Office of Industries
Working Paper ID-075
June 2021

Rare Earths and the U.S. Electronics Sector: Supply Chain Developments and Trends

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Abstract

The rise of rare earth elements (rare earths or REEs) as a key component in the electronics sector has become increasingly important as more advanced technologies integrate multiple REEs throughout their products and a variety of other sectors develop REEs containing consumer and industrial products. Historic bottlenecks and concerns for potential future disruption in both the production of raw, unprocessed REEs as well as REE processing has elevated both economic and national security concerns, and the possibility of increased production in the United States and third country markets has been noted as having the potential to decrease supply chain sensitivity.

This working paper will provide an overview of the current landscape for rare earths and the electronics industry. It will begin with an introduction to rare earths, followed by a brief look at the role of REEs in the contemporary electronics sector. It will then take a broader look at the challenges facing the REE sector, including the concentration of modern raw REE production and rare earths processing in China, as well as the rise of demand from a variety of competing industries, particularly by the automotive and energy sectors. It will conclude with an exploration of the search for alternatives to address these supply and demand challenges, noting countries expanding production (Australia and the United States) as well as those with the potential to expand the supply of raw and processed REEs (Vietnam, Brazil, and Russia). It will also look at ongoing efforts to reduce REE demand through reduced consumption and recycling.

U.S. International Trade Commission

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The authors would like to thank James Stamps, Karl Tsuji, David Coffin, Alex Melton, Kelsi Van Veen, and Bob Carr for their review and comments and Trina Chambers and Monica Sanders for their production support.

U.S. International Trade Commission

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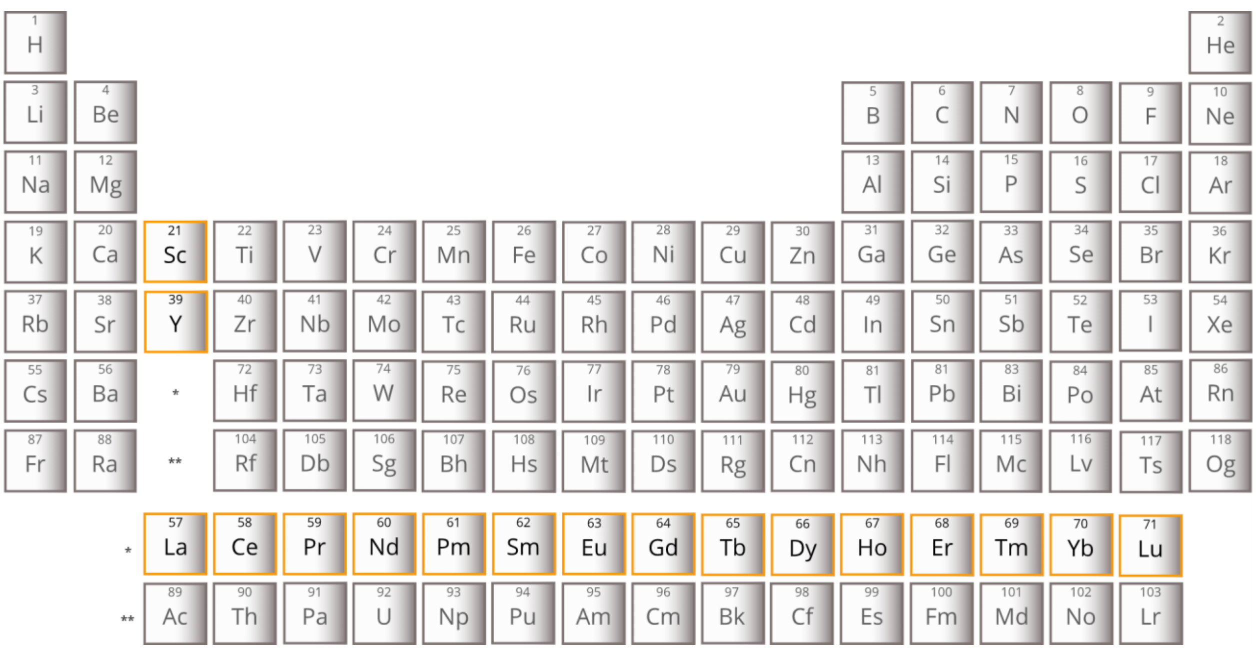
Introduction

An Introduction to Rare Earths

The U.S. Geological Survey (USGS) defines REEs broadly as "iron gray to silvery lustrous metals that are typically soft, malleable, and ductile and usually reactive, especially at elevated temperatures or when finely divided." The REE grouping includes the 15 lanthanide series elements as well as scandium and yttrium on the Periodic Table of Elements (figure 1).[1] In modern times these elements have become valued for their critical chemical and physical properties, including the magnetic properties which have been key in the development of a variety of durable magnets, including strong permanent magnets, that can withstand both heat and force without wearing down.[2] REE magnets are used in a variety of high-technology end-use applications, including in electronics (see the "REEs and Electronics" section below). Generally, REEs are classified by their respective atomic weight as either light (e.g., cerium, lanthanum, praseodymium, neodymium, samarium and scandium) or heavy (e.g., dysprosium, yttrium and terbium).[3]

Figure 1 Periodic table of elements, rare earths (orange)



Source: Compiled by Staff based on European Geosciences Union, "Rare Earth Elements: Geochemistry and Geopolitics," May 29, 2013.

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[1] The 15 lanthanide elements are lanthanum (Ln), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu). Helmenstine, Anne, "List of Elements in the Lanthanide Series," ThoughtCo, December 12, 2019.

[2] BBVA Open Mind, "The Rare-Earth War," February 26, 2021.

[3] Padhy, "Rare Earth Metal: Heavy vs. Light," August 17, 2017.

The first REE containing ore (i.e., raw rare earth), gadolinite, was first recognized in Ytterby, Sweden in 1788.[4] By 1803 two REEs were observed and identified: yttrium and cerium.[5] Over the next century there were dozens of false discoveries within the lanthanide series, largely attributable to the difficulty in separating the metals in the REE-containing ores, with the difficulty in isolating and properly identifying these metals were further hampered by the uncertainty of how many elements were within the lanthanide series.[6] The discovery in 1913 by British physicist Henry Moseley that determined there were a total 15 lanthanide elements,[7] in addition to scandium and yttrium,[8] assisted immensely and highlighted that element 61 (promethium) had yet to be observed.[9]

REE deposits consist primarily of bastnaesite and monazite along with other minerals. The largest bastnaesite deposits are located in China and the United States, while monazite deposits are more broadly dispersed (principally in Australia, Brazil, China, India, Malaysia, South Africa, Sri Lanka, Thailand, and the United States).[10] Despite its name, "rare" earths are fairly common in the earth's crust (figure 2), and some are as abundant as more commonly known elements such as tin.[11] However, REEs retain this moniker due to their generally low concentration within deposits, and that some REE deposits also contain radioactive elements.[12] After a bastnaesite or monazite deposit has been identified rare earth extraction is relatively simple, but separating and processing the rare earths into usable alloys and metals for use in mid-stream products is an involved process (figure 3).[13]

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[4] REE yttrium, ytterbium, terbium, and erbium were named after the Ytterby mines. Science History, "The History and Future of Rare Earth Elements," accessed March 8, 2021.

[5] Science History, "The History and Future of Rare Earth Elements," accessed March 8, 2021.

[6] For example, "didymium" was published as an element with atomic mass 138 in the periodic table until Carl Auer von Welsbach demonstrated that "didymium" was an alloy of two rare earth elements: neodymium and praseodymium in 1885. Science History, "The History and Future of Rare Earth Elements," accessed March 8, 2021.

[7] Until this point in time there had been debate as to how many elements would constitute the lanthanide series in the periodic table. Science History, "The History and Future of Rare Earth Elements," accessed March 8, 2021.

[8] Scandium and yttrium exhibit similar chemical properties to the elements in the lanthanide series but have different magnetic and electronic properties.

[9] Element 61, promethium (Pm) is generally recognized as being characterized at Oak Ridge National Laboratory in 1945. Marinsky, Glendenin, Coryell, "The chemical identification of radioisotopes," 1947, 2781–5.

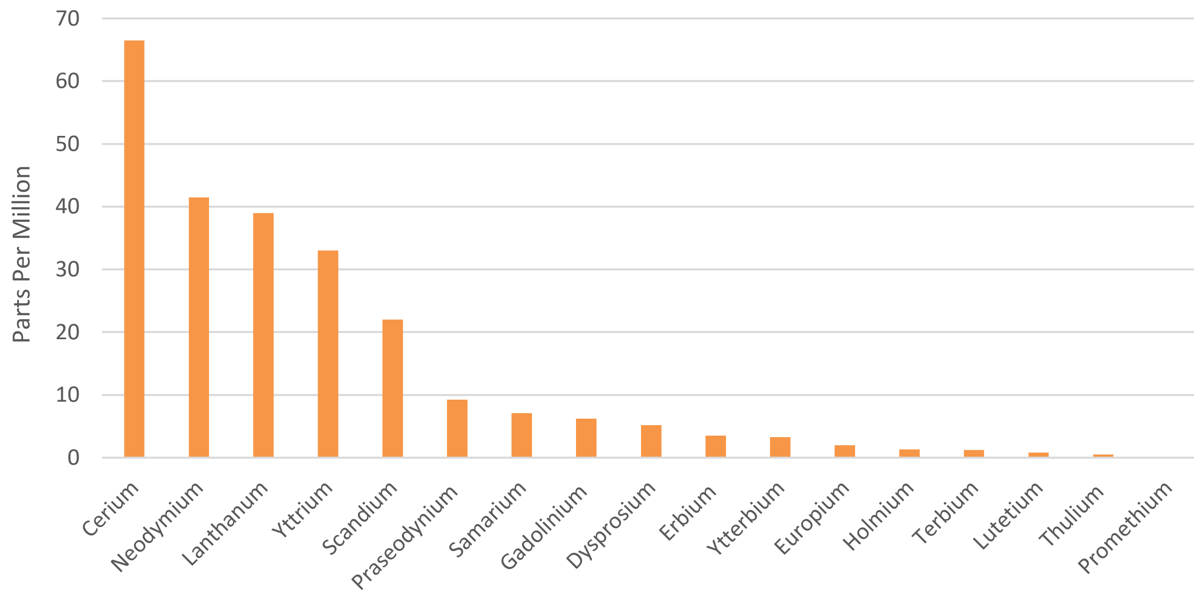
[10] Other minerals contains smaller levels of REEs, and include apatite, cheralite, eudialyte, loparite, and phosphorites Hurst, Cindy, "China's Rare Earth Elements: What Can the West Learn?," 2010, 4.

[11] Science History, "The History and Future of Rare Earth Elements," accessed March 8, 2021.

[12] Such as uranium and thorium which are part of the actinide series. Science History, "The History and Future of Rare Earth Elements," accessed March 8, 2021.

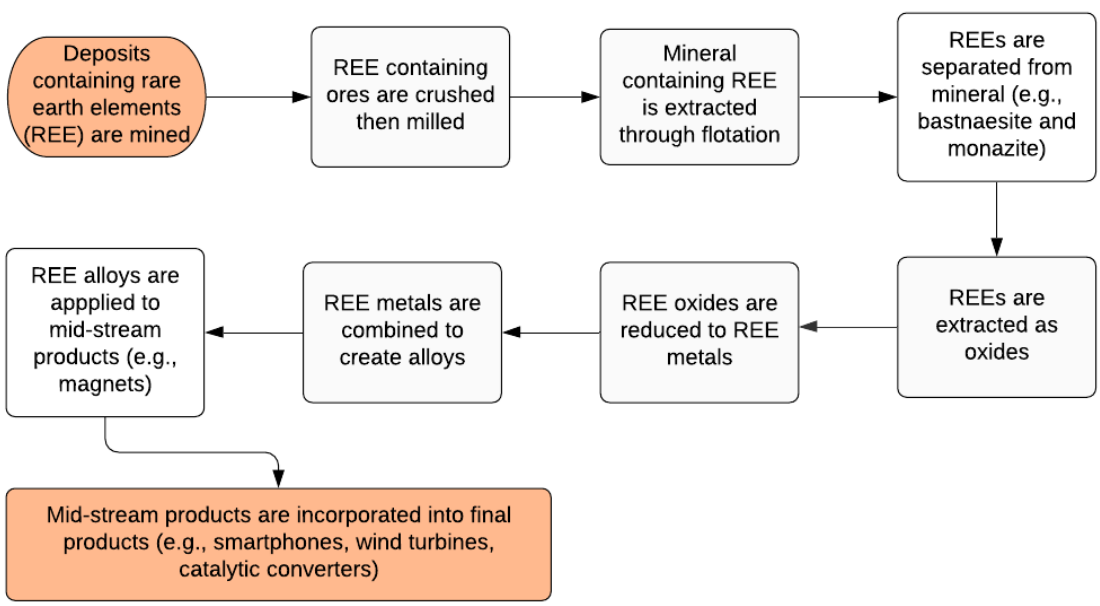
[13] Congressional Research Service, "An Overview of Rare Earth Elements and Related Issues for Congress," November 2020, 5.

Figure 2 Estimated concentration of rare earth elements in the Earth's crust (parts per million (ppm))



Source: U.S. Geological Survey (USGS), "The Principal Rare Earth Elements Deposits of the United States—A Summary of Domestic Deposits and a Global Perspective," 2010, 5.
Note: This figure uses the Lyde (1997) estimate of the concentration of rare earths elements in the Earth's crust.

