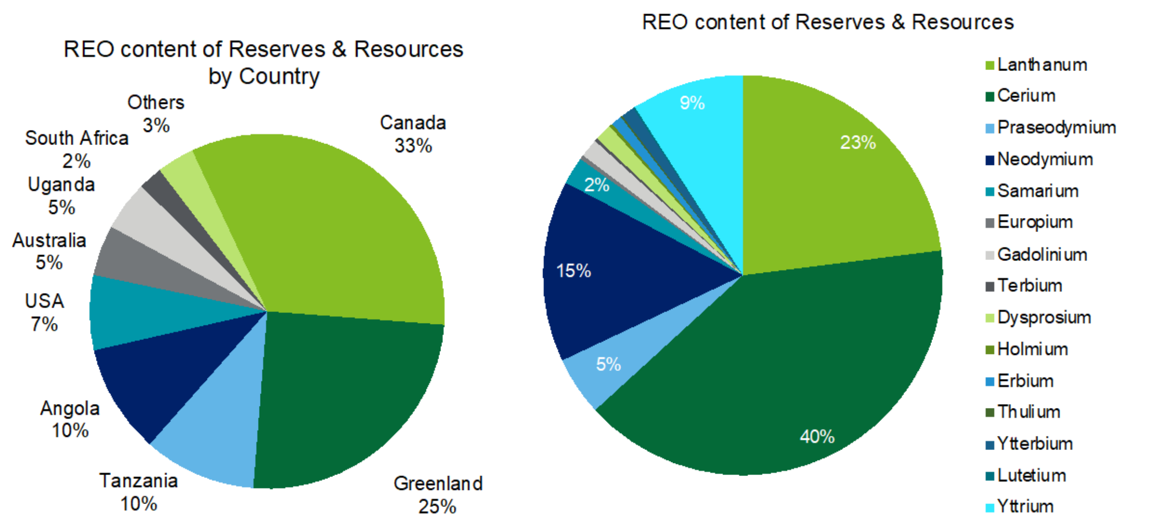
Figure 19: Aggregated Data for Reserve & Resource of 27 Projects



Source: Company data, Deloitte estimates.

There is no resource data available for the Serra Verde project in Brazil, but the Morro do Ferro project in Brazil is highlighted in Figure 19. Figure 20 shows the aggregated data of the REO reserves and resources for these 27 projects, broken down by country as well as REO in-situ grade distribution. LREE accounts for 85 percent of the REO content and HREE 15 percent. The actual recovery of REO, however, will vary with different recovery rates for each REO and within each orebody. The two most significant HREE projects are Round Top in the U.S. and Browns Range in Australia.

Figure 20: Aggregated Data for Reserve & Resource of 27 Projects



Source: Company data, Deloitte estimates.

8.5. The REE Projects in Brazil

There are six REE projects in Brazil that could be of significance:

- Serra Verde (Mineração Serra Verde): Under construction;
- Morro do Ferro (Mineração Terras Raras): Pre-feasibility stage;
- Araxá Niobium Mine (Brazilian Metallurgy and Mining Company): Feasibility stage;
- Araxá (Itafos): Advanced-exploration stage;
- Bahia (Energy Fuels): Pre-feasability stage; and
- Arara (Carlos Mena Resources): Data is not available.

The most advanced REE project in Brazil is the Serra Verde project in Goiás, which is operated by Mineração Serra Verde, a private company owned by Denham Capital Management and Arsago Mining Capital. Mineração Serra Verde completed a pre-feasibility study for this project in 2017. The project is expected to start production in 2022 (with a mine life of 24 years) and produce 5 kt/y of REO in concentrate. The project has ion-adsorption-type mineralization and a resource of 911 Mt, grading about 0.12 percent REO. LREE account for 0.08 percent, with NdPr accounting for approximately 17.5 percent of the total REO. Table 6 includes more information about this project.

The Morro do Ferro project is located near the city of Poços de Caldasa in Minas Gerais. It is owned by private company Mineração Terras Raras, where a deposit of 3.55 Mt of ore has been defined with an average content of 3.9 percent of REE. The company is currently undertaking scoping studies and applying for environmental licenses. CPRM reports that due to mineralogical complexity and its high thorium content (4.9 percent ThO_2), the ore from Morro do Ferro presents processing difficulties.

At the existing niobium mine in Araxá in Minas Gerais, the private company CBMM is examining the feasibility of extracting REE from existing mine tailings. These tailings would be processed into REPM powders in conjunction with the IPT.

Itafos [TSXV: IFOS] owns another advanced-stage exploration project in Araxá, in which niobium-rich laterites are being evaluated for the recovery of REEs as a by-product of niobium production. A technical report in January 2013 suggested that the project could have a production capacity of 8.7 kt/y of REO and niobium. However, further work on the project has been limited, and the company's latest presentation suggests that they are considering selling this project.

In May 2022, U.S.-based Energy Fuels [NYSE: UUUU] announced an agreement to acquire the Bahia project, located on the coast in the State of Bahia. The project comprises marine placers containing heavy mineral sands (HMS - ilmenite, rutile, and zircon) and REO in the form of monazite. The property has already been drilled and Energy Fuels plans to perform extensive exploration work over the next six months to further define and quantify the HMS resource. A Preliminary Economic Assessment (PEA) is anticipated in 1H2023. The company believes the Bahia project has the potential to produce approximately 3 to 10 kt/y of monazite sand concentrate containing approximately 1.5 to 5.0 kt/y of REO. Energy Fuels is a uranium mining company, supplying U_3O_8 to major nuclear utilities and initially intends to ship the monazite sand for concentration at its facilities in the U.S.

Carlos Mena Resources also holds the mineral rights for the Arara project in São Paulo, which has tin, niobium, tantalum, and REO occurrences. No further information is publicly available.

Separately, it is worth noting that in 2018, Minas Gerais inaugurated the laboratory-factory for rare earth magnets (LabFab ITR), which is being developed by Brazilian Research Centers and Federal Universities.[34]

[34] No further information on the progress of LabFab ITR is currently available

9. MARKET BALANCE AND PRICE OUTLOOK

The market outlook for individual REEs varies considerably depending on its end-use application. However, the economics of REE extraction are becoming increasingly reliant on magnetic REE and their corresponding market. Demand-pull factors, particularly REPM production in China and Japan, are expected to strongly influence the market balance for these elements.

The outlook for other REEs is more subdued, with more muted growth prospects. Furthermore, since REEs are mined together, the drive to increase the supply of magnetic REEs will likely result in significant oversupply of most other REE and negatively affect their pricing. This could alter the basket pricing for producers and affect market dynamics so that some oversupplied REEs are not recovered due to their low price.

Deloitte evaluated how the market balance could shift depending on certain supply and demand variables. The sections that follow provide more information on this analysis.

9.1. Sensitivity Analysis of Supply and Demand

Since REE data is limited, Deloitte based its supply and demand market analysis on NdPr, which serves as a close proxy for all REE. If mine production from new operations and Russian projects increases as expected, the two most important factors to consider are the growth in demand for NdPr used in REPMs (on the demand side), and the growth in Chinese NdPr production (on the supply side).

Table 8 shows the sensitivity of the supply and demand balance by varying these two assumptions from 2022 out to 2030. The Chinese production growth rate is based on existing reported quotas for 2021 and 2022 and assumes 90 percent recovery for overall mined production. The growth figures are based on an estimated balanced supply and demand of 50 kt/y of NdPr in 2020. The resultant data in Table 8 is the market balance for NdPr in 2030. Positive numbers signify a market surplus and negative numbers a market deficit.

Table 8: Sensitivity Analysis of REPM Demand Growth and Chinese Supply Growth for NdPr

		Chinese mine production growth rate			
		0%	3%	5%	7%
Rate of demand growth of NdPr for REPMs	3%	34,933	44,613	52,259	60,994
	6%	12,587	22,267	29,912	38,648
	9%	(16,239)	(6,559)	1,087	9,822
	12%	(53,164)	(43,483)	(35,838)	(27,102)
	15%	(100,149)	(90,469)	(82,823)	(74,088)

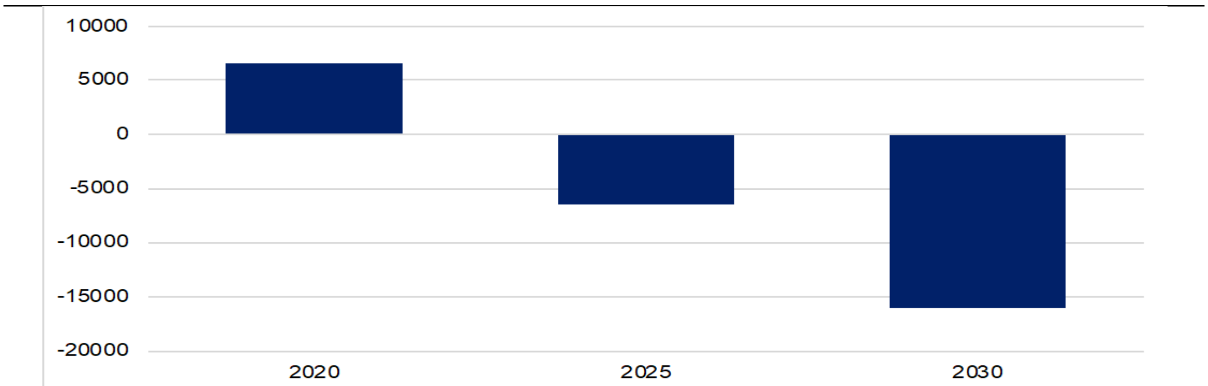
Source: Deloitte estimates. NB. A positive number is a market surplus, a negative number is a market deficit.

Based on current data, Deloitte estimates that demand growth for NdPr for REPMs will be between 6 and 12 percent, while the growth rate of Chinese production for NdPr is potentially 3 to 5 percent. These growth rates result in a range of outcomes (outline in black in the table above), in which the market could be balanced but could also be in surplus or in deficit.

An example can help put surplus and deficit scenarios into perspective. If China grows production at 3 percent from 2022 until 2030, and other projects come on stream as expected, the total recovered supply of NdPr would be approximately 112 kt/y. If REPM demand growth is 6 percent, total demand would be equal to approximately 90 kt/y. While an REPM demand growth of 9 percent would be equal to approximately 118 kt/y and an REPM demand growth of 12 percent would be equal to approximately 155 kt/y. The sensitivity of demand is also important as it results in significant swings in surplus or deficit as a percentage of total supply.

However, the consensus view is that neodymium and praseodymium (NdPr oxide) will likely experience market shortfalls toward the end of the decade. Figure 21 shows the supply and demand balance as forecast by Adamas Intelligence, which indicates a 16 kt/y deficit of NdPr oxide in 2030. This is based on the development of 55,000 t/y of new REO production capacity outside of China and 'substantial' production increases in China.

