Challenges and Opportunities in Global Supply Chains

The Role of Critical Minerals

By Nayantara Hensel

The strength and security of global supply chains are vital for the stability and growth of the global economy as well as for national security. However, supply chains, which form the foundations for a number of industries and products in the defense and non-defense markets. are highly dependent on a variety of factors and countries to provide key critical minerals as inputs.

The increasing demand for critical minerals in supply chains is driven by the growing needs for new and existing products from an expanding global population. Shortages in the supply for critical minerals are impacted by the time and cost constraints in developing the minerals in various countries; the role of global pandemics (such as COVID-19) on mining and product manufacturing; political instability in source countries; and transportation disruptions due to trade embargoes and blockages. Rising demand and shortages in supply can lead to higher prices, which contribute to rising inflation and slower global economic growth. Consequently, understanding the economic forces impacting the demand for and supply of these key inputs is important in developing current and future efforts to handle supply chain challenges. This article assesses the factors determining the supply and demand, as well as other challenges associated with these critical supply chain critical inputs and offers potential solutions.

The Role of and Demand for Rare Earth Minerals

Rare earth minerals are comprised of 17 elements (REEs),[1] and are used for key products in multiple sectors, including communications technology, energy, transportation, and defense. In the communications technology sector, yttrium, europium and terbium phosphors are used in flat panels and televisions, while lanthanum makes up as much as 50 percent of digital camera lenses, including smartphone cameras. In the medical sector

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The pit mine at the Molycorp Mountain Pass rare-earth facility in California's Mojave Desert in May. Image by John Gurzinski. From High Country News, June 16, 2015 (https://www.hcn.org/issues/47.11/why-rare-earth-mining-in-the-west-is-a-bust).

lutetium is used for hospital imaging through its inclusion in the detectors in position emission tomographs. In the energy sector, yttrium, europium, and terbium phosphors are used in many light bulbs, while europium is used in fluorescent lighting and gadolinium is used in rods in nuclear power plants.

The growing trend toward cleaner sources of energy and electric vehicles (EV's) has led to greater demand for magnets made from the neodymium and praseodymium alloys, which are used for wind turbine generators and electric vehicle traction motors.[2] Rare earths have uses in multiple industries—neodymium-iron-boron magnets are used in the communications technology sector in computer hard disks and CD–ROM and DVD disk drives, and they are also important in the transportation sector in several key subsystems within cars, including audio speakers, power steering and power seats, and electric windows.[3]

Rare earths are also very important within the defense sector. Praseodymium is used for satellites and aircraft engines, while neodymium is used for missile guidance systems. Promethium is used for batteries in missiles, while samarium is used for lasers and nuclear reactor control rods. Lanthanum is important for night vision goggles and the lenses of cameras that are used in reconnaissance, intelligence, and surveillance. Europium is used for plasma displays and LEDs, as well as nuclear reactor rods. Yttrium is used for microwave emitters and LEDs. Gallium is used for light-emitting diodes and computer chips. Not surprisingly, every F-35 jet has around 920 pounds of rare earth elements, especially for their targeting systems.[4]

Two types of permanent magnets which use rare earths are samarium-cobalt magnets and neodymium-iron-boron magnets. Samarium-cobalt magnets can survive higher temperatures and are used in aircraft, smart bombs, and precision-guided missiles. Neodymium-iron-boron magnets are lighter and smaller and are used in various weapons systems. Magnets using neodymium, praseodymium, samarium, dysprosium, and terbium are used in guidance and control electric motors and actuators in Tomahawk cruise missiles, the Predator unmanned aircraft, the Joint Air to Ground Fin Actuators, smart bombs, and Joint Direct Attack Munitions. Rare earths are used in radar, sonar, radiation and chemical detection technologies, in laser targeting devices, and for density amplification/energy storage in directed energy weapons and electronic warfare devices.[5]

The increasing demand for rare earths, as well as the impact of COVID-19 on production facility closures, led to the average rare earth export price increasing by 36 percent from November 2020 to November 2021. These higher input prices had a significant impact on the supply chains of finished products. The prices of terbium and dysprosium increased by 50 percent in 2021, while neodymium prices increased by around 80 percent. Partially due to the reduced impact of COVID-19 in 2022, many rare earth prices declined from their earlier heights. For example, neodymium prices peaked in February 2022, but, by December 2022, had declined 14 percent from the beginning of 2022, although this only partially offset the significant price gain from the previous year.[6]

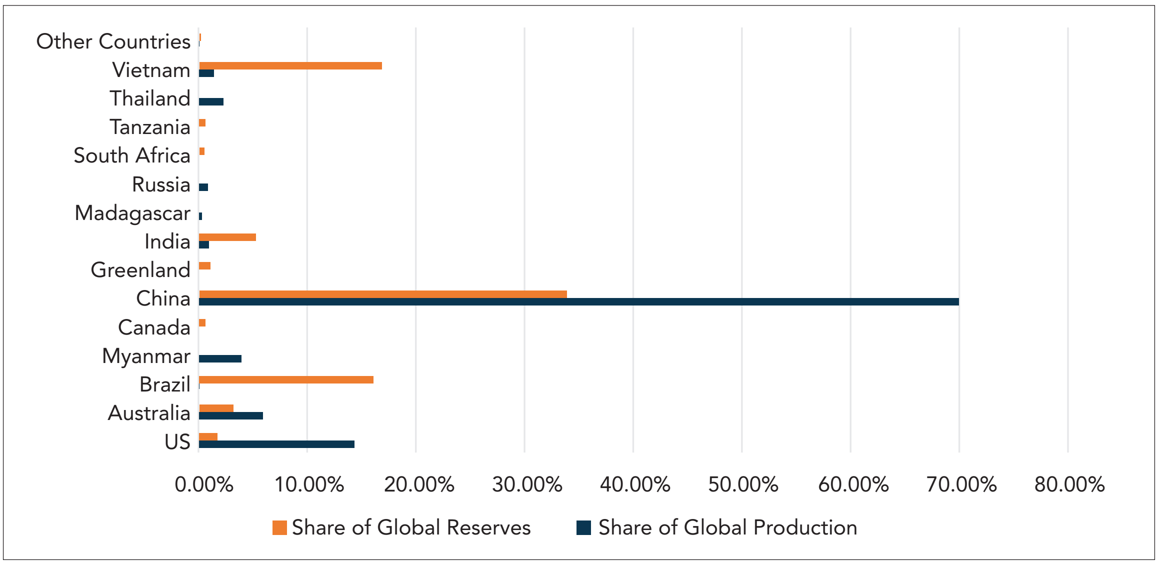
Significant Sources of Supply for Rare Earths

While China continues to be the leading producer of rare earths, there are significant opportunities for growth in supply as demand increases, which can mitigate price increases. As Figure 1 suggests, China produced 70 percent of rare earth mining in 2022, followed by the United States at 14.3 percent, Australia at 6 percent, and Myanmar at 4 percent. Although China had the highest share of both global reserves (33.8 percent) and global production (70 percent), there are substantial opportunities for growth and investment in other countries. Indeed, Vietnam and Brazil have low shares of global production (1.4

percent and 0.03 percent, respectively), however, they each have 16-17 percent of global reserves. On the other hand, the United States and Australia have the second and third highest shares of global production but have lower shares of global reserves (1.8 percent and 3.2 percent, respectively).

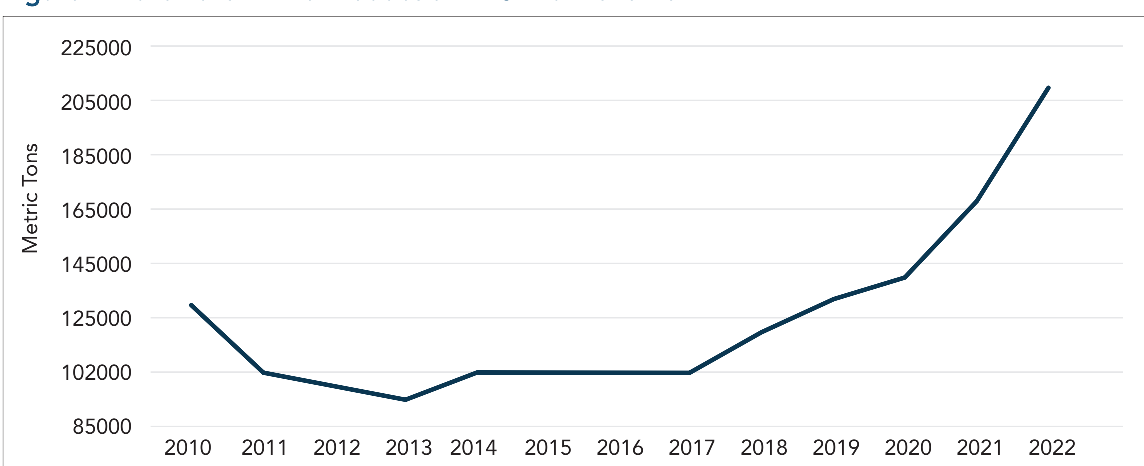
Although China's rare earth mine production increased from 105,000 metric tons in 2014 to 210,000 metric tons in 2022 (Figure 2), its share of global output declined from 86 percent in 2014 to 70 percent in 2022.[7] Much of this decline was due to the growth of U.S. rare earth mine production. Indeed,

