Research Report

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Time for Resilient Critical Material Supply Chain Policies

KEY FINDINGS

- China has used a variety of economic practices to capture a large portion of the rare earth supply chain. It has used this disproportionate market share to manipulate the availability and pricing of these materials outside China.
- Economic coercion by China in the past has usually been executed through denying access to Chinese domestic markets. Rare earth elements (REEs) have been the lone exception: China threatened to restrict access to Chinese exports in order to manipulate U.S. partner nations (Japan) to geopolitical ends.
- Projects planned to increase the extraction and processing capacity of REEs fall short of estimated future demand outside China; there are not enough to mitigate disruption.
- China could effectively cut off 40–50 percent of global rare earth oxide supply, which would affect prime manufacturers and suppliers of advanced components used in the U.S. Department of Defense's (DoD's) systems and platforms. The U.S. defense industrial base (DIB) has a limited time frame in which to respond to a disruption before industrial readiness suffers.
- The potential risks associated with a disruption could affect the broader U.S. economy and the DIB's ability to procure critical materials, as well as interrupt military operations in extreme cases.
- DoD has a variety of policies available to mitigate the effects of a disruption. Categorized as proactive or reactive policies, or both, depending on the policy's "time to impact," these policy options have yielded mixed results in past use.

Decades of offshore mining and processing of mineral commodities have resulted in the United States becoming dependent on foreign sources for critical manufacturing inputs, both for defense systems and clean energy technologies. Its greatest dependence is on China, which rose to prominence as a reliable producer and processor of many low-cost mineral commodities in the 1990s and 2000s but has since pursued mercantilist policies that have led to market volatility, disputes at the World Trade Organization (WTO), economic coercion, and threats of geopolitical retaliation. Although activity to develop production and processing outside China has increased, the time it takes for such projects to bear fruit—sometimes a decade or more—means that the risk of interruptions in critical material supply chains may need to be addressed with greater urgency.

China is the largest producer and processor of rare earth elements (REEs) worldwide and a key processor of critical lithium-ion battery (LIB) materials and components. We reviewed current global mining and processing activities (along with new and planned production and processing) of these materials, hypothesized plausible supply disruption scenarios based on China's previous behavior, and assembled a group of subject-matter experts to consider possible reactive policy actions to mitigate the impacts of such a disruption—should it occur—and proactive policy actions that might prevent such a disruption or provide a means to avoid its most severe impacts.

This project aimed to identify policy options for the U.S. Department of Defense (DoD) and the U.S. government for preventing or mitigating the effects of shocks to critical material supply chains on national security. We used two case studies to explore this problem: one focused on REE supply chains, where supply concentration in China is established; and one focused on LIB supply chains, where growing Chinese market share may be a sign of a deliberate state strategy of market concentration like historical efforts to dominate the rare earth mining and processing industries. This report is the product of a series of interviews with experts from government, academia, and private industry, including the Defense Logistics Agency, the National Energy Technology Laboratory, the Colorado School of Mines, the University of Pennsylvania, Benchmark Minerals Intelligence, and Redwood Materials, and informed by a literature review of general work on critical materials and reporting and scholarship specifically pertaining to the cases studied.[1] The project work culminated in a "Day After . . ." exercise with a small group of RAND subject-matter experts.[2] The workshop comprised four participants with backgrounds in economics; the Chinese defense industrial base (DIB), military, and economic policy; and critical materials policy. Participants elaborated on and added to policy options collected by the authors by postulating responses to a plausible disruption scenario to the rare earth supply chain.

The main conclusion of this analysis is that *timing is critical*: Current production and processing activities demonstrate that China's window for disruption of these critical material supply chains may be narrowing, but not eliminated, and remains a strategic geopolitical tool for its leadership. The U.S. DIB's ability to operate and provide DoD with capabilities in a disruption scenario is governed by their *time to survive* and *time to recover* whereas policy options to mitigate risk each have their own time needed for execution plus the time needed to affect supply chains (i.e., their *time to impact*). Accounting for policies' time to impact in conjunction with China's window of opportunity for disruption leads us to conclude that DoD and the U.S. government should implement proactive policies and investments to reduce these critical supply chain risks now.

Abbreviations

CFIUS	Committee on Foreign Investment in the United States
COVID-19	coronavirus disease 2019
DIB	defense industrial base
DLA	Defense Logistics Agency
DoD	U.S. Department of Defense
DoE	U.S. Department of Energy
DPA	Defense Production Act
ERMA	European Raw Materials Alliance
EU	European Union
EV	electric vehicle
JDAM	joint direct attack munition
LIB	lithium-ion battery
NdFeB	neodymium iron boron
OPEC+	Organization of the Petroleum Exporting Countries Plus
QUAD	Quadrilateral Security Dialogue
RDT&E	research, development, test, and evaluation
REE	rare earth element
REO	rare earth oxide
SBIR	Small Business Innovative Research
SOE	state-owned enterprise
STTR	Small Business Technology Transfer
USGS	U.S. Geological Survey
WTO	World Trade Organization

Insights into the Nature of the Raw Materials Problem

Critical Materials

As nations around the world combat climate change with policies aimed at eliminating internal combustion engines and increasing the use of clean energy, demand for associated raw materials, or *critical mate-*

rials, is rapidly increasing. Components in electric vehicles (EVs) and other clean- and renewable-energy technologies—such as permanent magnets found in electric motors and wind turbines—are highly dependent on critical, or "strategic," materials. Such materials are also vital to the construction of defense weapons and platforms.