Figure 21: Supply and Demand Balance for NdPr Oxide

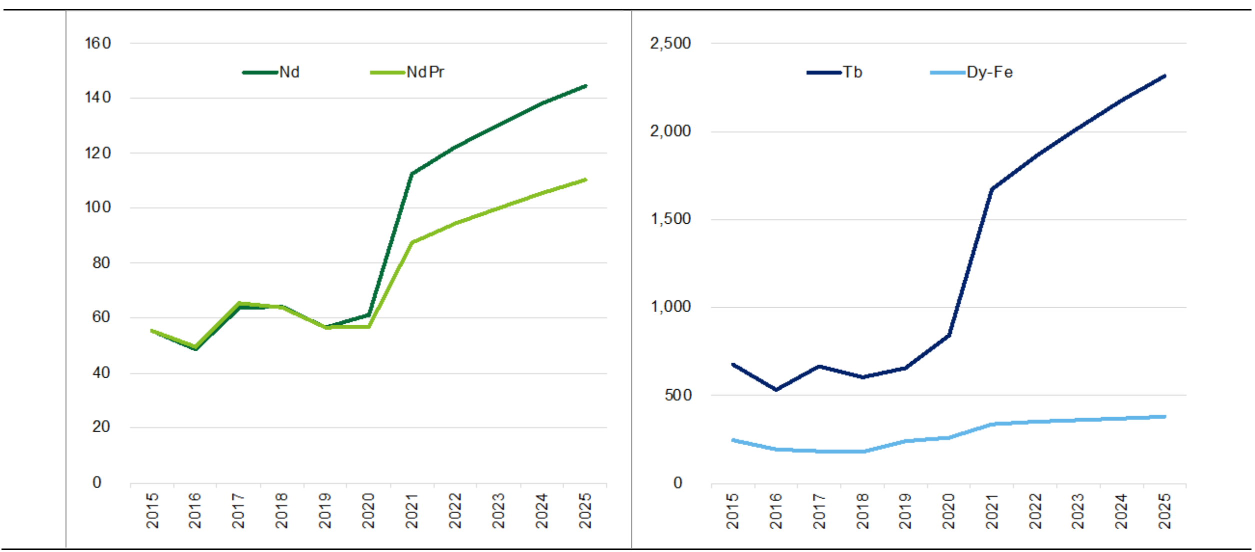


Source: Adamas Intelligence 2021.

9.2. Forecast REE Prices

Demand for neodymium, praseodymium, and terbium look extremely robust for at least the next decade. However, supply could remain constrained, which is likely to result in higher prices. Figure 22 gives a price forecast for these REE out to 2025.

Figure 22: Forecast REE Prices ($/kg)



Source: China Rare Earth Association, Frost & Sullivan.

10. ECONOMIC COMPETITIVENESS

Companies, investors, providers of finance, and governments should examine and compare project data to evaluate and benchmark potential REE projects. However, the exploration and development of an REE deposit is still very challenging as each deposit is a multi-element deposit (typically with a complicated mineralogy), which requires development of tailor-made beneficiation and cracking flow sheets. REE distribution is key to assessing the economics of an REE deposit and thereby its market acceptability.

In most metal exploration projects; the grade and price of the main commodity are the key parameters for evaluating an exploration project's feasibility for further development. For REE deposits, the evaluation is more complex. As a result, there is a wide range of parameters that can be used to evaluate the potential of any given REE project. The following metrics are frequently used for comparing REE projects:

- Ore grade (percent) – This is the total REE content of one unit of the ore, but it does not reflect the distribution or mineralogy of individual REEs or its ease of extraction.
- Individual REE grade (percent) – Some REEs are more valuable than other REE, such as praseodymium and neodymium, and these grades are sometimes reported separately.
- Ore tonnage – The volume of the ore hosting the economic part of the REE.
- Basket price ($/tonne) – This reflects the value of one unit (tonne) of REO extracted from the ore, based on the value of each REE and the distribution of those REEs within the in-situ orebody or recovered concentrate.

The sections that follow evaluate current mining operations and project feasibility studies using the metrics presented above.

10.1. Comparison of Current REE Mining Operations

There is limited data available for existing REE mining operations. These operations are principally located in China, which does not report production details or costs. Mt Weld and Mountain Pass mines are the two largest operations outside of China, but these companies also do not report detailed cost data.

Deloitte analyzed the cost data that was available for these two companies. For the nine months up to September 2021, MP Materials (Mountain Pass operator) reported overall production costs of $1,484/t REO, compared with a realized price of $7,043/t REO. For the 12 months up to June 2021, Lynas Rare Earths (Mt Weld operator) reported a cost of sales of $13,080/t REO (A$18,421/t), compared with revenue of $21,164/t REO (A$29,807/t). The main difference between the two cost structures is that Lynas produces finishes REO from its plant in Malaysia, and MP Materials currently ships a mined concentrate.

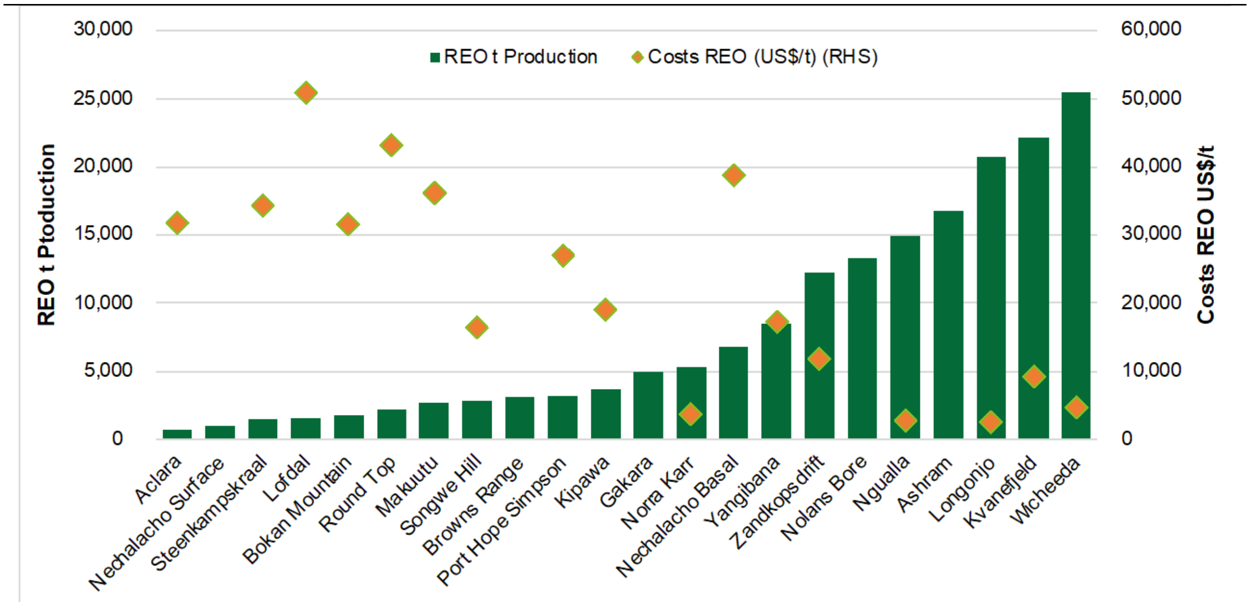
10.2. Comparison of Project Feasibility Studies

Deloitte collected data and analyzed information from 22 companies that produced recent feasibility, pre-feasibility, and scoping study reports for the market (typically a part of the process for project development). Not all companies report every item, but the key measures for economic competitiveness are shown in a series of charts for comparison, analysis, and discussion, where data is available. However, these reports were published over the past 10 years and have used different price assumptions, which means that they are not wholly comparable.

Serra Verde or Morro do Ferro, the two most advanced REE projects in Brazil, are operated by private companies and did not have any project detail available. As a result, Deloitte could not compare the competitiveness of these projects.

Figure 23 shows the projected REO production capacities and operating costs of these projects. Ideally, companies should include costs to transport the goods to port or other points of sale to make better cost comparisons, but this data is not often available. The weighted average mine operating cost for this group is $11,796/t REO. There also appears to be an inverse correlation between size and cost, suggesting economies of scale are achievable.

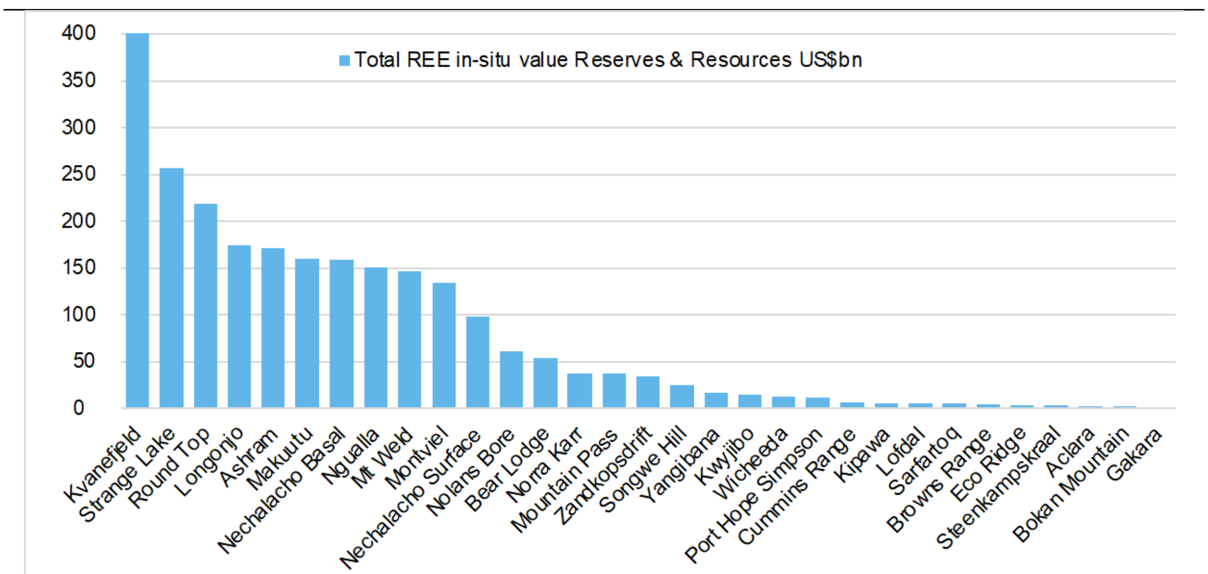
Figure 23: REE Projects: Production Capacity (t/y) and Operating Costs ($/t) REO



Source: Deloitte, company data.

While costs are important for any operation, they do not provide a full picture of profitability for REO operations. This is because each orebody contains a different proportion of REO and the price of each REO product varies considerably. Figure 24 shows the in-situ value of various orebodies based on recent FOB China REO prices and their REO distribution.

