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China's rare earths dominance and policy responses

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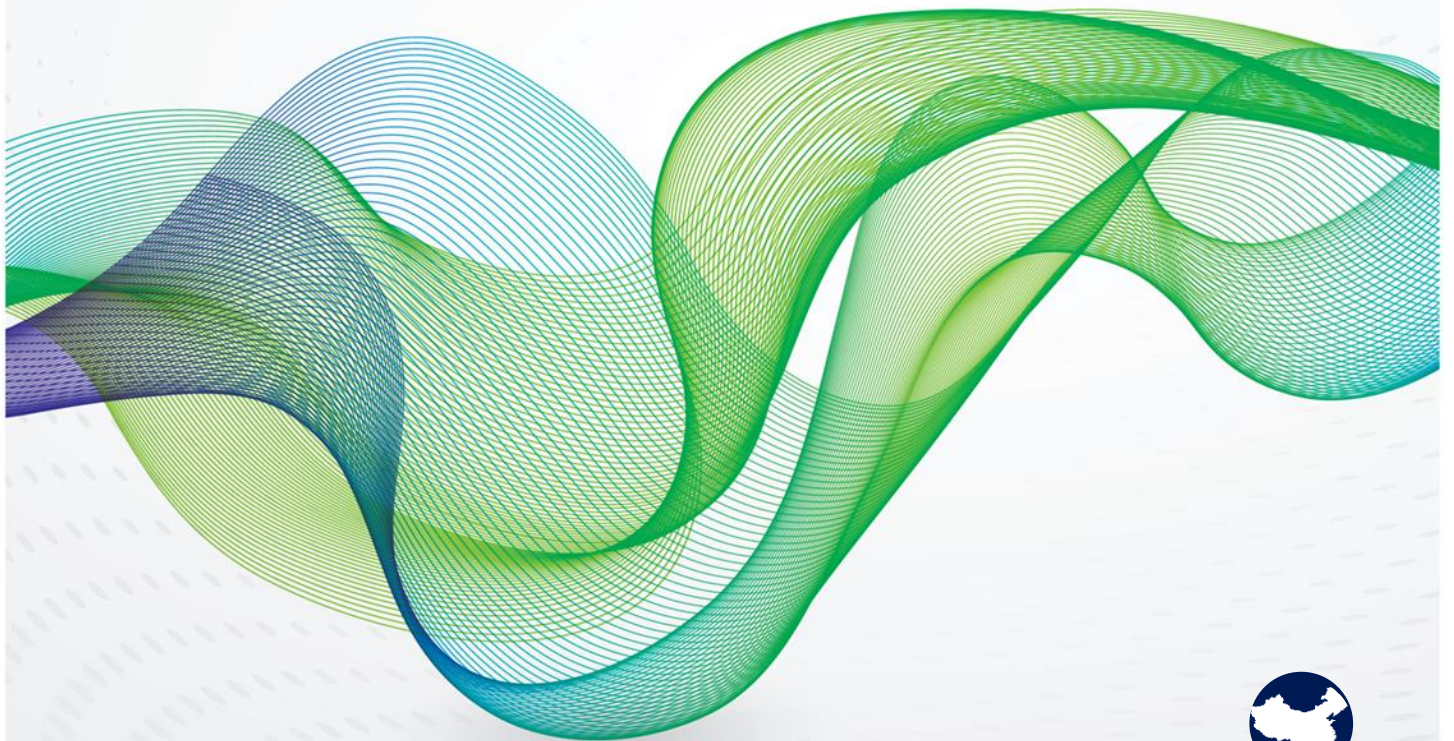
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June 2023

China's rare earths dominance and policy responses



CHINA



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Executive summary

- The rare earth elements (REEs) comprise a group of 17 elements. Whilst not geologically rare, their extraction and processing are complex, expensive, and environmentally hazardous.
- The REEs have many uses that make them especially valuable to the energy and defence industries, notably in the manufacture of energy storage, permanent magnets, catalysts, and lasers.
- China has achieved dominance of REE production and processing through a combination of early moves into the industry, state investment along the supply chain, export controls, low labour costs, and decades of weak environmental regulation that enabled illegal mines and processing plants.
- Demand for REEs is expected to continue to rise dramatically through 2030 and beyond, driven by their use in permanent magnets for electric vehicle (EV) motors (including hybrid vehicles) and wind turbines.
- Alternative technologies could substitute or reduce REE consumption in both EV and wind turbine drives. These include improved materials utilization and lower waste, hybrid drives with smaller permanent magnets, and improving the cost and performance of motors and magnet technologies without REE.
- Given the potential of these options, the future demand for REE is subject to high uncertainty, and will likely depend partly on policy support for reducing REE demand, as well as on market conditions such as prices and supply disruptions.
- These uncertainties on the demand side exacerbate supply-side challenges: investments in mining require long lead times as well as hard-to-find skilled workforce, among other issues.
- Driven by the desire to reduce supply chain risks and enhance national security, efforts are underway in Europe and the USA to reduce China's 90 per cent dominance of REE processing, which include diversifying REE demand by increasing recycling, enhancing the performance of low-REE permanent magnets, and expanding processing capabilities in other countries.
- While 2023 could mark a turning point in light of these efforts, China is virtually certain to remain the global leader in processing REEs through 2030, given the scale of its existing processing industry and position in global battery and electronics supply chains.



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1. Introduction

Rare earth elements (REEs) are key to the global energy transition as they are used in a variety of applications in energy storage and permanent magnets (alongside defence applications). Demand for REEs is expected to rise dramatically through 2030, driven by their use in permanent magnets for electric vehicle (EV) motors (including hybrid vehicles) and wind turbines. Consumer electronics, optics, and lasers also consume REEs, but demand in these non-energy fields is not expected to grow as substantially.

China currently dominates REE production and processing. The country is home to some of the most productive and lowest-cost REE-containing geological formations, which the government has been developing since the 1970s. China has encouraged domestic mining as well as processing of REEs, while also consolidating the domestic industry. The growth in Chinese domestic manufacturing of magnets, EV batteries, and wind turbines has further contributed to China's dominance of the full REE supply chain.

With rising tensions between China and the USA, and following the Russian invasion of Ukraine, fears of supply chain fragmentation and concerns around resource supply security have heightened. Although there have been discussions and analyses of China's dominance of REEs in the past, highlighted by an export ban by China in 2010, policy actions have accelerated more significantly in recent years. Efforts to reduce Chinese dominance of REEs in the West have included designating REEs as a critical material, streamlining approval processes for REE extraction, offering loans and other subsidies for REE processing, reducing the REE content of various devices, forming coalitions of countries working to expand production or processing outside China, and increasing information sharing.

This report looks to unpack China's dominance across the REE supply chain. It asks what are the conditions under which China will remain a significant actor in mining and processing through 2030, and describes the technology and policy developments that have the potential to reduce China's dominance.

It argues that despite efforts to counteract China's dominance of REE supplies, China is likely to remain critical to REE supply chains through 2030. However, 2022 and 2023 may represent a turning point, as the passage of the Inflation Reduction Act (IRA) in the USA and the Critical Minerals Act in the European Union clearly indicate a greater commitment of like-minded countries to diversify away from Chinese REEs.

2. REE geology, mineralogy, reserves, production, and processing

The REEs comprise a group of 17 elements, the 15 lanthanides plus scandium and yttrium. They have been classified into two groups. The light REEs (LREEs) are relatively common compared to the heavy REEs (HREEs). Whilst not geologically rare, their extraction and processing are complex, expensive, and environmentally hazardous.