Figure 3 Rare earths production process overview



Source: Hurst, Cindy, "China's Rare Earth Elements: What Can the West Learn?" 2010, 5.

Historically, mining REE deposits in certain locations is considered as not commercially viable or processing efforts are deemed too environmentally damaging.[14] Today current REE production is highly concentrated in only a few of countries (primarily China), and has led to concerns about production bottlenecks and supply chain sensitivity both in the supply of REEs as well as the processing of REEs for consumption. Both issues will be discussed further in the "REE Challenges for Electronics as Supply Bottlenecks Loom and Competing Demand Rises" section below.

REEs and Electronics

REEs have been used in electronics and advanced machinery for nearly three-quarters of a century. Demand for REEs in electronics began in earnest in the 1960s with the introduction of the first color television sets, which initially used europium to produce the color images on the screen.[15] Since then, demand for rare earths has steadily grown as consumer demand for electronics rose. Simultaneously, REEs have become increasingly integrated throughout electronic products (including screens, glass, batteries, and magnets), and the rise in industry demands for REEs, particularly in the renewable energy and automotive sectors, placed additional consumption demand on rare earths production.

Despite the small economic value of REEs relative to other sectors (one industry report estimated that the rare earths market size was $13.2 billion in 2019, while global smartphone sales were more than $400 billion in that year), REEs represent an integral component of modern electronics.[16] One of the most common, and important, uses of REEs in electronics is of neodymium in NIB (neodymium-iron-boron, NdFeB) magnets.[17] NIB magnets are more than 12 times stronger than conventional iron magnets, and are frequently used in electronic products, as well as in lasers and telecommunications systems (i.e., traveling wave tubes and wave radar amplifiers).[18] Additionally, dysprosium, is often added to protect these NIB magnets from high heat (e.g., generated from the motor within a smartphone).[19]

Smartphones are representative of the substantial contribution of REEs in the electronics sector:

- Depending on the model, a smartphone can contain yttrium, lanthanum, terbium, neodymium, dysprosium, gadolinium, and praseodymium;[20]

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[14] Commercial viability refers to the costs associated with mining sufficient quantity of REE ores (raw rare earths) and the high cost to process the REEs into commodities. For further information on the environmental challenges of rare earths mining, see Ives, Mike, "Boom in Mining Rare Earths Poses Mounting Toxic Risks," Yale School of the Environment, January 28, 2013, Standaert, Michael, "China Wrestles with the Toxic Aftermath of Rare Earth Mining," Yale School of the Environment, July 2, 2019.

[15] King, Hobart, "REE Rare Earth Elements and Their Uses," Geology.com, 2018.

[16] Global Market Insights, "Rare Earth Metals Market Industry Trends," June 2020; Statista, "Smartphone sales revenue worldwide 2013–2020," November 23, 2020.

[17] NIB magnets also contain small quantities of dysprosium and praseodymium. New Electronics, "Rare earth elements vital to electronics industry," September 13, 2011, Hurst, Cindy, "China's Rare Earth Elements: What Can the West Learn?," 2010, 13.

[18] New Electronics, "Rare earth elements vital to electronics industry," September 13, 2011, Hurst, Cindy, "China's Rare Earth Elements: What Can the West Learn?," 2010, 13.

[19] NIB magnet composition is typically: neodymium 29 percent, dysprosium 2–4 percent, praseodymium less than 1 percent, and other metals 66–68 percent. Dodd, Jan, "Rethinking the use of rare earths elements," WindPower Monthly, November 30, 2018.

[20] BBC, "You Old Phone is Full of Precious Metals," October 17, 2016.

- Neodymium, praseodymium, and dysprosium are fundamental to the sound system of most smartphone brands, and modern haptic-based smartphone models also use REEs for the vibration feedback in the home button;[21]
- Trace amounts of REEs are also used to produce colors in the screen, reminiscent of the early uses of REEs in electronics.[22]

Looking more broadly at other electronic products, other uses of REEs emerge, including:

- Certain fitness trackers use active matrix OLED (AMOLED) screens. OLED screens can contain as many as seven different REEs, including for use in color emission (yttrium, lanthanum, terbium, europium, gadolinium) as well as reducing ultraviolet light penetration (praseodymium, dysprosium);[23]
- NIB magnets are frequently used in laptops to provide more precise control in the motors that spin laptop hard disks and the arm that writes and reads data, which allows for greater storage capacity;[24]
- Erbium ions (of high energy state) are embedded in optical fibers, which release stored energy as light travels along the optical fiber, thereby amplifying signals;[25]
- Europium is used as a fluorescent for desktop computer monitors, as well as television monitors.[26]

The use of REEs has become fundamental to the electronics sector, allowing electronic products to process information more quickly and store data more efficiently, thereby enhance user experience. However, as described below, the U.S. electronics sector faces several significant challenges to procuring sufficient REE supplies for downstream products. Supply bottlenecks for both raw REEs as well as processed REEs can lead to pricing issues for REEs and potential supply disruptions. Additionally, the rise of competing REE demand from other industries could further squeeze the U.S. electronics sector.

[21] Visual Capitalist, Extraordinary Raw Materials in an iPhone 6," March 8, 2016.
[22] Apple, "iPhone 12 Pro Max Product Environmental Report," October 2020.
[23] Magyar, Tamas, Sandor Nagy, Janka Orsi, Richard Papp, "Chemical and material characterization of smartphones with special regards to OLED screens for recovery of valuable elements," ECOTERRA-Journal of Environmental Research and Protection, 2018, 20.
[24] New Electronics, "Rare earth elements vital to electronics industry," September 13, 2011.
[25] New Electronics, "Rare earth elements vital to electronics industry," September 13, 2011; Van Veen, Kelsi and Alex Melton, "Rare Earth Elements Supply Chains, Part 1: An Update on Global Production and Trade," Executive Briefing on Trade, U.S. International Trade Commission, December 2020.
[26] King, Hobart, "REE Rare Earth Elements and Their Uses," Geology.com, 2018.

REE Challenges for Electronics as Supply Bottlenecks Loom and Competing Demand Rises

Over the last 15 years, the largest challenge to the consumption of REEs in electronics, as well as other products (such as electric vehicles (EVs), wind turbines, and lasers), has been the risk of supply disruption. Generally, supply disruption in REEs can occur at two stages: the initial production of REEs into its' raw "unprocessed" form, and after REEs have been processed into workable alloys for incorporation into midstream products such as magnets and end-stream products like smartphones and wind turbines. Both stages are heavily concentrated in a few countries (particularly China), so the risk for disruption can be significant.

In addition to these ongoing REE threats to the electronics sector from the supply side, an additional concern has emerged for electronics manufacturers: the rise of demand from other competing commercial industries. While the electronics sector has historically represented a substantial share of REE consumption and was one of the first major industries to adopt REEs on a large scale, other industries (particularly in the renewable energy sector) have emerged with increasing demand for REEs.[27] This section will describe both the supply and demand threats to REE consumption in the electronics sector, and will be followed with a section exploring potential future sources of REEs (as well as the efforts to reduce and recycle REEs to create more effective closed loop REE supply chains).

The Evolution of REE Production and Potential Trade Disruptions

While REEs have been mined for over two centuries, their commercial value developed with the advent of the Atomic Age (i.e., post 1945). Between 1900 and the present, there were three periods of REE production: the 1900–40 period, when India and Brazil largely supplied the world's REE materials; the 1960–2000 period, when the United States (chiefly California) was the predominant supplier; and 2000–present, which witnessed the rise of China as the predominant producer of rare earths. For a more detailed historical discussion of these periods, see Appendix A.

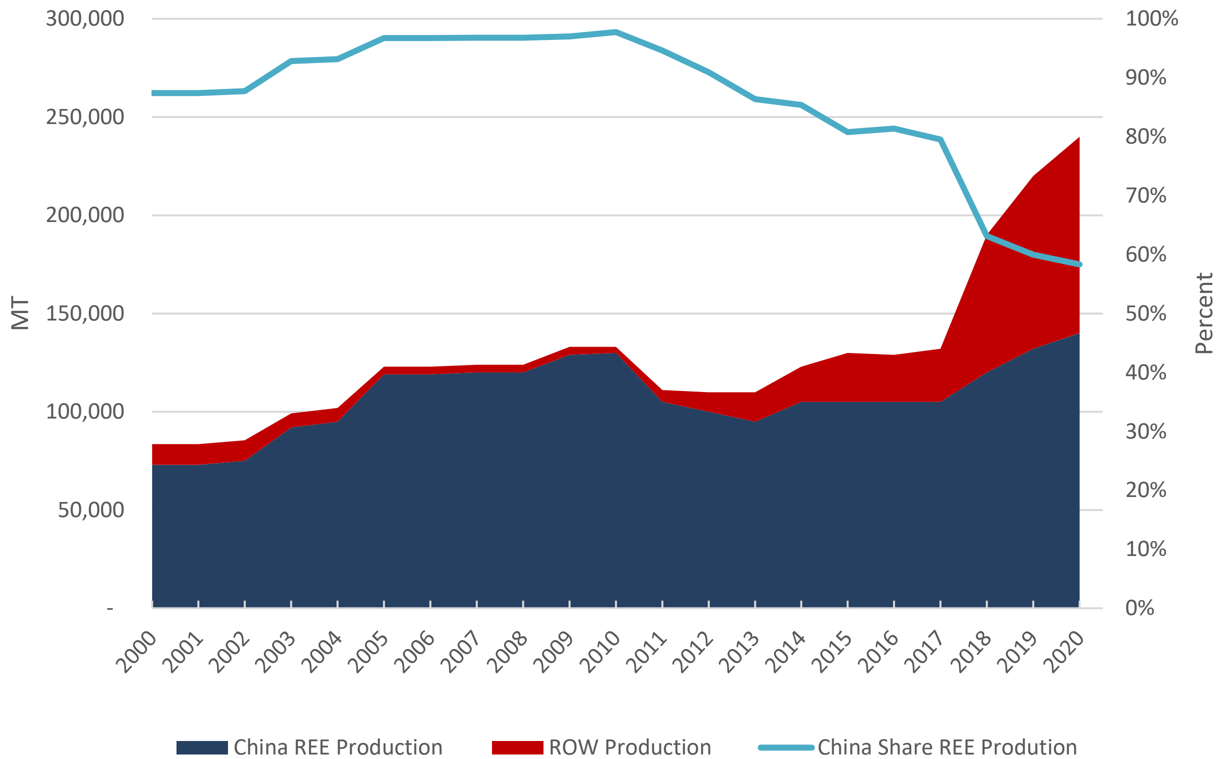
Since China emerged as the largest producer of REEs, consumers of rare earths have noted that the potential for supply disruption is significant. Incidents in 2010 and 2011–13 confirmed that price and supply instability can disrupt the provision of rare earths for midstream manufacturers (such as magnet producers) and downstream electronics manufacturers, noted below. This section will explore the supply chain challenges that have emerged over this century of both raw REEs and processed REEs.

The Risk of Raw REE Disruption

From 2000 onward, China represented the majority producer of the world's rare earths output: for multiple years, China produced more than 95 percent of the total raw earths consumed around the world, and since 2000 China's share of global REE production has not fallen below 59 percent (figure 4).

[27] REES are also widely used in a variety of military applications, but these will not be discussed in this paper.

Figure 4 China's production of raw REEs as a share of global production, metric tons (MT)



Source: U.S. Geological Survey, "Rare Earths," 2000–2020.
Note: REE mining production data is reported in rare earth oxide equivalent. It does not include production from further processing. For years 2015 to 2020, China REE production data only notes China's REE production quotas, and does not include undocumented production. This may undervalue China's REE production in the 2015–20 period.

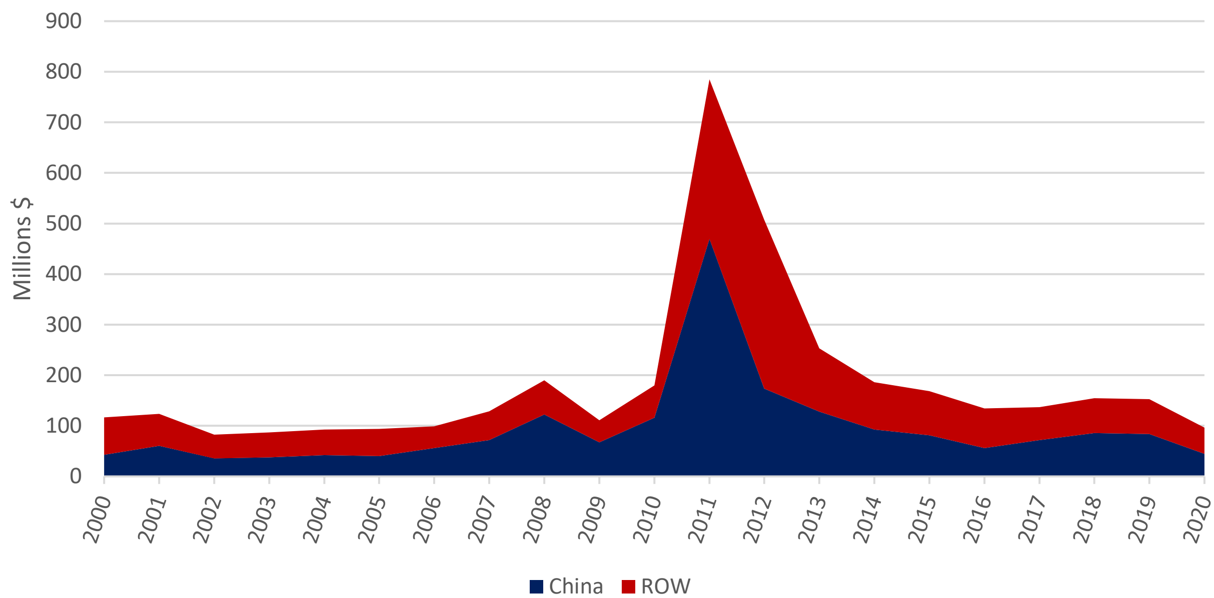
China's large share of global REE production raised concerns among downstream consumers that the potential for REE disruption is significant. In September 2010, Japanese authorities arrested a Chinese fishing boat in the disputed waters between China and Japan, resulting in the halt of raw rare earths exports from China to Japan (China's largest export market for rare earths).[28] The following month, it appeared that China had expanded this export limitation to the United States,[29] and China reduced its total export quotas by 40 percent. After a 2012 World Trade Organization (WTO) panel ruled in favor of the United States, Japan, and the European Union in a dispute settlement procedure against these export quotas, China eventually relaxed the quotas in 2016 and global REE prices stabilized.