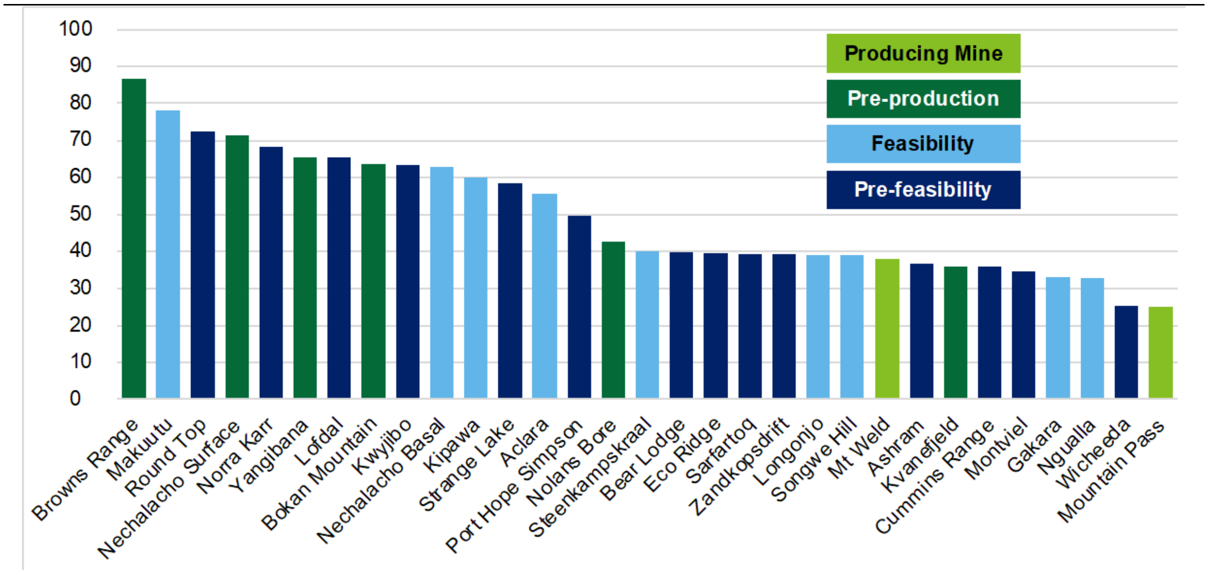
Figure 24: REE Projects: Total REE in-situ value Reserves & Resources $billion



Source: Deloitte, company data.

Another measure used by REE companies is the basket price of the REO. This is usually the in-situ value of one unit of ore after considering the different proportions of each REO and their corresponding price (sometimes the basket price can refer to the REO concentrate). Figure 25 shows this information below.

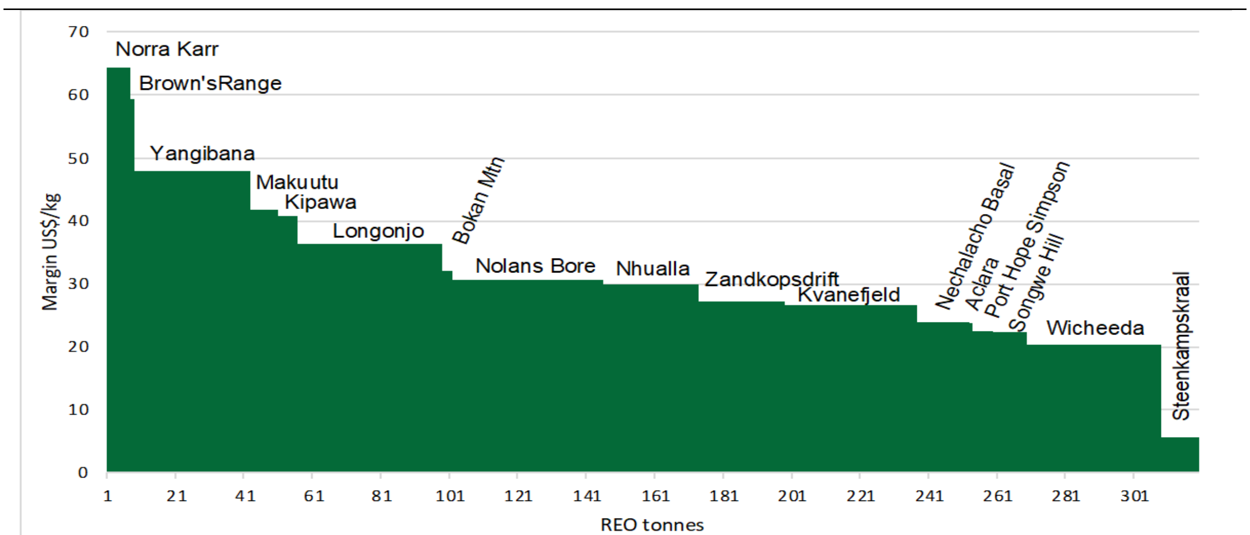
Figure 25: REE Projects: Basket Price $/kg Reserves & Resources



Source: Deloitte, company data.

Due to the basket-price effect, looking at a cost curve does not give a clear picture of the relative profitability of an REE project. Rather, it is necessary to look at the margin curve. Figure 26 shows a relatively steep margin curve for the projects where data is available.[35]

Figure 26: REE Projects: Margin Curve $/kg REO

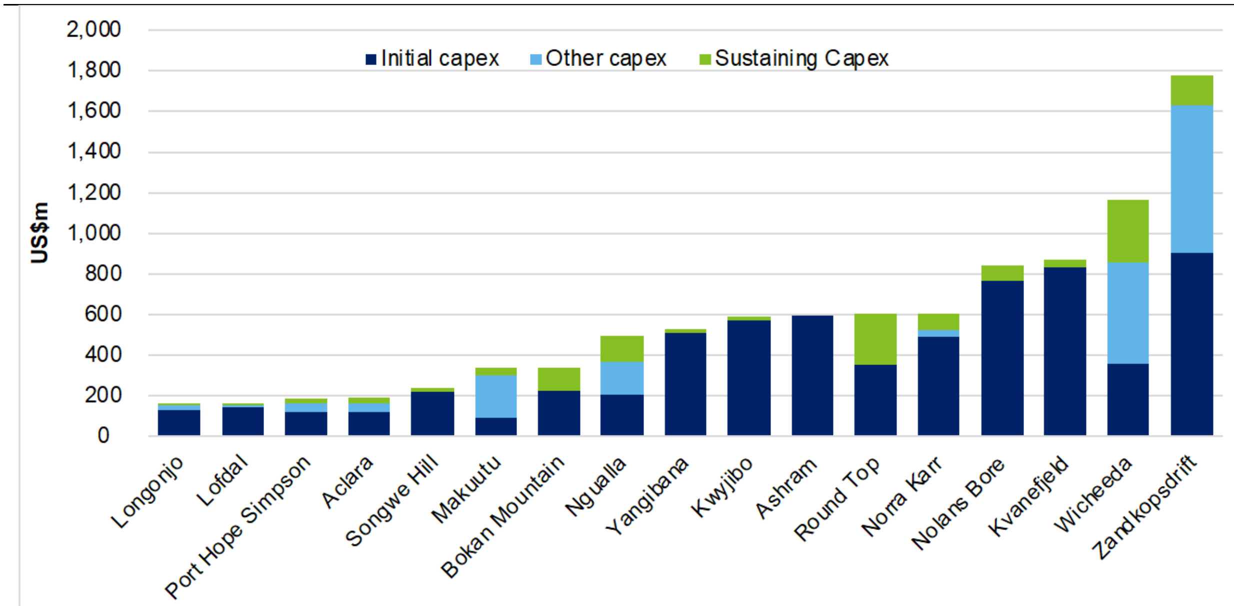


Source: Deloitte, company data.

[35] All things being equal, in a balanced market, the price will trade at the marginal price of the most expensive producer. This means other producers will make good profits if the curve is steep, and there will have to be a meaningful decline in price, for the producers to feel a squeeze on profits.

However, this data should only be used as a relative measure to evaluate a project's potential because there are several issues with using basket prices as used by the industry. Firstly, these figures relate to in-situ grades which will be different to final recovered grades due to mining and processing losses. The processing recovery varies for different REO at each project. Secondly, the prices used are based on separated REO products, whereas the mine produces a mixed REO concentrate that would be sold at a significant discount to these prices. Lastly, the prices used are just a snapshot in time and may not represent long-term average prices achievable over the life of mine (LOM).

Figure 27: REE Projects: LOM Capital Expenditure ($m)



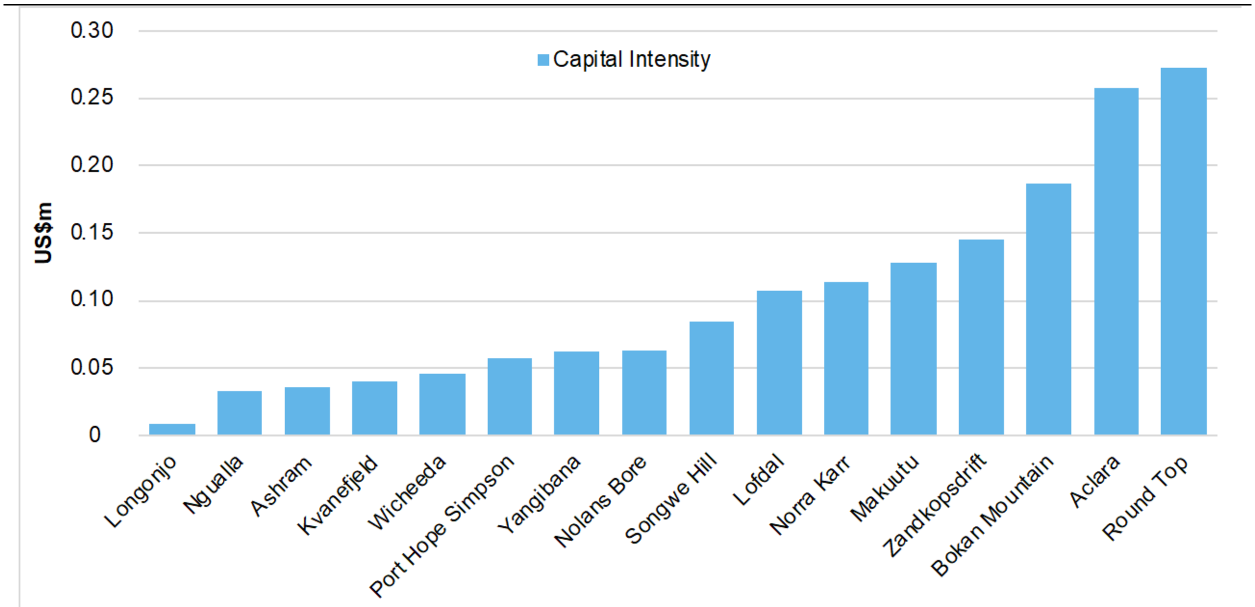
Source: Deloitte, company data.

Another important measure to assess the economics of a mining project is the capital expenditure (capex) required to establish and operate the mine. This includes the initial capex, subsequent capex investments (e.g., for later expansions), and sustaining capex (e.g., to replace plant and machinery). Figure 27 shows the capex for these projects.

Companies usually focus on the initial capex, but it is important to look at capex over the life of the mine for an individual project for comparison. The project capex can often vary due to the orebody location, depth, orientation, type of ore, recovery methods, and the amount of labor and energy consumed in the process. This then has an important bearing on the economics of the project.

Capital intensity is often used as a measure for comparison of projects and their quality. Figure 28 shows the capital intensity of the projects assessed, which is based on the capex over the life of the project divided by the average annual REO production. This gives the capital cost required to produce one tonne of REO.