The REEs have many uses that make them especially valuable to the energy and defence industries, notably in the manufacture of energy storage, permanent magnets, catalysts, and lasers. By consumption volume, neodymium is largest and likely to be the most rapidly growing REE. Four REEs are in notably high demand and therefore fetch a price significantly higher than the others. These are two HREEs (terbium and dysprosium) and two LREEs (praseodymium and europium)¹.

Rare earth elements occur in a variety of geological settings, but these settings tend to be rather unpredictable and are sometimes poorly understood². Most commercial or potentially commercial accumulations of REEs lie in alkaline plutonic rocks, especially in carbonatites. This is the setting for

¹ McNulty et al. (2022).

² Long et al. (2010).



the Bayan Obo mine in China's Inner Mongolia, and the Mountain Pass mine in California, USA. The REEs can also be concentrated in surface layers resulting from the weathering of underlying rocks such as laterites and bauxites. This is the case in Australia's Mount Weld mine and the Zhaibei deposit in southern China. These elements may also occur in river or marine placer deposits, or in the tailings from uranium mines. The Japanese have discovered REEs in deep seabed muds. Most types of REE accumulation yield mainly LREEs and a much smaller quantity of HREEs. This is due to fractionation in the cooling magma bodies. The notable exceptions are the clays of China's Zhaibei deposit and the deep seabed muds off the coast of Japan.

The mineralogy of REE ores is highly variable, often complex, and a key factor in the processing of the ores. Many minerals contain REEs, but bastnasite, monazite, and xenotime contribute almost 95 per cent of REE reserves, with the exception of deposits in clays and weathered crusts³. Processing is much cheaper and simpler for deposits in which the REEs are concentrated in a single mineral.

The scale of proven reserves of REEs across the world is very large—more than 400 times the current annual production⁴. These proven reserves occur on all populated continents, with China, Russia, Brazil, and Vietnam accounting for about 83 per cent of the total. Many REE deposits have been identified but not yet properly evaluated, notably in Africa.

Production of REEs is even more highly concentrated than the reserves, with China accounting for an estimated 70 per cent of global production in 2022. Far behind were the USA with 14.3 per cent and Australia with 6.0 per cent. Three countries in southeast Asia (Thailand, Vietnam, and Myanmar) together produced another 7.7 per cent⁵. The remaining countries accounted for just 2 per cent of global REE output. Importantly, the only producing deposits rich in HREEs lie in China. A number of countries are looking to develop their REE reserves (discussed below), but this is unlikely to fundamentally alter China's dominance over the period to 2030, given the length of time needed to commission REE mines and the challenges around processing.

Rare earth element ores are highly variable in their mineralogy and chemistry. As a result, the processing techniques required to isolate and refine the REEs have to be designed specifically for each deposit. Nevertheless, there are generally five main steps to the production of rare earth metals from the original host rock⁶.

1. Beneficiation involves crushing the rock followed by separating the rare earth oxides from other minerals by froth flotation, magnetic separation, electrostatic or gravity separation, or a combination of these processes. For example, the plant at the Bayan Obo mine in northern China uses gravity separation and froth flotation. Beneficiation increases the concentration of rare earth minerals from 1–10 per cent in the rock to commonly 50–60 per cent. This process is normally carried out close to the mine. The resultant concentrate can then be transported to a plant for further rare earth oxide separation and refining.
2. Chemical treatment, 'cracking', of the rare earth oxides to produce what is called a 'pregnant leach solution'. This commonly used process involves baking and acid digestion, as at Bayan Obo, though some plants use alkaline fluids. The southern Chinese clay deposits require only weak acids.
3. The rare earth oxides are then precipitated by dewatering.
4. The final step of separation aims to produce rare earth oxides with 99 per cent purity. This can involve one of five techniques: supercritical fluid, biosorption, electro-winning, solvent extraction, or ion exchange. The simplest is solvent extraction followed by precipitation.

³ Suli et al. (2017).

⁴ US Geological Survey (2023).

⁵ US Geological Survey (2023).

⁶ McNulty et al. (2022).



5. The final stage is refining of the ores to produce rare earth metals by electrowinning or electrochemical methods. Further purification to as high as 99.9 per cent rare earth metal is achieved by zone refining and electro-transport.

There are only two countries with significant REE processing capacity: China and Malaysia. China dominates this market, accounting for 90 per cent of rare earth metal production in 2019⁷. Most companies that mine REEs send their ores (after beneficiation) to China. The major exception is Lynas, which has built a processing plant in Malaysia to which it sends rare earth ores from its Mount Weld mine in Australia. Estonia has a small facility⁸, and France hosts a plant for recycling REEs⁹. As a result, the concentrates from many rare earth mines are transported to overseas locations for separation and refining.

The reason for the small number of separation and refining plants is that they account for as much as 80 per cent of the capital costs of the entire mine-to-metal supply chain, and 50–75 per cent of the operating costs¹⁰. The operating costs are highly variable and dependent on the costs of energy, reagents, and labour. Preferred locations are close to transportation infrastructure, cheap electricity, and producers of chemicals, and have access to a supply of natural gas¹¹. Environmental regulations will also affect the capital and operating costs.

Both the mining and processing of REEs produce hazardous materials that pose risks to the environment and human health. They also produce vast quantities of waste. One source estimated that the production of 1 tonne of rare earth metal produces 2,000 tonnes of solid waste¹². The nature and scale of pollutants produced varies along the process chain from mining to metal production¹³. In contrast to the hard rock accumulations, REEs in clay deposits are leached *in situ* with large quantities of ammonium sulphate, which can remain in soil and contaminate groundwater unless pumped off and treated or recycled. The nature and scale of pollutant production varies not just along the supply chain but also between REE accumulations. Techniques have been developed to reduce the scale of pollution through emissions treatment or recycling, but their application is not uniformly employed¹⁴.

3. How did China achieve pre-eminence in mining and processing?

China achieved its pre-eminence in REE mining and processing through a combination of early moves into the industry, state investment along the full length of the supply chain, export controls, low labour costs, and decades of weak environmental regulation and illegal mines and processing plants.

China's first discovery of REEs was made in 1927 at Bayan Obo in Inner Mongolia, and production started in the 1950s. The Bayan Obo mine is now the world's largest REE mine. The 1960s saw other discoveries in Shandong and Sichuan Provinces. Exploration in southern China revealed REE accumulations in clays in southern Jiangxi, Guangdong, Fujian, Hunan, and Guangxi. Realizing the importance of these discoveries, the State Council established a National Rare Earth Development and Application Leading Group in 1975. Thereafter, the government steadily ramped up research and development funding for mining and processing, and by the late 1980s China had become a major producer. Further investment in REE refining and processing followed in the 1990s that improved the quality of refined metal and reduced costs. By then, China was exporting rare earth metals in large quantities and at low prices, causing other producers to close or reduce output¹⁵.

⁷ IEA (2021).

⁸ Jiyeong Go (2022).

⁹ Warmington (2023); Atkins (2023).

¹⁰ Sykes (2013).

¹¹ Sykes (2013).