Figure 1: Share of Global Rare Earth Production and Share of Global Rare Earth Reserves by Country: 2022



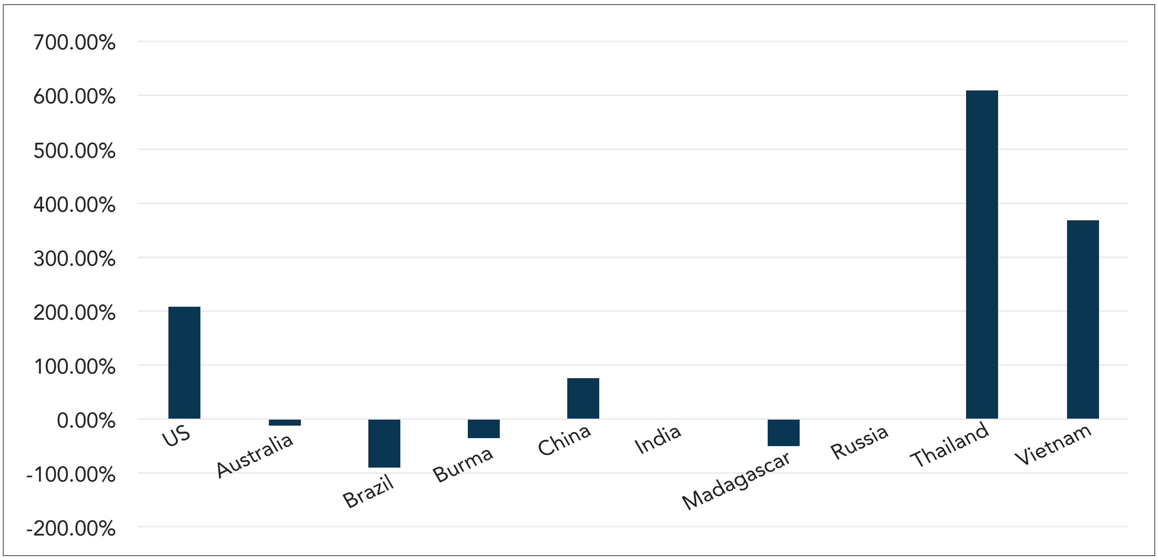
Source of underlying data: *USGS Mineral Commodity Summaries 2023*, p. 143.

Figure 2: Rare Earth Mine Production in China: 2010-2022



Source of underlying data: *USGS Minerals Yearbook, 2019, Volume III*, Area Reports--International; *USGS Mineral Commodity Summaries 2022*, p. 135; *USGS Mineral Commodity Summaries 2023*, p. 143; Statista Database.

Figure 3: Growth in Rare Earth Production: 2018-2022



Source of underlying data: *USGS Mineral Commodities Summaries, 2018*, pp. 132-133; *USGS Mineral Commodities Summaries, 2019*, pp. 132-133; *USGS Mineral Commodities Summaries, 2020*, pp. 132-133; *USGS Mineral Commodities Summaries, 2021*, pp. 132-133; *USGS Mineral Commodities Summaries, 2022*, pp. 134-135; *USGS Mineral Commodities Summaries, 2023*, pp. 142-143.

as is evident in Figure 3, while China's rare earth production increased by only 75 percent between 2018 and 2022, rare earth production in the United States increased by over 200 percent. Moreover, some countries with small, rare earth mining capacity, such as Thailand and Vietnam, grew significantly at their relatively low base levels.

China

The largest mine in China, located in northern China in Inner Mongolia, is the Bayan Obo deposit, which produces 70 percent of China's light rare earth deposits. It is the largest deposit of rare earths globally, has been in operation since 1957, and contains 40 million tons of rare earths reserves.[8]

China plays an even greater role in processing/refining than in mining. In 2021, China made up 85 percent of global REE refining, followed by the rest of Asia at 13 percent and Europe at 2 percent. While China's share of global mining of neodymium, which is important for magnets, was 62 percent in 2021, its share of global refining for neodymium was 84 percent. China currently dominates the worldwide permanent magnet market, controlling 87 percent of it.[9]

Since China has had more competition in the mining portion of the rare earth sector from other countries in recent years, it has increased its purchases of mined rare earths from other countries for refining/processing where it has much less competition. As a result, it has become more reliant on rare earth mining from other countries for both light and heavy rare earth oxides. Domestically mined and separated light rare earth oxides comprised around 90 percent of China's separated light rare earth oxides in 2015, but this share had declined to 70 percent by 2021. About 85 percent of heavy rare earth oxides developed in China in 2015 were from Chinese mines, but this declined to 53 percent in 2021.[10] Consequently, China is a monopsonist as the primary buyer of mined rare earths due to its role as (close to) a monopolist in the refining sector. The Chinese purchases from overseas mines include output from the United States and Australian mines, which currently have little or no refining processes since refining processes have environmental and health risks which involve the extraction of radioactive thorium from rare earths.[11]

The Chinese government has been engaging in consolidation of its rare earth industry to enable it to better influence prices, as well as to enable greater efficiency.[12] Consolidation efforts in 2016 led to the development of six licensed groups whose production and refining have been controlled by the Chinese government through granting annual quotas. Further consolidation of rare earth units from Chinese state-owned enterprises (SOE's) in 2021 was part of the Chinese government's plan to enable the creation of a large rare earth SOE in the south and one in the north. In December 2021, the China Rare Earths Group, located in the Jiangxi province in southern China, was formed through the merger of Aluminum Corp of China (Chinalco), China Minmetals Corp, and Ganzhou Rare Earth Group to control rare earth production in the south regarding the heavy and medium rare earths. Indeed, it would control 62 percent of the supplies in heavy rare earths. The Chinese government intends to further consolidate the firms in northern China, which focus on light rare earths.[13]

Myanmar

In recent years, China has outsourced some of its rare earth mining to Myanmar due to Myanmar's cheap labor and has focused more on refining, which has resulted in Myanmar becoming the fourth largest global producer of rare earths at 4 percent in 2022. Unfortunately, however, as of March 2022, the Kachin state of Myanmar had 2700 mining collection pools in about 300 separate locations which creates significant environmental hazards. Moreover, political instability can disrupt Myanmar's supply chains; indeed, Myanmar's revenues from rare earth mining have been a source of funding for the leaders of groups supporting Myanmar's military regime.[14]

Between May 2017 and October 2021, Myanmar exported over $1 billion of rare earths (over 140,000 tons) to China. Companies, such as Minmetals and Rising Nonferrous Metals, are partially dependent on Myanmar's heavy rare earth mining and subsequently supply their processed rare earths to large Chinese magnet companies, such as Yantai Zhenghai, Magnetic Material, JL MAG, and Zhong Ke San Huan, which, in turn, provide their magnets to global automobile manufacturers, electronics companies, wind turbine manufacturers, etc.[15]

Australia

Australia, which currently provides 6 percent of global rare earth mining, has a growing rare earth mining industry with a number of rare earth firms, 35 of which were traded on the Australian Stock Exchange as of early November 2022. The largest is Lynas (market value of $7.9 billion), followed by Iluka ($3.8 billion), Arafura ($530 million), and Hastings ($450 million). Both Lynas and Iluka are in the S&P/ASX200.[16]