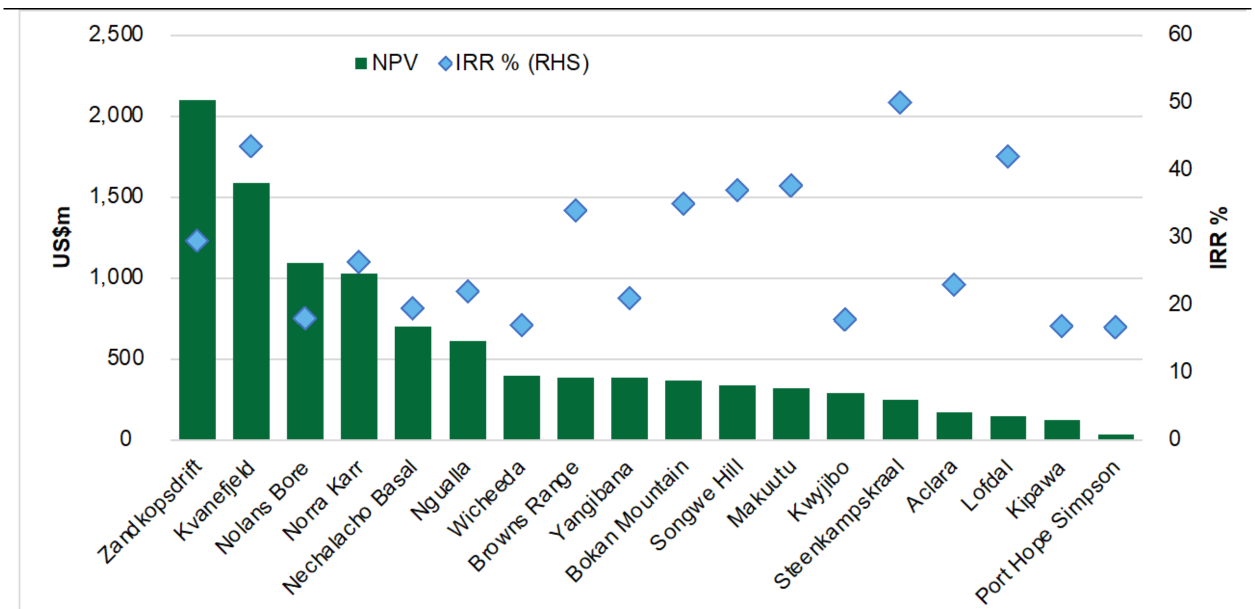
Figure 28: REE Projects: Capital Intensity $m/REO t



Source: Deloitte, company data.

The ultimate measure of a project's economic viability is the Net Present Value (NPV) and Internal Rate of Return (IRR). Figure 29 shows these indicators; however, these are not totally comparable because of varying price assumptions used. The figure shows post-tax values and does not include all projects because some only reported pre-tax data. The median IRR of this group was 25 percent, which suggests generally good returns (the average is distorted by a few high values).

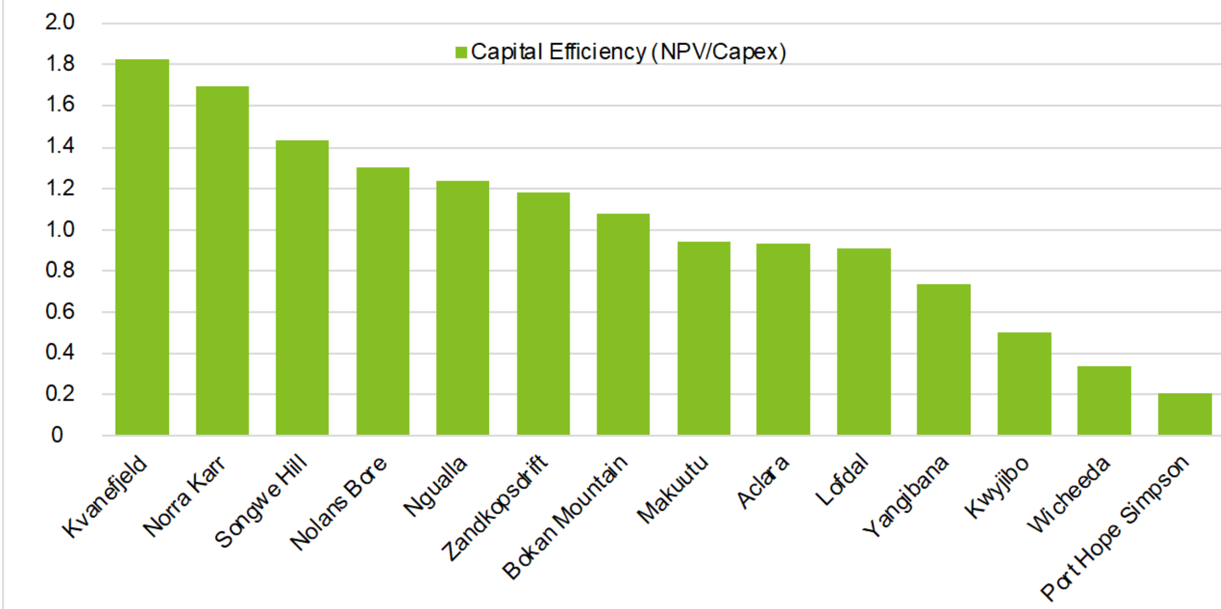
Figure 29: REE Projects: NPV ($m) and IRR (%)



Source: Deloitte, company data.

Capital efficiency, which is the ratio of the NPV divided by the capex, is another useful measure for comparing projects. Figure 30 shows the capital efficiency of the REE projects assessed.

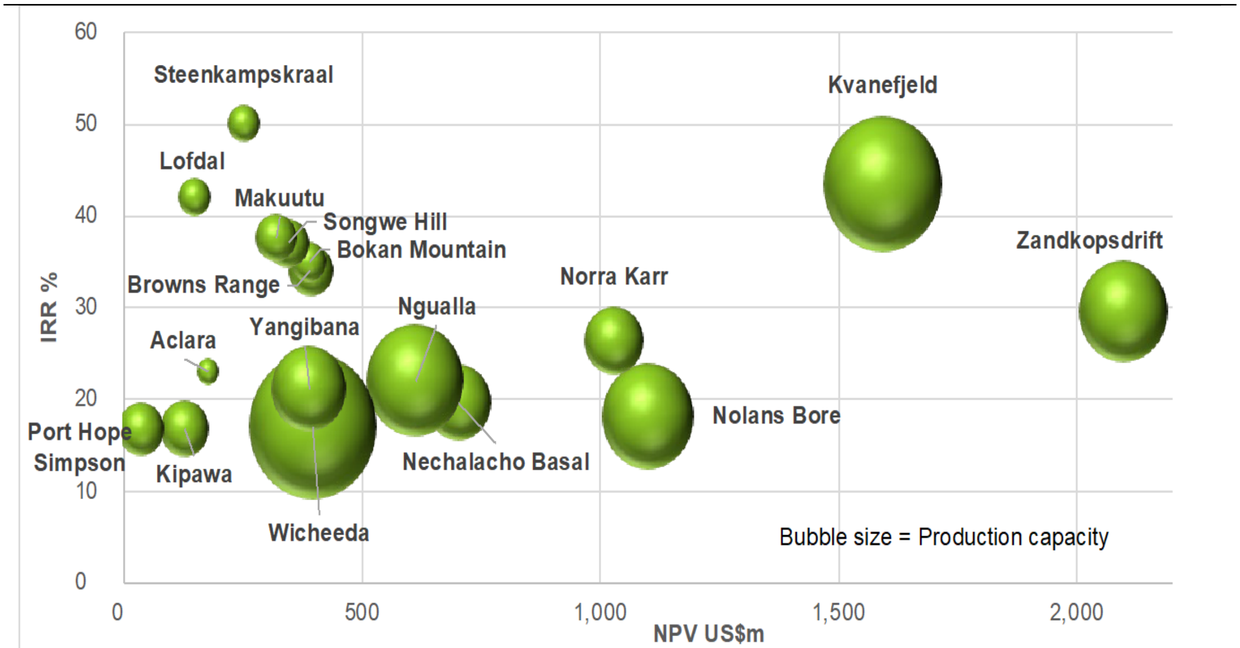
Figure 30: REE Projects: Capital Efficiency (NPV/Capex)



Source: Deloitte, company data.

Figure 31 shows NPV and IRR data in a bubble chart, in which the bubble size represents planned production capacity. The figure shows some projects bunched in the bottom left-hand corner. While all projects may ultimately receive project finance, particularly if the market is in deficit, data indicates that the companies in the lower left will find financing more difficult and competitive.

Figure 31: REE Projects: NPV versus IRR with Project Capacity



Source: Deloitte, company data.

11. CONCLUSIONS AND KEY RECOMMENDATIONS

This chapter provides a summary of the overall market analysis for REEs, outlines issues surrounding REE market capacity, and explains how these could impact the future financing of the REE industry. This section also includes potential threats and opportunities in the market and summarizes key recommendations for the REE industry in Brazil, with the aim of helping the government in its long-term strategic planning and future policy action for REE development and commercialization.

11.1. REE Market Capacity

Accurate data on the REE market is difficult to find. However, available data suggests that the current market supply-demand balance will likely remain tight out to 2030. Demand for REE is set to expand dramatically over the next decade due to the increased use of REPMs in EVs and wind turbines, among other technologies. The rate of demand growth for REPMs out to 2030 will be an important factor in determining whether the market will be in balance. This market will drive demand for neodymium, praseodymium and other magnetic REO more specifically. As a result, other REO are expected to remain in oversupply.

From a supply perspective, few new mines are likely to come on stream – and most of these projects will be required to satisfy demand. Progress with many of these projects has been slow, due to the difficulty in achieving optimum processing and recovery of REE and the low prices experienced until recently. Capacity increases from the two mining operations in the United States and Australia, as well as from prospective expansion projects in Russia, will also be important to the market balance.

China currently controls 61 percent of REE mining capacity, 86 percent of REO processing facilities, 93 percent of RE metals processing operations, and 67 percent of REPM production. The ultimate deciding factor in achieving a balanced market could be how China 'controls' different stages of the supply chain as well as the rate of continued growth in REE mine production in China. The market outlook is sensitive to this growth.

Research and development (R&D) initiatives continue to investigate ways of reducing REE consumption and improving recycling recovery. Most of the substitution potential has already been reached and recycling progress has been slow due to technological and economic issues. Deloitte does not expect any changes in these factors to significantly impact the market balance out to 2030.

There are many announced projects that currently lack financing and teams capable of project execution. REEs are a small industry and the number of capable, technically trained engineers with appropriate experience is very limited. As a result, labor could also become a limiting factor in developing sufficient capacity.

11.2. REE Project Financing

The relatively small size of the REE industry, historically low REO prices, and the existence of only two non-Chinese REE mining companies (along with a handful of exploration companies), has meant that investor interest in this sector has been low. Nevertheless, the recent step-up in REO prices has seen renewed interest in some REE exploration and development companies.

Timely development of both mining and processing capacity is now critical. The lead time to develop a mine after outlining a resource is at least 5 to 10 years, so the timely availability of financing will be key. China is already the market leader in REE and appears prepared to continue investing and financing REE projects – not only in China but also in other countries. This initiative needs be matched by Western institutions and governments to strengthen and provide resilience to the global supply chain.

11.3. Global Economic Opportunities

Economic deposits of REE are generally a scarce resource in the world. The pipeline of economic projects has not been developed fast enough to match future expected demand at this moment in time. This will enable REE mines and projects over the next 10 years to ride this wave of positive sentiment – and likely higher prices – out to at least 2030. One partial solution to increasing supply is for planned mining operations to consider enlarging their processing capacity, where REE resources and capital are available, to capture a larger share of above-normal profits that may be available over the next decade and beyond.

Existing REE production in Brazil is low and derived from tailings recovery. However, Brazil currently has two advanced REE projects – Serra Verde (expected to commence production in 2022) and Morro do Ferro (currently in the pre-feasibility stage and could come on stream in the next few years). Brazil has the third largest resource base and significant potential to expand REE production from new and existing niobium mining operations in the Araxá region, where most of these resources are located.