Prior to the relaxation of trade restrictions, this disruption in exports had a significant impact on rare earths pricing, and subsequently contributed to trade distortions. Between 2010 and 2011, the prices of neodymium rose nearly 600 percent (from $19 to $129 per pound), samarium rose nearly 700 percent (from $8.40 to $66 per pound), terbium rose over 640 percent (from $275 to $2054 per pound), and europium increased nearly 900 percent (from $270 to $2672 per pound), and reports indicate that price

[28] Bradsher, Keith. "Amid Tension, China Blocks Vital Exports to Japan." New York Times, September 22, 2010.
[29] Wiggin, Addison, "The Truth Behind China's Rare Earths Embargo," Forbes, October 20, 2010.

of dysprosium rose by nearly 20-fold.[30] Subsequently, U.S. imports of rare earths experienced a 338 percent increase in value from 2010 to 2011 due principally to these price increases (figure 5), while the import of rare earths by quantity experienced a much more subdued increase in that period.[31]

Figure 5 U.S. imports of rare earths compounds from China and the rest of the world (ROW), 2000–20 (million $)



Source: Global Trade Atlas (GTIS), (HS 2846) (accessed March 15, 2021).
Note: This figure is of compounds derived from ores containing rare earths under HTS 2846 ("Compounds, inorganic or organic, of rare-earth metals, of yttrium or of scandium, or of mixtures of these metals").

Industry representatives and government agencies noted that the 2010–13 period highlighted that many industries were sensitive to the concentration of rare earths production in China. Subsequently, production of raw rare earths in a variety of countries began to rise, including Australia, Thailand, and the United States, contributing to efforts to diversify production of raw rare earths which in turn reduced China's estimated global production share. Despite additional production coming online, China remains the single largest producer of raw rare earths in the world, and in 2020 produced more than three times as much REE as the second largest producer, the United States (140,000 metric tons of rare earth oxides [REO] and 38,000 metric tons of REOs, respectively).[32] A discussion of both China and the United States' production trends is explored in further detail in Appendix A.

[30] Statista, "Prices of the five most critical rare earths between September 2010 and October 2011 (per kilogram)," November 6, 2011; Edmondson, James, "Will Rare-Earths be Eliminated from Electric Vehicle Motors?" Advanced Batteries and Energy Storage, November 2, 2020; Bradsher, Keith, "Supplies Squeezed, Rare Earth Prices Surge," New York Times, May 2, 2011.
[31] U.S. Geological Survey, "Rare Earths 2013," January 2013.
[32] REE mining production data is reported in REO equivalents. It does not include production from further processing. U.S. Geological Survey, "Rare Earths 2021," January 2021.

Potential Processing Bottlenecks

As already noted in figure 2, before rare earths can be used in final products, such as smartphones and fiber optical cables, they must be processed first. Processing involves extracting the REOs from the ore and then separating it from the other elements present, but the desired REE can often represent as little as 1 percent of the quantity of the mined deposit. Extracting the REO and subsequently isolating the REE (metal), or alloys (mixed metals) must be achieved prior to incorporating rare earths into midstream products, such as magnets, for final use. These stages often require significant capital investments, as well as advanced technical capabilities (particularly given the high-purity product demands of many REE consumers).[33]

As China's production of raw rare earths grew in the 1990s and early 2000s, it simultaneously became the world's largest processor of rare earths. With only a few major processors outside of China—notably facilities in Estonia and Malaysia—China maintains a significant position throughout the REEs supply chain, and by some estimates processes upwards of 95 percent of all REE even as its share of raw production has recently declined (and China is the only country with the ability to process all types of REEs).[34] China also spared its processing capacity from trade disruption during the 2010–13 period (e.g., limited supplies of raw rare earths to the United States and Japan) conversely China did not appear to impose similar restrictions on its processed rare earths.[35]

Similar to developments in the production of raw rare earths, there are indications that there is international interest in diversifying the entire production process of rare earths.[36] The United States, Canada, Russia, Australia, and several other countries have announced investments in creating or expanding their raw earths processing capacity.[37] Many of these developments, which will be discussed in further detail in the "The Search for Alternatives" section below, reflect significant interests from both governments as well as private sector industries (including the electronics sector) in moving the rare earths supply chain beyond China.

Growing Demand

Accompanying the well-known supply-side challenges in both the production of raw rare earths and in processed REEs, growing demand from a variety of industry sectors could also create challenges for electronics manufacturers attempting to source REEs. One 2021 assessment estimated that with the growth of the renewable energy and EV sectors, that by 2028 global demand for neodymium would

[33] Van Veen, Kelsi and Alex Melton, "Rare Earth Elements Supply Chains, Part 1: An Update on Global Production and Trade," Executive Briefing on Trade, U.S. International Trade Commission, December 2020.
[34] Outside of China the two major processing facilities for rare earths are Canadian firm Neo Performance Materials' processing facility in Estonia, and the Australian firm Lynas' facility in Kuantan, Malaysia. Kozak, Frederick, "The Top 5 Rare Earths Companies for 2021," Investor Intel, January 8, 2021; Gerden, Eugene, "Analysts expect further competition in the global REE mining sector," Resource World, October 2020; Ahmed, Nafeez, "We Don't Mine Enough Rare Earth Metals to Replace Fossil Fuels With Renewable Energy," Vice, December 12, 2018.
[35] Bradsher, Keith. "Amid Tension, China Blocks Vital Exports to Japan." New York Times, September 22, 2010.
[36] Nikkei Asia, "Quad tightens rare-earth cooperation to counter China," March 11, 2021.
[37] Tegler, Eric. "The U.S. is Trying to Secure Rare Earth Elements for National Security. That goes Beyond Simple Investment," Forbes, February 6, 2021; Saskatchewan.ca, "Saskatchewan to Create Canada's First Rare Earths Processing Facility at SRC," August 27, 2020; Gerden, Eugene, "Analysts expect further competition in the global REE mining sector," Resource World, October 2020; Kruger, Colin, "Rare earths market draws a crowd as new Lynas rivals gear up," Sydney Morning Herald, March 5, 2021.

necessitate an additional 7,000 metric tons of neodymium production every year, roughly equal to all current U.S. neodymium metal-consumption capacity.[38]

Demand, as does supply, for REEs differs by REE, with one academic noting, "there is no single 'rare earth market' to speak of, but rather, multiple markets for the 17 elements with widely divergent availabilities and applications."[39] Hence, there is significant potential for future shortages for some REEs while others maintain a balanced market. A 2012 assessment found that demand for dysprosium and neodymium, both used heavily in electronic products (i.e., NIB magnets), would likely exceed projected supply by 2025, and the supply-demand imbalance for dysprosium would likely worsen as supply for other REEs would likely not exceed demand.[40] A subsequent 2021 assessment found that current supplies of neodymium, praseodymium, dysprosium, and terbium are likely to only narrowly exceed their respective demands, while other rare earths markets like cerium and lanthanum likely will remain with excess supply commercially confirming the findings in 2012.[41]

Despite the rise of demand for REEs overall, the consumer electronics' share of REE demand appears to be falling. While one 2008 assessment found that the electronics sector constituted the largest end-use consumer of REEs, by 2020 this demand had fallen below the automotive sector, with the renewable energy sector not far behind.[42] Both the automotive and energy sectors are experiencing substantial changes in their industries which have contributed to elevated REE demand, which are described in greater detail in Appendix B.[43]

The Search for Alternatives

Acknowledging both demand and supply challenges for the rare earths sector, industry stakeholders have explored options to diversify the REE supply chain. On the supply side, this means elevating production of raw rare earths outside of China to diversify supply, as well as increasing processing

[38] Barrera, Priscila, "Rare Earths Outlook 2021: REE Magnet Supply to Remain Tight," Investing News, January 20, 2021.

[39] Cerium, for example, constituted approximately 42 percent of all rare earths production in 2018, while promethium is estimated to be the third rarest element to naturally occur in the Earth's crust. Grand View Research, "Rare Earth Elements Market Size, Share & Trends Analysis Report by Product (Cerium, Dysprosium, Erbium), by Application (Magnets, Catalyst), by Region, and Segment Forecasts, 2019–2025," September 2019; U.S. Geological Survey (USGS), "The Principal Rare Earth Elements Deposits of the United States—A Summary of Domestic Deposits and a Global Perspective," 2010, 5; Klinger, Julie, "Historical geography of rare earth elements: From discovery to the atomic age," Extractive Industries and Society, 2015, 2.

[40] MIT, "Rare Earth Elements Supply and Demand," 2013.

[41] Barrera, Priscila, "Rare Earths Outlook 2021: REE Magnet Supply to Remain Tight," Investing News, January 20, 2021.

[42] The Geological Society of London, "Rare Earths Elements Briefing Note," 2011, 4; Barrera, Priscila, "Rare Earths Outlook 2021: REE Magnet Supply to Remain Tight," Investing News, January 20, 2021.

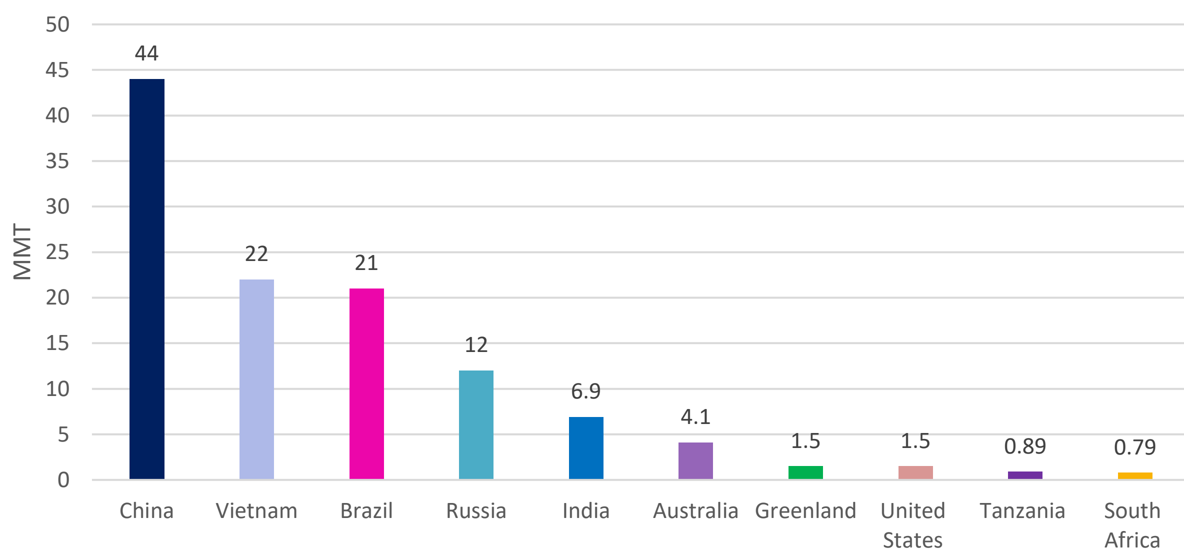
[43] Kruger, Colin, "Electric vehicles, wind turbine demand drive Lynas's bumper profit," Sydney Morning Herald, February 26, 2021.

capacity globally to reduce the possibility of bottlenecks and unexpected supply disruptions.[44] On the demand side, several industry consumers of rare earths have explored multiple options to decrease their dependence on rare earths, including reducing consumption of rare earths in favor of other technologies as well as increased recycling to facilitate closed loop rare earths consumption. This section will explore both the supply and demand initiatives, beginning with leading potential sources of raw rare earths production and processing—Australia, the United States, Vietnam, Brazil, and Russia—and concluding with a brief review of industry efforts to reduce REE demand through reductions in REE consumption and REE recycling.

Efforts to Increase Diversified Production

In 2020 four countries represented approximately 82.5 percent of the 120 million tons of global mineable reserves of rare earths on land (figure 6): China (36.7 percent), Brazil (17.5 percent), Vietnam (18.3 percent), and Russia (10 percent).[45] The other largest reserves are held by India, Australia, Greenland, the United States, Tanzania, and South Africa. Combined, these 10 countries represent more than 95 percent of known global REE reserves.