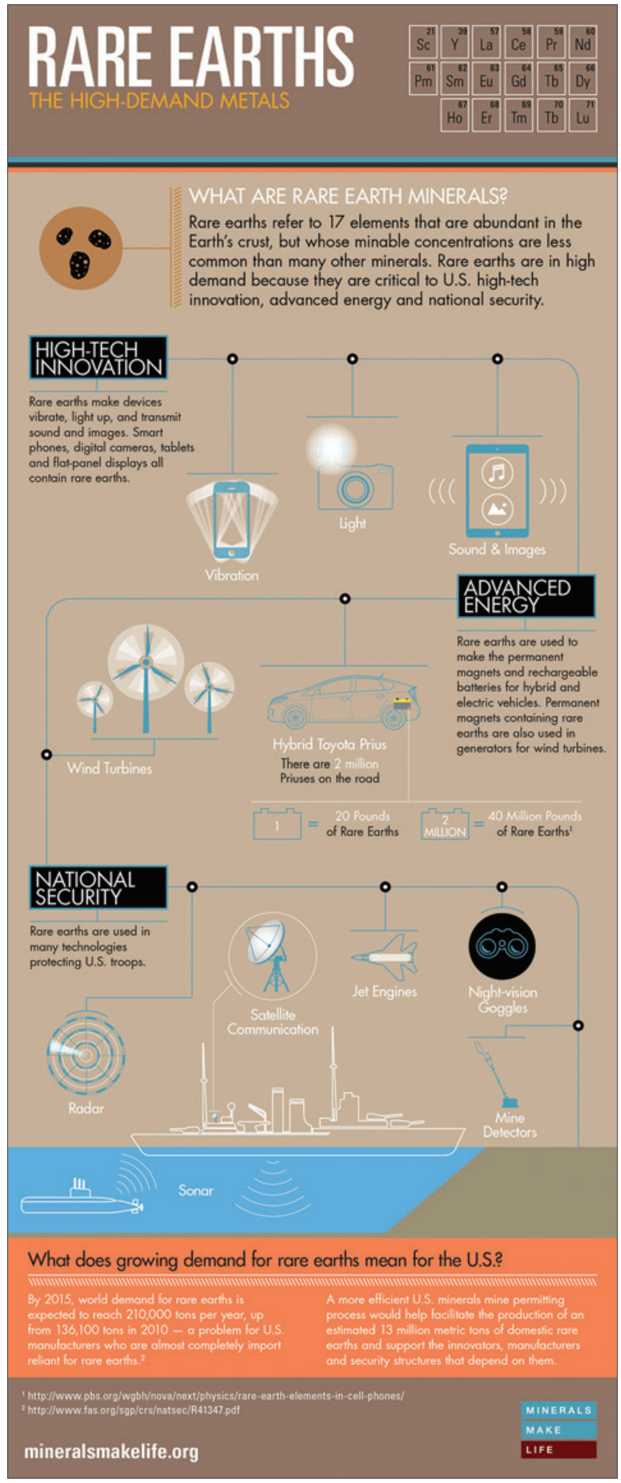
Lynas is the second largest producer of neodymium-praseodymium globally and extracts its rare earths from the Mt. Weld mine in western Australia, which is the largest non-Chinese rare earth mine and possesses among the highest-grade rare earth deposits in the world. Mt. Weld's production of neodymium-praseodymium has shown significant growth in recent years. The ore undergoes some processing at the concentration plant at Mt Weld, and then the rare earth concentrate is sent for greater processing to the Lynas material plant near Kuantan, Malaysia. Lynas relies, however, on China to turn its oxides into metal. In an effort to meet the rising demand for rare earths by further expanding rare earth supply, Lynas is developing a new Kalgoorlie Rare Earths Processing Facility in western Australia, as well as developing a separation facility in the United States.[17]

Iluka, the second largest Australian rare earth mining company, is also developing a processing facility for rare earths and received a $1.2 billion loan to develop a refinery in Eneabba, which is north of Perth.[18]

Arafura Resources is developing the Nolans mine in northern Australia which is focused on both mining and processing neodymium-praesodymium (NdPr) oxides and is expected to open in 2024. The $1 billion facility has received $300 million in government funding. In November 2022, Arafura completed an agreement to provide Hyundai and Kia Corp with NdPr oxides, as well as an agreement in July 2022 with GE Renewable Energy to provide key inputs for its wind turbine manufacturing. Arafura also signed an agreement to further assist South Korea in its rare earth supply with the Korea Mine Rehabilitation and Mineral Resources Corporation (KOMIR).[19]

Hastings Technology is developing two rare earth mines in western Australia—the Yangibana mine, with a substantive NdPr content, and the Brockman mine. Hastings hopes to begin production in 2024 and has signed agreements with the German companies Schaeffler and Thyssenkrupp.[20]

Australian Strategic Materials (ASM) plans to develop a complete supply chain for rare earths and is developing a Dubbo mine in New South Wales, which contains rare earths, as well as other key minerals. The mine is expected to be in operation by 2025. As is the case with Arafura, ASM is collaborating with South Korea, which is trying to reduce its dependence on China for rare earths. In November 2021, ASM announced the commissioning of a metals



Infographic by and with permission from the National Mining Association.

Workshop of a rare earth production enterprise in Jiangxi province, central China. China is the largest source of rare earth imports to the United States. Photo by Humphery (Shutterstock Stock Photo ID: 1410095642).

plant in South Korea, and in December 2021, ASM formed a joint venture with Korea Mine Rehabilitation and Mineral Resources Corporation (KOMIR).[21]

Australian rare earth mining firms have followed several different strategies for funding. First, several Australian firms have obtained government support, such as the Australian government's $1.2 billion loan to Iluka. Second, Australian firms have collaborated with each other—indeed, Iluka will also process rare earths from other Australian companies, including Northern Minerals. Third, Australian firms have collaborated with other non-Chinese nations. Following the unofficial export ban that China briefly imposed on Japan in 2010, the Japanese government, in an effort to reduce its exposure to Chinese rare earths, provided funding for Lynas' development of the Mount Weld deposits, as well as funding the development of Lynas' processing plant in Malaysia.[22] Fourth, Australian firms have received funding from other overseas companies, as is evident in Arafura's agreements with General Electric and Hyundai to supply rare earths for the production of wind turbines and EVs.

United States

The United States, the second largest rare earths producer, provides 14.3 percent of global rare earth mining, but it lacks refining facilities. MP Materials' Mountain Pass Mine[23] in the northeast portion of the Mojave Desert is the only rare earth production mine in the United States.[24] With the substantial increase in global demand, MP Materials produced the highest levels of rare earth concentrate in its history in 2022 at 43,000 metric tons. Nevertheless, due to the lack of separation and refining facilities in the United States, the United States imported about 74 percent of rare earth metals and compounds on average from China during 2018-2021. Moreover, about 7.7 percent of MP Materials is held by China's Shenghe Resources.[25]

MP Materials hopes to develop a complete rare earth supply chain by 2025 which would include mining, separation, refining, and magnet making. MP Materials received $35 million from the Department of Defense (DOD) to build a processing facility for heavy rare earths at Mountain Pass, California in February 2022, as well as $9.6 million to develop a processing facility for light rare earths in 2020. By 2024, MP Materials plans to create around 350 jobs in the magnet supply chain and is also investing $700 million.[26]

In April 2022, MP Materials began construction of a rare earth magnet facility in Fort Worth, Texas, and hopes to begin developing neodymium alloys in late 2023 and to develop completed neodymium magnet production by 2025. MP also signed an agreement with GM to provide the magnets for 500,000 GM EV's annually. The rare earths used at the Fort Worth manufacturing plant would come from the Mountain Pass mine.[27]

The U.S. government also funded Australia's largest, rare earths mining company, Lynas, to develop both a heavy rare earths and a light rare earths separation facility in Texas using rare earths extracted from its Mount Weld mine in western Australia. In 2021, DOD provided Lynas with $30.4 million to build a light rare earths processing facility in Texas in partnership with Blue Line Corp. In June 2022, DOD provided Lynas with an $120 million to develop a heavy rare earth separation facility in Texas which is expected to open in 2025.[28]

As in Australia, companies in the United States are expanding into the rare earth sector as global demand increases. American Rare Earths has undertaken preliminary analysis of its mining sites in Wyoming and Arizona, which suggests that they could be the two largest U.S. rare earth sites, with key rare earth elements (neodymium, praseodymium, dysprosium, and terbium) that can be used in wind turbines and in EV's.[29] In mid-October, 2022, Ucore Rare Metals completed an agreement with the State of Louisiana to develop a rare earth separation facility.[30]

Other Countries

The global demand for rare earths has further stimulated the development of sources of supply in several other locations. One example is Canada, whose reserves were estimated at over 14 million tons as of 2021. The Australian firm Vital Metals owns the only operating rare earth mine in Canada, the Nechalacho mine, located in Canada's Northwest Territory, which began mining in June 2021. By 2025, Vital Metals hopes to produce 5000 tons of rare earths from the Nechalacho Mine, which contains neodymium and prasesodymium. Vital Metals is also developing a rare earth processing facility in Saskatoon and plans to ship the rare earth carbonates from the Saskatoon mine to its partner, REEtec, which has separation / purification facilities in Norway. Canada also has a number of rare earth projects at different stages of development.[31]

A second example is the purchase by Australian firm Neo Materials in August, 2022 of the rare earth mining rights for the Sarfartoq deposit on Greenland's western coast, thus enabling Neo, which produces technology products,[32] to reduce its exposure to the fluctuations in global rare earth ore prices.[33]

A third example is the discovery by the Swedish mining firm LKAB in mid-January 2023 of what may be the largest deposit of rare earths in Europe (1 million tons of rare earth oxides) in the Per Geijer Deposit located in north Sweden (20 miles from the Arctic Circle). In collaboration with REEtec, the plan is to extract the minerals and then have them separated in REEtec's Norwegian facility, however obtaining permits may take up to 10-15 years due to environmental concerns.[34]

A fourth example is the discovery in Norway of significant offshore deposits in the manganese crusts in the Greenland Sea and the Norwegian Sea in late January 2023. The estimates of rare earths include 1.7 million tons of cerium, and, possibly, yttrium, neodymium, and dysprosium, as well as other minerals (magnesium, copper, cobalt, and zinc), many of which are on the European Commission's list of critical minerals.[35]

Finally, a fifth example is in Africa, where there are several existing rare earth mining operations, as well as mining operations under development. The existing mine operations include the Namibia Critical Metals' Lofdal heavy rare earths mine, which contains deposits of terbium and dysprosium, and the Steenkampskraal mine in South Africa which contains 86,900 tons of rare earth oxides, including significant deposits of praseodymium and neodymium.[36] Australia's Peak Rare Earths Limited is developing the Ngualla Tanzania Rare Earth Project in southern Tanzania with mines containing neodymium and praseodymium deposits, as well as the Teeside refinery in the UK for processing these deposits.[37] The UK firm Pensana is developing the Longonjo mine in neodymium and praseodymium in Angola and has been exploring the adjacent areas in Coola and Monte Verde. It is also developing a rare earth processing facility in the UK.[38] The Guernsey-based Rainbow Rare Earths has two African rare earths projects—the Phalaborwa Project in South Africa and the Gakara Project in Burundi, East Africa.[39]

National Security Issues

The dependence of the United States and other countries on China for rare earths enables China to use rare earth exports controls/bans as a strategic weapon. As a result, the concerns of various countries regarding China's potential bans have led them to increase their efforts in developing alternative sources of rare earths.