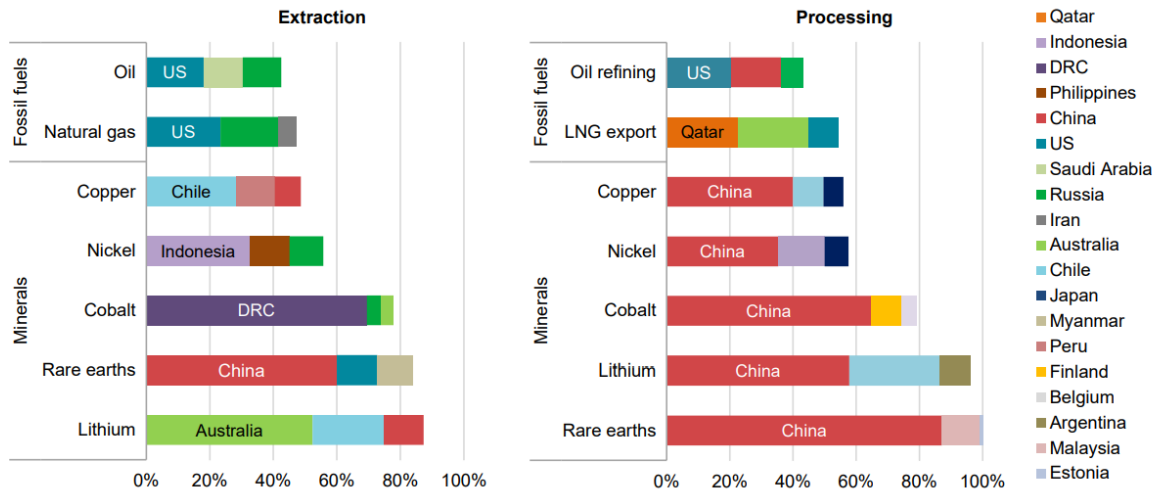
¹² McNulty et al. (2022).

¹³ Zapp et al. (2022).

¹⁴ Zapp et al. (2022).

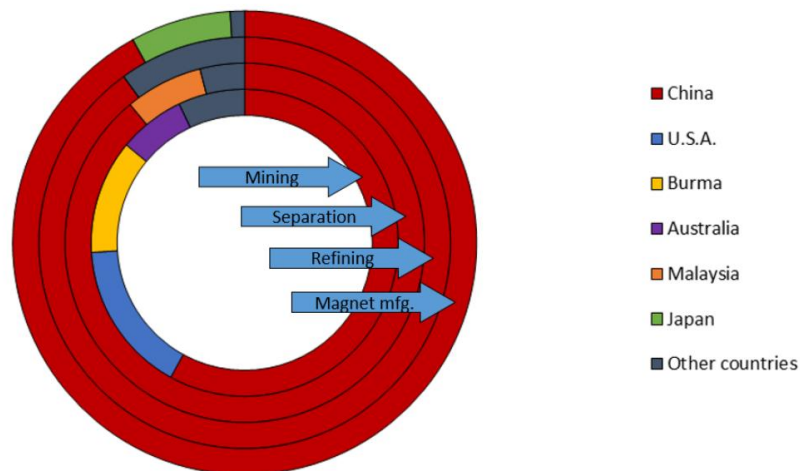
¹⁵ Aguiar de Medeiros and Trebat (2017); Kalantzakos (2018); Shen et al. (2020).

Figure 1: Share of top five countries in critical element extraction and processing (not limited to REE), 2019



Source: IEA (2021)

Figure 2: Share of top countries in REE processing for permanent magnets, 2019



Source: US Department of Energy (2022)

In 1990, the Chinese government classified REEs as ‘protected and strategic minerals’. This meant that foreign companies were excluded from mining REEs and could only process them in joint ventures with Chinese enterprises, subject to government approval¹⁶. Increasing its control over the industry, the government introduced quotas for exports of REEs in the early 2000s that were steadily reduced. In 2005, these were supplemented by production quotas, a ban on the export of rare earth concentrates, and the imposition of an export tax on rare earth oxides and metals¹⁷.

The mining and processing of REEs were having severe environmental and health impacts due to a combination of weak regulation, outdated techniques, and illegal mining¹⁸. At Bayan Obo, beneficiation was releasing water containing 5 per cent radioactive thorium and high concentrations of other pollutants. The high rate of leakage from the tailings dam was due to the absence of a lining. In addition,

¹⁶ Kalantzakos (2018).

¹⁷ Aguiar de Medeiros and Trebat (2017); China State Council (2005).

¹⁸ Kalantzakos (2018).



the workers were suffering from a range of health problems¹⁹. Whilst China's large processing plants had installed scrubbers to clean up the acidic gases released by the cracking process, many small- and medium-scale plants may not have done so²⁰. A study in the city of Baotou near the Bayan Obo mine revealed that citizens' hair contained significantly enhanced concentrations of potentially toxic elements²¹.

The environmental damage was much greater in southern China, where REEs were being extracted from clays by *in situ* leaching and where many mines were illegal. The low recovery of REEs from leaching had led to high concentrations of REEs in tailings which had then leaked into rivers and soils, reducing their acidity²².

In response to the rising concern over excessive capacity in mining and processing, pollution, and poor resource management, in 2010 the government announced a plan to consolidate the industry. The number of mines would be reduced from 123 to fewer than ten, and the number of processing plants from 73 to 20²³. A wider strategy to reform the REE industry was set out by the State Council in 2011 and 2012²⁴. Priorities included:

- Controlling the capacities of rare earth mining and processing, and improving controls over rare earth exports;
- Merging companies into a small number of dominant enterprises whilst removing technologically backward enterprises;
- Improving technological and environmental standards, and imposing more efficient resource and environmental taxes;
- Encouraging technological development in the downstream industry;
- Improving coordination between different ministries, different levels of government, and industry;
- Completing the legal and regulatory systems for rare earths.

Further consolidation to just six enterprises carrying out mining and processing was announced in 2015.

As part of the government's efforts to clamp down on illegal mining and trade of REEs within China, the Ministry of Commerce in 2010 reduced the quota by 37 per cent from that in 2009 to 30,259 tonnes, a level that was less than half of that in 2005. The quota declined by a further 15 per cent in 2011, with HREEs being distinguished from LREEs for the first time. The government also introduced quotas for mining and processing, as well as starting to build REE strategic reserves. The government also increased the tax imposed on exports of rare earth ores, oxides, and compounds, and for the first time introduced an export tax on end products. These strategies resulted in a reduction of the share of production being exported from 90 per cent in 2000 to 20 per cent in 2012²⁵.

The government also reformed its resource tax in a bid to extract more fiscal revenues from the sector. Historically, China's resource taxes were based on the quantity of mineral extracted. After a substantial increase in 2011, the tax rates were Yuan 60/tonne (US\$9.20/tonne) for LREE ore and Yuan 30/tonne (US\$4.60/tonne) for HREE ore. In 2015, the government transformed resource tax to be based on value, following international practice. For rare earth concentrates, the tax rates were 11.5, 9.5, and 7.5 per cent of sales value for Inner Mongolia, Sichuan, and Shandong, respectively, and 27 per cent for

¹⁹ Zapp et al. (2022); Nayar (2021).

²⁰ Zapp et al. (2022).

²¹ Lijun Dai et al. (2022).

²² Wen-shen Liu et al. (2019); Qiuying Zhang et al. (2020).

²³ Zhang Qi (2010).

²⁴ China State Council (2011); People's Republic of China (2012).

²⁵ Kalantzakos (2018); Shen et al. (2020).



HREEs. This change reduced not only the profits of the large state-owned enterprises, but also their competitiveness with illegal enterprises which avoided paying the tax²⁶.

In 2016, the Ministry of Industry and Information Technology issued a Rare Earth Industry Development Plan (2016–2020).²⁷ It noted a number of achievements during the previous Five-Year Plan period related to industrial consolidation. The six REE industrial groups had integrated 22 of the 23 mining enterprises, and 54 of the 59 processing enterprises. The annual capacity of small-scale processing enterprises had been reduced from 400,000 to 300,00 tonnes, and a large number of illegal mines and processing plants had been closed. Measures to improve environmental protection included fully enclosing the mining area and tailings pond at Baiyun Obo, and enhancing management of the exploitation of clays in southern China. Finally, a system to trace the mining and processing of rare earths had been created. Remaining challenges included the persistence of illegal mining, trading and processing, and overcapacity of REE mining and processing, all resulting in low prices for REE products. The plan called for the strengthening of resource management and environmental protection in both mining and processing, further industry consolidation, and the promotion of overseas resource exploitation. Downstream, the plan emphasized the need for innovation and industrial development in products such as magnets, hydrogen storage, catalysts, and alloys. Targets for the period 2015–2020 included:

- Improving industry profitability from 5.8 per cent to 12.0 per cent;
- Improving expenditure on R&D by key enterprises from 3 per cent of operating costs to 5 per cent;
- Reducing separation and smelting capacity from 300,000 tonnes to 200,000 tonnes, and at the same time increasing output from 100,000 tonnes to up to 140,000 tonnes;
- Enhancing recovery rates for mineral processing, and for separation and smelting;
- Reducing the proportion of rare earth materials for products to be exported, and increasing the market share of high-end products and devices.