Figure 6 Estimated rare earths reserves by country, 2020 million metric tons (MMT)

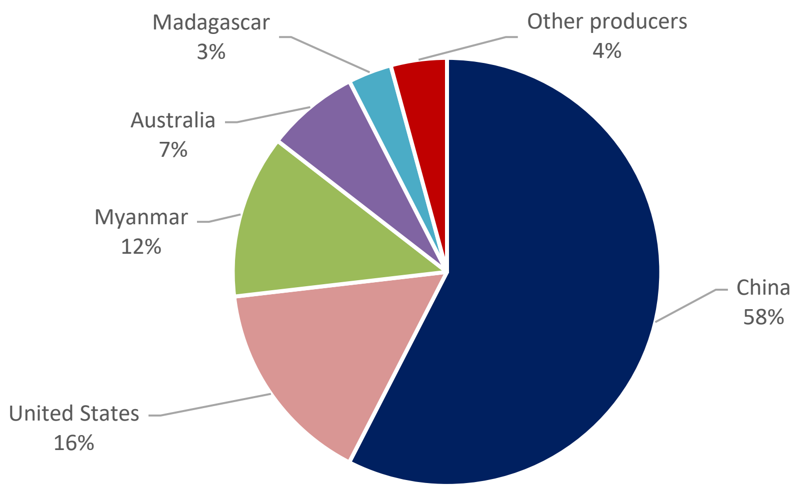


Source: U.S. Geological Survey, "Rare Earths 2021," January 2021.
Note: Does not include global reserves of scandium, which the USGS classifies separately. Measured in metric tons of rare earths oxide (REO) equivalent.

[44] Several industry experts have noted concern that the January 2021 military coup in Myanmar, which in produced an estimated 30,000 metric tons of rare earths in 2020, could disrupt trade in heavy rare earths. China, a substantial imported of Burmese-produced raw rare earths for further processing, has been particularly concerned at the threat of supply disruption. Merriman, David, "Rare earths: Myanmar coup d'etat creates more uncertainty for heavy rare earth supply," February 2, 2021; Asia Times Financial, "Myanmar crisis poses risks to global rare earth supply chain," February 2, 2021.
[45] Van Veen, Kelsi and Alex Melton, "Rare Earth Elements Supply Chains, Part 1: An Update on Global Production and Trade," Executive Briefing on Trade, U.S. International Trade Commission, December 2020; U.S. Geological Survey, "Rare Earths 2021," January 1, 2021.

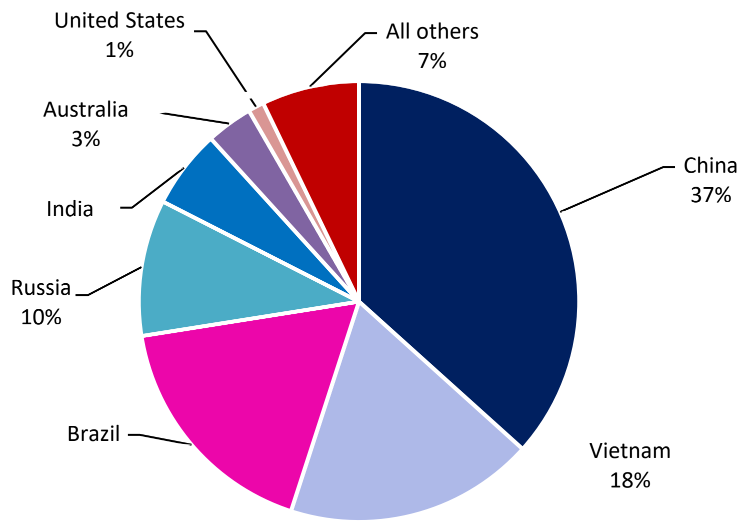
Given the high cost and technical expertise required to mine and process rare earths, production has not typically mirrored supply. Indeed, neither of the large shares of global production held by China from 2000 to the present nor of the United States from 1960 to 2000 (described in Appendix A) reflected existing supply, but rather a combination of technical capacity, investment, and domestic as well as global demand. The contrast between production and reserves in 2020 are represented in figures 7 and 8.

Figure 7 Mine production of raw rare earths, by leading countries, 2020 (total global production: 243,000 metric tons)



Note: Does not include scandium, which is broken out separately by the U.S. Geological Survey.
Source: U.S. Geological Survey, "Rare Earths 2021," January 2021.

Figure 8 Shares of estimated global REE reserves, by leading countries (2020 total global reserves: 120 million metric tons)



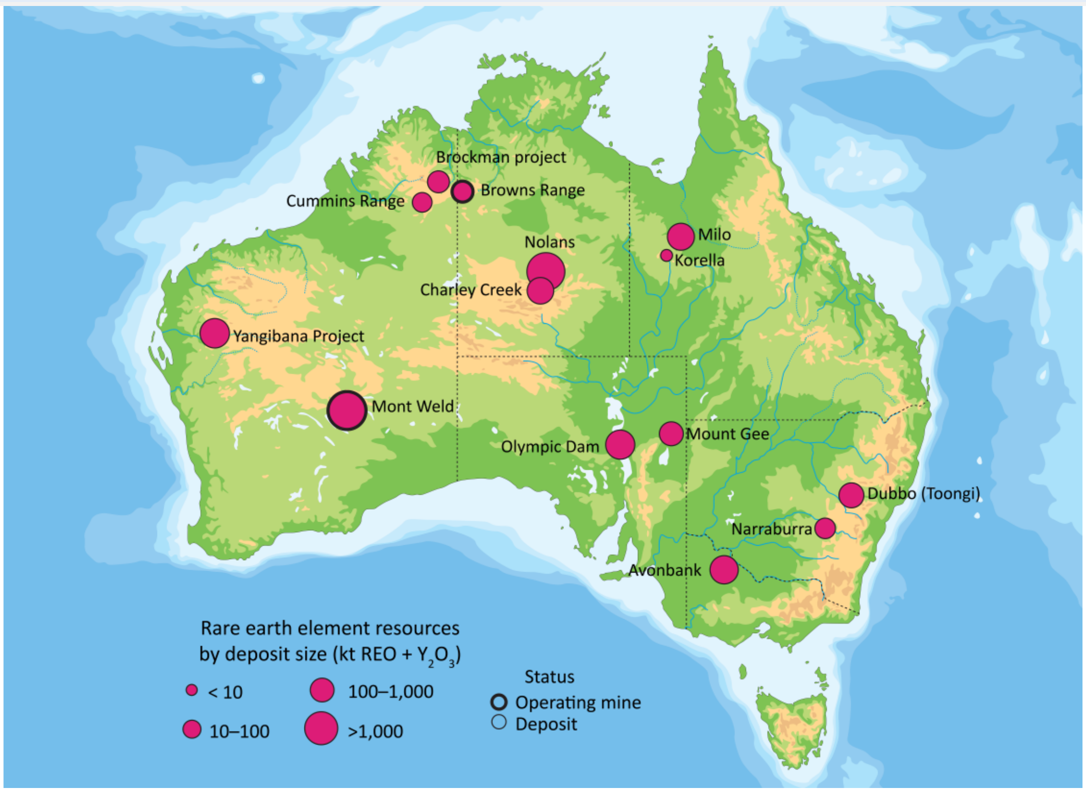
Note: Does not include scandium, which is broken out separately by the U.S. Geological Survey.
Source: U.S. Geological Survey, "Rare Earths 2021," January 2021.

As figure 8 shows, there is substantial available supply of rare earths ores in a variety of countries that are not currently major producers or exporters of rare earths, particularly Vietnam, Brazil, and Russia. Australia and the United States, the first two countries explored in this section below, are currently producing well above their shares of global reserves, a reflection of ongoing investment and technical capacity in these two countries.

Australia

After China, Australia has frequently been the largest producer of REEs during the past several years; Australia was the second largest producer of REEs from 2015–18 and was the only major competitor to China in this period. By 2019 though Australia was supplanted by the United States when California's Mountain Pass mine resumed production after a three-year hiatus.[46] In the 2015–20 period, Australia produced between 12,000 and 21,000 metric tons of REOs, and last year produced 17,000 metric tons of REO (as the world's fourth largest producer in 2020, after China, the United States, and Myanmar).[47]

Figure 9 Known rare earths deposits and mines in Australia, 2019



Source: Compiled by staff based on Plastow, Killian, "Why everyone's talking about Australia's rare earth," New Daily, December 8, 2019.

[46] In this period, one industry report notes that Australia produced around 10 percent of the world's raw rare earths supply, while China produced 85 percent, and the rest of the world produced the remaining 5 percent. Sharp, Neil, "Why are rare earth elements so crucial for electronics manufacturing," JJS Manufacturing, October 3, 2019; U.S. Geological Survey, "Rare Earths 2021," January 2021.
[47] U.S. Geological Survey, "Rare Earths 2021," January 2021.

Australia has the sixth-largest highest known reserves of rare earths, 3.4–4.1 million metric tons, though this only equates to around 3 percent of the global supply.[48] However, its ability to elevate production relative to its supply reflects an important factors that will likely contribute to Australia's future rare earths production. Firstly, Australia's extensive mining capabilities beyond rare earths has provided it with substantial technical resources and market investment well beyond its share of global reserves.[49]

Secondly, its location in the Asia-Pacific region provided Australia with a unique opportunity during the early rare earths disputes between China and Japan in 2010. During this dispute, Japan's unmet demand led to significant investment from Japanese firms and ultimately there was sufficient capital raised that facilitated REE production by the Australian firm Lynas Corps, Ltd. With the funding available Lynas, subsequently began production (at Mt. Weld in the state of Western Australia) in 2011 and currently produces nearly all of Australia's mined rare earths, including neodymium, praseodymium, lanthanum, and cerium.[50]

Finally, Australia's current raw rare earths production is processed outside of China, at Lynas' processing facility in Kuantan, Malaysia. This provides Australian mining with a unique capacity to sidestep both raw materials and processed REE supply chain bottlenecks in providing downstream consumers with REEs.[51] Lynas is also investing in additional processing capabilities in Kalgoorlie, Western Australia, thereby even further expanding processed REE production beyond China.[52] Several other Australian firms are also investing in exploring, assessing, and developing rare earths deposits, including in the Northern Territories, New South Wales, and other locations in Western Australia beyond the Mt. Weld deposit (figure 9), providing future potential resources if investment and demand align.

United States

Similar to Australia, the United States now produces raw rare earths at a level far above its share of global reserves. At 1.5 million metric tons of REEs, the United States ties for seventh in global reserves along with Greenland (with each representing approximately 1 percent of global reserves).[53] Despite elevated production relative to its reserves (in 2020, the United States produced 38,000 metric tons of REEs and 16 percent of global raw REEs), U.S. production as a share of global production is far below the 1960–1995 period when the United States was the predominant global producer (for further information, see Appendix A).

Current raw earths production in the United States is almost entirely located in the Mountain Pass mining facility in southern California along the Clark Mountain Range near the Nevada border.[54] The bastnasite deposit represents the only major source of raw rare earths mining in North America, and the only mine in the Western Hemisphere with known production above 1,000 tons.[55] The mine produces cerium, lanthanum, neodymium, and europium. Unlike Australia's facilities, however, all raw rare earths

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[48] Tibballs, Scott, "Rare Earths in Australia," March 9, 2021.
[49] Tibballs, Scott, "Rare Earths in Australia," March 9, 2021.
[50] Lynas, "Lynas Rare Earths," 2021.
[51] Lynas is also currently planning an additional rare earths processing facility in Kalgoorlie Western Australia, further expanding processing capability. Lynas, "Lynas in Western Australia FAQs," May 2020.
[52] Lynas, "Lynas in Western Australia FAQs," May 2020.
[53] U.S. Geological Survey, "Rare Earths 2021," January 2021.
[54] U.S. Geological Survey, "Rare Earths 2021," January 2021
[55] U.S. Geological Survey, "Rare Earths 2021," January 2021.

mined in the United States are exported to other countries (principally China) for processing. The United States currently lacks sufficient processing capacity to meet its own rare earths production needs.[56]

In addition to the Mountain Pass mine, there are several other locations in the United States that are potentially suitable for mining, and there are indications of commercial interest for many of the locales. In western Texas, the Round Top Mountain deposit contains nearly all rare earths, including neodymium and dysprosium, and all heavy rare earths.[57] The existence of heavy rare earths in this area, particularly dysprosium, is noteworthy since the United States currently does not produce any heavy rare earths and U.S. producers must rely on heavy rare earths production in China and elsewhere to fill heavy rare earth demand.[58] Two rare earths firms, USA Rare Earth LLC and Texas Mineral Resources Corp, have announced collaborative efforts in developing this area for rare earths mining.[59]

Other U.S. locations have been explored by firms for raw REE deposits, and some are in early development. In Nebraska, a niobium mining facility in Elk Creek is under construction by NioCorp, which will also produce scandium.[60] The Bear Lodge region in northeastern Wyoming contains several rare earths, and a demonstration project is currently being completed to establish viability for future mining. Similarly in Alaska, eight regions have been identified as likely containing rare earths, with the Bokan Mountain region currently under exploration for future development by U.S. firm Ucore.[61] In Utah, U.S. firm Energy Fuels announced it would purchase 2,500 metric tons of monazite sands from the Offerman Mineral Sand Plant in southern Georgia for a three-year period to process and extract neodymium and praseodymium.[62]