11.4. Key Recommendations

Brazil has a window of opportunity to ramp up its REE output over the next few years. The REE market is expected to be in deficit over the next decade, and if prices rise as a result (as is currently the case), the REE market could offer attractive returns for investors. The Government of Brazil should therefore look to further develop its resources and encourage investment in the longer term by:

- **Increasing access to, and circulation of, up to date REE resource data to domestic and international exploration companies to promote REE development in Brazil.** Increasing access to data may require gathering and distributing more extensive information from those regions that are considered to have significant REE potential. Legacy CPRM geological data, reports, and studies should be made more broadly available online in a range of languages. Brazil should also undertake appropriate marketing of these documents to expand their circulation and increase their impact.
- **Pursuing a faster and larger expansion of its existing REE production.** Brazil should accelerate discussions with the country's two REE proposed projects, bring forward the timing, and expand the scale of their planned operations.[36] Any expansion should satisfy economic return requirements, but the Government of Brazil could help expedite the projects by providing streamlined approvals, infrastructure and/or workforce skills support, credit guarantees, higher capital allowances, and tax reductions, if required and appropriate.
- **Expediting the assessment of the potential of the Araxá region.** Brazil has the potential to produce REE as a by-product from an existing niobium mine in Araxá in Minas Gerais. CBMM, a private entity, has been exploring the feasibility of producing REE from an existing niobium mine in Araxá in Minas Gerais for several years. The status of this project is currently unknown, but Brazil should verify whether it can become a significant source of future REE production. Again, the project should satisfy economic return requirements, but the Government of Brazil could assist by providing credit guarantees, higher capital allowances, and tax reductions.

[36] Brazil has two advanced REE projects – Serra Verde (expected to begin production in 2022) and Morro do Ferro (at the pre-feasibility stage).

- **Developing downstream processing facilities to capture more of the REE value chain.** Downstream REE processing is currently concentrated in China, but Brazil could process REO concentrates as part of a strategy to develop a downstream REPM industry. Processing REO concentrates would capture more of the REE value chain, provide skilled employment, and allow Brazil to produce REPMs. These are a key input into electric motors for EVs and wind turbines, and could be part of a strategy to also develop these industries further. Brazil could begin to achieve this by building a facility to process REO concentrate to produce REE. CBMM has also been working with the Institute for Technological Research (IPT) to assess the possibility of processing REO into REPM powders.
- **Undertaking a comparative review of Brazil's exploration and mining policies versus those of other countries with REE projects.** This review should analyze whether Brazil's government can encourage REE exploration and mine development through legal, regulatory, and environmental, social, and governance (ESG) improvements. Such improvements may include simpler licensing and permitting processes, lower royalties, preferential tax rates, and more robust environmental policy.[37] The ultimate objective of such policy improvements should be to encourage development and stability for investors looking to develop Brazil's mineral sector as a whole, and REE specifically. The Pro-Strategic Minerals policy which focuses on simplifying the environmental licensing process by facilitating a dialogue between different environmental agencies in the country is a right step in this direction.

[37] Effectively mitigating and managing the environmental impact of REE projects is challenging. It is a complicated process to isolate individual REEs into nearly-pure metal oxides due to their complex physio-chemical properties. Techniques, such as dry processing (dry processing techniques include gravity methods for separation of REEs and pilot techniques such as separation from coal ash and tailings) cause less harm to the environment; though the potential to create radioactive particles (e.g., uranium and thorium) as a by-product would require strict dust control measures to mitigate exposure risks to workers and surrounding communities.

ANNEX 1 – TYPICAL RARE EARTH DEPOSIT TYPES

REEs can be incorporated into a range of different mineral types, such as carbonates, oxides, silicates, and phosphates, each of them related to specific geological environments. The geology and exploration of REE deposits can be complex but important and this annex gives a summary of the main geological types of REE deposits[38] for reference when benchmarking REE deposits.

Alkaline Igneous Rock Deposits

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

Carbonatite Deposits

Carbonatites are unusual magmas with less than 50 percent modal carbonate minerals, most commonly found in continental-rift tectonic environments, often associated with alkaline igneous rocks. These low-degree mantle melts may contain high concentrations of REE and crystallized REE carbonates and REE fluorocarbonates as well as REE phosphates. The carbonatite-associated deposits are dominated by LREE-enriched REE minerals. Significant carbonatite deposits include Mountain Pass (United States), Mt. Weld (Australia), Bayan Obo (China), and Longonjo (Angola).

Granite and Pegmatite Deposits

Granite and pegmatite hosted REE deposits are associated with highly evolved, residual melts formed by the fractional crystallization of a fertile granite body. Deposits of this type were the first to be exploited in the early twentieth century, for example the Yrrerby deposit in Sweden. However, these are rarely promising exploration targets due to their small tonnage and complex mineralogy, but often have potential for by-products such as beryllium, fluorine, and niobium.

Vein and Skarn (Hydrothermal) Deposits

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

Iron Oxide-Apatite Deposits

The iron oxide-apatite deposits of the Kiruna type in the Sveofennian belt are also enriched in REE due to apatite, including Kiruna, Malmberget, and Grangesberg-Blotberget deposits in Sweden. Some iron-oxide copper gold deposits such as Olympic Dam in Australia carry the mineral apatite, which has the potential to produce REE as a by-product. The REE-bearing apatite is currently treated as waste during iron ore processing.

[38] Development of a Sustainable Exploitation Scheme for Europe's Rare Earth Ore Deposits.

Placer Deposits

Some of the REE-bearing minerals, such as monazite and xenotime, are relatively resistant to weathering and can be transported by sedimentary processes. As a result, they can become concentrated in heavy mineral sands deposits, referred to as placers. Such placers can form in rivers, in arid environments (dunes), or in beach and shallow marine environments. Currently, mineral sand mining operations in India, Malaysia, and Australia, which mine cassiterite (Sn), rutile (Ti) and/or zircon (Zr), also stockpile monazite and/or xenotime from which REE can be produced as by-products.

Bauxite Deposits

Accumulation of residual clay minerals or karst limestone surface followed by chemical weathering under tropical conditions can lead to the formation of bauxite deposits. This process has the potential to generate near-surface bauxite due to crystallization of authigenic REE-bearing minerals, accumulation of residual phases and the adsorption of ions on clays and other mineral surfaces. The Mediterranean bauxite deposits have potential to produce REE as a by-product from aluminum production.

Ion-Adsorption Deposits

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

Table 9: Some of the Most Common REE Minerals

Mineral	Formula	Weight % REO	Type of Deposit	Other Variants
Carbonates and Fluorocarbonates				
Ancylite*	$SrCe(CO_3)_2(OH)H_2O$	43	C	La
Bastnäsite*	$CeCO_3F$	75	C, A, H	La,Nd,Y
Huanghoite	$BaCe(CO_3)_2F$	40		
Parisite*	$CaCe(CO_3)_3F_2$	50	C	Nd
Synchysite	$CaCe(CO_3)_2F$	51	C, H	Nd,Y
Phosphates				
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	-	C, IA	
Cheralite*	$CaTh(PO_4)_2$	variable		
Churchite	YPO_42H_2O	51		Nd
Florencite	$(Ce)Al_3(PO_4)_2(OH)_6$	32	H	Sm
Monazite*	$CePO_4$	70	C, P, H, A	La,Nd,Sm
Xenotime*	YPO_4	61	H, A, P	Yb
Oxides				
Aeschynite	$(Ce, Ca, Fe, Th)(Ti,Nb)_2(O,OH)_4$	32	H	Nd,Y

Mineral	Formula	Weight % REO	Type of Deposit	Other Variants
Cerianite	CeO_2	100	A, C	
Loparite	$(Ce, La, Nd, Ca, Sr)(Ti, Nb)O_3$	30	A, C	
Yttropyrochlore	$(Y, Na, Ca, U)_{1-2}Nb_2(O,OH)$	17		
Silicates				
Allanite*	$CaNdAl_2Fe_2+(Si2O_7)O(OH)$	23	A	La,Nd,Y
Britholite	$(Ce, Ca,Sr)_2(Ce, Ca)_3(SiO_4PO_4)_3(O,OH,F)$	23	H	Y
Eudialyte	$Na_{15}Ca_6Fe_3Zr_3Si(Si_{25}O_{73})(O, OH, H_2O)(Cl, OH)_2$	9	A	
Fergusonite	$CaNdAl_2Fe^{2+}(SiO_4)Si_7O_7)O(OH)$	53	A	Nd,Y
Gadolinite	$Ce_2Fe^{2+}Be_2O_2(SiO_4)_2$	60	H, A	Y
Gerenite	$CaNdAl_2Fe^{2+}(SiO_4)(SiO_7)O(OH)$	44		Y
Kainosite	$Ca_2Y_2(SiO_3)_4(CO_3)H_2O$	38		
Keiviite	$Y_2Si_2O_2$	69		Yb
Steenstrupine	$Na_{14}Ce_6(Mn^{2+})_2(Fe^{3+})_2Zr(PO_4)_7Si_{12}O_{36}(OH)_{23}H2O$	31	A	
Fluorides				
Fluocerite	CeF_3	83	H	La

Source: EURARE, based on Wall (2014) and Goodenough (2016). H = hydrothermal, C = carbonatite, A = alkaline igneous, P = placers, IA = iron-oxide-apatite deposits. * Potential ThO_2 and/or UO_2 content.

ANNEX 2 – MINING AND BENEFICIATION OF RARE EARTH

Most commodity exploration projects follow the same principal pathway from discovery of the occurrence through to exploration and mining. For REE, traditional geophysical methods cannot be applied if the occurrence is not genetically associated to sulfide systems. Also, sometimes pilot testing of the REE mining and recovery process will take place before full scale development occurs.

As a result of the wide range of mineralogy of REE ores, several different technologies can be applied for the exploitation of these ores. Some are mined as the main product from hard-rock deposits; some are mined as by-products from large-scale iron mining operations; some are extracted from heavy-mineral sand dredging operations; and some are leached out from ion-adsorption clay deposits. Invariably the whole content of REO is initially extracted from the mine within the ore, irrespective of their value, because of the complex mineralogy.

Mining of REE

Large, low-grade, near-surface ore deposits are amenable to open-pit mining methods. These methods typically involve the removal of overburden, extraction of the ore by digging or blasting, and the removal of the ore by conveyor belt or truck for stockpiling prior to processing.

Land-based placer deposits are amenable to strip mining using scrapers, bulldozers, and loaders to collect and transport the typically poorly consolidated ore to the processing plant. Drilling and blasting are typically not required, except in deposits where materials have become cemented. Hydraulic mining methods can also be used to extract ore from loosely consolidated placer deposits.

For ion-adsorption clay deposits, mining is simpler than other types of deposits due to their near-surface, unconsolidated nature, although they are relatively low grade. No drilling or blasting is required which considerably reduces extraction costs.

Mining typically leads to the extraction of waste rock which is commonly stored in stockpiles at the mine area. Subsequent processing also produces waste (tailings) which must be stored.

Figure 32: Mt Weld REE Mine, Australia

Source: Lynas Rare Earths

REO Concentration

REE mineralogy and textures are very complex, grades are typically low, and a unique beneficiation flowsheet is required for each deposit. Some deposits also contain radioactive materials uranium and thorium. Only bastnäsite, monazite and xenotime are regularly commercially processed for REE. Processing designs for beneficiating apatite, eudialyte, steenstrupine, and allanite are still at pilot stage. The beneficiation process does not alter the chemical composition of the ore; rather, these processes are intended to liberate the mineral ore from the host material and concentrate it.