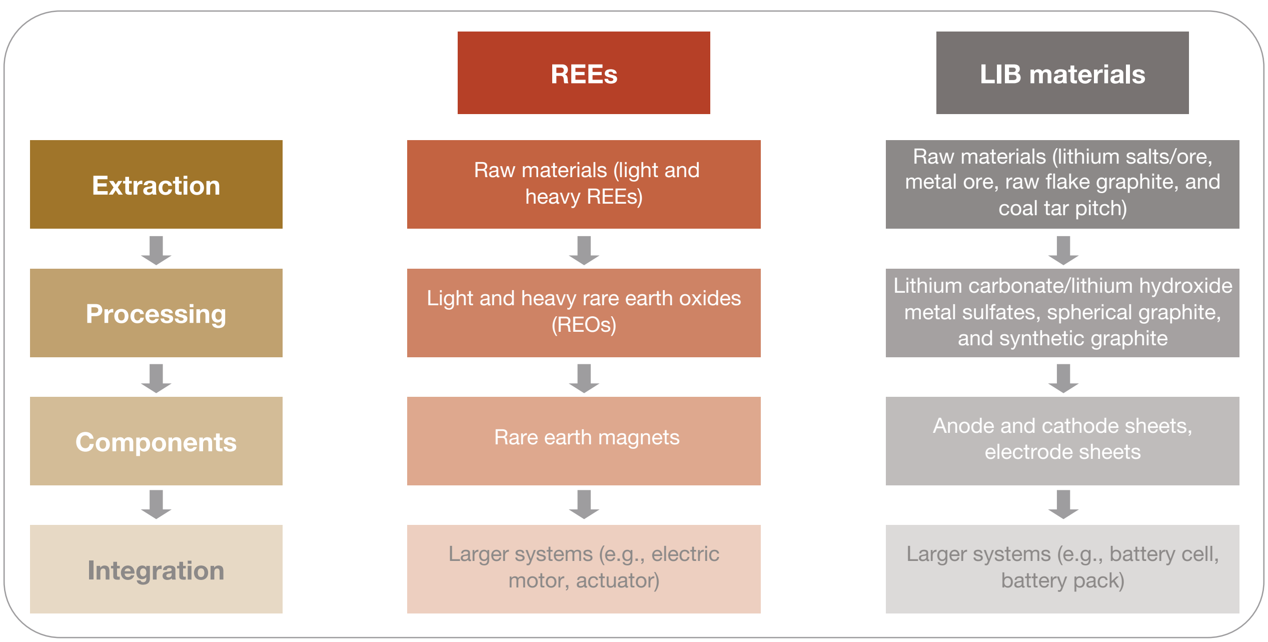
Critical material supply chains are susceptible to two modes of risk: lack of capacity and lack of diversity. Over time, demand for production inputs is likely to rise in a growing market. If production capacity cannot keep pace with a growing market, then pricing pressure can drive up the cost of critical materials. Those who cannot afford the higher prices simply lose out and must settle for lower quality or lower performing substitute materials. Likewise, overcapacity and production can push prices lower. Lack of diversity in supply chains can lead to the development of constraints or bottlenecks that may be susceptible to disruption. Like other supply chains, much of critical or strategic material supply chains are concentrated outside the United States, causing the United States to rely on foreign imports. However, efforts aimed at increasing and diversifying supply can take decades to implement. Given these factors, consumers around the globe, including the U.S. DIB, could experience material shortages over the next several years because of insufficient planning.[3]

Strategic materials are geographically dispersed around the globe and can be found within the borders of U.S. allies, neutral countries, and near-peer competitors alike. Not only is the geographic location of mineral ores, salts, and other forms of raw materials important but also the location of upstream and midstream supply chain sectors. These components of the supply chain work to turn raw minerals into processed, value-added chemicals used as inputs to downstream consumers that focus on component manufacturing and integrating those components into larger systems and platforms. To better characterize the vulnerabilities of a supply chain, it must be analyzed in its entirety. Notionally, supply chains dependent on critical materials have four sectors: extraction, processing, component manufacturing, and integration. Figure 1 illustrates these notional sectors for the REE and LIB supply chains.

Constraint of any one of these four sectors of the supply chain could serve as a point of origin for disruption. Globalization has incentivized U.S. com-

FIGURE 1

Notional Supply Chains Dependent on Critical Materials Processing and Extraction



SOURCE: Adapted from Summers, "Understanding the Rare Earth Element Supply Chain."
NOTE: REEs are the pure elements in the periodic table, REOs are the result of processing extracted raw material into a purified chemical form.

panies to relocate their production and services outside the United States for economic advantages; thus, today, the first three sectors of a critical materials supply chain are likely to be sourced from a near-peer competitor, such as China.[4]

Lack of diversity in supply chains is inherently risky, especially for countries with little or no domestic capacity.[5] If suppliers of defense systems and their components cannot be assured an adequate supply of strategic material inputs, DoD cannot be assured of acquiring the systems they require—potentially risking a lack of future preparedness. Modernization requires the development and fielding of advanced systems that, in turn, incorporate processed materials.[6]

If competition with China escalates to conflict, the United States could lose access to these strategic materials. Alternatively, the fear of losing access to these materials could limit the U.S. government's ability to respond to geopolitical activity.[7] The advantages of market dominance are not lost on Chinese leadership. As far back as 1992, then–Comrade Deng Xiaoping said,

> The Middle East has its oil, China has rare earth: China's rare earth deposits account for 80 percent of identified global reserves, you can compare the status of these reserves to that of oil in the Middle East: it is of extremely important strategic significance; we must be sure to handle the rare earth issue properly and make the fullest use of our country's advantage in rare earth resources.[8]

In other words, the world has let itself become dependent on China for its supply of critical materials, and now China could use this control to influence other nations' geopolitical actions—much as oil- and gas-producing nations such as Russia or other members of the Organization of the Petroleum Exporting Countries Plus (OPEC+) have done.

U.S. allies and partners also recognize the mercantilist nature of China's actions. The European Union (EU) has established the European Raw Materials Alliance (ERMA) in the hope of supporting domestic extraction and processing.[9] The EU also adopted the New Industrial Strategy for Europe to focus these efforts.[10] Thierry Breton, the EU Commissioner for Internal Market, was quoted as saying,

> The Commission's in-depth review of critical supply chains and key technologies has highlighted the EU's high level of foreign dependency on inputs required for our green and digital transition and our continent's resilience. The EU depends on others—mainly China—for the import of permanent magnets, as well as the rare earth elements they are made of. The European Raw Materials Alliance plays a key role in addressing these dependencies.[11]

These efforts by U.S. allies and partners seek to establish free access to such materials at a fair market price because China has not demonstrated itself to be reliable, nor a free market, for critical materials.