In processing rare earths, U.S. government agencies, U.S. firms, and some foreign firms have expressed a significant interest in creating domestic processing capability for U.S. and foreign-origin raw rare earths. Over the last year, several initiatives have been announced to support the production of processing capabilities in the United States:

- In February 2021, Australian firm Lynas announced it had won a contract under the Defense Production Act (DPA) to establish a light rare earths separation facility in Hondo, Texas (in addition to its heavy earths facility already under construction).[63] Although the facility is expected to initially serve Lynas' Australian REE production and assist its Malaysian processing

[56] Reuters, "Factbox: Rare earths projects under development in U.S.," April 22, 2020. Also see Appendix A for a discussion of the evolution of U.S. REE production.
[57] Vinski, Jim, "The U.S. Needs China for Rare Earth Minerals? Not for Long, Thanks to This Mountain," Forbes, April 7, 2020.
[58] Kozak, Frederick, "The Top 5 Rare Earths Companies for 2021," Investor Intel, January 8, 2021
[59] Global Newswire, "USA Rare Earth's Rare Earth & Critical Minerals Pilot Plant Development and Processing Facility Officially Opens," June 11, 2020.
[60] Mining Technology, "Elk Creek Niobium Project, Nebraska," n.d. (accessed March 16, 2021).
[61] Lasley, Shane, "Alaska is rich in critical rare earths," Mining News North, June 22, 2020.
[62] The firm, which will also be extracting uranium from the sand, also announced it would work with the Canadian firm Neo Materials to further process REEs in Neo Materials' processing facility in Estonia. Bomgardner, Melody, "Utah-based Energy Fuels plans rare earths production," CE&N, December 21, 2020; Hui, Mary, "A US-Europe rare earths partnership is sandwiched by China," March 12, 2021.
[63] Reuters, "Pentagon awards $30 million in rare earths funding to Australia's Lynas," February 1, 2021; McCrae, Michael, "Lynas wins U.S. Defense contract to build REE plant in Texas," Kitco News, February 2, 2021.

operations, it may expand to including processing U.S. raw REE production.[64] The U.S. Department of Defense, which concluded the technology investment agreement with Lynas over production of this facility, estimates that the successful completion of this project could support the production of 25 percent of the world's processed REOs.[65]

- In January 2021, the U.S. Department of Energy provided funding for the creation of two rare earths processing facilities in Wyoming: a $22 million grant to General Atomics in Upton, Wyoming to separate and process REEs extracted in a demonstration project at Bear Lodge; and a $500,000 grant to the University of Wyoming in Laramie for research into the generation of REEs using microwave plasma on REOs;[66]

- In November 2020, MP Materials announced it would spend $200 million following a DPA grant to restart its light REEs processing facility to serve its Mountain Pass Mine in California.[67] The firm also indicated it may be able to operate throughout the supply chain by establishing a facility to produce NIB magnets;[68]

- In Alaska, Ucore announced in October 2020 its plan to open a rare earths separation and purification facility in Ketchikan to serve as a processing facility for U.S. raw REE production, with an eventual goal of also establishing a REE mine in the nearby Bokan Mountain (which may contain more than 30,000 metric tons of REEs, 40 percent of which are estimated to be heavy REEs);[69]

- In June 2020, USA Rare Earth and Texas Mineral Resources Corp, jointly developing mining capacity at the Round Top mountain in Texas, announced a pilot processing facility in Wheat Ridge, Colorado.[70] The facility is expected to be able to separate rare earths into heavy and light REEs, as well as recover critical non-REE metals such as lithium, uranium, beryllium, and hafnium.[71]

Vietnam

Vietnam has the second largest known reserves of rare earths on land, at 22 million metric tons (18 percent of global supply).[72] This represents nearly one-half of China's known rare earths reserves and is

[64] Reuters, "Pentagon awards $30 million in rare earths funding to Australia's Lynas," February 1, 2021; McCrae, Michael, "Lynas wins U.S. Defense contract to build REE plant in Texas," Kitco News, February 2, 2021.
[65] Defense.gov, "DOD Announces Rare Earth Element Award to Strengthen Domestic Industrial Base," February 1, 2021.
[66] Wyoming News, "Wyoming initiatives receive federal funding for rare earth mineral research," January 22, 2021.
[67] Reuters, "Factbox: Rare earths projects under development in U.S.," April 22, 2020; Kozak, Frederick, "The Top 5 Rare Earths Companies for 2021," Investor Intel, January 8, 2021.
[68] Kozak, Frederick, "The Top 5 Rare Earths Companies for 2021," Investor Intel, January 8, 2021.
[69] Lasley, Shane, "Alaska is rich in critical rare earths," Mining News North, June 22, 2020; Lasley, Shane, "Ucore unveils Alaska2023 rare earths plan," Metal Tech News, October 7, 2020.
[70] Global Newswire, "USA Rare Earth's Rare Earth & Critical Minerals Pilot Plant Development and Processing Facility Officially Opens," June 11, 2020.
[71] Global Newswire, "USA Rare Earth's Rare Earth & Critical Minerals Pilot Plant Development and Processing Facility Officially Opens," June 11, 2020.
[72] U.S. Geological Survey, "Rare Earths 2021," January 2021.

more than 10 times larger than known U.S. reserves.[73] Vietnam's rare earths are largely concentrated in monazite and zircon deposits in the northwestern provinces of Lào Cai and Lai Châu, bordering southern China.[74] The largest deposits, Mau Xe North, Mau Xe South, and Dong Pao, contain cerium, lanthanum, neodymium, praseodymium, yttrium, gadolinium, and europium.[75] The Dong Pao deposit alone contains approximately 7 million metric tons of rare earths, more than double all global REE production from 2000 to 2020.[76]

Despite these substantial reserves, Vietnam produces very little rare earths. Before 2018, Vietnam had not produced more than 400 metric tons of rare earths in a given year, and between 2000 and 2011 the USGS estimates that Vietnam produced no substantial quantities of raw rare earths.[77] Between 2018 and 2020, raw production of rare earths began to increase, with 400 metric tons of production in 2018, followed by 1,300 metric tons in 2019, and 1,000 metric tons in 2020.[78] While this represents only a very small portion of global supply, the volume of rare earths supply has drawn investor interest during periods of disruption. In 2010, several Japanese firms, including Toyota, announced investment in REE mining in Vietnam, coinciding with investments from Japanese firms in increasing production capacity in Australia.[79] Although this early interest did not appear to translate to substantial REE production, increased interest in diversification of supply may elevate interest in building out Vietnamese REE capacity.

Brazil

Broadly, Brazil shares several similarities with Vietnam with respect to rare earths. First, it has substantial reserves of rare earths deposits and ranks third in the world for estimated supply (21 million metric tons, approximately 17 percent of global supply). Rare earths deposits stretch along Brazil's coast, in addition to those further inland in the states of Minas Gerais and Goias, and further north near the borders of Suriname and Guyana.[80] These deposits contain a variety of REEs, including neodymium and cerium.[81]

Also similar to Vietnam, such despite large reserves, Brazilian production of raw rare earths is low. Recent production over the last few years has not exceeded 2,000 metric tons annually, and in several

[73] U.S. Geological Survey, "Rare Earths 2021," January 2021.
[74] Kushnir, Imrich, "Mineral resources of Vietnam," Act Montanistica Slovaca, 2000, 7.
[75] Kushnir, Imrich, "Mineral resources of Vietnam," Act Montanistica Slovaca, 2000, 7.
[76] Kushnir, Imrich, "Mineral resources of Vietnam," Act Montanistica Slovaca, 2000, 7.
[77] U.S. Geological Survey, "Rare Earths," 2000–2021 editions (for full list of USGS Rare Earths reports, consult bibliography).
[78] U.S. Geological Survey, "Rare Earths 2021," January 2021.
[79] Some investment announcements preceded the disruption of Chinese rare earths exports to Japan, though several announced followed the disruption. In May 2010, Showa Denko Rare Earth Vietnam announced the competition of a new rare metal facility to produce dysprosium for use in neodymium magnetic allows. SDK, "Ensuring Stable Supply of High-Performance Magnetic Alloys," May 11, 2010; Yuasa, Shino, "Japan to Mine Rare Earths in Vietnam," Manufacturing.net, October 22, 2010; Watts, Mark, "Toyota expects Vietnam rare earth mining rights by end of year," Metal Bulletin, June 29, 2011.
[80] U.S. Geological Survey (USGS), "Rare earth element mines, deposits, and occurrences: Global Map," n.d. (accessed March 17, 2021).
[81] U.S. Geological Survey (USGS), "Rare earth element mines, deposits, and occurrences: Global Map," n.d. (accessed March 17, 2021).

years between 2000 and 2018 estimated annual production was below 500 metric tons.[82] However, there is a growing interest in research and development of rare earth deposits in Brazil. In February 2021, Brazilian firm Brazil Minerals announced it had acquired the minerals rights for rare earths of nearly 20,000 acres in northeastern Brazil.[83] Although in very early stages of development, Brazil Minerals has announced a longer term interest in investment and development of metals and minerals for the "Green Energy Revolution," including lithium and titanium, in addition to rare earths.[84]

Russia

Rounding out the top four countries for reserves, Russia contains an estimated 12 million metric tons of REO equivalent, approximately 10 percent of global supply (and approximately eight times more than estimated U.S. supply).[85] These deposits are mostly concentrated in Siberia, along the Kola Peninsula, on the northern edge of Lake Baikal, and in Russia's Arctic region.[86] These locations share difficult terrain and weather conditions, and historically have made rare earths production in Russia challenging.[87]

Contemporary Russian production of rare earths is comparatively low (with an estimated 2,700 metric tons of REE production annually in 2019 and 2020).[88] During the Cold War, the Soviet Union was a significant producer of REEs for its domestic market, due in part to an interest in extracting other materials in deposits that contain rare earths (particularly uranium).[89] However, with the fall of the Soviet Union, rare earths production fell; although official statistics are inconsistent, in most years production in Russia was estimated to be between 2,000 and 3,000 metric tons annually from 2000 to 2020.[90]

Some projects in Russia are in development, though the country's mines have struggled with technical capacity issues and financing difficulties. This includes the Tomtorskoye deposit north of the Sakha Republic (with an eventual investor goal of 16,000 metric tons of REEs annually), and the Zashikhinskoye deposit in the Irkutsk Oblast.[91] The Tomtorskoye deposit, if successfully developed, could provide promising returns for Russia's REE mining capacity; by some estimates, the Tomtorskoye deposit is the second largest single deposit of REEs in the world, after the Bayan Obo deposit in China (the principal source of REE mining in China).[92]

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[82] U.S. Geological Survey, "Rare Earths," 2000–2021 editions (for full list of USGS Rare Earths reports, consult bibliography).
[83] Yahoo Finance, "Brazil Minerals, Inc. Adds Large Rare Earths Project," Newsfile Corp., February 9, 2021.
[84] Yahoo Finance, "Brazil Minerals, Inc. Adds Large Rare Earths Project," Newsfile Corp., February 9, 2021.
[85] U.S. Geological Survey (USGS), "Rare earth element mines , deposits, and occurrences: Global Map," n.d. (accessed March 17, 2021).
[86] U.S. Geological Survey (USGS), "Rare earth element mines, deposits, and occurrences: Global Map," n.d. (accessed March 17, 2021).
[87] Cotting, Ashleigh, Toby Woodall, and Jose Miguel Fidel Javier, "Russia struggling to capitalize on rare earths reserves," SP Global, July 3, 2019.
[88] U.S. Geological Survey, "Rare Earths 2021," January 2021.
[89] Mineral Prices, "Russia plans to become a global leader in rare earth metals production," March 5, 2021.
[90] U.S. Geological Survey, "Rare Earths," 2000–2021 editions (for full list of USGS Rare Earths reports, consult bibliography).
[91] Cotting, Ashleigh, Toby Woodall, and Jose Miguel Fidel Javier, "Russia struggling to capitalize on rare earths reserves," SP Global, July 3, 2019.
[92] Cotting, Ashleigh, Toby Woodall, and Jose Miguel Fidel Javier, "Russia struggling to capitalize on rare earths reserves," SP Global, July 3, 2019.