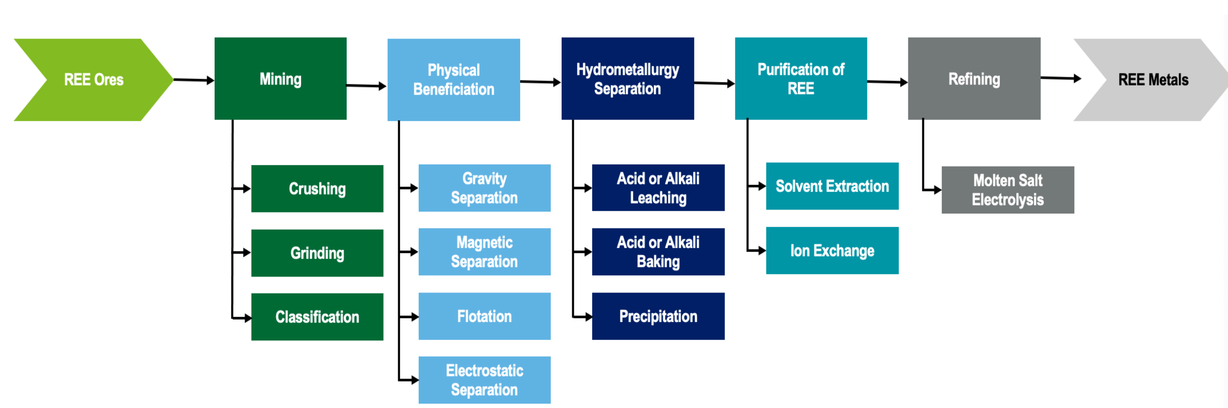
Once a hard rock deposit has been mined, the rock is crushed and ground at the entry point of the processing plant. This liberates the target minerals so that they can be separated from the tailings during the beneficiation process. The optimal beneficiation methods vary according to the grain size, mineralogy, and texture of the ore. These characteristics are different for every REE deposit. Where the ore has a coarse grain size, it can be crushed coarsely, and it may be possible to concentrate the minerals using physical methods such as gravity or magnetic separation. Finer grained rare earth minerals need to be separated using methods such as froth flotation.

For ion-adsorption clay deposits, the REO are either leached directly in a tank or leached in-situ with a reagent of ammonium sulphate which is collected and then channeled into tanks where ammonium carbonate is used as a precipitating agent to produce a concentrate.

Placer deposits show considerable variation in mineralogy and chemical composition and so the beneficiation methods can vary but often involves gravity separation which is effective for separating minerals with significant differences in density.

These processes produce an REO mineral concentrate. At the end of this concentration phase, the total REE content of the concentrate may be 50 percent for bastnäsite, 53 percent for monazite, and upwards of 90 percent for ores derived from ion-adsorbed clays.

Figure 33: REE General Processing Route



Source: Deloitte

Hydrometallurgy Separation

Once the ore minerals have been concentrated through beneficiation, leaching (or cracking) of the concentrate to dissolve and separate the REE from the minerals, using acid or alkaline solutions (hydrometallurgy), depending on the mineralogy and gangue materials. Typically, the acid route is the most common, accounting for at least 90 percent of extraction methods. Hydrometallurgical treatment is well developed for some of the commonly processed rare earth minerals such as monazite. The typical commercial product of the leaching step is a mixed REO carbonate grading 25 to 60 percent REO. The concentrates can then be transported for REE purification.

REE Purification

For REE purification, the three main methods utilized are fractional step method, the ion exchange method, and the solvent extraction method. Ion exchange and solvent extraction are the main processing technologies applied on an industrial scale.

Fractional Step: The fraction step method is based on different solubilities but is a long process for the extraction for each element, which reduces then feasibility of this method at large scale.

Ion Exchange: The ion exchange method was developed initially to remove uranium and thorium), but later used to purify REE. Again, the process is long and discontinuous and no longer preferred, although it is still used to produce high purity products.

Solvent Extraction: The main method for REE purification is now solvent extraction (SX). This method centers on a leach solution of REE which is forcibly stirred with an immiscible organic solvent which extracts the preferred elements and separation occurs.

Generally, purification of the LREE is relatively straight forward, but the HREE are more difficult to separate and requires specialized process technology. Reportedly, outside of China, only NPM Silmet in Europe (a subsidiary of Neo Performance Materials [TSX: NEO]) and Sumitomo Corp. of Japan have the technology to be able to separate HREE. An insoluble salt is precipitated from the solution, which is dried or calcined at high temperatures. REE compounds with a purity of 99.99 percent can be produced using this method. A conventional SX-plant has a multitude of mixer-settlers and tends to have a high capital cost.

Other separation and purification technologies have also been patented, including RapidSX and Molecular Recognition Technology. Ucore [TSXV: UCU] is planning to use RapidSX technology for its Bokan Mountain project in Alaska. A 60 to 70 percent saving in capital expenditure on equipment is projected for the 2,000 t/y LREE and HREE separation and purification facility. Operating costs are reported to be competitive with SX operators located in China and process time much quicker.

Once the REEs have been separated and purified, the remaining step is the electrowinning of high-purity REE metal. Neodymium and praseodymium can be produced separately, or as an alloy (didymium), using an oxyfluoride molten salt electrolysis process.

Recoveries of REEs can vary considerably depending on the ore type and the mineral content and grade. For beneficiation, estimated global average recoveries for lanthanum, cerium, and yttrium are approximately 75 percent, for neodymium and praseodymium approximately 70 percent, dysprosium approximately 65 percent and the remaining REE around 50 to 60 percent[39]. Metallurgical recoveries are about 90 percent.

[39] Alkane Resources presentation 2017

Radioactive Materials

Radioactive elements (thorium and uranium) are commonly associated with REE-bearing minerals, where the concentration depends on the mineral, the formation of the rocks, and the geographical position of the deposit. Uranium and thorium are either incorporated into the lattice of the REE minerals or in associated minerals within the ore mineral assemblage. This is particularly the case for alkaline igneous and carbonatite associated REE mineralization, and typical for placers.

The presence of radioactive elements causes various problems in the environment and waste management. The extraction of thorium and uranium is necessary to ensure having a low radioactive product, while the loss of REE is minimized and ensuring minimum radioactivity in the downstream processes, and to mitigate the environmental and safety issues. Uranium and thorium content is therefore an important factor for evaluating the attractiveness of REE deposits, as management of highly radioactive ores can add to costs and is a key challenge for the permitting of a project.

The utilization of conventional hydrometallurgical processes such as selective precipitation, leaching, and solvent extraction for the extraction of radioactive elements is often conducted using complex industrial processes. Depending on the process requirements and limitations, either one- or multi-step processing would be applied to efficiently separate radioactive elements from REE. The uranium and thorium will typically exit the extraction circuit, and either be collected as a by-product or become radioactive waste.

ANNEX 3 – RARE EARTHS AND USES

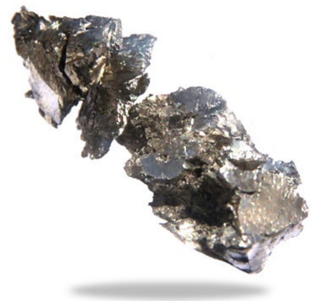
The REE are a group of 17 chemically similar metallic elements including the 15 Lanthanides, along with scandium, and yttrium. Table 8 lists the REE and their main applications.

Table 10: REE Main Uses

Rare Earth Element	Application	
Light rare earths		
Lanthanum (La)	Battery alloys, metal alloys, auto catalysts, petroleum refining, polishing powders, glass additives.	
Cerium (Ce)	Battery alloys, metal alloys, auto catalysts (emissions control), petroleum refining, polishing powders, permanent magnets.	
Praseodymium (Pr)	Battery alloys, metal alloys, auto catalysts, polishing powders, glass additives, and coloring ceramics.	
Neodymium (Nd)	Permanent magnets, battery alloys, metal alloys, auto catalysts, glass additives, and ceramics.	
Promethium (Pr)	Watches, pacemakers, and research.	
Samarium (Sm)	Magnets, ceramics, and radiation treatment (cancer).	
Europium (Eu)	Phosphors.	
Heavy rare earths		
Gadolinium (Gd)	Ceramics, nuclear energy, and medical (magnetic resonance imaging, X-rays).	
Terbium (Tb)	Fluorescent lamp phosphors, magnets especially for high temperatures, and defense.	
Dysprosium (Dy)	Permanent magnets.	
Holmium (Ho)	Permanent magnets, nuclear energy, and microwave equipment.	
Erbium (Er)	Nuclear energy, fiber optic communications, and glass coloring.	
Thulium (Tm)	X-rays (medical) and lasers.	
Ytterbium (Yb)	Cancer treatment and stainless steel.	
Lutetium (Lu)	Age determination and petroleum refining.	
Other rare earths		
Yttrium (Y)	Battery alloys, phosphors, and ceramics.	
Scandium (Sc)	High strength, low weight aluminum scandium alloys	

Source: MRS Energy & Sustainability 2018

Figure 34: Neodymium, Praseodymium and Dysprosium Properties

Neodymium	Praseodymium	Dysprosium
		
Neodymium is a silvery-white metal that is moderately reactive and quickly oxidizes to a yellowish color in air. The metal is soft and ductile. The oxide is a pale white powder.	Praseodymium is a soft, silvery, malleable, and ductile metal, valued for its magnetic, electrical, chemical, and optical properties.	Dysprosium has two paired electrons giving it the ability to detect radiation, improve permanent magnets, store digital data, precisely aim lasers, emit sonar pings, or glow in the dark.
Atomic number 60	Atomic number 59	Atomic number 66
Atomic weight: 144.2	Atomic weight: 140.9	Atomic weight: 162.5

Source: Hastings Technology Metals.

Permanent Magnets

Neodymium, praseodymium, dysprosium, and terbium are important REE constituents in producing high-strength permanent magnets (PMs), such as those found in motors in EVs, hard disk drives, loudspeakers, and generators in wind turbines. There are two main types of rare earth-bearing permanent magnet: neodymium-iron-boron magnets (NdFeB) and samarium-cobalt magnets (SmCo). Sometimes praseodymium, gadolinium, and cerium are also used in the manufacture of PMs in place of Nd, although they generally produce weaker magnets.

EVs are the largest consumers of rare earth-bearing permanent magnets (REPMs), followed by generators used in direct drive (gearless) wind turbines, which can contain up to 1,200 kgs of REPMs. However, the forecast growth in demand for electric vehicles is likely to be the most important driver of increased demand for REPMs in the coming decades.

Catalysts

Rare earth elements (cerium, lanthanum, and neodymium) are primarily used in two different types of catalytic application: (1) automotive catalysts that convert pollutants in engine exhaust gases into non-toxic compounds; and (2) catalysts used in petroleum refining, or fluid catalytic cracking (FCC). Automotive catalysts account for approximately 20 to 25 percent of total REO demand in the catalyst sector and REE-based catalysts used in FCC account for approximately 65 to 75 percent of the total REO catalyst demand.