The Biden administration has emphasized securing critical supply chains following the ongoing coronavirus disease 2019 (COVID-19) pandemic via executive orders to provide a 100-day supply chain review and a follow-up fact sheet on progress made to date.[12] Among the materials reviewed are LIB materials and the 17 REEs. Both of these material classes have been identified—currently or in the past—as candidates for Title III funding in the Defense Production Act (DPA).[13]

We use two supply chains as case studies to examine the importance of critical materials to DoD, risks and consequences of a supply disruption, and potential mitigating policy actions. Because of limited resources, we analyze the REE supply chain and leverage that effort to extract relevant findings applicable to the supply chains of other critical materials, using the LIB supply chain as an example.

Lithium and Other Battery Materials

The pace of developing new supply is so slow—and projected quantities needed for EVs are so great—that global lithium supply is not projected to catch up with demand until 2030 at the earliest.[14] The Defense Logistics Agency procures about $200 million worth of LIB materials annually to power DoD equipment, weapons, and platforms, positioning DoD as a small actor in a fast-growing market.[15] As future operational concepts evolve to include distributed force employment in austere environments and reliance on more-sophisticated, remote, or autonomous systems, demand for mobile power will grow. Because "[w]eapon system and platform batteries require high reliability, safety, cybersecurity, integrated monitoring, performance/advanced integrated pack design, and design mitigations that do not readily conform to the commercial market," the defense market is at higher risk of disruption than the commercial market.[16]

Raw material deposits are available outside China for some LIB materials,[17] but Chinese firms, in the form of state-owned enterprises (SOEs) and private enterprises, have systematically invested in or acquired foreign companies that supply these raw materials. Furthermore, Chinese firms exercise control over much of the processing capacity for lithium (55 percent), cobalt (65 percent), copper (40 percent), nickel (35 percent),[18] spherical graphite (99 percent),[19] and synthetic graphite (78 percent).[20] Countries such as Japan and South Korea have subsidized their local markets for decades to capture downstream market share in LIB cell manufacturing,[21] but they still rely on Chinese suppliers for processed material inputs. China now controls 92 percent of the global cathode capacity and 91 percent of global anode capacity. Additionally, China has made sizable investments in cell manufacturing capacity for which it now controls 79 percent of the market.[22]

Given the history of intervention in similar markets, the inclusion of "new energy vehicles" in the Made in China 2025 initiative, and Chinese dominance in processing and cell capacity, the potential now exists for supply chain disruption to the detriment of DoD and the broader U.S. economy.[23] In a future in which EVs replace gas-powered vehicles, the world might be soon trading its reliance on Russia and OPEC+ member nations for reliance on China.

To provide recommendations on developing a strategy to mitigate disruption concerns, we turn our attention to policy decisions in a market with similar activity—that of REEs.

Primer on the REE Supply Chain: Past Events and Future Paths?

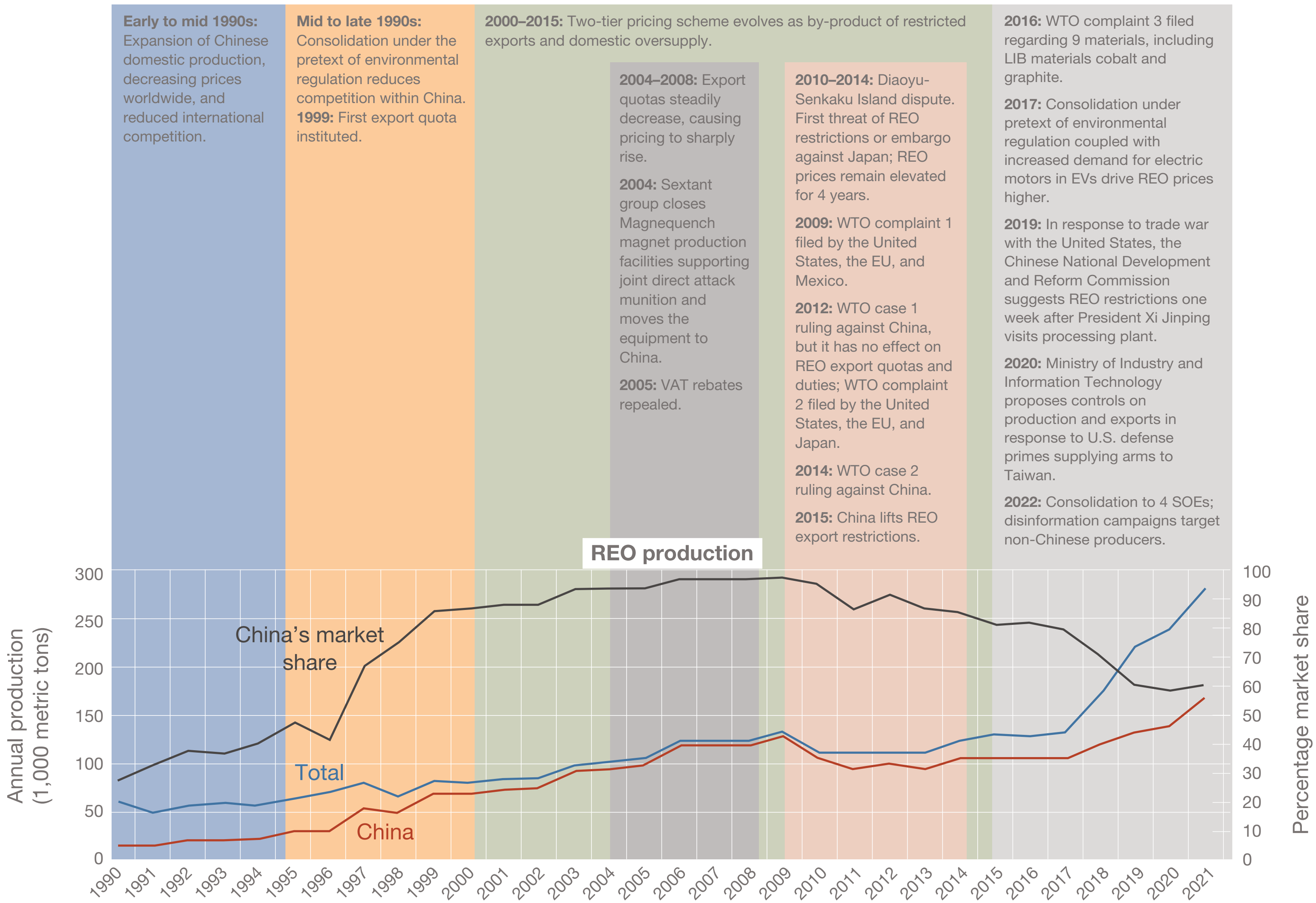
To better understand potential policy options for mitigating a supply disruption, it is helpful to assess the events leading to the consolidation and manipulation of the REE supply chain—the root cause of which these policy options should target.