The expansion of Japan's sources of rare earths was partially driven by the Chinese government's blockage of all rare earth exports to Japan in June 2010 as tensions increased over a fishing trawler incident in the East China Sea. The ban was subsequently lifted, but it led to Japan reducing its rare earth imports from China by diversifying its import sources and by developing domestic sources. Japan's imports of rare earths from China declined from 90 percent of its rare earths in 2010 to 60 percent by 2021. Japan currently imports 11 percent of its rare earths from France and 19 percent from Vietnam, as well as has provided funds for Australia's Lynas Mt. Weld development. Japan is also developing a rare earth extraction project near the Ogasawara islands.[40]

The incident between China and Japan provides lessons to the United States and other countries in developing strategies to diversify rare earth risk and expand reliable overseas and domestic sources of rare earths. A second incident, which further emphasized for the United States the need to develop its domestic rare earth sector, occurred in 2019 when China considered using rare earth export controls as part of its trade war, but ultimately did not implement them.[41]

A recent incident which further heightened the risk of U.S. supply chain dependencies on Chinese rare earth inputs occurred in the fall of 2022. DOD had to suspend deliveries of F-35 fighter jets in September 2022 because its aircraft engine (manufactured by Honeywell) contained a magnet with a samarium and cobalt alloy from China which was not in compliance with U.S. procurement laws. In early October 2022, deliveries resumed due to the passage of a waiver which allowed these alloys from China to be included in the engine. While the Pentagon suggested that alternatives could be considered in the future, China currently produces 70 percent of samarium-cobalt rare earth magnets and 85 percent of neodymium magnets. The need for these magnets for a variety of military purposes can lead to China in the short- and medium-term developing stricter export controls on rare earths to increase their bargaining power.[42]

Further concerns have arisen regarding the U.S. dependence on China for rare earths since this could limit the ability of the United States to apply economic pressure on China if China escalates its pressure on Taiwan. Indeed, in February 2022, China placed sanctions on Raytheon and Lockheed Martin and suggested that this could include their imports of rare earths, in response to the U.S. approval of the two firms providing $100 million in maintenance services to Taiwan's missile defense systems.[43]

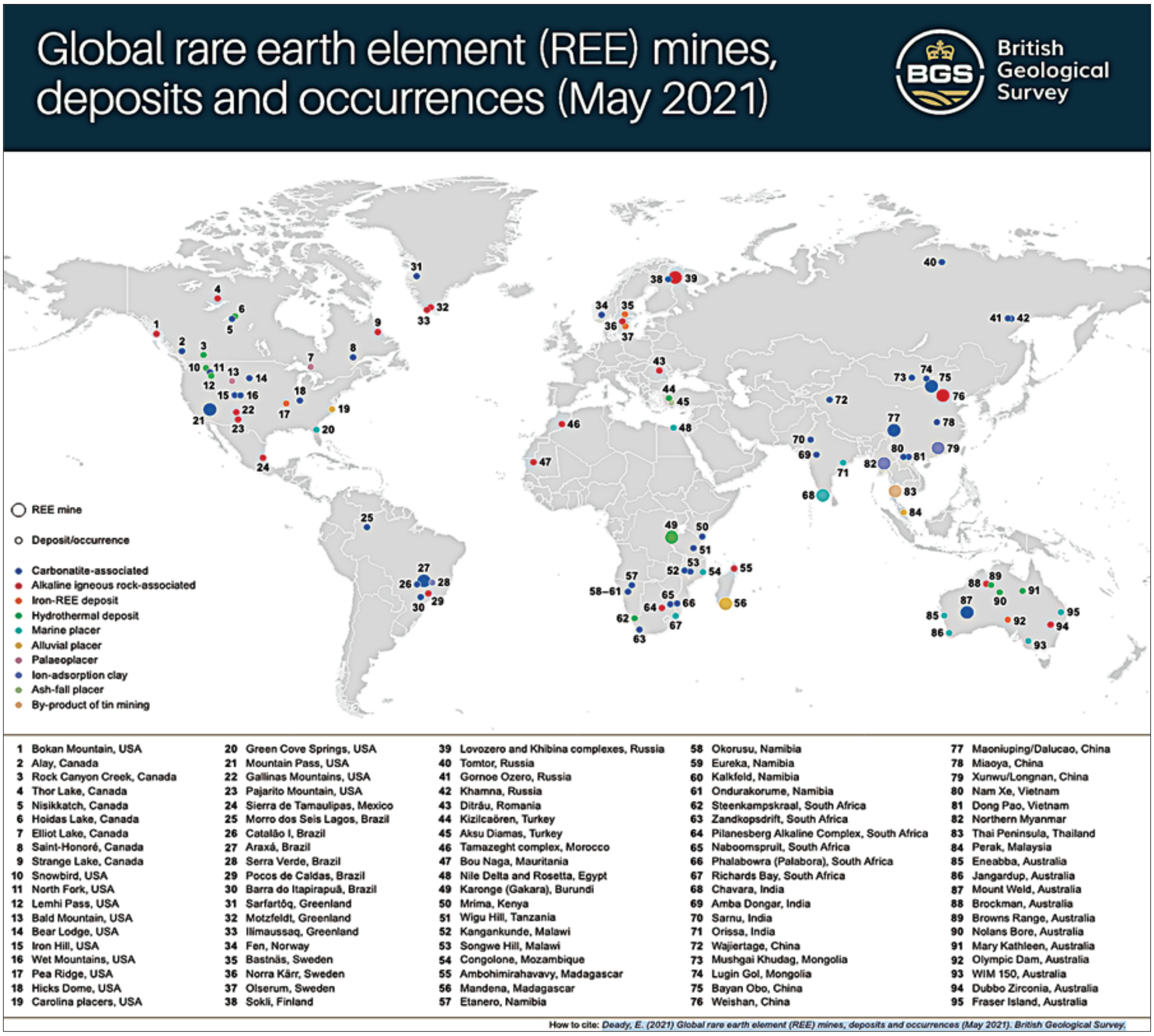
The Role of Other Critical Minerals in Supply Chains and the U.S. National Defense Stockpile

While rare earths are key in supply chains for a number of industries and products, other critical minerals are also very important; these include lithium, nickel, cobalt, graphite, and manganese. Indeed, the USGS 2022 List of Critical Minerals included these five minerals, as well as 16 of the 17 rare earth minerals.[44]

The National Defense Stockpile

The stockpiles for critical minerals in various countries are particularly important in managing the risk of price increases driven by shortages in global supply. Selling stockpile reserves can lower the prices of critical minerals used by manufacturers as inputs, but the decline in reserves would need to be replenished in the future. Consequently, since stockpiles only provide protection in the short- and medium-term, it is important to develop domestic production in critical minerals in mining, separation, refining, processing, and recycling.

The Bayan Obo mine located in the Inner Mongolia region of China is the world's biggest rare-earth element mine. The U.S. depends on China for 80 percent of its rare-earth metal consumption. Photo by Google Earth, March 8, 2021.



Deady, E. (2021) Global rare earth element (REE) mines, deposits and occurrences (May 2021). British Geological Survey.