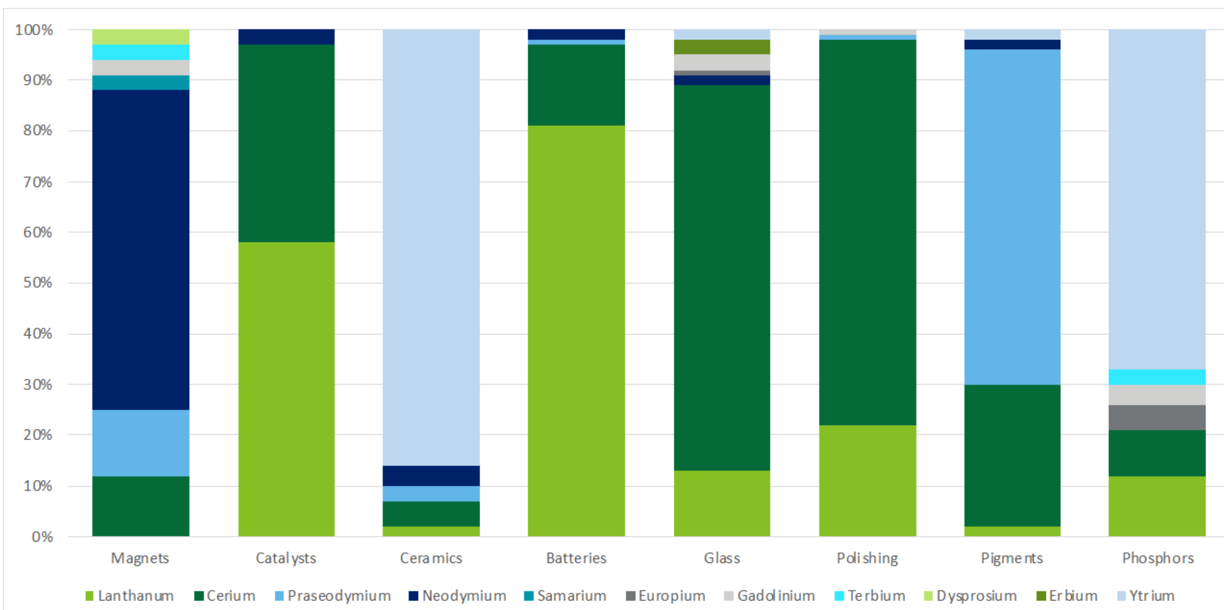
The use of cerium and cerium compounds (such as cerium carbonate) in auto-catalysts improves oxidation efficiency by allowing the catalyst to operate at higher temperatures. This has led to a reduction for platinum and other precious metals used in auto-catalysts and has reduced overall costs. FCC is used by oil refiners to obtain lighter fraction petroleum distillates (such as LPG) from high-molecular weight hydrocarbons. Lanthanum-based catalysts are used to improve the thermal stability and selectivity of zeolites used in the cracking process. Lanthanum-based catalysts also increase the yield compared with REE-free zeolite catalysts.

Ceramics

REEs are used to produce decorative ceramics, functional ceramics, structural ceramics, bio ceramics and many other types of ceramics used in everything from jet engine coatings to ceramic cutting tools, dental crowns, ceramic capacitors, ceramic tiles, and more.

Yttrium and cerium are the most used REEs in the production of ceramics, although neodymium, gadolinium, samarium, and lanthanum are also utilized. The addition of REEs in ceramics typically improves strength, wear resistance and high-temperature performance. For example, yttrium-bearing refractory ceramics are used to line furnaces and crucibles used in metallurgical industries. REO-bearing ceramics are used in electrical applications, such as the manufacture of resistors, capacitors, and thermistors, in which they typically improve the capacitance and dielectric properties. Engineering ceramics can contain yttrium oxide, high-performance ceramics that are used in demanding environments such as gas turbines and car engines, or in the manufacture of high-speed cutting tools and high-performance bearings.

Figure 35: Distribution of REE Demand in End-use Applications 2021



Source: Roskill 2021

Batteries

REEs are used to produce anode materials for nickel-metal hydride (NiMH) batteries. NiMH batteries are used in hybrid electric vehicles, consumer electronics, cordless power tools, home appliances, and other applications of rechargeable batteries. The main REEs used in batteries are lanthanum, cerium, neodymium, and praseodymium. Large NiMH batteries containing up to 17 percent REE by weight.

Metallurgical and Alloys

Rare earth mischmetal (a mixture of LREE metals) is used during production of some types of steel, as well as ductile iron making. REEs are also used to produce a variety of different alloys, such as ferro-cerium, ferro-holmium, ferro-gadolinium, ferro-dysprosium, and a growing list of others.

REEs are primarily added to alloys to: (i) increase their strength at high temperature; (ii) improve their resistance to oxidation and/or corrosion; and (iii) improve ductility (workability). The amount of REE added to cast steels, and high strength low alloy (HSLA) steels is low, typically less than 1 percent. However, the amount added to some high-performance stainless steels, and to magnesium- and aluminum-based, alloys can be as high as 5 percent. These lightweight alloys are generally used in the automotive sector to manufacture vehicle frames and engine blocks; they are also widely used in the aerospace sector. Some substitution has taken place in metallurgy, such as REEs used to remove impurities during casting which are increasingly being substituted for less expensive metals, such as magnesium and calcium.

Phosphors

REEs are used in phosphors for energy efficient lamps, display screens and avionics, light emitting diodes (LEDs), and are added to fiat currency in some nations as an anti-counterfeit measure. REE-based phosphors emit luminescence with specific colors when activated by light-energy. For example, yttrium and europium compounds are used to produce red phosphors; green phosphors contain terbium compounds; while blue phosphors are cerium based. The use of REE-based phosphors in modern lighting applications has led to more energy efficient lighting that has a much longer lifespan. However, LEDs contain REEs in only very small amounts compared with other lighting technologies and consequently with the growth of LEDs relative to other types of lighting, the demand for REEs in the category has declined.

Glass and Polishing

REEs such as cerium, are used to polish optical glass, hard disk drive platters, LCD display screens and gemstones, among a long list of applications. Cerium is also used as an additive in UV-filtering glass and container glass, whereas lanthanum, yttrium, and gadolinium are used to produce high quality optical glass used in camera lenses, microscopes, and telescopes.

Neodymium, praseodymium, erbium, and cerium are also used to impart red, green, pink, or yellow brown colors to glass products; they may also be used to remove impurities (such as iron oxides) from clear glass that may otherwise cause unwanted coloration. REO of lanthanum, gadolinium, and yttrium are applied to optical glass products as coatings. Lanthanum oxide is commonly used in the manufacture of camera lenses, in which low dispersion and a high refractive index are desirable properties. Cerium-based compounds are typically added to glass bottles and sunglasses lenses to reduce the effects of UV radiation (sunlight).

The most used REE-based polishing compound is cerium oxide, used to finish the surface of several glass products, for example display panels, flat glass, optical glass, and glass used in consumer electronics. Cerium oxide is favored as a polishing compound because it removes glass by both chemical dissolution and mechanical abrasion making it more efficient than silica- or zirconia-based compounds.

Other applications

Minor amounts of REEs are used in a long list of other end uses and applications, including many in defense, medicine, agriculture, high-tech, and chemical industries. Cerium is the most widely REE in many of these applications. Laser, microwave, and gemstone applications tend to utilize HREE (yttrium, gadolinium, erbium, and ytterbium), while many of the other applications (such as textiles, medicines, and paints) are heavily reliant on LREE (lanthanum, cerium, and neodymium).

The addition of REEs to paint improves resistance to fading, but also reduces paint drying times. REEs are also used in some biological applications, for instance medicines, fertilizers, and water treatment. Examples include cerium- and neodymium-based medicines used to treat conditions such as motion sickness and thrombosis; the use of cerium and lanthanum in fertilizers to increase crop yield, and the use of cerium and lanthanum to remove phosphates during water treatment.

ANNEX 4 – REE PERMANENT MAGNETS

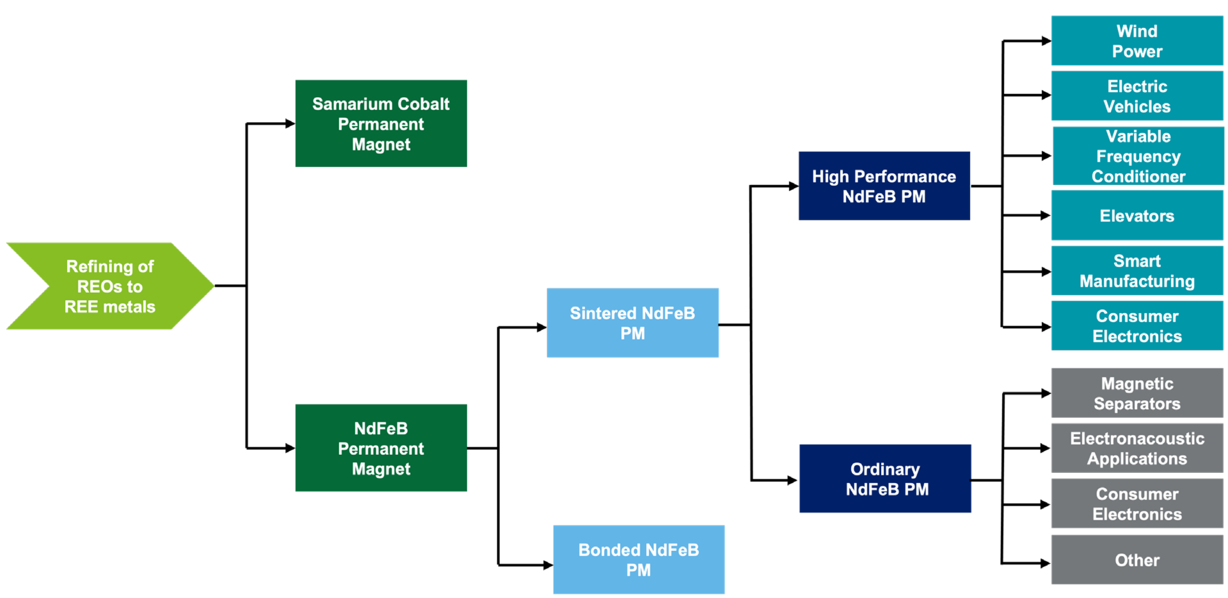
Types of Rare Earth Permanent Magnets

A permanent magnet (PM) is an object made from a material that is magnetized and creates its own persistent magnetic field. There are various types of permanent materials and an REE permanent magnet (REPMs) is one type of permanent magnet made from alloys of the lanthanide group of REE. Neodymium-iron-boron permanent magnets (NdFeB PMs) can be regarded as the most widely used type of REPMs.

Generally, an NdFeB PM is a permanent magnet that is mainly made from an alloy of neodymium, iron, and boron to form the $Nd_2Fe_{14}B$ tetragonal crystalline structure. A neodymium magnet's basic structure is composed of a rectangular prism that has a high potential for storing magnetic energy. NdFeB PMs can be classified into sintered NdFeB PMs and bonded NdFeB PMs.

Bonded NdFeB PMs are formed by injection molding of powder with a resin matrix, giving high dimensional accuracy. Sintered NdFeB PMs are formed through heating the powder at high temperature in a mould. With sintering, the various shapes of magnets needed to go through mechanical processing (such as wire cutting, slicing, and grinding) since there is large contraction in the mould. Sintered NdFeB is a hard and brittle material that is difficult to process, so there is a large loss during processing and the final surface needs to be electroplated. This makes sintered NdFeB PMs much more expensive than bonded NdFeB PMs, but the performance of sintered NdFeB PMs is much higher (more than x5) than bonded NdFeB PMs.