In the early 1980s, a Chinese chemist invented a cheaper method of separating REEs that led to high-quality production, starting China on its path to market dominance.[24] In the early to mid 1990s, Chinese firms expanded and increased domestic production of extracted REO ore, and by the mid to late 1990s, consolidation led to an increase in Chinese market share and the introduction of export quotas. These export quotas, discussed in more detail in subsequent sections, would lead to two-tier pricing schemes to the benefit of China's domestic suppliers, which secured their market share for 15 years. In the early 2000s, the United States relocated its rare earth magnet production to mainland China, further solidifying China's competitive advantage. China's market share would remain elevated until the 2010s when complaints filed with the WTO ended the two-tier pricing practice in 2015. New supply from outside China and the end of Chinese export quotas led to a decrease in China's overall market share, but issues remain. A brief timeline of Chinese REE market activity is presented in Figure 2. China's

In a future in which EVs replace gas-powered vehicles, the world might be soon trading its reliance on Russia and OPEC+ member nations for reliance on China.

FIGURE 2

Brief Timeline of China's REE Market Activity with Rare Earth Mining Data



SOURCE: Features information from USGS, *Mineral Commodity Summaries* 2022.

NOTE: USGS data represent extracted quantities of REO ore. JDAM = joint direct attack munition; VAT = value-added tax.

market share of extraction and production has fluctuated over time. As of 2022, 120 million tons of REO reserves are believed to exist worldwide,[25] and China accounts for 44 million tons, about 37 percent of the global reserves.[26] As shown in Figure 2, China's share of extraction peaked in the late 2000s, when it provided upward of 95 percent of global REE output; it now accounts for 55 percent.[27] However, China accounts for about 80 to 90 percent of processing and separates nearly all heavy REEs; because of this dominance in the market, the processing sector is where the risk of disruption is greatest.[28] It is the same sector that China leveraged when Japan was threatened with REO restrictions in 2010.[29] In fact, nearly all rare earth ore mined in the United States (43,000 tons in 2021) is sent to China for separation and purification.[30] This dominance resulted from China's ambitious mining programs, an inability to enforce national policies that led to illegal mines, and a disregard for pollutants and by-products that create environmental waste.[31]

This control has also benefited China downstream of the supply chain. For example, permanent magnets—one of many downstream REE products—are a high-value commodity essential to many defense and commercial applications.[32] China enjoys a 92-percent market share of REE magnet production,[33] including magnets essential to electric motors and actuators used in defense systems and munitions (e.g., Javelin, JDAM) and aircraft (e.g., F-35). Permanent magnets are also a key component in EV motors. The magnets rely on heavy REEs whose processing sector is controlled almost entirely by China. Other defense applications of REEs include coatings for jet engines, missile guidance systems, antimissile defense systems, satellites, and communication systems.[34] Light REEs are important to catalysis for oil and gas production but are easier to procure than their heavy counterparts. Thus, heavy REEs are more valuable by weight than light REEs.

Consolidation

Chinese REE producers and processors are heavily influenced and regulated by the Chinese government, or Party-state. Three times since 1990 (the mid 1990s, 2017, and 2022—see Figure 2), the Party-state has instructed REE suppliers to consolidate production through acquisitions and mergers. Although the Party-state issued these instructions under the pretext of environmental regulations and crackdowns on illegal mining operations,[35] it also put these firms in a better position to compete on the global market through economies of scale. Most recently, China has continued to strengthen the position of its domestic suppliers by consolidating three of its six SOEs into one larger SOE, China Rare Earth Group, which will focus on medium and heavy REEs. Further mergers are planned that will create one SOE focused on light REEs.[36]

In 2004, the Committee on Foreign Investment in the United States (CFIUS) oversaw the acquisition of the U.S.-based REE magnet producer Magnequench by a group with Chinese ownership. To mitigate any losses in U.S. magnet capacity, CFIUS stipulated that the group keep facilities inside the United States for a set time frame. When that time expired, the group simply closed its U.S. operation and exported the production equipment to the Chinese mainland. This move eventually aided in the establishment of REE magnet production capacity inside China and subsequent market dominance by institutionalizing the benefits of co-locating the raw material extraction, processing, and component manufacturing sectors.[37] Through consolidation, China continues to signal its goals of raising its global competitiveness, increasing its pricing power, and growing its production efficiency.

Export Quotas and WTO Complaints

China has demonstrated a pattern of using export bans, quotas, duties, and other restrictions to artificially limit the availability of raw materials globally. The impact on supply has essentially been to create two-tier pricing schemes that benefit domestic producers of REE and downstream components (e.g., magnets).[38] China imposed these restrictions for REEs, including export quotas, in the early 2000s (see Figure 2).