The National Defense Stockpile, which receives its funding from the Treasury Department but is managed by the Defense Logistics Agency, is key for critical minerals in the supply chain. Concerns have arisen regarding the reduced capacity of the National Defense Stockpile to cover DOD's needs during global supply chain disruptions or other geopolitical challenges, including with China. The risks in the stockpile have been evident in its decline in value, which has been due to the selloff of key materials. The value of the stockpile has declined from almost $42 billion in 1952 to $21.9 billion in 1989 to $888 million as of 2021.[45]

In February 2022, DOD, DOE, and the State Department issued an agreement to collaborate in rebuilding the critical material stockpiles for defense and energy needs. Moreover, the strategic stockpile received a $125 million investment in FY 2022 from DOD, and $253 million was proposed for FY 2023, with the objective of providing $1 billion to the stockpile in future years.[46]

Key Minerals in the National Defense Stockpile

Under the authority of the Defense Production Act (DPA), the Biden administration in March 2022 requested that DOD designate lithium, nickel, cobalt, graphite, and manganese as vital to national security and provided authorization for increasing their supplies domestically.[47]

Lithium is a key input in supply chains in a variety of products, however its most important usage currently is in batteries—80 percent of lithium is used in batteries for electric vehicles. Global lithium mining increased over 20 percent between 2021 and 2022 partially due to the growth in the market for lithium-ion batteries. Lithium prices also increased significantly; U.S. lithium carbonate prices in fixed contracts almost tripled between 2021 and 2022. Australia is the leading lithium mining producer, followed by Chile, China, and Argentina. The United States has one commercial-scale lithium brine operation in Nevada and only two companies in the United States produce downstream lithium compounds. During 2018-2021, U.S. lithium imports averaged 51 percent from Argentina and 40 percent from Chile.[48]

Of the estimated global total of lithium deposits of 98 million tons, Bolivia has the greatest amount of lithium deposits for exploration at 21 million tons, followed by Argentina at 20 million tons.[49] The United States has 12 million tons of lithium deposits; those in Imperial County in California are among the largest global lithium deposits. Due to the growing demand for lithium, Berkshire Hathaway Energy Renewables, EnergySource Minerals, and Controlled Thermal Resources (CTR) have been developing lithium extraction facilities in Imperial County. The United States is also developing lithium battery recycling programs—Redwood Materials is partnering with Ford and Volvo in lithium battery recycling.[50]

Nickel plays a crucial role in the growing demand for batteries (especially lithium-ion batteries) in electric vehicles, in addition to its traditional role in stainless steel production. Although earlier lithium-ion batteries only used cathodes comprised of 1/3 nickel, the new lithium-ion batteries are using cathodes comprised of at least 60 percent nickel to increase vehicle range and increase the energy density of the batteries. The United States mines 0.5 percent of nickel globally through the Eagle Mine in Michigan; its nickel concentrate is exported to Canada and overseas since there are no U.S. processing facilities. Although Indonesia is the largest producer of nickel and mines at 48 percent globally, U.S. primary nickel imports during 2018-2021 averaged 45 percent from Canada, followed by Norway, Australia, and Finland.[51]

Recent supply chain disruptions involving nickel have been partially driven by political tensions in Russia. Although Russia mines 6.7 percent of global nickel overall, it is the largest global producer of class I nickel needed for batteries. While the United States is less dependent on Russia's nickel, Russia is the source of around 15 percent of global nickel exports to countries such as Finland and the Netherlands.[52] The average annual nickel price on the London Metals Exchange (LME) increased significantly between 2021 and 2022; indeed, its substantial increase in March 2022, partially due to the concerns regarding the Russia/Ukraine crisis, resulted in a halt in trading for a week.[53] Concerns over nickel and its role in lithium-ion batteries for EV's have led companies to find alternatives, such as the lithium iron phosphate (LFP) batteries, which don't use cobalt or nickel.[54]

Cobalt is used in the cathodes of lithium-ion batteries in both defense and non-defense products, in alloys which are temperature-resistant, and which are used in DOD's jet engines, in the magnets used in electronic warfare and stealth technology, and in the alloys found in munitions. The United States uses about 40 percent of its cobalt for superalloys (largely in aircraft gas turbine engines) and 35 percent is used in a variety of chemical applications. The value of cobalt consumed in the United States grew from $340 million in 2021 to $530 million in 2022. The largest consumer of cobalt, however, is China; 80 percent of its consumption is used in the production of rechargeable batteries. While almost 70 percent of cobalt is mined in the politically unstable Democratic Republic of Congo, 80 percent of it is consumed by China, where it is refined and processed.[55]

DOD does not rely on Chinese cobalt due to the "specialty metals clause" in 10 USC 4863 which requires DOD suppliers and contractors to buy cobalt-based alloys and steel products—with over 0.25 percent cobalt—which are produced in the United States or by other allies. Michigan's Eagle Mine, which produces nickel and copper, also produces cobalt-bearing nickel concentrate which is exported for processing to Canada and other countries. The United States is also developing a cobalt-copper-gold mine and mill in Idaho. During 2018-2021, U.S. imports of cobalt averaged 22 percent from Norway, followed by Canada, Finland, and Japan.[56]

The United States has 1 million tons of deposits, with the bulk of them located in Minnesota. Various companies, such as U.S. Strategic Metals, Glencore, Electra, and Jervois have been developing cobalt mining projects in the United States. Global sources of cobalt deposits include Congo and Zambia; moreover, over 120 million tons of cobalt exist beneath the Pacific, Atlantic, and Indian Oceans.[57]

Graphite is key in supply chains for advanced semiconductors and high-capacity batteries for EV's (including in the production of lithium-ion batteries) and is used extensively in brake linings, batteries, and lubricants, as well as in steelmaking, refractory applications, and powdered metals.[58] China produces 65 percent of graphite globally, followed by Mozambique (13 percent). Ukraine's halt in production between February and August 2022 due to the conflict with Russia led to a decrease in its production from 10,000 tons in 2021 to 3,000 tons in 2022.

Since 1990, the United States has completely relied on import sources and does not produce graphite domestically. During 2018-2021, U.S. imports of graphite averaged 33 percent from China, 18 percent from Mexico, and 17 percent from Canada. Nevertheless, about 95 companies in the United States used 72,000 tons of natural graphite in 2022 (an increase from 45,000 tons in 2021). Not surprisingly, the U.S. Defense Logistics Agency in October 2021 added graphite to the list of minerals needed in the government stockpile. U.S. companies are showing greater interest in developing the market—Graphite One is developing graphite extraction from its mine in Alaska, which is the largest U.S. source of graphite.[59]

Manganese is largely used in steel production. While there has been no U.S. production of manganese ore[60] since 1970, the U.S. imports of manganese during 2018-2021 averaged 67 percent from Gabon, followed by 19 percent from South Africa. South Africa has about 38 percent of global manganese reserves, while the United States has low grade deposits which are likely to have significant costs of extraction.[61]

Solutions to Critical Material Challenges

The supply chains of a variety of products face similar challenges regarding input shortages of critical minerals, which can result in shortages of completed products and higher prices. These higher prices can contribute to rising inflation and slower economic growth. In recent years, the impact of tensions with China, as well as shortages driven by the Russia-Ukraine conflict and COVID-19, have motivated governments and companies to develop solutions.

U.S. Government Support of Critical Inputs

In February 2021, President Biden issued Executive Order 14017 to assess the weaknesses in critical supply chains and to develop strategies. The

Members of the Oklahoma National Guard walk in the Strategic National Stockpile Warehouse. Photo by: Tech. Sgt. Kasey Phipps/OK ANG.

Executive Order required a detailed 100-day supply chain review regarding critical input risks from several key government agencies, including DOD (with an emphasis on the strategic stockpile), Department of Commerce (including an emphasis on risks in semiconductor manufacturing), Department of Energy (with an emphasis on critical input needs for high capacity batteries, including EV batteries), and the Department of Health and Human Services (including an emphasis on risks with pharmaceutical ingredients).[62]

In the June 2021 follow-up and assessment of February's EO 14017, the Biden administration announced a number of initiatives, including that: (a) the DOE would release a National Blueprint for Lithium Batteries; (b) DOI, USDA, and EPA would identify sites where critical minerals could be manufactured in the United States; (c) DOD would issue grants for critical materials under DPA Title III; (d) DOE would provide $3 billion in loan guarantees for energy technologies; (e) Department of Commerce would provide $75 billion to the semiconductor industries, and the United States would strengthen collaboration with Japan, South Korea, and other allies in semiconductor chips; and (f) a Supply Chains Disruptions Task Force would be established across agencies to evaluate supply and demand challenges.[63]

In February 2022, the Biden-Harris Plan to Revitalize American Manufacturing and Secure Critical Supply Chains focused on new efforts to strengthen the security of mineral supply chains.[64] Moreover, the Biden administration's national security strategy, published in October 2022, identified the importance of developing critical mineral supply chains.[65]

The Bipartisan Infrastructure Law, the CHIPS and Science Act, and the Inflation Reduction Act provided over $135 billion for building the EV sector, including battery manufacturing and critical minerals. The $7 billion from the Bipartisan Infrastructure Law is intended to support critical minerals and key inputs for EV battery manufactures, while the Inflation Reduction Act provides tax credits for using U.S.-based battery and critical mineral components for the EV's or components from U.S. trade partners, instead of China. In October 2022, DOE awarded $2.8 billion in grants from the Bipartisan Infrastructure Law to 20 manufacturing and processing companies for projects across 12 states which supported the development of lithium, graphite, and nickel for EV batteries. Moreover, the American Battery Material Initiative provides federal funds to support battery supply chains, including critical minerals.[66]

Global Collaboration

Global collaboration between countries through joint cooperation initiatives, as well as through providing funds to other countries, is important in mitigating supply chain challenges. The Partnership for Global Infrastructure and Investment is an example of global cooperation among the G7 countries. The Partnership supports low- and middle-income countries in developing infrastructure investment, including mining, refining, and processing critical minerals. Similarly, the Mineral Security Partnership, between Australia, Canada, Finland, France, Germany, Japan, the Republic of Korea, Sweden, the United Kingdom, the United States, and the European Commission has been established to develop strategic opportunities in the supply chains by stimulating government and private sector investments.[67]

Another aspect of global collaboration is through providing funds to other countries and firms. For example, the European Commission completed an agreement with Kazakhstan in November 2022 for Kazakhstan to provide green hydrogen and critical raw materials, including rare earths, cobalt, and lithium.[68] Similarly, the United States provided funds to Australia's Lynas to expand the U.S. rare earths sector; Japan funded Australia's Lynas; and South Korea invested in Australia's Arafura and ASM. Overseas corporate investments have also helped in diversification of sources, as was evident in the investment of Australia's Neo Resources in Greenland, the investment of Australia's Peak Rare Earths Limited and the UK firm Pensana in Africa, and the investment of Australia's Vital Metals in Canada.