Figure 36: REPMs Supply Chain



Source: Deloitte

Sintered NdFeB PMs can be further classified into high-performance NdFeB PMs and ordinary NdFeB PMs. In China, only a few manufacturers have the capability of manufacturing high-performance NdFeB PMs. High-performance NdFeB PMs are mainly used in energy saving and environmental protection products, such as wind generators and EVs, while other NdFeB PMs are mainly used in magnetic separators, electroacoustic applications, and others.

Apart from NdFeB permanent materials, the other form of REPMs is samarium cobalt magnetic materials which only account for approximately 1 percent of the entire REPMs and are mainly used for military applications. Theoretically, samarium cobalt magnets can be used as alternatives in NdFeB PMs' downstream applications. Practically, they cannot be widely used due to the scarcity and the extremely high price of the raw materials of samarium cobalt magnets[40].

The exact composition of REE within an NdFeB permanent magnet can vary, with different proportions of the different elements leading to different magnetic properties. Neodymium and praseodymium can in principle be substituted by other elements (gadolinium and cerium), but this is often limited by the operating condition specifications. In the past few years, most research has focused on the optimization of the use of dysprosium and terbium, which are both costly and poorly available. These two elements are used to improve a magnet's resistance to demagnetization, allowing for higher working temperatures. The use of terbium is currently limited as it has the same function as dysprosium but is significantly more expensive.

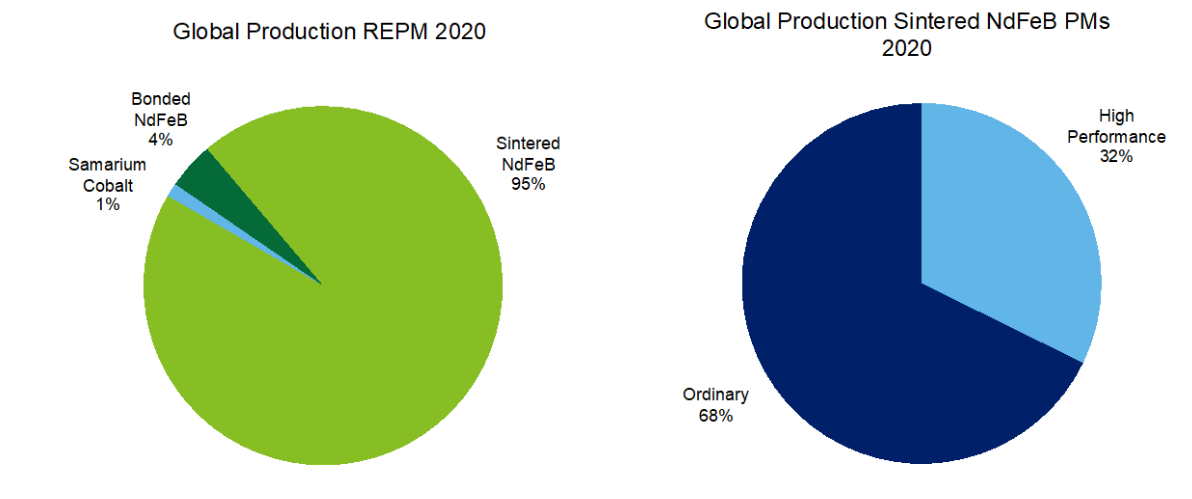
Compared with other REPMs, NdFeB PMs have several advantages. NdFeB PMs are much more powerful than other REPMs and can therefore be used on a smaller scale to produce the same magnetic fields. Moreover, they have a higher resistance to losing magnetic properties, while weaker REPMs can sometimes become demagnetized under certain conditions. The benefit of moderate temperature stability enables NdFeB PMs to work in relatively high-temperature environments. With the advantages of high efficiency and low energy consumption, good control performance and strong stability, as well as small size, light weight, and diversified structure, NdFeB magnetic motors are widely used in various industries such as wind generators and the EV manufacturing industry.

In 2020, global production volumes of REPMs totaled 217.4 kt with a growth CAGR of 7.7 percent from 2015 to 2020. Production is forecasted to continue growing at a similar CAGR out to 2025 with volumes reaching approximately 310.2 kt.[41] China is not only the largest producer of REPMs but also the largest consumer and a net exporter. In 2020, China produced 196.2 kt of REPMs, 90 percent of global production, and is expected to produce 284.2 kt in 2025 (92 percent). Since 2015 (earliest data), production volumes have marginally exceeded consumption. In 2020, global consumption of REPMs totaled 209.5 kt.

[40] JL Mag Rare Earth Prospectus Jan 2022

[41] Frost and Sullivan 2021

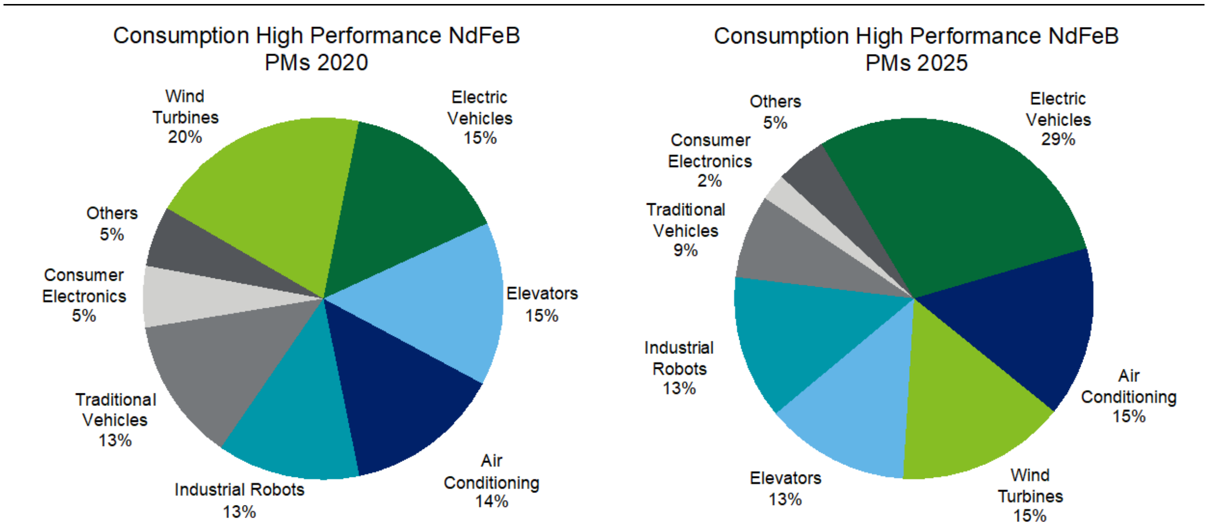
Figure 37: Production of REE Permanent Magnets 2020



Source: JL Mag Rare Earth.

High-performance NdFeB PMs are mainly used in wind turbine generators, energy-saving variable frequency air-conditioners (VFAC), energy-saving elevators, EVs, industrial robots, and others.

Figure 38: Consumption of High Performance NdFeB Permanent Magnets 2020 and 2025F



Source: JL Mag Rare Earth, Frost & Sullivan.

Technology Issues

Key technologies and raw material formula have a great influence on the performance and the quality of REPMs. For example, the grain boundary diffusion (GBD) technology is used in the manufacturing process of high-performance NdFeB PMs. In this process, post formation of the magnet, a target of pure dysprosium or terbium in a vacuum furnace is used to generate a vapor that diffuses into the surface layers of the magnet. Adhesive and electrodeposition coatings have also been deployed. Several groups, including Hitachi Metals, Shin-Etsu, Showa Denko, and various Chinese companies own intellectual property (IP) covering the GBD processes.

The interrelationship between these patents is believed to be complex with various cross-licensing arrangements and similar claims across different patents[42]. GBD is still in its rapid development phase and is far from mature[43]. This technology enables manufacturers to decrease the consumption of medium and heavy REEs (by 50 to 70 percent[44]), reduce the cost of raw materials, and increase the coercivity and the performance of NdFeB PMs.

The formula adopted in processing the REE raw material is usually proprietary and confidential to each manufacturer and often determines the product quality. These key technologies and raw material processing formula result in higher technical barriers for new entrants into the REPMs market. Less Common Metals reports that the IP situation for NdFeB is complex with over 600 patents owned by Hitachi Metals, covering both materials and processing. The main patents expired in 2014 and it is believed that the remaining key material patents expired by mid-2021. Many Chinese producers supply magnets globally without a license.

The global REPMs market is relatively fragmented, with the top three REPMs producers accounting for approximately 15.4 percent. Leading producers include JL Mag Rare Earths (5.8 percent global share), Beijing Zhong Ke San Huan High-Tech, Ningbo Yunsheng, Yantai Zhenghai Magnetic Material, Arnold Magnetic Technologies, ADAMS Magnetic Products, Bunting Magnetics, Eclipse Magnetics, Hangzhou Permanent Magnet Group, Ningbo NGYC Materials, Ningbo Ketian Magnet, and Thomas & Skinner.

Table 11: Typical Composition of NdFeB Alloy Permanent Magnets

Main Elements	Weight Percentage
Iron	64.2 - 68.5
Neodymium	29.0 – 32.0
Boron	1.0 – 1.2
Dysprosium	0.8 – 1.2
Aluminum	0.2 – 0.4
Niobium	0.5 – 1.0

Source: Neodymiummagneti

[42] Less Common Metals

[43] Grain Boundary Diffusion Sources and Their Coating Methods, MDPI 2021.

[44] Frost & Sullivan

Figure 39: Neodymium-Iron-Boron Magnets

Source: Garnet Automazione & Robotica

ANNEX 5 – LIST OF RARE EARTH PRE-FEASIBILITY PROJECTS

Table 12: Significant Active REE Projects at Pre-Feasibility

	Property Name	Country	Company Operator	REO tonnes	Grade REO	Grade NdPr Oxide
1	Ashram	Canada	Commerce Resources	4,686,113	1.88%	0.41%
2	Montviel	Canada	Geomega Resources	3,876,555	1.45%	0.10%
3	Round Top	USA	USA Rare Earth	3,036,757	0.63%	0.05%
4	Zandkopsdrift	S. Africa	Frontier Rare Earths	885,347	1.89%	0.39%
5	Norra Karr	Sweden	Leading Edge Mat.	550,000	0.50%	0.14%
6	Wicheeda	Canada	Defense Metals	498,578	2.93%	0.31%
7	Port Hope Simpson	Canada	Search Minerals	246,220	1.58%	0.32%
8	Kwyjibo	Canada	SOQUEM	236,081	2.86%	0.58%
9	Cummins Range	Australia	RareX	216,500	1.15%	0.23%
10	Morro do Ferro	Brazil	Miner. Terras Raras	149,501	3.77%	0.73%
11	Sarfartoq	Greenland	Hudson Resources	143,245	1.72%	0.42%
12	Lofdal	Namibia	Namibia Critical Metals	90,499	0.17%	0.02%
13	Brockman	Australia	Hastings Tech. Metals	87,586	0.21%	N/A

Source: Deloitte, company reports

Deloitte Financial Advisory Services LLP
1919 N. Lynn Street
Arlington, VA 22209
Phone: +1 571 882 5000
Fax: +1 571 882 5100