In 2009, the United States, the EU, and Mexico jointly filed a complaint with WTO against China for the use of export quotas for raw materials, but this complaint did not include REEs. Three years later, the WTO ruled against China, and the quotas were lifted only for those materials listed in the complaint; thus, China did not lift quotas on REEs. The same year, 2012, the United States, the EU, and Japan filed a second WTO complaint, this time for REEs and other materials. It was not until 2015 that China ended the quotas, a full six years after the initial WTO complaint had been filed. But China still did not lift the export quotas on unlisted materials, including raw materials for LIBs, for which a third WTO complaint was filed in 2016.[39] The 2016 WTO complaint remains unresolved, and given China's unwillingness to voluntarily end export quotas not specifically named in WTO complaints, China might repeat its WTO violations of export quotas, duties, and other restrictions.[40]

Disinformation Campaigns

In 2022, the Australian Strategic Policy Institute and Mandient tracked a network of social media accounts, dubbed DRAGONBRIDGE, that engaged in disinformation campaigns against non-Chinese rare earth companies among others.[41] The targets included Lynas Rare Earths (including CEO Amanda Lacaze), USA Rare Earth, Appia Rare Earths & Uranium, and Oklahoma governor Kevin Stitt who publicly called for breaking U.S. reliance on Chinese REE suppliers. The Lynas campaign posed as Texas residents in an attempt to stir protests against Lynas' planned REE processing plant in Texas. The campaigns against USA Rare Earth and Appia were limited to online criticism over the environmental and health impacts of REE mining and processing. These efforts leveraged previous imagery from a 2019 protest of Lynas' Malaysian processing plant. The group had been linked to previous campaigns against the Quadrilateral Security Dialogue (QUAD; Australia, India, Japan, and the United States) and to "oppose Japanese plans to deploy missile units in southern Okinawa Prefecture."[42]

Current Activity

Motivated by the Chinese market activity outlined above, efforts are underway to rebuild a U.S. REE supply chain.[43] The Mountain Pass mine in Southern California, owned by MP Materials, is the only active domestic REE mine. The company received a $35-million award from DoD to build separation facilities to process heavy REOs.[44] It also has begun construction on a permanent magnet factory that will start deliveries in 2023, while also entering a long-term supply agreement with General Motors.[45] USA Rare Earth is working to establish a Texas-based mine that provides heavy REEs, named Round Top, and has begun to build a "mine-to-magnet" facility to include the necessary processing equipment for separating REEs from one another.[46] In Utah, Energy Fuels is recovering REE carbonate from monazite, a waste product of heavy mineral sands production in the United States (Georgia), Australia, and elsewhere, and sending the material to Neo Performance Materials in Estonia—the only commercial producer of separated REOs in Europe. This development is important because monazite is also a by-product of zircon and titanium production, which potentially opens a large, alternative source for REEs. The facility in Estonia also separates materials from Russian suppliers.[47] Other potential locations for REE mining projects in the United States include mines in Alaska and Wyoming.[48] REE extraction and processing facilities have large industrial footprints, are costly ($500 million to $1 billion), are slow to become operational (13–19 years),[49] must abide by rigorous environmental laws and regulations,[50] and require a skilled workforce in a declining profession. Rebuilding the U.S. REE supply chain will be a long, expensive process.

Currently, the only major REO processing plant outside China is in Malaysia and operated by Lynas Rare Earths, an Australian mining company that extracts heavy and light REE-containing deposits. However, the Malaysian plant processes mainly light REEs and continues to send material to China for separation.[51] DoD awarded a DPA Title III technology investment agreement to Lynas in the amount of $30.4 million to aid Lynas in establishing a domestic processing capability for light REEs.[52] Lynas was awarded an additional $120 million to develop a heavy REO separation facility in Texas—the target of the Chinese disinformation campaign noted earlier in this report.[53] The domestic Lynas facilities are targeted to become operational in 2025. Should the heavy REO separation facility become operational, it will be one of very few such facilities outside China. Smaller quantities of mining and processing capacity are also located in France, India, Japan, Kazakhstan, Myanmar, Thailand, and Vietnam.[54]

In 2022, DoD announced plans to increase its REO, lithium, and cobalt stockpiles.[55] Given the long lead times required to develop the needed capacity, DoE is pursuing nontraditional sources of REEs, such as recycling and waste streams, but these efforts are years to a decade away (or longer) from implementation.[56]

Since 2010, over 150 bills have been introduced to either the U.S. House of Representatives or the Senate that have included provisions related to REEs. These bills have sought to introduce tax credits, tax deductions, funding for mining and processing capacity, funding for research and technology, research into global market practices of foreign governments, and more.