Alternative Technologies and Substitutions

The challenges regarding the shortages of critical inputs can partially be addressed through: (a) the development of alternative technologies which would create similar inputs and/or would reduce environmental risks; and (b) the substitution of critical inputs which are in short supply with inputs that have a greater supply.

A Northeastern University team is creating alternative technologies through artificially developing the tetrataenite mineral, with magnetic properties that can replace the use of rare earths in magnets. This project has been supported by a $2.1 million DOE grant. Similarly, Austrian scientists and a University of Cambridge team are making tetrataenite by adding phosphorus to the iron-nickel alloy.[69] Moreover, a Chinese group has developed a method that uses electric currents in rare earth separation via electrokinetic mining to minimize the risks of radioactive contaminants, which can limit rare earth production.[70]

The substitution of one critical input with another can assist companies with challenges of higher costs from input shortages. This is evident in the efforts to substitute lithium-ion batteries that use nickel in EV's with the lithium iron phosphate (LFP) batteries, which do not use cobalt or nickel as inputs and cost less. The substitution helps to mitigate the shortages in nickel and the increases in price, which have been partially driven by the Russia-Ukraine conflict. Moreover, the development of EV batteries which use less cobalt can reduce geopolitical risks since a significant share of cobalt is mined in the Congo and refined in China.

Another option to handle shortages of critical inputs involves recycling. GM has collaborated with Ultium Cells LLC and Li-Cycle in recycling battery materials, which include cobalt, nickel, lithium, graphite, copper, manganese, and aluminum. Other battery recycling firms include Redwood Materials. [71]

Conclusions

Critical inputs in supply chains have faced significant challenges in recent years, which have been driven by rising demand for their usage in new products, as well as by supply shortages. These supply shortages have been impacted by the time and funding needed for critical input development, geopolitical tensions with key source countries (including China and Russia), and COVID-19's impact on production and transportation networks. Countries and companies have focused on the need to develop domestic supply chains for products, ranging from the initial mining of the critical inputs to the production of the final products, as well as the diversification of their global sources of inputs. Rising input prices have affected final product prices, however, which have contributed to overall inflation in many countries and slower economic growth. Consequently, solutions to the challenges facing critical inputs are key in supporting global stability and economic growth.

The support and collaboration between countries and firms is important for reinforcing critical input development because each faces limitations: countries providing funds for critical resource development also face overall budgetary constraints, while investments by firms are limited by financial constraints. Nevertheless, despite limitations in the short- and medium-term, the benefits of diversifying and strengthening the global supply chain in the longer-term outweigh the costs.

Cross-country and domestic collaboration between governments and companies in providing financial support and in locating critical input sources enables companies to manage their risk in the short-term to enable a positive return in the longer-term. Strategies which can create benefits in the longer-term include: (a) the development of domestic sources for mining, refining, and processing inputs, as well as stable transportation networks; (b) the development of alternative, reliable, non-domestic locations for critical inputs to diversify geographic risk; (c) the creation of new technologies to handle environmental constraints and input shortages; and (d) the development of substitutions between critical inputs.

The strength and stability of global supply chains, which are significantly impacted by the availability of critical inputs, provide the foundation for global economic growth, stability, and security. The rapid demand for new types of products requiring critical inputs, ranging from electric vehicles and computers to weapons systems, as well as the capabilities to meet the growing needs for these products, highlights the important role of current efforts in handling supply chain challenges, as well as the potential impact of these efforts on the future global economy. PRISM

Notes

[1] These include yttrium, scandium and the 15 lanthanide elements (cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, promethium, samarium, terbium, thulium and ytterbium. (Calam, Chris. "Can You Name All 17 Rare Earth Elements?" *ThermoFisher Scientific*, March 3, 2016. https://www.thermofisher.com/blog/mining/can-you-name-all-17-rare-earth-elements/; Mitchell, Jason. "China's stranglehold of the rare earths supply chain will last another decade." *Mining Technology*, April 26, 2022).

[2] US Geological Survey, "The Rare Earth Elements: Vital to Modern Technologies and Lifestyles." *USGS Mineral Resources Program,*, November, 2014; Mitchell, Jason. "China's stranglehold of the rare earths supply chain will last another decade." *Mining Technology*, April 26, 2022; Li, Yung. "Here's why China's trade war threat to restrict rare earth minerals is so serious." *CNBC*, May 30, 2019; Mercer, Phil. "Australia challenges China in mining for essential elements." BBC News, October 18, 2022.

[3] US Geological Survey, "The Rare Earth Elements: Vital to Modern Technologies and Lifestyles." *USGS Mineral Resources Program,* November, 2014; Feng, John. "China's Rare Earth Metals Monopoly Could be Coming to an End." *Newsweek*, November 2, 2022; Subin, Samantha. "The new US plan to rival China and end cornering of market in rare earth metals." *CNBC*, April 17, 2021.

[4] Kenlan, Alyk Russell. "Rare Elements of Security." *Air Force Magazine*, November 1, 2020.

[5] Grasso, Valerie Bailey. "Rare Earth Elements in National Defense: Background, Oversight Issues, and Options for Congress." *Congressional Research Service Report R 41744,* September 17, 2013, pp. 9-11. A number of rare earths are used for density amplification and energy storage in directed energy weapons and electronic warfare devices, including electromagnetic railguns, jamming devices, and area denial systems. For example, the long range acoustic devices and area denial systems in the Stryker vehicle use rare earths. Moreover, radar, sonar, radiation and chemical detection technologies—the sonar transducers, various types of radars, enhanced lambda ray detection devices, and Multipurpose Integrated Chemical Agent Alarms (MICAD)-- use neodymium, yttrium, lanthanum, and lutetium. Rare earths such as terbium, yttrium, and europium are used in laser targeting devices, laser Avenger counter-IEDs, SaberShot photonic disruptors, and FCS vehicles with laser weapons. Permanent magnets which use neodymium, praseodymium, samarium, dysprosium, and terbium can be found in electric device motors for CHIPS Future Combat, Integrated Starter Generators, hub-mounted electric traction drive technologies, the Zumwalt DDG-1000 guided missile destroyer, and Joint Strike Fighters.

[6] Zhou, Qian and Sofia Brooke. "China Merges Three Rare Earths State-Owned Entities to Increase Pricing Power and Efficiency." *China Briefing*, January 12, 2022; Daly, Tom. "Minmetals confirms China rare earths merger, creating new giant." *Reuters*, December 22, 2021; Data on neodymium based on neodymium historical data from Trading Economics https://tradingeconomics.com/commodity/neodymium as of December 30 2022.

[7] Zhou, Qian and Sofia Brooke. "China Merges Three Rare Earths State-Owned Entities to Increase Pricing Power and Efficiency." *China Briefing*, January 12, 2022; *USGS Mineral Commodity Summaries*, January 2022, p. 135; *USGS Mineral Commodity Summaries*, January 2023, p. 143.

[8] Mitchell, Jason. "Opinion: the Western world must end China's stranglehold of rare earths." *Mining Technology*, November 9, 2022.

[9] Mitchell, Jason. "China's stranglehold of the rare earths supply chain will last another decade." *Mining Technology*, April 26, 2022; The White House, "FACT SHEET: Securing a Made in America Supply Chain for Critical Minerals," February 22, 2022. https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/22/fact-sheet-securing-a-made-in-america-supply-chain-for-critical-minerals/.

[10] "Green energy transition, structural changes to sustain much higher rare earth prices." *Mining.com*, October 31, 2022.

[11] Mitchell, Jason. "Opinion: the Western world must end China's stranglehold of rare earths." *Mining Technology*, November 9, 2022.

[12] In an effort to further control prices, China increased its mining quota of rare earths due to the substantial demand for the fifth consecutive year, increasing it by 25 percent in August 2022 from the prior year. About 31 percent of China's national quota of mining (52,719 metric tons) and 29 percent of the national quota in smelting (47,129 metric tons) was provided to the China Rare Earth Group for 2022. (Kelemen, Barbara and Alexander Stonor. "Can the West Shake Its Dependence on China's Rare Earths?" *The Diplomat*, September 17, 2022; Zhou, Qian and Sofia Brooke. "China Merges Three Rare Earths State-Owned Entities to Increase Pricing Power and Efficiency." *China Briefing*, January 12, 2022).