In an effort to expand domestic capacity, in March 2021 the Russian government announced an initiative to increase raw rare earths production. The new program, which foresees approximately $4 billion in funding, would be jointly led by the Russian Ministry of Industry and Trade and the state nuclear corporation Rosatom, and would fund the construction of 10 new plants to produce REE.[93] In addition to expected REE production of 7,000 metric tons by 2024 and 30,000 metric tons by 2030, this initiative would also support the production of lithium, niobium, and tantalum.[94] Although the focus of these efforts would principally be to serve Russia's domestic market initially, the extent of future production could support REE exports to the global market.[95]

Decreased Consumption

Beyond REE supply, government agencies and firms are also reportedly looking at technologies that can reduce REE demand. In Europe, several programs have been initiated to reduce rare earths use in several industry sectors. The British firm GreenSpur Renewables developed the world's first permanent magnet synchronous generators using ferrite rather than rare earths.[96] The German firm Enercon developed a gearless design for wind turbines that does not require rare earths,[97] while the EU-funded EcoSwing project seeks to replace the permanent magnets used in machinery with superconductors that reduce REE use by more than 95 percent.[98]

In the United States, some firms have begun investing in research to find alternatives to rare earths, or to more efficiently use rare earths. For example, the University of Houston and Brookhaven National Lab announced a 2016 research grant exploring the capacity to produce high-temperature superconductor (HTS) magnets to replace permanent magnets used in wind turbines, which would reduce REE magnet demand in wind turbines by over 95 percent (from more than 100 kilograms of neodymium and dysprosium in certain NIB magnets to approximately 100 grams in HTS magnets).[99] In another project, researchers at Northeastern University developed iron-nickel alloys to replace neodymium and dysprosium demand.[100] Transitioning from rare earth lighting products to light-emitting diode technology is a promising way to reduce REE use. One estimate reports that U.S. consumption of rare earths per unit of manufactured products has fallen, but overall demand for REE products has risen, contributing to higher overall demand).[101]

Both the wind turbine and automotive sectors have expressed interest in pursuing REE alternatives, given their high consumption and increasing demand. One 2017 report found that alternatives to NIB

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[93] Basov, Vladimir, "Russia plans to become a global leader in rare and rare earth metals production," Kitco, March 4, 2021.
[94] Basov, Vladimir, "Russia plans to become a global leader in rare and rare earth metals production," Kitco, March 4, 2021.
[95] Basov, Vladimir, "Russia plans to become a global leader in rare and rare earth metals production," Kitco, March 4, 2021.
[96] Sustainalytics, "Implications of the use of rare earth elements in the wind energy market," July 11, 2019.
[97] Sustainalytics, "Implications of the use of rare earth elements in the wind energy market," July 11, 2019; Dodd, Jan, "Rethinking the use of rare earths elements," WindPower Monthly, November 30, 2018.
[98] Sustainalytics, "Implications of the use of rare earth elements in the wind energy market," July 11, 2019; Dodd, Jan, "Rethinking the use of rare earths elements," WindPower Monthly, November 30, 2018.
[99] Arpa, "Impact Sheet: University of Houston (REACT)," June 20, 2016.
[100] U.S. Department of Commerce, "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals," January 2020, 18.
[101] King, Hobart, "REE Rare Earth Elements and Their Uses," Geology.com, 2018.

magnets used for wind turbines could likely be generated without the heavy use of rare earths along with efficiency improvements, but that such investment would be dependent on REE pricing given the high cost of pursuing and creating such technologies.[102] In the automotive sector, older generation magnets (such as aluminum nickel cobalt, samarium cobalt, and ferrite magnets) have been suggested as possible alternatives to NIB magnets, though they face limitations in the higher risk of demagnetization, lower coercivity, and higher expense (particularly given supply chain sensitivity around cobalt in recent years).[103]

Despite the industry interest in alternative products that do not rely on rare earths, these early stages of research and development for alternatives (including more efficient use) face several challenges in addition to those previously highlighted above (i.e., higher cost, and reduced efficiency and efficacy). Principally, alternatives to some products do not appear to exist within current technological capabilities. A 2013 study found that of the 17 rare earths, five of them were unlikely to be replaceable with other materials if a disruption occurred or supply fell. The five identified REEs include dysprosium (used heavily in the electronics, automotive, and renewable energy sectors), europium and yttrium (which are more often used in electronics, particularly in flat panel displays), and thulium and ytterbium (which are more frequently used in military and industrial applications, especially lasers).[104] Dysprosium and europium were found to be particularly difficult to replace, given their unique properties and their use in both commercial and military applications.[105] Given the significant use of dysprosium across REE consumers, finding alternatives to this element could prove particularly challenging.

Recycling

One other potentially promising source of reduced reliance on new production of REEs is in recycling. Similar to the use of alternative technologies for more efficient REE use, recycling of REEs is in early stages of development. Reflecting the substantial largely untapped resource of existing REEs in finished goods, the Rare Earth Technology Alliance estimated in 2019 that less than 1 percent of the world's rare

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[102] Pavel, Cladiu, et al, "Substitution strategies for reducing the use of rare earths in wind turbines," Resources Policy, June 2017.

[103] In the case of samarium cobalt magnets samarium is less sensitive to disruption then neodymium and dysprosium. Els, Peter, "Reducing the industry's reliance on rare earth metals," Automotive IQ, November 21, 2017; Graedel, T. E., E. M. Harper, N. T. Nassar, and Barbara Reck, "On the materials basis of modern society," School of Forestry and Environmental Studies, Yale University, October 11, 2013, 4.

[104] Using a 1 to 100 scale, where a value of 1 means the product is eminently replaceable and 100 meaning the product is completely irreplaceable, the 5 most restricted rare earths were scored the following way: dysprosium 100, europium 100, yttrium 95, ytterbium 88, and terbium 88. For the remaining rare earths, several were viewed as sensitive to disruption (lanthanum, scandium, lutetium, erbium, holmium, thulium, and gadolinium), while others were less sensitive (praseodymium, neodymium, and samarium). Promethium was not studied in this report, likely due to its extremely limited availability as well as it nearly non-existent use. Graedel, T. E., E. M. Harper, N. T. Nassar, and Barbara Reck, "On the materials basis of modern society," School of Forestry and Environmental Studies, Yale University, October 11, 2013, 4.

[105] Dennehy, Kevin, "For metals of the smartphone age, no Plan B," Yale News, December 2, 2013.

earths are currently being recycled, while the majority is discarded.[106] Additionally, the U.S. government has also noted an interest in recovering REEs from coal and coal byproducts.[107]

Some firms have recently started to incorporate recycling of REEs into their supply chains to create a closed loop process and reduce industry sector sensitivity to supply disruption and pricing pressure from increased demand. The U.S. technology manufacturer Apple likely represents the firm with the most advanced plan to integrate rare earths recycling into their supply chain to reduce demand for newly mined REEs. In October 2020, Apple announced its most recent smartphone model, the iPhone 12, would incorporate 100 percent of the rare earths used in its magnets be supplied from recycling. [108] As these magnets constitute 98 percent of the rare earths used in the iPhone, this would represent a potentially significant development for the largest U.S. smartphone manufacturer (and supplier of approximately half of all smartphones purchased in the United States in 2020).[109]

Beyond electronics, other sectors are researching closed loop supply chains of rare earths to insulate their industries from supply disruption. The Chinese-owned wind turbine producer Goldwind currently smelts its old magnets containing rare earths in order to produce new magnets, and other turbine manufacturers are exploring similar endeavors.[110] One industry expert noted that the wind turbine sector may be able to more easily recycle their REEs than other sectors due to the large size of the magnets and the standardization model employed by many turbine generators.[111] However, another industry expert noted that in order for wind turbine manufacturers to be able to recycle their batteries and magnets, it will be necessary to integrate the recycling as a design element throughout the production process (to ensure batteries and magnets can be more easily extracted once they reach the end of their service life cycle).[112] This difficulty is also reflected in a U.S. Commerce Department report on critical minerals, which noted: "…minerals embedded in existing products or waste streams represent a largely untapped reservoir of potential supply due to the complexity of extracting critical minerals from an end-of-life product."[113]

Conclusion

As technologies have advanced over the last 20 years, the value of rare earths has become increasingly ingrained in the modern global economy. The electronics sector uses rare earths in a variety of applications, and most modern technology would not be possible without them. This is also increasingly relevant for other sectors, particularly in renewable energy, and in the automotive sector as it transitions to EV production (Appendix B).

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106 Sharp, Neil, "Why are rare earth elements so crucial for electronics manufacturing," JJS Manufacturing, October 3, 2019.
107 Van Veen, Kelsi and Alexander Melton, "REE Supply Chains Pt. II: The U.S. Searches for Supplies Outside of China," Executive Briefing on Trade, June 2021.
108 Apple, "iPhone 12 Pro Max Product Environmental Report," October 2020.
109 Counterpoint, "US Smartphone Market Share, By Quarter," February 21, 2021; Apple, "iPhone 12 Pro Max Product Environmental Report," October 2020.
110 Dodd, Jan, "Rethinking the use of rare earths elements," WindPower Monthly, November 30, 2018.
111 Dodd, Jan, "Rethinking the use of rare earths elements," WindPower Monthly, November 30, 2018.
112 Dodd, Jan, "Rethinking the use of rare earths elements," WindPower Monthly, November 30, 2018.
113 U.S. Department of Commerce, "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals," January 2020, 17.

However, this increased demand has coincided with supply challenges, characterized principally by concentrated production and processing of rare earths in China. In the 2010–13 period, this concentration of production became particularly acute following decisions by the Chinese government to limit rare earths exports to downstream consuming industries, thereby substantially increasing prices for a variety of REEs and leading many manufacturers and investors to explore mining and processing opportunities in other countries.

Looking ahead, the diversification of global REE supply appears increasingly likely as U.S. and Australian mining capacity has already expanded and there are several projects under development to support the creation of new REE processing facilities. Other countries with significant REE reserves, particularly Vietnam, Brazil, and Russia, represent potential sources of future raw REE production, though current production in these countries remains low.

Beyond supply, many consumers of rare earths are also looking at ways to alter production processes to reduce rare earths demand. For some, particularly in the electronics sector, the integration of recycling into supply chains could contribute to reduced demand, while in other sectors reduced use of REEs through other technologies could become a more attractive option.

Appendix A: The Three Periods of Modern Global REE Production

1900–1940's: The India and Brazil Period

Before the 20th century, rare earths were often limited primarily for scientific research, and failed to gain any significant commercial value. This changed with the invention of gas mantle lanterns in the 1880s, which made use of cerium to illuminate large areas and to maintain lighting for extended periods.[114] By 1930, over 5 billion lanterns were sold, substantially expanding demand for cerium and moving rare earths into the commercial sphere.

During this early period, Brazil and India represented the majority of rare earths (chiefly cerium) production for both European and U.S. manufacturers. This also coincided with the collapse of a nascent rare earths mining and production industry in the United States, at the time in the Carolinas, due to the greater production capacities in India and Brazil.[115] By 1940, however, a British blockade of Indian ports prevented Germany and other Axis powers from procuring rare earths and limited their use in Europe. After World War II India decolonialized, and the new Indian government moved to severely limit the export of REE-containing monazite ore due to their interest in developing India's domestic nuclear industry, as monazite also contains uranium.[116] These restrictions coupled with limited capacity in Brazil coincided with a rise in global REE demand, so early REE consumers looked to other countries to meet REE demand. Until the ascent of U.S. REE production in California in 1960, global demand was met by a variety of smaller sources, though principally the Steenkampshraal Mine in South Africa.[117]

1950–2000: The U.S. Period

In 1953, The California Mountain Pass facility began operations and the era of significant U.S. REE production began. The California Mountain Pass area was originally thought to have significant deposits of uranium, which prompted interest of the U.S. Atomic Energy Commission (AEC). Analysis from the AEC determined that collected samples were bastnaesite, which did not contain uranium. Eventually both monazite and bastnasite were discovered at Mountain Pass.

After several firms attempted to secure rights to the area, the Mountain Pass was finally acquired by the Molybdenum Corporation of America (MolyCorp), which in 1953 began mining bastnaesite and producing europium.[118] As noted in the REE and Electronics section, europium was key to the creation of color television screens, and by 1960, the facility was able to produce 100 pounds of europium a day at

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[114] Klinger, Julie. "Historical geography of rare earth elements: From discovery to the atomic age." Extractive Industries and Society, 2015.
[115] Klinger, Julie. "Historical geography of rare earth elements: From discovery to the atomic age." Extractive Industries and Society, 2015.
[116] Klinger, Julie. "Historical geography of rare earth elements: From discovery to the atomic age." Extractive Industries and Society, 2015.
[117] Klinger, Julie. "Historical geography of rare earth elements: From discovery to the atomic age." Extractive Industries and Society, 2015.
[118] Hurst, Cindy, "China's Rare Earth Elements: What Can the West Learn?," 2010, 6.

99.99 percent purity and thousands of metric tons of REEs annually.[119] As mining operations progressed, the facility began to mine and process lanthanum, cerium, neodymium, and praseodymium (much more commonly used elements in today's electronics, particularly the latter two).[120]

During this period, the national security uses for rare earths became increasingly apparent. As Cold War concerns oriented the United States and Soviet Union towards producing more efficient and effective weapons and exploring applications of uranium (often contained in REE ores), rare earths would be incorporated into radar (samarium), enhanced aluminum in fighter planes (scandium), and laser-guided weapons and precision-guided missiles (yttrium).[121] The modern F-35 aircraft, for example, now contains 920 pounds of rare-earth materials, exceeding some wind turbines.[122] This increased use of REEs made U.S. production of nearly all the global market's supply of rare earths in this period even more important.[123]

Until the 1990s, the Mountain Pass facility was the only major rare earth producer for the global market (while other production existed during this period, it was often solely for domestic use, particularly in the Soviet Union and China).[124] However, in the 1980s, it was discovered that the Mountain Pass mining facility was leaking toxic wastewater between the separation plant and evaporating ponds, and more than 40 spills were identified between 1984 and 1993.[125] In 1996, the pipeline feeding wastewater into containment ponds ruptured 11 times, and the facility was ordered to clean up the area.[126] Subsequent lawsuits contributed to the discontinuation of mining operations by 2002, just as China's share of production and export of raw rare earths began to rise substantially. While the Mountain Pass facility was eventually able to reopen with a new program that recycled wastewater and removed the risk of major environmental spills in 2012, the absence of U.S. REE production in the 2002–12 period contributed to China's rise as the predominant global producer of REEs.[127]

U.S. production rose briefly during the 2012–15 period, during which it produced between 2,000 and 5,000 metric tons of REEs, but stopped again in 2016 and 2017 when the Mountain Pass facility ceased production as Molycorp filed for bankruptcy. A new firm, MP Materials, eventually acquired ownership of the mine, and U.S. production steadily rose (18,000 metric tons in 2018, 28,000 metric tons in 2019, and 38,000 metric tons in 2020, figure A.1).