Future Demand

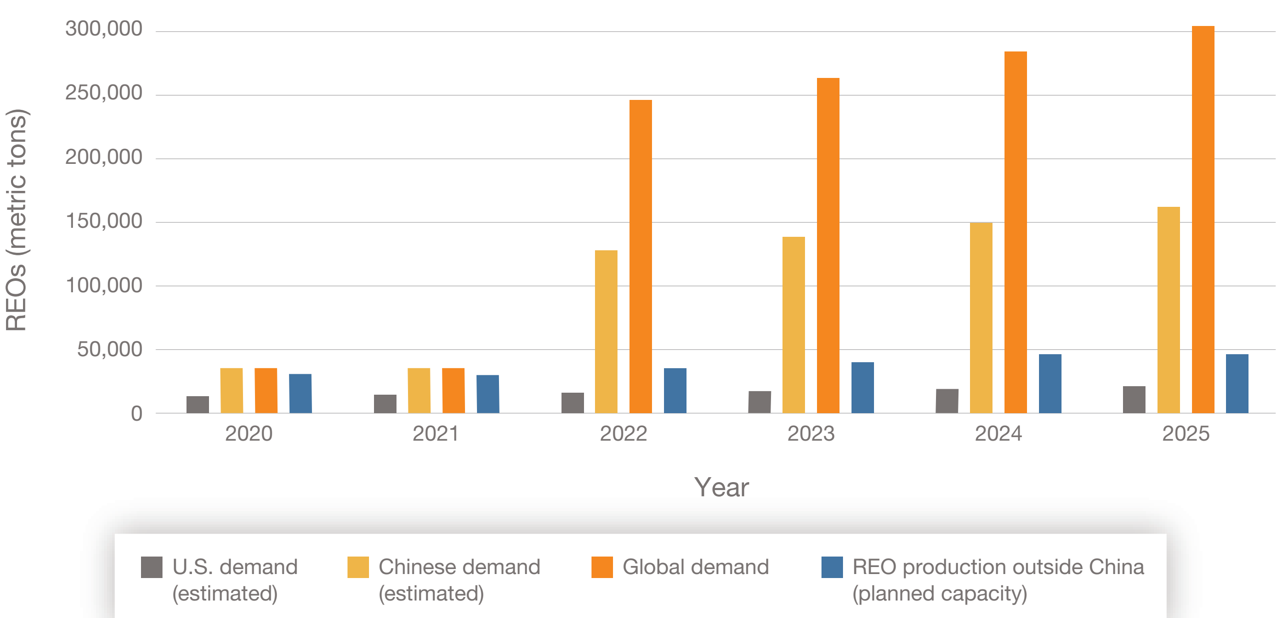
Given current trends, the global demand for REOs is expected to increase by about 100,000 metric tons (46 percent) by 2025 (see Figure 3). China consumes over half of all REOs and is expected to maintain that level of demand to 2025. U.S. demand for REOs is considerably smaller, only about 7 percent of global demand. Future non-Chinese REO processing capacity projected to be online by 2025 is about 47,000 tons per year, or 15 percent of the expected 2025 global demand. Projected REO demand outside China in 2025 is about 140,000 tons.

Plans for future processing capacity will not support demand outside China in 2025. Beyond 2025, projected yields for processing projects outside China are about 134,000 metric tons (almost three times the existing non-Chinese processing capacity in 2022) *if and only if* all planned projects reach fruition.

This still is not enough to completely meet demand outside China, even without considering any growth in demand past 2025.

FIGURE 3

Current and Projected Global Demand and REO Processing Outside China



SOURCES: Features information from Ilankoon et al., "Constraints to Rare Earth Elements Supply Diversification." Chinese processing data are based on estimates from Research and Markets, *Investigation Report on the Chinese Rare Earth Market 2021–2025*. U.S. data are derived from USGS, *Mineral Commodity Summaries 2022*.

NOTE: The year refers to the initiation of an activity. This figure assumes a roughly linear demand increase between 2020 and 2025 for all demand and that U.S. market share is maintained.

A Potential REE Supply Chain Disruption Scenario

History of the Threat

China has a history of using economic coercion to influence the geopolitical decisionmaking of other nations. However, China's economic coercion is usually accomplished by restricting access to domestic markets,[57] the lone exception being the threat of REO export restrictions to Japan in 2010.[58] An incident between a Chinese fishing vessel and the Japanese Coast Guard motivated China to threaten to cease REO exports to Japan, resulting in price increases for four years afterward. More recently, various Chinese entities have released materials with similarly veiled threats; see Figure 2 and its discussion).[59] On May 21, 2019, "Xi Jinping visited a rare earths magnet-maker in Ganzhou, southeastern Jiangxi province, rattling global markets . . . a few days later, China's powerful state planning body threatened to use rare earth exports as leverage in the trade war with the US."[60]

In October 2020, China's Ministry of Industry and Information Technology "proposed draft controls on the production and export" of REO to U.S. defense companies supplying arms to Taiwan, such as Lockheed Martin, Boeing, and Raytheon.[61]

While recent activity in the global REO market is aimed at increasing mining and processing capacity outside China, they do not close the gap. Hence, China still has a window of opportunity to wield such an economic weapon should it care to influence geopolitical decisionmaking abroad. This puts the United States and its allies and partners at risk, making this a critical time.

Nature of the Threat and Scale of Impact

If China chose to impose stricter export quotas or outright deny exports altogether, it could effectively cut off 40 to 50 percent of global REO supply, which would affect primes and suppliers of advanced components for DoD systems and platforms (see Figure 3). Disruption could also be executed without export controls via regulatory mechanisms (e.g., enforcement of environmental or technical standards), thereby avoiding any additional WTO complaint filings. In such a scenario, Chinese SOEs would likely prioritize long-term contracts with domestic firms over those with foreign firms.[62] An environmental crackdown on illegal REE mining in China occurred in summer 2017 on a smaller scale than the suggested scenario, which more than doubled prices, and prices have remained elevated since.[63]

However, a global export ban is not a likely scenario.[64] The resulting disruption would have significant effects on prices in the global market, punishing countries that had no role in such a provocation, just as it did when China first threatened to restrict REO exports to Japan in 2010.[65] The sustainability of a global disruption is also low. Any hopes of recuperating lost revenue from foreign customers by capturing those sales would likely result in Chinese firms being unable to scale up their REO-component (e.g., magnet) manufacturing facilities in an effective time frame. Instead, a targeted disruption aimed at the United States and its allies and partners (such as QUAD member nations) is more likely; however, this scenario would likely result in WTO complaint filings.

China still has a window of opportunity to wield such an economic weapon should it care to influence geopolitical decisionmaking abroad. This puts the United States and its allies and partners at risk.

Because Chinese SOEs enjoy a dominant market share of world NdFeB magnet production, similar disruptions could be inflicted further downstream in the supply chain and possibly to greater effect.