The National Mineral Resources Plan (2016–2020) addressed many of the same upstream topics. In addition, it reiterated that REEs were strategic minerals that required careful monitoring and an early warning mechanism.²⁸ However, the classification of REEs as being of strategic importance reflects the advantages China's abundant resource base brings to the country, rather than the nation's dependence on imports²⁹. The National Mineral Resources Plan identified 24 national mining planning areas for REEs, and six REE energy resources bases (Inner Mongolia, Sichuan, Jiangxi, Hunan, Guangxi, and Fujian) which would account for 80 per cent of REE production by 2020³⁰.

Further industry consolidation was announced in December 2021, reducing the number of major players in REE mining and processing from six to four. The new China Rare Earth Group would control about 70 per cent of the nation's REE production³¹. A draft of Regulations on the Administration of Rare Earths published in January 2021 addressed many of the governance challenges raised by earlier documents and reflected tightening state control over the industry³².

By 2020, the output of China's REE mines had reached 140,000 tonnes, up from 105,000 tonnes over the period 2014–2017. The share of world output of REE mines was then 58 per cent, down from 92 per cent in 2010. In contrast, China's share of REE processing capacity amounted to 90 per cent of the global total. Output from mines continued to rise to 168,000 tonnes in 2021, of which 148,850 tonnes was from ores in rocks, and 19,150 tonnes was from HREE-rich clays. The total processing output

²⁶ Shen et al. (2020).

²⁷ MIIT (2016).

²⁸ Ministry of Natural Resources (2016).

²⁹ Andersson (2020).

³⁰ Ministry of Land and Resources (2016).

³¹ Sun Yu and Mitchell (2021).

³² MIIT (2021).



amounted to 162,000 tonnes³³. By 2022, China's REE mine production had risen again to 210,000 tonnes, 70 per cent of the global total. Output is likely to rise again in 2023 in response to increasing domestic demand, as 'first batch quotas' for mine output and for smelting and separation were both raised by 20 per cent³⁴.

The scale of China's international trade in rare earth products has fluctuated greatly. Exports of REE compounds and metals rose from 34,832 tonnes in 2015 to peak at 53,031 tonnes in 2018, before declining to 35,448 tonnes in 2020. Imports of REE ores rose from 10,666 tonnes in 2015 to peak at 70,600 tonnes in 2018, and then declined to 47,641 tonnes in 2020³⁵. Both exports and imports of rare earth oxides declined substantially during 2022³⁶, and exports declined further in the first three months of 2023³⁷.

Neither the 14th Five-Year Plans nor the 2023 government Work Reports directly address REEs. In the short term, the government's focus is likely to remain on improving enterprise management and meeting domestic REE demand. Imports of REE ores are likely to remain high as growing overseas processing capacity is unlikely to keep pace with rising demand due to long lead times. In contrast, exports of REE compounds and metals are unlikely to rise significantly, and may even decline as domestic demand grows. Reports are circulating that China may even ban the export of certain rare earth metal technologies, such as magnets, in retaliation for the US ban on semiconductor exports³⁸.

4. Rare earth prices

Given China's outsized role in REE supply chains, prices are heavily impacted by policy and market changes in the country. That said, unlike prices for major global commodities, prices of REEs are assessed and reported by a small number of firms. Frequent and transparent price assessments are therefore hard to come by. The price discovery process is still nascent and there is no widely used public exchange for rare earths. Firms such as Argus and Benchmark Minerals release price assessments based on surveys of traders, consumers, and other market participants. Analyst firms and pricing forums such as Adamas Intelligence, Stormcrow Capital, Technology Metals Research and Asian Metal also offer rare earth price assessments.

Publicly available data are anecdotal but point to volatility, including a number of spikes in REE prices over the past 15 years, reflecting both policy and market dynamics due to the high concentration in the market. In turn, price volatility has contributed to concern among policy makers about the resilience of supply chains dependent on rare earths from China. Market volatility and limited visibility around future prices make investments in technology and manufacturing less attractive as firms may have difficulty operating profitably. What is more, with limited substitutable materials and technologies, users of materials and magnets struggle to respond quickly to high price environments, while technological substitutions that eventually occur under sufficiently high prices can lead to swings in demand and reduced performance³⁹.

Rare earths have experienced two major price spikes over this period, both related to China. The first and most extreme spike occurred in 2010–2011, and resulted from China's decision to restrict rare earth exports and clamp down on illegal mining. More recently, prices spiked again in 2021–2022 as a result of Covid-related bottlenecks and market perceptions of rising demand from clean energy.

Generally, price volatility has tended to occur across the various REEs, reflecting the concentration of supply in China and the extraction of many REEs from the same ores. Prices for neodymium have

³³ Avic Securities (2022).

³⁴ Global Times (2023).

³⁵ Avic Securities (2022).

³⁶ SMM (2022).

³⁷ Reuters (2023).

³⁸ Oki (2023).

³⁹ US Department of Energy (2022).

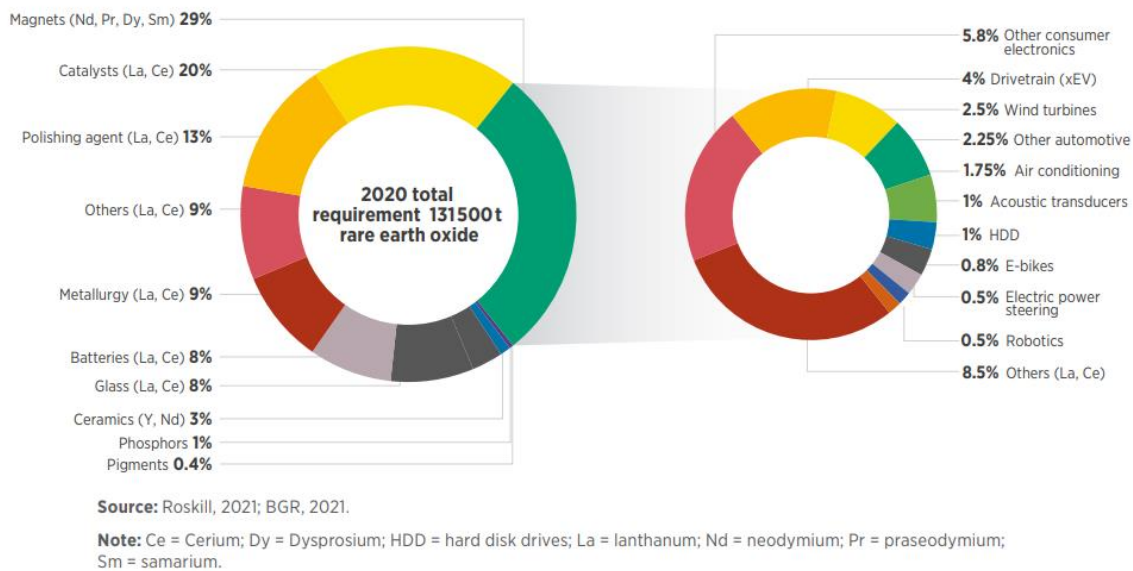
ranged between US\$50/kg and US\$280/kg since 2011. The high occurred in early 2022 at the height of global supply chain interruptions related to Covid. Current prices are around US\$80/kg. Dysprosium currently trades at roughly US\$528/kg, up from US\$238/kg in 2018. Dysprosium has shown higher volatility than neodymium, rising from a low in 2003 of US\$28.50/kg to a peak price of US\$3,410 in early 2011, at the height of fears around Chinese supply. Praseodymium and terbium prices surged threefold and sevenfold in 2022, before slipping back slightly⁴⁰. Spot markets exist for various rare earth metal oxides, including on the Shanghai Metals Exchange, as well as in two dedicated rare earth exchanges in Jiangxi and Inner Mongolia, China⁴¹. Understanding these markets, as well as the price discovery process, is an important area for future research.