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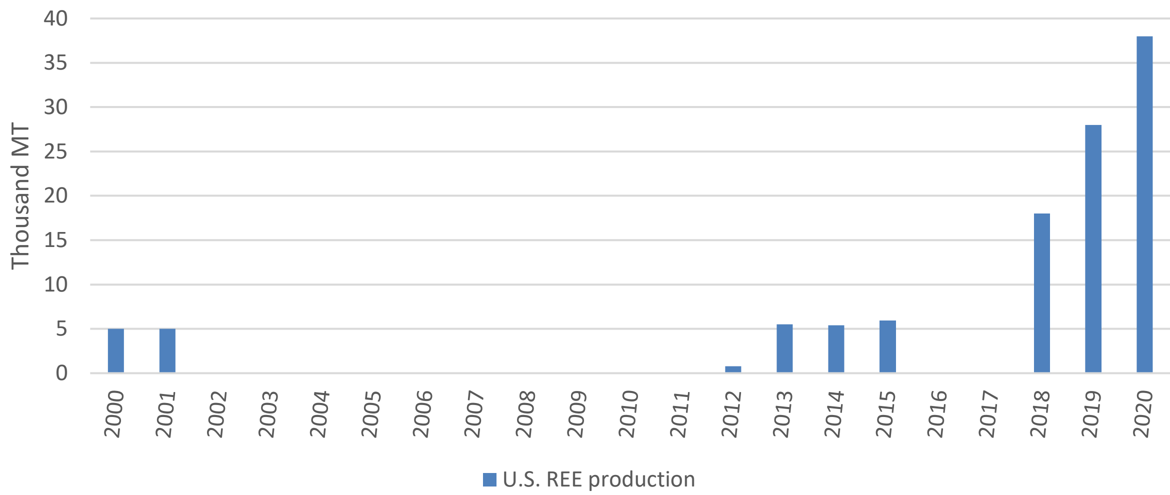
[119] Hurst, Cindy, "China's Rare Earth Elements: What Can the West Learn?," 2010, 6.
[120] Hurst, Cindy, "China's Rare Earth Elements: What Can the West Learn?," 2010, 6.
[121] VanEck, "Unearthing The Rare Earths Investment Opportunity," Seeking Alpha, March 4, 2021.
[122] Parman, Russell, "An elemental issue," U.S. Army, September 26, 2019.
[123] Parman, Russell, "An elemental issue," U.S. Army, September 26, 2019.
[124] Parman, Russell, "An elemental issue," U.S. Army, September 26, 2019; Klinger, Julie. "Historical geography of rare earth elements: From discovery to the atomic age." Extractive Industries and Society, 2015.
[125] Mencher, Brooks, "U.S. rare earth mine revived," SF Gate, November 12, 2012.
[126] Green, Jeffrey, "The collapse of American rare earth mining, and lessons learned," Defense News, November 12, 2019.
[127] Green, Jeffrey, "The collapse of American rare earth mining, and lessons learned," Defense News, November 12, 2019; Magnuson, Stew, "Mining Company Determined to Restore U.S. Rare Earth Supply China," National Defense, November 20, 2020.

Figure A.1 U.S. production of rare earths, 2000–2020 (thousand metric tons, MT)



Source: U.S. Geological Survey, "Rare Earths," 2000–2021 editions (for full list of USGS Rare Earths reports, consult bibliography).

2000–Present: The China Period

As U.S. production fell in the early 2000s with the suspension of operations at the Mountain Pass mine, China would attain its contemporary position as the world's predominant producer and exporter of the world's rare earths. However, efforts to mine and process rare earths in China began decades earlier. Rare earths were first discovered in China in 1927 by geologist Ding Daoheng and a team of German, Swiss, and Danish experts in Bayan Ob, and was confirmed by chemist He Zuolin in 1937.[128] With the improvement of separation technology in China to extract rare earths from uranium REE ores in the 1960s and 1970s, China was able to begin processing its own production of raw rare earths (up until the advancement of separation techniques, China needed to export its raw REE production for processing), which helped support increased production of rare earths in China.[129]

Between 1978 and 1999, China mined rising amounts of REEs, though almost entirely for domestic consumption; between 1978 and 1989, production rose around 40 percent annually.[130] This coincided with the 1986 proposal of a plan to accelerate the development of high-value technology in China, which premier Deny Xiaoping approved as Program 863 of the National High Technology Research and Development Program.[131] The aims of this project was to gain a position in the development of technological products by gaining a position at several links in the supply chain, including the mining of rare earths.[132] Subsequently, the role of China as a producer *and exporter* of raw and processed rare earths became even more prominent.

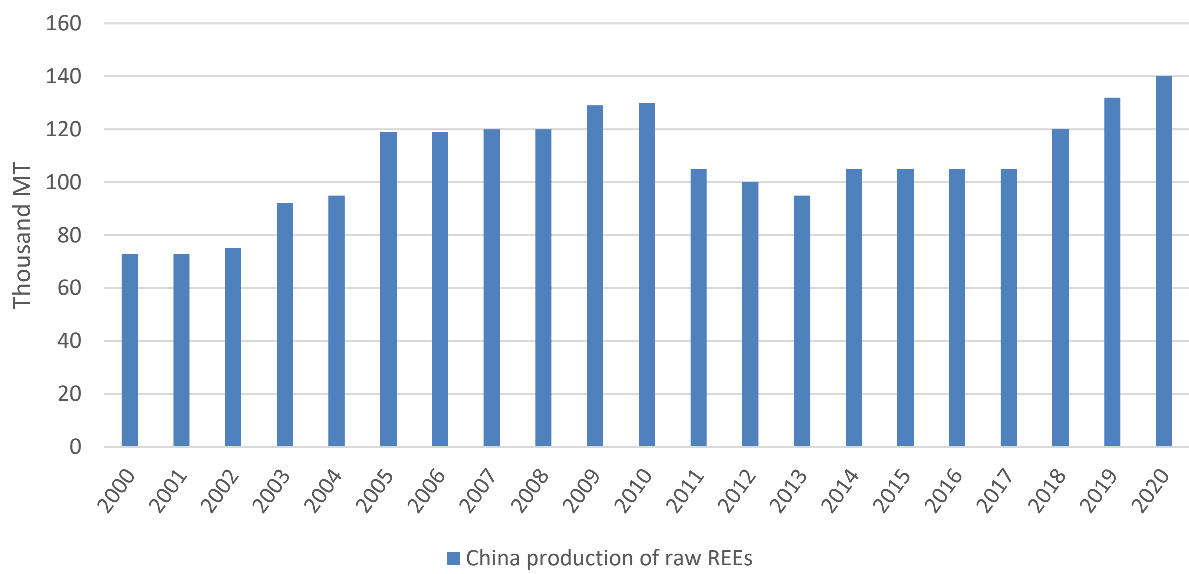
In the early 1990s, China began to export increasing amounts of rare earths. These exports began to coincide with the environmental issues impacting MolyCorp operations at the California Mountain Pass

[128] Klinger, Julie. "Historical geography of rare earth elements: From discovery to the atomic age." Extractive Industries and Society, 2015.
[129] Hurst, Cindy, "China's Rare Earth Elements: What Can the West Learn?," 2010, 6.
[130] Hurst, Cindy, "China's Rare Earth Elements: What Can the West Learn?," 2010, 6.
[131] Hurst, Cindy, "China's Rare Earth Elements: What Can the West Learn?," 2010, 6.
[132] Hurst, Cindy, "China's Rare Earth Elements: What Can the West Learn?," 2010, 6.

operating facility.[133] Additionally, the rise of REE exports from China began to impact global prices, depressing REE prices as supply was able to keep pace with rising demand.[134] During this period, U.S. production kept relatively stable at around 20,000 metric tons annually in the first half of the 1990s, but sank to almost no production by the end of the decade.[135]

With the suspension of operations at the Mountain Pass facility in 2002, coinciding with low REE prices, Chinese production was established as the predominant source for the world's REE demand. This period was also characterized by a substantial rise in not just China's market share in the rare earths market, but also the volume of production. Between 1960 and 1990, global REE production rarely exceeded 40,000 metric tons and often was at or below 20,000 metric tons.[136] By the early 2000s, global production rose by 20,000 metric tons every few years, with nearly all of it from China; in 2000, global production was around 80,000 metric tons, by 2005 rose to more than 120,000 metric tons, and by 2020 had reached more than 240,000 metric tons (figure A.2).[137]

Figure A.2 China production of raw rare earths, 2000–2020 (thousand metric tons, (MT))



Source: U.S. Geological Survey, "Rare Earths," 2000–2021 editions (for full list of USGS Rare Earths reports, consult bibliography).

During the 2010–13 period, China reduced its quotas on the production and export of rare earths (the notable dip can be seen in figure a.2 above). As was noted in the Challenges section of this paper, this contributed to a substantial rise in prices for a variety of REEs, in some cases increasing prices 20-fold. However, these restrictions were loosened following a WTO dispute-settlement ruling favoring by the

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133 Parman, Russell, "An elemental issue," U.S. Army, September 26, 2019; Klinger, Julie. "Historical geography of rare earth elements: From discovery to the atomic age." Extractive Industries and Society, 2015.

134 Parman, Russell, "An elemental issue," U.S. Army, September 26, 2019; Hurst, Cindy, "China's Rare Earth Elements: What Can the West Learn?," 2010, 6.

135 Parman, Russell, "An elemental issue," U.S. Army, September 26, 2019.

136 Parman, Russell, "An elemental issue," U.S. Army, September 26, 2019.

137 U.S. Geological Survey, "Rare Earths," 2000–2021 editions (for full list of USGS Rare Earths reports, consult bibliography).

United States, Japan, and the European Union, and prices began to stabilize as REE production and exports from China returned to pre-2010 levels.

In contemporary production, China still represents the world's largest producer of raw REEs and processed REEs, though its share of production in the former has fallen. In 2020, China's share of global production fell to its lowest level in the 21st century: 59 percent of the estimated 240,000 metric tons of raw global REE production was from China, while production in other countries rose. U.S. production was second at 38,000 metric tons (15.8 percent of production), followed by Myanmar (12.5 percent), Australia (7.1 percent), and Madagascar (3.3 percent).[138] The remaining 3 percent of production was produced by Brazil, Burundi, Russia, India, Thailand, and Vietnam.[139]

Appendix B: The Rise of REE Demand in the Autos and Renewable Energy Sectors

Several other industry sectors beyond electronics also utilize rare earths in their manufacturing processes, often in similar capacities (particularly in magnets). Two such industries, the automotive and renewable energy sectors, are briefly described in this appendix. They are discussed in further detail in part because both industries are characterized by substantial ongoing shifts that will likely accelerate demand of certain REEs. In the case of the automotive sector, the increased manufacturing of electric vehicles (EV) will likely contribute to a rise in REE demand for that sector as EVs often incorporate more REEs in their designs than gasoline- or diesel-powered vehicles. Similarly, the energy sector is experiencing a similar transformation, as the rise of more sustainable energy practices (namely switching from coal and natural gas to wind-generated power) will also likely coincide with a rise in REE demand as these newer technologies incorporate disproportionately more REEs.