Although our work took place before the previously mentioned disinformation campaigns began, we must consider that Chinese threats of disruption have now been accompanied by efforts to block or delay the establishment of competing REE mines and processing capacity. Chinese information operations are now a reality for the U.S. REE supply chain and might be expected in the future for similarly consolidated critical material supply chains that align with China's strategic interests.[66]

Potential Risks of an REE Supply Chain Disruption

The ongoing COVID-19 pandemic and Russian invasion of Ukraine has highlighted the vulnerabilities of supply chains that lack diversity and depend on foreign inputs; this led us to assess the continuing risks associated with a REO supply chain disruption. Because of the limited project scope and resourcing, a quantitative supply chain risk assessment was not possible; however, we conducted a qualitative assessment of the potential risk from a disruption scenario (i.e., a 40- to 50-percent reduction of REO exports from China). Drawing from our workshop with subject-matter experts, we generated a list of hazards to illustrate the potential range of impacts of a potential disruption scenario.[67] Table 1 lists the potential

TABLE 1

Potential Hazards of an REE Supply Chain Disruption

Potential Hazard	Consequence	Competition	Industrial Readiness	Operational	Examples of Red Flags
REO domestic and partner nation customers are unable to receive REO inputs	REO-dependent components become unavailable to DoD customers, primes, suppliers, etc.	X	X	—	PRC issues warnings in state-controlled media
REO domestic and partner nation customers receive only limited REO inputs	REO-dependent components become unavailable to DoD customers, primes, suppliers, etc.	X	X	—	PRC issues warnings in state-controlled media
REO prices skyrocket	REOs become too expensive for some customers; program cost overruns	X	X	—	Exports from PRC begin to decrease
DoD critical or sole suppliers go out of business	REO-dependent components become permanently unavailable to DoD customers, primes, suppliers, etc.	—	X	X	Domestic companies show financial vulnerability
DoD critical or sole suppliers are acquired by a Chinese SOE	U.S. and its allies' foreign dependence increases	—	X	X	Domestic companies show financial vulnerability
Spare REO components are out of stock during conflict	DoD unable to deliver needed capabilities during conflict	—	X	X	Conflict with China or China-backed regime
Capability with an urgent operational need is unable to receive REO components[a]	DoD unable to deliver needed capabilities during conflict	—	X	X	Conflict with China or China-backed regime

NOTE: This table is not meant to be an exhaustive list. Hazards may affect DoD at multiple levels depending on the context of a disruption. The impacts of these hazards were grouped into three categories: hazards that would (1) restrict the broader U.S. economy's access to REOs (competition); (2) restrict the DIB's ability to deliver needed capabilities (industrial readiness); and (3) restrict the DoD's ability to operate during a conflict (operational). PRC = People's Republic of China (i.e., China).

[a] An urgent operational need is defined as "[c]apability requirements identified as impacting an ongoing or anticipated contingency operation. If left unfulfilled, urgent operational needs result in capability gaps potentially resulting in loss of life or critical mission failure" (Defense Acquisition University, "Types of Urgent Operational Needs [UONs])."

vulnerabilities, should REOs, or similar strategic materials, be cut off from U.S. primes and component suppliers. This list is not intended to be exhaustive but rather suggests areas for future research.

We found that hazards from a supply disruption could affect DoD at the competition, industrial readiness, and operational levels. Consequences at the operational level would likely require several (un)fortuitous events to coincide. For example, a spare component that depends on REOs (e.g., an electric motor) could be out of stock during a disruption. In this case, disruption could cause a platform or weapon system to be sidelined during a conflict. This results from one hazard (DIB unable to receive REO inputs) compounding on another (spares out of stock). Another set of coincidental events might include China using intelligence to selectively deny material to a supplier during conflict, but this would require considerable coordination and technical knowledge.

Hazards with consequences at the competition or industrial readiness levels are probably less likely to depend on compounding events and, instead, are likely more dependent on first-order effects such as lacking direct access to material inputs. Defense suppliers that deliver components dependent on REOs are constrained by two factors: (1) the *time to survive* (i.e., time left until a company is at risk of bankruptcy) and (2) the *time to recover* (i.e., the time needed to find alternative sources of supply and resume operations which, ideally, is less than the time to survive).[68] Should a disruption last longer than a company's time to survive, the likelihood of losing that supplier increases. This is illustrated by the swath of small businesses that closed during the COVID-19 pandemic.[69] Should domestic firms cease production, DoD would need to find and validate alternative suppliers, which might be exceedingly difficult in a deliberate scenario. Companies with poor financial standing during a disruption are likely to be vulnerable to bankruptcy or acquisition by Chinese firms, regardless of whether the disruption was deliberate or not. More research is needed to quantify the risk of critical material supply chain disruptions.

The timing of such a disruption scenario is uncertain,[70] and prediction is a fruitless endeavor. But as new mining, processing, and REO component production opens outside China (such as the planned capacity shown in Figure 3), the jolt of a deliberate supply disruption lessens. Still, as stated earlier, future planned production and processing of REOs outside China is not enough to support demand. And lessening influence on global market prices could possibly impel China to execute a disruption of critical materials—a "use it before you lose it" approach.

Plausible Alternative Scenarios

As previously stated, a deliberate global supply disruption is unlikely. However, several alternative scenarios are more likely and could generate similar consequences, including

- China takes environmental damage seriously and enforces new regulations.
- An industrial accident disables a major Chinese supplier, followed by regulatory crackdowns.
- China implements a deliberate, but limited, disruption to the U.S. or to its allies and partners without triggering WTO ramifications.

Implications for a LIB Disruption Scenario

Findings from our analysis of the REE supply chain can help support analysis and development of other critical material supply chains. The LIB supply chain shares several similarities with the REO supply chain in that Chinese firms exercise control over much of the processing capacity for lithium. Although the graphite supply chain most closely resembles the REO supply chain, in that 70 percent of flake graphite extraction and nearly 100 percent of spherical graphite production are sourced from China (in addition to processing capacity), where they differ is in the location of lithium, cobalt, copper, and nickel deposits and China's share of their extraction. For example, much of the global lithium ore is extracted from Australia, while reserves of salt brines are largely located in South American countries such as Chile and Argentina with large resources located in Bolivia.[71] China has its own reserves of salt brines to use as feedstock for its processing plants, but it imports lithium carbonate and lithium hydroxide, mostly from South America where Chinese companies have signed long-term supply contracts with South American producers and have bought shares in these companies.[72] With these investments, China aims to secure access to raw material feedstock for its downstream production capacity.