[13] Chang, Felix. "China's Rare Earth Metal Consolidation and Market Power." *Foreign Policy Research Institute*, March 2, 2022; Zhai, Keit. "China Set to Create New State-Owned Rare Earths Giant," *Wall Street Journal*, December 3, 2021; Bloomberg, "China Cements Rare Earths Dominance With New Global Giant." *Bloomberg News*, December 22, 2021; Mitchell, Jason. "Opinion: the Western world must end China's stranglehold of rare earths." *Mining Technology*, November 9, 2022; Zhou, Qian and Sofia Brooke. "China Merges Three Rare Earths State-Owned Entities to Increase Pricing Power and Efficiency." *China Briefing*, January 12, 2022. Ganzhou Rare Earth Group, China Minmetals, and Chinalco each own 20.33 percent of the China Rare Earths Group while the State-owned Assets Supervision and Administration Commission owns 31.21 percent. The China Iron and Steel Research Institute Group holds 3.9 percent and the Grinn Group Corporation holds 3.9 percent. (Zhou, Qian and Sofia Brooke. "China Merges Three Rare Earths State-Owned Entities to Increase Pricing Power and Efficiency." *China Briefing*, January 12, 2022; Bloomberg, "China Cements Rare Earths Dominance With New Global Giant." *Bloomberg News*, December 22, 2021).

[14] RFA Staff, "China-led rare earth mining in Myanmar fuels rights abuses, pollution: report." *Radio Free Asia*, August 9 2022.

[15] RFA Staff, "China-led rare earth mining in Myanmar fuels rights abuses, pollution: report." *Radio Free Asia*, August 9 2022; Kang, Dake; Vicgoria Milko, and Lori Hinnant. "'The Sacrifice Zone': Myanmar bears cost of green energy." *AP News*, August 9, 2022.

[16] Uren, David. "Breaking China's near monopoly on rare earths will be easier said than done." *The Strategist*, Australian Strategic Policy Institute, November 8, 2022.

[17] Mitchell, Jason. "Opinion: the Western world must end China's stranglehold of rare earths." *Mining Technology*, November 9, 2022; Uren, David. "Breaking China's near monopoly on rare earths will be easier said than done." *The Strategist*, Australian Strategic Policy Institute, November 8, 2022; "All Eyes on Australia in 2022 as a Global Rare Earths Production Leader." *Investor Intel*, January 6, 2022.

[18] Uren, David. "Breaking China's near monopoly on rare earths will be easier said than done," *The Strategist*, Australian Strategic Policy Institute, November 8, 2022.

[19] "All Eyes on Australia in 2022 as a Global Rare Earths Production Leader." *Investor Intel*, January 6, 2022; Roberts, Peter. "Iluka Progresses Sovereign Rare Earths Capability." *AU Manufacturing Forum*, November 9, 2022; Iyer, Archishma. "Australia's Arafura inks rare-earth supply deal with Hyundai and Kia." *Reuters*, November 6, 2022; Mercer, Phil. "Australia challenges China in mining for essential elements." *BBC News*, October 18, 2022; Parker, Tom. "Rare earths: Australia's next big players," *Australian Resources and Investment*, May 3, 2022.

[20] "Top 3 Rare Earths (NdPr) Junior Or Near Term Producers To Consider." *Seeking Alpha*, October 14, 2022.

[21] Parker, Tom. "Rare earths: Australia's next big players." *Australian Resources and Investment*, May 3, 2022; "All Eyes on Australia in 2022 as a Global Rare Earths Production Leader." *Investor Intel,* January 6, 2022.

[22] Uren, David. "Breaking China's near monopoly on rare earths will be easier said than done." *The Strategist*, Australian Strategic Policy Institute, November 8, 2022; Roberts, Peter. "Iluka Progresses Sovereign Rare Earths Capability." *AU Manufacturing Forum*, November 9, 2022.

[23] The Mountain Pass Mine has produced rare earths since the early 1950's and significantly expanded production in the 1960's as the only global supplier of europium for color televisions. It further expanded with the usage of neodymium, lanthanum, and other rare earths in batteries and magnets by the 1980's. The mine was acquired by Unocal in 1977, which became part of Chevron in 2005, but was closed in 2002 due to a toxic spill, and sold in 2008 to Molycorp, which led to its revival. Molycorp completed an initial public offering in July 2010, and restarted the mine in 2012. Unfortunately, Molycorp filed for Chapter 11 bankruptcy in 2015 and the mine closed again. MP Materials purchased the mine in 2017, restarted production, and finally went public in 2020 (Gorman, Steve. "California mine digs in for 'green' gold rush." *Reuters,* August 30, 2009; Musser-Lopez, Ruth and Mark Gutglueck, "Mountain Pass Rare Earth Mine in Northeast Mojave Desert Operating Again." *San Bernardino Sentinel*, August 6, 2021; Scheyder, Ernest. "US rare earths miner MP Materials to go public in $1.47 billion deal." *Reuters*, July 15, 2020; Subin, Samantha. "The new U.S. plan to rival China and end cornering of market in rare earth metals." *CNBC,* April 17, 2019; *SEC 10-K for Molycorp for the Fiscal Year Ended December 31, 2011*, pp. 1-2).

[24] Musser-Lopez, Ruth and Mark Gutglueck, "Mountain Pass Rare Earth Mine in Northeast Mojave Desert Operating Again." *San Bernardino Sentinel*, August 6, 2021.

[25] Reuters Staff. "US senator 'worried' about Chinese stake in MP Materials." *Reuters*, March 31, 2022; *USGS Mineral Commodities Summaries 2023*. pp. 142-143; Mahoney, Noi. "US companies move to break China's dominance of rare earth industry." *Freight Waves,* June 27, 2022

[26] Subin, Samantha. "The new U.S. plan to rival China and end cornering of market in rare earth metals." *CNBC,* April 17, 2019; Feng, John. "China's rare earth metals monopoly could be coming to an end." *Newsweek,* November 2, 2022; The White House, "FACT SHEET: Securing a Made in America Supply Chain for Critical Minerals," February 22, 2022. https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/22/fact-sheet-securing-a-made-in-america-supply-chain-for-critical-minerals/.

[27] Mahoney, Noi. "US companies move to break China's dominance of rare earth industry." *Freight Waves*, June 27, 2022.

[28] Subin, Samantha. "The new U.S. plan to rival China and end cornering of market in rare earth metals." *CNBC*, April 17, 2019; Feng, John. "China's rare earth metals monopoly could be coming to an end." *Newsweek*,, November 2, 2022; Mahoney, Noi. "US companies move to break China's dominance of rare earth industry." *Freight Waves*, June 27, 2022.

[29] Reuter, Dominick. "The US has a critical need for rare earth minerals that enable clean energy, and this exploration company may have found the largest deposits in North America." *Business Insider*, April 30 2022.

[30] Neill, Alastair. "Ucore Steps into the American Rare Earths Processing Ring in Louisiana." *Investor Intel*, October 19, 2022.

[31] CBC News, "Canada's 1st rare earth mining project starts production, July 15, 2021; "Top 3 Rare Earths (NdPr) Junior Or Near Term Producers To Consider." *Seeking Alpha*, October 14, 2022; *Government of Canada's Rare Earth Elements Facts*. Last modified February 3, 2022. https://www.nrcan.gc.ca/our-natural-resources/minerals-mining/minerals-metals-facts/rare-earth-elements-facts/20522. Accessed December 23, 2022; Lazenby, Henry. "Vital Metals pivots to Nechalacho permitting as plant capex double." *The Northern Miner*, December 22, 2022.

[32] Neomaterials website, "Applications We Enable." https://www.neomaterials.com/, Accessed December 23, 2022.

[33] Bradsher, Keith. "A Supplier of Rare Earth Metals Turns to Greenland in a Bid to Cut Reliance on Russia." *New York Times*, August 22, 2022.

[34] Bye, Hilde-Gunn. "Europe's Largest Deposit of Rare Earth Metals Found in Northern Sweden." *High North News*, January 13, 2023; Reuters Staff. "Sweden's LKAB find Europe's biggest deposit of rare earth metals." *Reuters*, January 13, 2023; He, Laura. "Sweden finds the largest rare earth deposit in Europe. It could help cut dependence on China." *CNN*, January 13, 2023.

[35] Reuters Staff and Laura Paddison. "Norway discovers huge trove of metals, minerals, and rare earths on its seabed." *CNN Business*, January 30, 2023.

[36] Baskaran, Gracelin. "Could Africa replace China as the world's source of rare earth elements? Brookings, December 29 2022.

[37] "Top 3 Rare Earths (NdPr) Junior Or Near Term Producers To Consider." *Seeking Alpha*, October 14, 2022; Peak Rare Earth website: https://peakrareearths.com. Accessed December 23, 2022.

[38] Pensana website: "Pensana Granted Major New Rare Earth Exploration Project." May 4, 2020. https://pensana.co.uk/wp-content/uploads/2020/09/4-May-2020-Pensana-granted-major-new-rare-earth-exploration-project.pdf ; "Pensana begins construction on $195m rare earths facility in UK." *Mining Technology*, July 25, 2022; Top 3 Rare Earths (NdPr) Junior Or Near Term Producers To Consider." *Seeking Alpha*, October 14, 2022.

[39] "Top 3 Rare Earths (NdPr) Junior Or Near Term Producers To Consider." Seeking Alpha, October 14, 2022.; https://www.rainbowrareearths.com/. Accessed December 23, 2022; https://www.reuters.com/markets/companies/RBWR.L/. Accessed December 23, 2022.