Autos

The automotive sector has historically been a significant consumer of rare earths. Similar to the incorporation of rare earths throughout electronic products, motor vehicles also frequently contain numerous parts incorporating rare earths; a modern non-electric vehicle, can include neodymium (in motors and speakers), yttrium (used to stabilize the zirconia in oxygen content sensors for fuel), cerium (directly in catalytic converters, and indirectly in windshields, mirrors, and lenses), and europium and terbium (in optical displays).[140] By 2021, approximately 85 percent of automakers were using neodymium-incorporated permanent magnet motors, and there are projections that automotive demand for rare earths will rise by 25 percent this year.[141]

Beyond the established rare earths demand in gasoline- and diesel-powered vehicles, the automotive sector is experiencing an additional rise in demand with the introduction and mass production of EVs. Similar to gas-powered vehicles, EVs can incorporate rare earths throughout the vehicle, including in the engine, screens and mirrors, glass, and frame. But they also incorporate REEs into the electric battery, which contributes to elevated REE demand. One industry report noted that, despite the COVID-19

[138] U.S. Geological Survey, "Rare Earths 2021," January 2021.
[139] U.S. Geological Survey, "Rare Earths 2021," January 2021.
[140] Gschneidner, Karl and Vitalij Pecharsky, "Rare Earth Elements," Encyclopedia Britannica, January 17, 2019.
[141] Barrera, Priscila, "Rare Earths Outlook 2021: REE Magnet Supply to Remain Tight," Investing News, January 20, 2021.

epidemic causing a fall in consumer demand for a variety of REE-incorporated products (including electronics), demand for NIB magnets in passenger electric vehicles rose 21 percent from 2019 even as global consumption of NIB magnets fell 10 percent.[142]

Other important trends in the EV sector to note include:

- The modern Tesla, one of the largest EV producers, requires more than four pounds of neodymium and praseodymium, primarily for batteries but also for screens and speakers.[143] Additionally, one industry report estimated that the electric motor in a Prius can require between two to four pounds of neodymium.[144]

- One industry report found that REE demand for battery EV and hybrid (both plug in and conventional) sectors will increase by 30 to 50 percent every year as battery EV/hybrid sales increase 20 to 40 percent annually;[145]

- One 2019 assessment found that converting the United Kingdom's 31 million vehicles from non-electric to electric would require nearly all of the world's current production of neodymium, and if the United States similarly converted its 276 million registered motor vehicles, neodymium production would have to rise by more than nine-fold;[146]

- The International Aluminum Institute estimated that the use of rare earths in sub-frames and the body parts of vehicles was projected to rise from 2.4 pounds on average in 2015 to 14.3 pounds by 2020;[147]

- Using EIA data, the Edison Group estimates that rare earths demand for EVs will rise in line with increased production, with dysprosium demand in EVs reaching 6,000–13,000 metric tons by 2030, neodymium between 20,000–40,000 metric tons (2017 demand was below 1,500 metric tons), and praseodymium 5–10,000 metric tons (current demand is below 1,000 metric tons).[148]

In addition to ongoing growth in consumer demand for EVs, several governments around the world have begun initiatives to increase EV use to reduce domestic carbon emissions. Initiatives to phase out diesel–powered vehicles or increase EV and hybrid vehicle use have been announced in the United Kingdom, Canada, Norway, and California (among other countries and regions).[149]

This combination of rising interest on the part of both government and manufacturers in the increased production of EVs will likely contribute to an increase in demand for rare earths (one industry expert

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[142] Barrera, Priscila, "Rare Earths Outlook 2021: REE Magnet Supply to Remain Tight," Investing News, January 20, 2021.
[143] Kruger, Colin, "Rare earths market draws a crowd as new Lynas rivals gear up," Sydney Morning Herald, March 5, 2021.
[144] Bradsher, Keith, "China Tightens Grip on Rare Minerals," New York Times, August 31, 2009.
[145] Barrera, Priscila, "Rare Earths Outlook 2021: REE Magnet Supply to Remain Tight," Investing News, January 20, 2021.
[146] Natural History Museum (UK), "Leading scientists set out resource challenge of meeting net zero emissions in the UK by 2050," June 5, 2019.
[147] Grand View Research, "Rare Earth Elements: Market Analysis, 2016–2027," 2020, 21.
[148] Long, Ryan, "Electric vehicles and rare earths," Edison Group, January 29, 2019.
[149] Gill, Chris and Jim Pollard, "New energy vehicles driving demand for China's rare earths," Asia Times Financial, December 6, 2020.

noted that EV REE demand by 2035 would consume 100 percent of current neodymium and praseodymium production).[150] Automotive manufacturers have also indicated shifts in favor of increased EV production:

- In January 2021, U.S. firm General Motors Co., (the manufacturer of the EV Chevrolet Bolt) announced that it would phase out the production of all gasoline- and diesel-powered engines by 2035 for both sedans and pickups/SUVs;[151]
- Ford Motor Co. announced in February 2021 a phase out of fossil-fuel vehicles in its European market by 2026;[152]
- Jaguar Land Rover noted in February 2021 that all of its cars and most of its SUVs will operate on batteries by 2030;[153]
- British luxury automaker firm Bentley Motor Ltd. announced a phase-out diesel-powered vehicles by 2030;[154]
- Japanese automaker Nissan Motor Co. Ltd. announced a phase-out diesel-powered vehicles within the 2030s; [155]
- Mitsubishi Motors Corp. announced in 2019 that it would halt the development of new diesel-powered engines,[156]
- Volkswagen Group announced that innovations in its battery technology could decrease EV costs by nearly one-half, in addition to increasing battery recycling to preserve useable materials (which may include rare earths).[157]

Depending on the extent to which production capacity of rare earths can expand in line with increased EV production, some analysts have expressed concern that REE prices may experience growing pressures reminiscent of the supply bottlenecks in the 2010–13 period.[158]

[150] Mineral Prices, "Rare earths demand set to rise, as new windfarms suck in supply," February 8, 2021.
[151] Eisenstein, Paul, "GM to go all-electric by 2035, phase out gas and diesel engines," NBC News, January 28, 2021.
[152] Boudette, Neal and Jack Ewing, "Ford says it will phase out gasoline-powered vehicles in Europe," New York Times, February 2021.
[153] Gill, Chris and Jim Pollard, "New energy vehicles driving demand for China's rare earths," Asia Times Financial, December 6, 2020.
[154] Gill, Chris and Jim Pollard, "New energy vehicles driving demand for China's rare earths," Asia Times Financial, December 6, 2020.
[155] Gill, Chris and Jim Pollard, "New energy vehicles driving demand for China's rare earths," Asia Times Financial, December 6, 2020.
[156] News Wheel, "Mitsubishi is Stopping Development of Diesel Engines," December 30, 2019.
[157] Cunningham, Eddie, "Electric cars could be up to 50pc cheaper thanks to new battery," Independent (Ireland), March 15, 2021.
[158] Kruger, Colin, "Electric vehicles, wind turbine demand drive Lynas's bumper profit," Sydney Morning Herald, February 26, 2021.

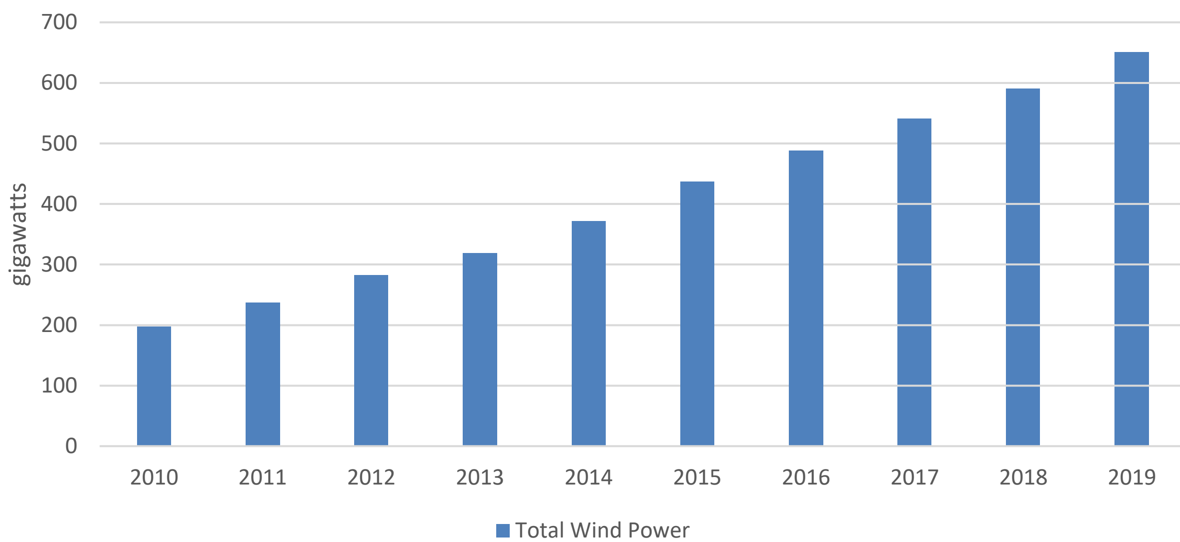
Renewable Technologies

Another major emerging sector for the rare earths industry is renewable energy technologies. Similar to the rising demand of the automotive sector, the rise of rare earths demand in the energy sector is characterized by existing demand expanding as the sector itself shifts into new, low emission technologies. REEs are used extensively in non-renewable energy production and distribution, but renewable energy sources (particularly wind turbines) represent a larger share of rare earths than older technologies. This will likely add additional demand to REE production as renewable energies are increasingly brought online.

Wind Power

Installed wind power-generating capacity has risen substantially over the last 10 years, driven by a combination of government renewable energy mandates and credits, and increased commercial and business interest. Between 2010 and 2019, U.S. wind power production rose by 216 percent (and wind's share of total U.S. power generation increased from 2.3 to 7.3 percent of production), and global installed capacity of wind power increased by over 230 percent (figure B.1).

Figure B.1 Global installed wind capacity 2010–19, gigawatts



Source: Statista, "Global cumulative installed wind power capacity from 2001 to 2019 (in megawatts)," 2020.

The rise in wind power generation has coincided with a rise in demand for rare earths in the sector. Similar to other sectors, wind turbines often incorporate REEs into magnets; in the case of wind turbines, many manufacturers use REE-incorporated permanent magnets in turbines due in part to the permanent magnets' ability to maintain efficiency when wind speed is low, and is both lighter and cheaper to maintain than alternatives.[159] Wind turbines consume significant quantities of rare earths; one wind turbine can consume more than 300 pounds of neodymium and praseodymium, and some contain nearly one metric ton of REEs. For a large wind farm, this can translate to several metric tons of

[159] Mineral Prices, "Rare earths demand set to rise, as new windfarms suck in supply," February 8, 2021.

REEs.[160] One 2019 study found that if wind energy were used to power the approximately 2 billion EVs estimated to come online in the next few years, the wind turbines alone would require 10 years' worth of the current global production of neodymium and dysprosium.[161] Another study indicated that demand for rare earths for use in wind turbine magnets would grow at nearly 10 percent annually for the next several years, and the market size for wind energy would rise 12 percent annually from $23 billion in 2019 to $81 billion by 2030.[162]

Looking at the U.S. market, a 2019 assessment based on U.S. Department of Energy data estimated that approximately 17,000 metric tons of neodymium (used primarily in wind turbine magnets) would be required to meet the needs of expanding U.S. offshore wind capacity (the equivalent of 20 million hybrid and electric cars).[163] Offshore wind farms can have particularly large demand for rare earths relative to land-based wind farms due to larger generators composed of NIB magnets used for offshore turbines, which are more efficient as they use fewer parts. In certain instances, these turbines can include more than a metric ton of rare earths, which would equate to the rare earths demand of more than 45,300 smartphones.[164]

Beyond the U.S. market, other major energy consuming nations are increasingly shifting generation to wind with large-scale projects, which will likely accelerate demand for the REEs used in wind turbines. In February 2021, the South Korean government announced the construction of a $43 billion, 8.2 gigawatt offshore wind farm, which would require approximately 410 metric tons of neodymium and praseodymium.[165] Similar expansions of wind capacity in Europe and China will also likely contribute to elevated REE demand in this sector.[166]

Solar Panels

Solar energy represents a smaller share of renewable energy production than wind in both the United States and globally,[167] reducing the pressure the sector might have on demand for rare earths. Additionally, rare earths are less integral and used in lesser quantities in solar photovoltaic (PV) cells than in wind turbines, further reducing the potential for solar to create substantial burdens on the

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[160] Kruger, Colin, "Rare earths market draws a crowd as new Lynas rivals gear up," Sydney Morning Herald, March 5, 2021.
[161] Natural History Museum (UK), "Leading scientists set out resource challenge of meeting net zero emissions in the UK by 2050," June 5, 2019.
[162] Mineral Prices, "Rare earths demand set to rise, as new windfarms suck in supply," February 8, 2021; Global Newswire, "Offshore Wind Energy Market Global Sales are Expected to Reach US$ 81 Billion by 2030, as stated by insightSLICE," Digital Journal, February 17, 2021.
[163] Fishman, Tomer and T.E. Gradel, "Impact of the establishment of US offshore wind power on neodymium flows," Nature Sustainability, March 25, 2019.
[164] The Australian, "Rare earths a rare opportunity," 2020; Stone, Maddie, "Offshore Wind Has a Looming Rare Earths Problem," Gizmodo, April 5, 2019.
[165] Mineral Prices, "Rare earths demand set to rise, as new windfarms suck in supply," February 8, 2021.
[166] For example, In Sweden, GE announced that it would be constructing Europe's largest onshore wind farm with a 753-MW, 137-turbine facility in Önusberget, while China announced it had added 71.7 GW of wind power capacity to its production in 2020 (likely due in part to the expiration of certain subsidies for onshore wind projects in 2021). Proctor, Darrell, "GE turbines will Supply Europe's Largest Onshore Wind Farm," February 15, 2021; Xu, Muyu and David Stanway, "China doubles new renewable capacity in 2020, still builds thermal plants," Reuters, January 21, 2021.
[167] Morrison, Ryan, "Solar and wind power generated a Tenth of the world's electricity in the first half of 2020 as coal sees biggest fall since 1990," Daily Mail, August 20, 2020.

supply of REEs.[168] While solar panels often use other materials which may be sensitive to similar supply disruptions, including indium, selenium, and tellurium,[169] their use of REEs is often minimal and are unlikely to have the sensitivity to rare earths disruptions of neodymium, dysprosium, praseodymium that would cause concerns in the wind, automotive, or electronics sectors.[170]

[168] Rollet, Catherine, "Are rare earths used in solar panels?" PV Magazine, November 28, 2019.
[169] Moore, Sarah, "Using Rare Metals in Solar Panels," CleanTech, August 27, 2019.
[170] Rojak, Hillman, "What Rare Earths Metals Are in Solar Panels?" Revimage, September 28, 2016.

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