5. Demand for rare earths

Demand for REEs is expected to rise strongly for the next several decades, driven mainly by demand for permanent magnets in wind turbines and EV motors. For key drivers of demand—permanent magnets in wind turbines and EV motors—there are no direct substitutes for REE that offer similar performance characteristics. However, technology options exist for reducing demand, especially in the EV space, albeit with cost and efficiency trade-offs. Due to substitution and adoption of alternative technologies, demand for manganese, cobalt, and other critical materials has already fallen short of expectations⁴².

Each REE has a distinct set of end-uses, with varying demand growth expectations. Demand for neodymium and dysprosium is linked to the growth in demand for permanent magnets in wind turbines as well as in EV motors. Although demand for REEs is also strong in consumer electronics (such as hard drives) and in industrial motors, these sectors are not expected to account for substantial demand growth⁴³. Demand for other elements is driven by lasers and glass fibres for communications and military purposes⁴⁴.

Figure 3: REE consumption by mass and application, 2020



Source: Gielen and Lyons (2022)

⁴⁰ tradingeconomics.com, [Neodymium](#); Strategic Metals Invest (2023).

⁴¹ Reuters (2020).

⁴² For example, the forecasted 2030 demand for cobalt to supply EV batteries has fallen by 60 per cent since 2019 (Bullard, 2023).

⁴³ US Department of Energy (2022).

⁴⁴ Goodenough et al. (2018).



Table 1: Expected magnets contained in global demand for selected NdFeB magnet applications, thousand tonnes

Application	Part of Energy Sector Industrial Base??	Demand in 2020		Projected Demand in 2030 (high growth)		Projected demand in 2050 (high growth)	
		Amount (kt)	Share	Amount (kt)	Share	Amount (kt)	Share
Offshore wind turbines	Yes	16.9	14.2%	139.2	36.0%	273.7	36.3%
Electric vehicles	Yes	7.3	6.1%	114.1	29.5%	266	35.3%
Consumer electronics (hard disk drives, cell phones, loudspeakers, other)	No	35.1	29.4%	41	10.6%	65.4	8.7%
Industrial motors	No	36.0	30.2%	53.7	13.9%	85.7	11.4%
Non-drive/train motors in vehicles	No	9.4	7.9%	18.3	4.7%	29.3	3.9%
Other sintered magnets (power tools, electric bikes)	No	6.5	5.5%	9.6	2.5%	15.3	2.0%
Bonded magnets	No	8.0	6.7%	11.1	2.9%	17.7	2.3%
Total	-	119.2	100.0%	387	100.0%	753.2	100.0%

Source: US Department of Energy (2021)

The International Energy Agency forecasts that under its Sustainable Development Scenario (SDS), REE demand from clean energy will rise sevenfold between 2020 and 2040. Under the SDS, overall neodymium demand rises from 30,000 tonnes in 2020 to over 90,000 tonnes in 2040, with demand from -EV batteries, and wind turbines accounting for 40 per cent of demand. Demand for REEs from wind turbines, driven by neodymium demand for permanent magnets, will rise from 4,000 tonnes in 2020 to 12,000 tonnes in 2040, but increased adoption of alternative technologies could reduce this to 8,000 tonnes. Neodymium demand for EV motors rises fifteenfold, from under 2,000 tonnes to over 25,000 tonnes under the SDS⁴⁵.

Given the long lead times for potentially expanding rare earths extraction and processing capability, and the absence of substitutes, this increase in demand is anticipated to result in a shortage of REEs, even assuming that industry continues to pursue various avenues for reducing REE consumption. The uncertainty around the scale and scope of demand—and the potential for technological gains to change the outlook materially—also impacts investments. This is compounded by the long lead times to develop the mines, and the complexity of processing.

On the EV side, a 2023 analysis found that meeting the International Energy Agency's EV and clean energy capacity forecasts will require EV manufacturers to substantially reduce REE consumption by adopting traction motors without REE⁴⁶. Various announcements from vehicle and battery manufacturers suggest that recent high prices are leading automakers to undertake greater efforts to avoid REE consumption. Tesla announced in March 2023 that its new vehicle motors would be free of REEs⁴⁷. Tesla's announcement alone would reduce REE demand by 3–4 per cent if fully implemented⁴⁸. Audi, BMW, Mercedes, and Renault have opted for other designs, and have made progress to improve performance and avoid limitations of non-permanent magnet motors⁴⁹.

These developments on the EV side, in which various companies opt for a variety of motor design with and without REEs, match the expectations of a 2017 study of potential REE substitutes in EV motors⁵⁰.

⁴⁵ IEA (2021).

⁴⁶ Severson et al. (2023).

⁴⁷ Loveday (2023).

⁴⁸ Hui (2023).

⁴⁹ Edmondson (2023).

⁵⁰ Pavel et al. (2017).



While motors with permanent magnets offer the greatest range and performance advantage over alternatives, especially for urban driving, lower-priced and lower-range vehicles may opt for alternatives.

Permanent magnets used in wind turbines tend to contain 2.7–3.4 tonnes of REEs per turbine, compared to just 2–4 kg per EV. The large amount and proportion of REE in wind turbines helps the economics of recovering REEs for end-of-life recycling. Permanent magnets are limited to the largest turbines, especially offshore turbines, due to their greater efficiency, longer life, and lower maintenance requirements⁵¹. The NdFeB permanent magnet has a stronger magnetic field than alternatives, reducing the weight and dimensions of large turbines. No external power system is needed, resulting in greater efficiency and simpler design.

China presently dominates the manufacturing of permanent magnets, both for the highest-performing sintered NdFeB magnets as well as for bonded NdFeB magnets. NdFeB technology was developed in 1983 by General Motors and Sumitomo Corp. While both companies produced permanent magnets in the USA for several years, high costs and the closure of the Mountain Pass mine in the USA resulted in the shift of production towards Asia—first to Japan, and then to China. Most of the main intellectual property portfolio of NdFeB magnets has expired, though US and Japanese firms continue to develop intellectual property in the field⁵². Although China has roughly 90 per cent of world NdFeB capacity, Germany and Japan have some market share, and Japanese firms also own manufacturing facilities in Malaysia and Thailand⁵³. Following official designation of NdFeB batteries as a critical national security technology in 2021, US policies are expected to boost domestic US manufacturing of NdFeB magnets, reaching an estimated 50 per cent self-sufficiency for sintered NdFeB magnets by 2030, though the USA would remain dependent on imported bonded NdFeB magnets⁵⁴.