[40] Feng, John. "China's rare earth metals monopoly could be coming to an end." *Newsweek*, November 2, 2022; Mahoney, Noi. "US companies move to break China's dominance of rare earth industry." *Freight Waves,* June 27, 2022; Lee, Annie. "Japan looks 6,000 meters under the sea for rare earths to counter China." *Bloomberg News*, October 31, 2022.

[41] Bloomberg, "China Cements Rare Earths Dominance With New Global Giant." *Bloomberg News*, December 22, 2021.

[42] Xuanzun, Lin and Li Xuanmin." US waiver for Chinese alloy on F-35 jets exposes dependence on rare-earth products from China." *Global Times*, October 9, 2022.

[43] Associated Press, "China sanctions Raytheon, Lockheed over Taiwan deal." *Defense News*, February 22, 2022; Kelemen, Barbara and Alexander Stonor, "Can the West Shake Its Dependence on China's Rare Earths?" *The Diplomat*, September 17, 2022.

[44] Burton, Jason. "US Geological Survey Releases 2022 List of Critical Minerals." *USGS National News Release*, February 22, 2022.

[45] Mahoney, Noi. "US companies move to break China's dominance of rare earth industry." *Freight Waves,* June 27, 2022; Medsger, Matthew. "Strategic Stockpile down to 4 percent of Cold War era value, Moulton urges action." *Boston Herald*, May 1, 2022; Harris, Bryant. "Congress and Pentagon seek to shore up strategic mineral stockpile dominated by China." *Defense News*, May 23, 2022.

[46] The White House, "FACT SHEET: Securing a Made in America Supply Chain for Critical Minerals," February 22, 2022. https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/22/fact-sheet-securing-a-made-in-america-supply-chain-for-critical-minerals/; Medsger, Matthew. "Strategic Stockpile down to 4 percent of Cold War era value, Moulton urges action." *Boston Herald*, May 1, 2022.

[47] Medsger, Matthew. "Strategic Stockpile down to 4 percent of Cold War era value, Moulton urges action." *Boston Herald*, May 1, 2022.

[48] Geological Survey (USGS), *USGS Mineral Commodities Summaries 2022,* pp. 100-101; US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2023,* pp. 108-109.

[49] Ibid.

[50] US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2022*. pp. 100-101; US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2023*. pp. 108-109; The White House, "FACT SHEET: Securing a Made in America Supply Chain for Critical Minerals," February 22, 2022. https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/22/fact-sheet-securing-a-made-in-america-supply-chain-for-critical-minerals/.

[51] Meredith, Sam and Matt Clinch. "Nickel falls 8 percent to hit limit down in chaotic trade on London Metal Exchange." *CNBC*, March 17, 2022; Burton, Mark; Jack Farchy; and Alfred Cang, "Behind the Nickel Mess on the London Metal Exchange." *Washington Post*, June 13, 2022; US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2023*, pp. 122-123; "Nickel's price surge could threaten automakers' ambitious electric-vehicle plans." *CNBC*, March 8, 2022.US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2022,* pp. 122-123.

[52] "UPDATE: Knotty nickel supply chain highly exposed to new price shocks." *Mining.com*, July 22, 2022; OECD, "The supply of critical raw materials endangered by Russia's war on Ukraine": August 4, 2022.

[53] US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2022*, pp. 114-115; US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2023*, pp. 122-123. Some of the data in the text were calculated from data in the *USGS Mineral Commodities Summaries 2023.* Indeed, on March 8, 2022, nickel prices increased by 250% on the London Metal Exchange, resulting in a halt in trading for a week and the cancellation by LME of $3.9 million in trades on March 8 to rewind LME's market back to the closing price on the previous day—March 7. (Meredith, Sam and Matt Clinch ."Nickel falls 8% to hit limit down in chaotic trade on London Metal Exchange." *CNBC*, March 17, 2022; Burton, Mark; Jack Farchy; and Alfred Cang, "Behind the Nickel Mess on the London Metal Exchange." *Washington Post*, June 13, 2022).

[54] "Nickel's price surge could threaten automakers' ambitious electric-vehicle plans." *CNBC*, March 8, 2022.

[55] Canberry, Sean. "United States Seeking Alternatives to Chinese Cobalt," *National Defense Magazine*, August 3 2022; US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2023*, pp. 60-61; US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2022,* pp. 52-53.

[56] Ibid.

[57] Canberry, Sean. "United States Seeking Alternatives to Chinese Cobalt," *National Defense Magazine*, August 3 2022; US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2023*, pp. 60-61.

[58] US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2023,* pp. 82-83.

[59] Underlying data for the percentages is from the *US Geological Survey (USGS) Mineral Commodities Summaries 2023,* p. 83; "Graphite One Reports Graphite Added to the U.S National Defense Stockpile List." *Yahoo Finance*, October 7, 2021; US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2022*, pp. 74-75; US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2023,* pp. 82-83; Lasley, Shane. "Pentagon adds graphite to stockpile list." *North of 60 Mining News*. October 8, 2021.

[60] Ore which contains 20 percent or more of manganese.

[61] US Geological Survey (USGS), *USGS Mineral Commodities Summaries 2023*, pp. 114-115. Some of the data in the text is calculated from the tables in the summary.

[62] White House, "FACT SHEET: Biden-Harris Administration Driving U.S. Battery Manufacturing and Good-Paying Jobs." October 19, 2022; The White House, "Executive Order on America's Supply Chains." February 24, 2022. https://www.whitehouse.gov/briefing-room/presidential-actions/2021/02/24/executive-order-on-americas-supply-chains/; "Fact Sheet: Biden-Harris Administration Announces Supply Chain Disruptions Task Force to Address Short-Term Supply Chain Discontinuities, June 8, 2021.

[63] White House, "FACT SHEET: Biden-Harris Administration Announces Supply Chain Disruptions Task Force to Address Short-Term Supply Chain Discontinuities," June 8, 2021. https://www.whitehouse.gov/briefing-room/statements-releases/2021/06/08/fact-sheet-biden-harris-administration-announces-supply-chain-disruptions-task-force-to-address-short-term-supply-chain-discontinuities/.

[64] The Biden Harris Plan also included funding for DoE and DoD to develop reserves in the US for rare earths, nickel. cobalt and lithium, as well as to refine and recycle materials, and for DoD to collaborate with other government agencies in strengthening the National Defense Stockpile. (Burke, Sharon E. "Russia is a mineral powerhouse — and its war with Ukraine could affect global supplies." *Boston Globe*, March 9, 2022; White House, "The Biden-Harris Plan to Revitalize American Manufacturing and Secure Critical Supply Chains in 2022," February 24, 2022, https://www.whitehouse.gov/briefing-room/statements-releases/2022/02/24/the-biden-harris-plan-to-revitalize-american-manufacturing-and-secure-critical-supply-chains-in-2022/). The need to develop the domestic rare earth sector was further emphasized with various legislative proposals. In January 2022, Senators Cotton and Kelly proposed legislation to create a DOD stockpile of critical minerals and required that defense companies cease purchasing Chinese rare earths by 2026. In April 2022, Senators Rubio and Hyde-Smith proposed a bill in which DOE would provide funding for domestic production of finished rare earth products. (Reuter, Dominick. "The US has a critical need for rare earth minerals that enable clean energy, and this exploration company may have found the largest deposits in North America." *Business Insider*, April 30, 2022).

[65] Feng, John. "China's rare earth metals monopoly could be coming to an end." *Newsweek,* November 2, 2022.

[66] White House, "FACT SHEET: Biden-Harris Administration Driving U.S. Battery Manufacturing and Good-Paying Jobs." October 19, 2022.; Uren, David. "Breaking China's near monopoly on rare earths will be easier said than done." *The Strategist*, Australian Strategic Policy Institute, November 8, 2022.

[67] White House, "FACT SHEET: Biden-Harris Administration Driving U.S. Battery Manufacturing and Good-Paying Jobs." October 19, 2022.

[68] Lillis, Joanna. "EU taps Kazakhstan for rare earths, green hydrogen." *EurasiaNet*, November 9, 2022.

[69] Stening, Tanner. "Researchers may have just solved the rare earths crisis. No, it doesn't exactly involve mining meteorites." *News@Northeastern*, October 17, 2022; Bloomberg News, Charlie Zhu and Winnie Zhu. "Researchers Find Possible Replacement for Rare Earth in Magnets." *Bloomberg*, October 24, 2022; "New approach to 'cosmic magnet' manufacturing could reduce reliance on rare earths in low-carbon technologies." *Science News*, October 24, 2022.

[70] Normile, Dennis. "It's electric! Technique could clean up mining of valuable rare earth elements." *Science*, November 1, 2022; Timmer, John. "Toxic cleanup technique can get more rare earth metals out of ores." *Ars Technica*, November 3, 2022..

[71] Subin, Samantha. "The new U.S. plan to rival China and end cornering of market in rare earth metals," *CNBC*, April 17, 2019; GM News. "GM Joins initiative to Certify Sustainability and Human Rights in EV Supply Chain." November 30 2021. https://news.gm.com/newsroom.detail.html/Pages/news/us/en/2021/nov/1130-sustainability.html.