Partly in response to concerns about REE prices and supply, the wind industry began shifting away from permanent magnets for certain segments of the turbine market, particularly for onshore wind turbines outside of China. According to one estimate, gearbox turbines without permanent magnets account for 52 per cent of the onshore wind market, predominantly outside China, while permanent magnet designs accounted for roughly 75 per cent of the offshore wind market⁵⁵. While one forecast for 2050 suggests REE demand for wind turbine permanent magnets could rise by a factor of 11–26 times in order to meet global wind energy targets, according to the IEA demand for wind permanent magnet rare earths will rise from around 4,500 tonnes in 2020 to between 8,000 and 12,000 tonnes in 2030⁵⁶. A March 2023 forecast from Benchmark Minerals anticipates a more modest rise in wind permanent magnet demand (of which REEs may account for roughly one-third by weight) from 12,000 tonnes in 2022 to 15,000 tonnes in 2027⁵⁷. The Benchmark forecast is lower than the IEA and other analyses due to recent trends towards substituting other drive technologies and lower REE consumption in permanent magnets.

There are various possibilities for reducing the REE demand of the wind sector, including finding substitutes for REEs in permanent magnets, reducing the REE content of permanent magnet designs, and improving the cost and performance of non-REE drives. There is unlikely to be a direct substitute for REE permanent magnets with different materials, but a sustained increase in REE prices could induce manufacturers to reduce the REE content of permanent magnets by 43 per cent⁵⁸. Reducing waste from manufacturing processes could also reduce REE demand.

IRENA also estimates that various technologies could compete with high-REE permanent magnets in the largest turbines⁵⁹. Hybrid drives that combine gearbox with direct drive using permanent magnets require a substantially smaller amount of permanent magnet material, though this also entails greater

⁵¹ US Department of Energy (2022).

⁵² Ormerod (2021).

⁵³ BIS (2023).

⁵⁴ BIS (2023).

⁵⁵ Gielen and Lyons (2022).

⁵⁶ Jiashuo Li et al. (2020); IEA (2021).

⁵⁷ Benchmark Minerals (2023).

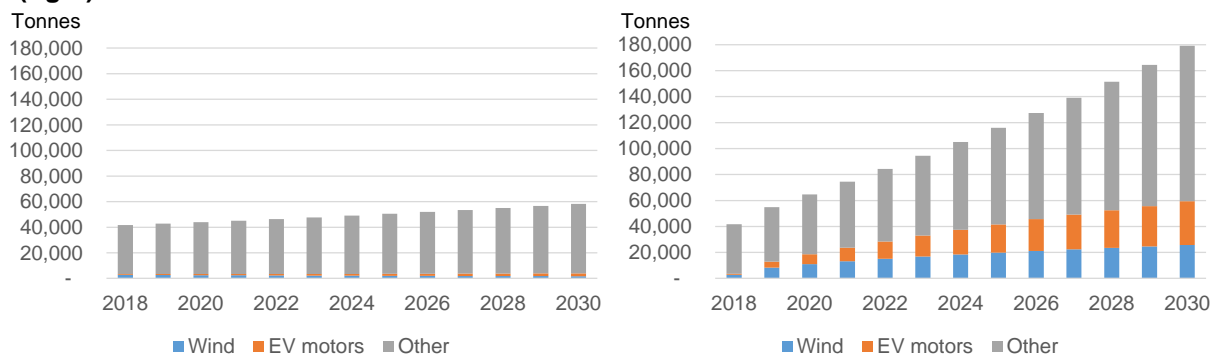
⁵⁸ US Department of Energy (2022).

⁵⁹ Gielen and Lyons (2022).

maintenance, a larger and heavier magnet overall, and lower efficiency. Improvements in magnets that fill the gap in efficiency between ferrite magnets and NdFeB magnets could also help reduce the demand for REE permanent magnets. High-temperature superconductors (HTS) have also been under development for wind turbine applications for many years, though these remain at an early stage of development, with the first HTS turbine being installed in Denmark in 2018⁶⁰. Novel motor designs without REE permanent magnets could offer high efficiency and low maintenance, though these remain at the laboratory stage⁶¹. Siemens is also working on nanotechnology to replace REEs in permanent magnets: the magnet uses an iron–cobalt compound in which nanometre-sized magnetic rods are fixed in a matrix, replicating or approaching the performance of permanent magnets⁶².

Aside from technologies to reduce overall REE demand in wind and EV motors, there are also efforts underway to change the relative mix of different REE ingredients of wind turbine permanent magnets and EV motors. By weight, neodymium is the most important REE for wind permanent magnets and EV motors. However, there is significant neodymium demand for other applications, whereas wind and EVs are likely to dominate demand for relatively expensive dysprosium. Currently, wind turbine NdFeB permanent magnets have a composition of around 28 per cent neodymium and 4–5 per cent dysprosium⁶³. Praseodymium is also present in small amounts. Dysprosium improves resistance to demagnetization at high temperatures. Some manufacturers of permanent magnets have sought to reduce the proportion of dysprosium in some wind turbine magnets to below 1 per cent⁶⁴. Praseodymium can also substitute for a portion of neodymium in NdFeB magnets without a significant loss in performance⁶⁵. Similarly, in the automotive sector, where high-performance motors may use up to 11 per cent dysprosium by magnet weight⁶⁶, Toyota has designed REE motors that reduce neodymium content by replacing it with lanthanum and cerium, and also eliminate dysprosium and terbium⁶⁷.

Figure 4: Forecasts of neodymium demand by application, 2018–2030, low (left) and high (right) scenarios



Source: Alves Dias et al. (2020)

⁶⁰ Dodd (2018).

⁶¹ Sandia National Laboratories (2022).

⁶² Froböse (2023).

⁶³ Alves Dias et al. (2020).

⁶⁴ Alves Dias et al. (2020).

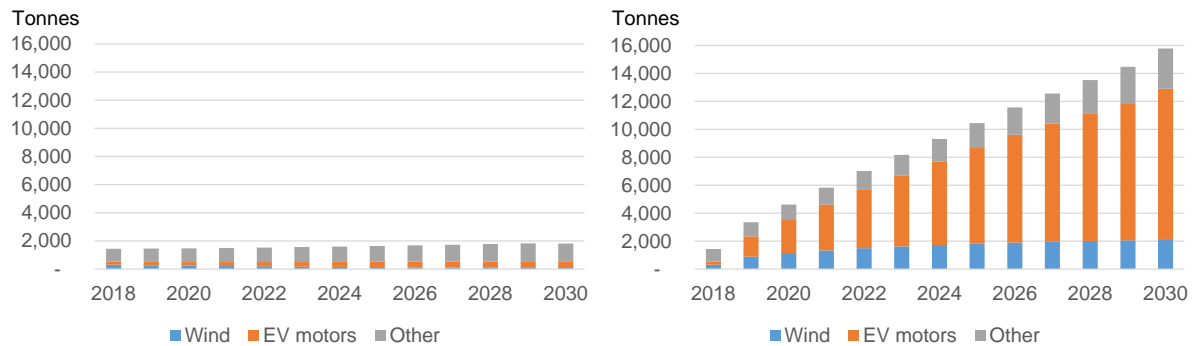
⁶⁵ Constantinides (2017).

⁶⁶ Constantinides (2017).

⁶⁷ US Department of Energy (2022); Alves Dias et al. (2020).



Figure 5: Forecasts of dysprosium demand by application, 2018–2030, low (left) and high (right) scenarios



Source: Alves Dias et al. (2020)

Outside of wind and EV motors, REEs are used in dual-use applications such as lasers, hard drives, and lighting. As noted, while the volume of REE demand for these electronics and other applications is substantial, growth is likely to be less than in the EV and wind turbine fields. Further, as the US Department of Energy notes, REE demand for US military applications is quite small compared to domestic civilian demand or the likely global demand shortfall. US military REE demand is ‘significantly less than capacity of even a moderate-scale NdFeB magnet plant’⁶⁸. For this reason, the US Department of Energy recommends against stockpiling REEs for military use, and instead suggests diversifying civilian supplies overall.

Recycling of permanent magnets is considered the most economically attractive way to recover REEs because of the size of such magnets, and the total amount of elemental neodymium and praseodymium used. Current REE recovery focuses on swarf—the residue waste from manufacturing permanent magnets. Nine per cent of NdFeB magnet material is recovered from the manufacturing process, generally located near or at the location of magnet manufacturing⁶⁹.

The current method of extracting REEs from permanent magnets, called countercurrent solvent extraction, is energy-intensive and time-consuming, and involves environmentally hazardous solvents. New methods for extracting REEs are under development, including one involving organic compounds from the University of Pennsylvania, and another from the Oak Ridge National Laboratory that reduces recycling costs by extracting REEs jointly without separating the individual elements⁷⁰. Two companies are also using hydrogenation to extract REE from end-of-life permanent magnets in the UK, though the volumes are still small⁷¹. While the cost and timeline for commercializing new extraction and recycling technologies are unknown, sustained high REE prices would likely bring these or other recycling techniques into volume production.

In sum, most forecasts anticipate that demand for REEs will rise dramatically through 2030, driven by use of permanent magnets in EV motors and large wind turbines. No ideal substitutes exist, and many potential substitutes are at an early stage of development that makes it unlikely they will have an impact on the REE market by 2030. The industry nevertheless has multiple pathways for substantially reducing REE demand in EVs and wind turbines. These include reducing REE consumption for existing technologies, and improving the performance and efficiency of various systems that can fill the gap between REE permanent magnets and devices without REE. Many of these technologies are being developed in the West, which suggests that policies to accelerate innovation in reducing or substituting REEs could build upon existing R&D and technology strengths.

⁶⁸ US Department of Energy (2022).

⁶⁹ US Department of Energy (2022).

⁷⁰ Hyong-Min Kim and Jariwala (2021).

⁷¹ US Department of Energy (2022).



6. What steps are other countries taking on REEs?

The reduction of rare earth export quotas by China in 2010 and 2011 triggered immediate reactions by major importers. In addition to making a complaint to the World Trade Organization, the USA, the European Union, and Japan held a series of trilateral workshops⁷². More substantial actions were taken individually. Japan, dependent on China for 82 per cent of its rare earths, started to build partnerships and make investments in countries hosting rare earth deposits. These included Australia, where the Japan Organization for Metals and Energy Security (JOGMEC) invested in Lynas's mine;⁷³ Kazakhstan, where Sumitomo invested in an REE processing plant⁷⁴; Vietnam, where JOGMEC established a joint REE research centre⁷⁵; Namibia, where JOGMEC formed a joint venture to extract resource rich in HREEs; and India⁷⁶.

In the USA, both defence and energy were identified as priorities for REEs⁷⁷. The US Department of Defense produced a report on Strategic and Critical Minerals in 2013 that recommended stockpiling HREEs. As of 2023, the Defense Logistics Agency was in the process of stockpiling 600 tonnes of neodymium, 70 tonnes of praseodymium, and 100 tonnes of NdFeB battery block⁷⁸. The Department of Energy established a Critical Minerals Institute to promote R&D cooperation between companies, universities, and national laboratories⁷⁹.

The EU launched a Raw Materials Initiative in 2010, followed by a Critical Raw Materials Report in 2014, and several EU Member States produced their own raw materials strategies. Germany, for example, developed partnerships focused on REEs with Kazakhstan and Mongolia⁸⁰.

Since 2020, the combination of increasing demand for REEs and growing tensions with China have triggered more intensive efforts by Western nations to reduce their reliance on China for REEs. In these, the USA and Australia have been playing leading roles as the second and fourth largest REE producers in the world: the former as a producer–consumer, and the latter as a producer.

In February 2021, US President Biden signed an Executive Order on America's Supply Chains⁸¹. Eleven months later, a bipartisan bill was introduced in the Senate to block US defence contractors from buying Chinese REEs and allowing the Pentagon to build a stockpile⁸². By February 2022, the Department of Defense had invested over US\$100 million in US REE supply chain resilience⁸³. In September 2022, the Department of Energy issued a call for bids for a Rare Earth Demonstration Facility (US\$156 million) for the extraction of REEs and other critical minerals from unconventional sources such as mine waste⁸⁴.

The 2022 Inflation Reduction Act (IRA) also included several items specifically geared towards REEs. The IRA includes a tax credit of 10 per cent of the production cost for 'critical components', which includes rare earths. The IRA allows the US Department of Energy to provide up to US\$40 million in loan guarantees for critical materials projects, and allows the president to direct up to US\$500 million of economic incentives to critical materials, which President Biden did in designating battery materials as a priority for domestic manufacturing under the Defense Production Act⁸⁵. Starting in 2025, to be

⁷² Kalantzakos (2018).

⁷³ Kalantzakos (2018).

⁷⁴ Paxton (2012).

⁷⁵ Fuyuno (2012).

⁷⁶ Hui (2021).

⁷⁷ Kalantzakos (2018).

⁷⁸ BIS (2023).

⁷⁹ Ames National Laboratory: [CMI Partners](#), accessed March 2023.

⁸⁰ Kalantzakos (2018).

⁸¹ The White House (2021).

⁸² Scheyder (2022).

⁸³ US Department of Defense (2022).

⁸⁴ US Department of Energy (2021).

⁸⁵ Serpell (2022).



eligible for US purchase subsidies, an EV battery may not contain any critical minerals that were extracted, processed, or recycled by a ‘foreign entity of concern’—presumably including China⁸⁶.

The IRA includes targets for the percentage of battery materials that should come from the USA or free-trade agreement partners. However, since REEs make up a small share of total materials by weight, this provision is likely to have a greater impact on the main battery materials such as lithium, nickel, aluminium, manganese, and cobalt. Setting overall percentage targets for battery or magnet inputs by weight has been criticized for this reason⁸⁷. Even within REEs, demand for neodymium is far larger by weight than that for the relatively rare and costly dysprosium.

Realizing that international cooperation was needed, the USA led the establishment of a Minerals Security Partnership in June 2022 to ‘bolster critical mineral supply chains essential for the clean energy transition’. The first meeting, in September 2022, was attended by official partners Australia, Canada, Finland, France, Japan, Republic of Korea, Norway, Sweden, United Kingdom, USA, and the European Union. Mineral-rich countries such as Argentina, Brazil, the Democratic Republic of the Congo, Mongolia, Mozambique, Namibia, Tanzania, and Zambia also attended⁸⁸.

Government policies and financial support from the Departments of Defense and Energy have driven a rise in investment in both mines and processing plants in different parts of the USA. For example, the Department of Defense awarded a US\$35 million contract to MP Materials Corporation to build the country’s first HREE processing and separation plant at the Mountain Pass mine⁸⁹, and funded Lynas to build a separation plant in Texas⁹⁰. The Department of Energy provided funds towards an REE mine and processing plant in Wyoming⁹¹. Other REE mines and processing plants are being, or could be, developed in Nebraska⁹², Montana⁹³, and Georgia and Utah⁹⁴. Another mine with HREEs and a processing plant is under construction in Alaska with support from the state government, but creates environmental risks⁹⁵. Overseas, US firm Energy Fuels announced in February 2023 that it had acquired 17 REE mineral concessions in Brazil, the exploitation of which would feed its processing plant in Utah⁹⁶.

Canada is also active in the REE industry, in part in cooperation with the USA. A plant is being built in Quebec, which has plentiful hydroelectricity, to process ores from the Elk Creek mine in Nebraska⁹⁷. Vital Metals put Canada’s first REE mine into production in 2021, in Northwest Territories⁹⁸, and is building a processing plant in Saskatchewan⁹⁹.

In Australia, Lynas is building the country’s first REE processing plant near its Mount Weld mine in Western Australia in order to reduce the company’s dependence on its facility in Malaysia, as well as providing capacity for concentrates from other mines¹⁰⁰. A further processing plant is being built in Western Australia with a federal government loan to process an existing stockpile of ores from a mineral

⁸⁶ Connors et al. (2022).

⁸⁷ Trost and Dunn (2023).

⁸⁸ US Department of State (2022).

⁸⁹ US Department of Defense (2022).

⁹⁰ Gross (2020); Menon and Sharma (2022).

⁹¹ Lasley (2021).

⁹² Anon. (2021).

⁹³ Ahmad (2023).

⁹⁴ Green Car Congress (2020).

⁹⁵ Brehmer (2021); Goyal (2020).

⁹⁶ Energy Fuels (2023).

⁹⁷ Jamasmie (2023).

⁹⁸ Lamberink (2021); NS Energy (2021).

⁹⁹ Lamberink (2021); NS Energy (2021).

¹⁰⁰ Peacock (2022a).



sands project and later receive concentrates from other mines¹⁰¹. At least four other REE mines are being developed, in Western Australia¹⁰², New South Wales¹⁰³, South Australia¹⁰⁴, and Northern Territory¹⁰⁵. The deposit in South Australia is the only one hosted in HREE-rich clays, while the project in the Northern Territory faces potential environmental challenges.

In Northeast Asia, both Japan and South Korea are entirely dependent on imports for their REE supplies. Japan's early moves succeeded in reducing its dependence on China for REEs from 80 per cent in 2010 to 60 per cent in 2020. This has come largely from JOGMEC's investment in Lynas¹⁰⁶. Information on JOGMEC's involvement in Vietnam is sparse¹⁰⁷, but Vietnam's REE output soared from 400 Mt in 2021 to 4,300 Mt in 2022¹⁰⁸. Toyota's JV to mine and process REEs in India has made little progress due to the weak policy regime¹⁰⁹. Of greater potential significance was the discovery in 2020 of HREE-rich clays in the deep ocean off the coast of Japan¹¹⁰. Pumping from a depth of 6,000 metres is planned to start in 2024¹¹¹, but is likely to involve significant technical and environmental challenges.

South Korea hosts potential REE reserves but these have not yet been exploited¹¹². In 2021, the government decided to increase its stockpiles of critical minerals, including REEs¹¹³. Three Korean private equity firms have taken a share of the Dubbo REE mine in Australia's New South Wales¹¹⁴, with the aim of processing the output in Korea to manufacture magnets¹¹⁵. In February 2023, the governments of Korea and Mongolia signed a Memorandum of Understanding relating to the exploitation of REEs in western Mongolia¹¹⁶.

Progress to enhance REE supply chains has been rather slower in Europe. Since 2020, different EU institutions have called for action and published strategies¹¹⁷. In 2023, the EU published a draft Critical Raw Materials Act including targets for 2030 that specify benchmarks of 10, 40, and 15 per cent, respectively, for the amount of mineral extraction, processing, and recycling that should take place in the EU, and setting a 65 per cent threshold for the maximum annual consumption from any stage of production or processing that can come from a single third country¹¹⁸. The Act requires monitoring critical raw materials supply chains, coordination of strategic raw materials stocks among EU Member States, and auditing/stress-testing of strategic raw materials supply chains for large companies. The EU is also developing a blockchain system to trace REEs to ensure that they are not linked to toxic pollution¹¹⁹.

After Brexit, the United Kingdom has so far made limited moves to secure REE supplies. Pensana plans an REE processing plant in north-east England to produce magnets. The rare earth oxides will come from the Longonjo mine in Angola¹²⁰. The processing project has received undisclosed amounts of government investment, and operation is due to start at the end of 2023. However, the project faces commercial and environmental risks, and needed to raise another US\$250 million at the end of 2022¹²¹.

¹⁰¹ Peacock (2022b); NS Energy: [Eneabba Rare Earths Mining](#), accessed March 2023.

¹⁰² Casey (2022).

¹⁰³ Australian Strategic Minerals Ltd (ASM): [Overview](#).

¹⁰⁴ Bradbrook et al. (2023).

¹⁰⁵ Casey (2022).

¹⁰⁶ Hui (2021).

¹⁰⁷ Thanh Lich (2019).

¹⁰⁸ Pistilli (2023).

¹⁰⁹ Bhattacharya (2022).

¹¹⁰ Anon. (2020).

¹¹¹ Foster (2023).

¹¹² Reuters (2010).

¹¹³ Kim Byung-wook (2021).

¹¹⁴ Yu Kun-ha (2021).

¹¹⁵ Kim Bo-eun (2022).

¹¹⁶ Kushhov (2023).

¹¹⁷ European Commission (2020); ERMA (2021); European Parliament (2021).

¹¹⁸ European Commission (2023).

¹¹⁹ Onstad (2022).

¹²⁰ Slater (2022); Anon. (2019).

¹²¹ UK Government (2022); Dempsey (2022).



Taken together, these moves mark a potential turning point in international policies to address Chinese dominance of REEs. However, the impact is likely to be modest over the period to 2030 given the length of time needed to commission REE mines and processing plants. On its side, China seems more focused on improving the management of its domestic REE mining and processing enterprises, and on ensuring adequate supplies for its own manufacturers.

7. Conclusions

Rising tensions between China and the USA, fears of supply chain fragmentation, and concerns about the availability of critical resources for the energy transition have generated considerable attention to China's role in REE supply chains. While there have been discussions and analyses of China's dominance of REEs for years, highlighted by an export ban by China in 2010, policy actions have accelerated more significantly only over the past few years. Recent efforts to reduce Chinese dominance of REEs in the West have included designating REEs as a critical material, streamlining approval processes for REE extraction, offering loans and other subsidies for REE processing, reducing the REE content of various devices, forming coalitions of countries working to expand production or processing outside China, and increased information sharing.

And while policy activity has accelerated over the course of 2022-2023, these moves are unlikely to dramatically limit China's dominance over these supply chains in the near term. China has achieved dominance of REE production and processing through a combination of early moves into the industry, decades of weak environmental regulation that has enabled illegal mines and processing plants, as well as state investment along the supply chain, export controls, low labour costs, and scale.

As the energy transition continues, demand for REEs is expected to rise dramatically through 2030 and beyond, driven by their use in permanent magnets for EV motors (including hybrid vehicles) and wind turbines. But there is considerable uncertainty around future demand estimates. Alternative technologies could reduce REE consumption in both EV and wind turbine drives, depending partly on policy support for reducing REE demand, as well as on market conditions such as prices and supply disruptions. At the same time, efforts to spur supplies are complicated by the demand and pricing uncertainties, the long lead times in developing new mining and processing capabilities, and ESG (environmental, social, and governance) concerns in these supply chains.

It is increasingly clear that beyond the uncertainties around both supply and demand, given China's expected dominance in the next decade, the concentration of REE processing currently poses the largest risk, in that 90 per cent of REE processing is in China, as opposed to 70 per cent of mining. Like mining, processing takes many years to set up, and due to environmental and other regulatory constraints is unlikely to scale up in Europe or the UK at sufficient speed or scale to meaningfully reduce risks of disruptions before 2030. However, scale-up in the USA, Canada, and Australia is already taking place. Capital costs and knowhow are the critical variables in REE processing, so any effort to promote a shift in REE processing will require addressing both of these, likely through long-term incentives and policies.

Understanding the complexity of these supply chains, and how and why China has become dominant in them, is an important first step. A critical next step will be a clear-headed and rational assessment of the potential risk this poses for consumers, governments, business, and the energy transition.



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