Like the processing of REOs, the processing of LIB raw materials is largely controlled by Chinese companies.[73] Thus, these supply chains share similar vulnerabilities to a disruption scenario at the processing phase, and foreign consumers of LIB raw materials, such as Japan, South Korea, and the United States, are at risk. Battery companies also face time constraints like those described in the REO supply chain disruption scenario. We also found that the nature and scale of the disruption threat for LIB materials is similar to that for REOs. Our workshop participants highlighted the fact that the amount of REO supply that China could effectively remove from the global market was equivalent to its market share. This implies that the scale of disruption to other materials, such as those processed for LIBs, is proportional to Chinese market share of that material. In such a scenario, Chinese SOEs are also likely to prioritize domestic firms over foreign firms, but a long-term export ban would likely not be sustainable.

We found that, in general, the REO supply chain risks also likely would apply to other strategic materials with global processing capacity centralized in China. Critical materials whose extraction is largely controlled by Chinese firms (such as graphite) are at higher risk, because the supply chain for these materials more closely resembles the REO supply chain. Likewise, production of components dependent upon these strategic materials that make up China's large market share (LIB cathodes, anodes, and cells) place the component/subcomponent sector at similar risk. Supply chains dominated by China in all three phases (excluding integration into systems or platforms) are at highest risk. For lithium and cobalt (and to a lesser extent copper and nickel), the processing and the component/subcomponent manufacturing sectors are at risk, while graphite is at risk in all three sectors.

Although Chinese officials and outlets have not made any explicit threats of disrupting LIB supply chains, China remains committed to capturing market share of new energy vehicles as part of their Made in China 2025 initiative. The execution of information operations in the REE supply chain is also worrisome for other critical materials.

In response to supply chain constraints, diversification would likely be the best means of mitigating risk of disruption. As we noted earlier in this report, proactive policies—such as the mapping of resources, stockpiling, and investment in domestic capacity for extraction, processing, and component/subcomponent manufacturing—have already been enacted to maintain access to these materials at fair market prices.

Expert Insights into Risk Mitigation and Policy Options

To better assess the policy options available to DoD in the event of a critical material supply chain disruption, we conducted a workshop using a "Day After . . ." exercise to identify policy options for "risk mitigation and resolution in contentious strategy and policy environments."[74] The exercise had four participants with backgrounds in economics; the Chinese DIB, military, and economic policy; and critical materials policy. We then synthesized the participants' suggestions with research conducted prior to the workshop.

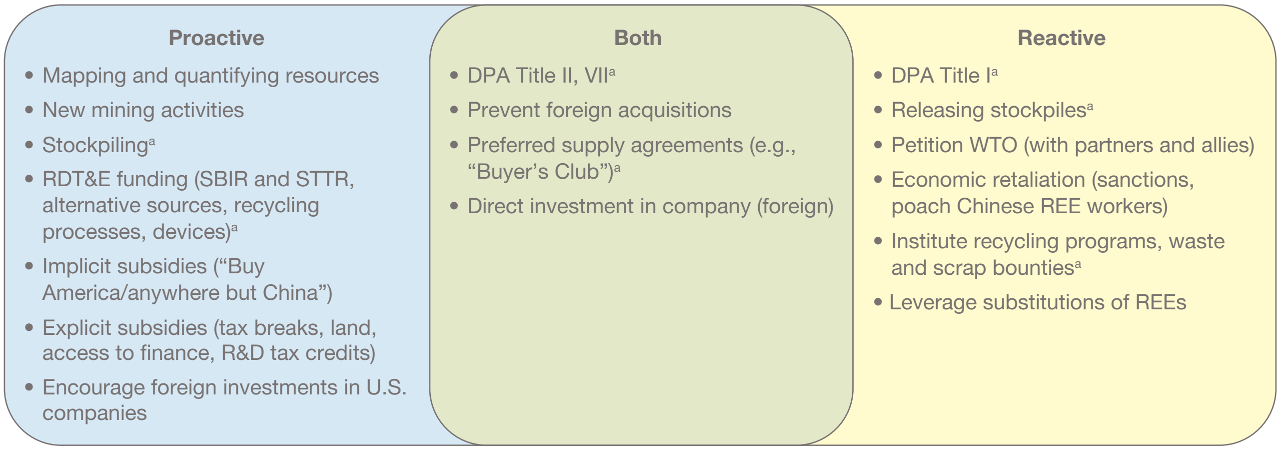
Policy Options in the Interim

The "Day After . . ." exercise yielded two classes of policy options in the face of a disruption scenario—reactive and proactive—with several actions applicable to both. Figure 4 presents these policy actions; Appendix A presents an annotated list with descriptions, action owners, and approximate time to impact for each policy. In a reactive stance, the United States would wait until a scenario presents itself, essentially leaving the market to govern itself. In a proactive stance, the United States would nudge the market toward a more diversified (i.e., more resilient) economic position before a disruption scenario occurs.

Through this exercise, we found that DoD has limited options to act unilaterally and an appropriate response to a disruption scenario would most

FIGURE 4

Identified Proactive and Reactive Policy Options



NOTE: This figure is for illustrative purposes only. A complete list of the policies and actions to prevent or mitigate the effects of disruption is presented in Appendix A. R&D = research and development; RDT&E = research, development, test, and evaluation; SBIR = Small Business Innovative Research; STTR = Small Business Technology Transfer.

[a] Option available to DoD.

likely require a whole-of-government approach. This is because even though some policies are owned by DoD, they need executive approval (e.g., DPA). Other policy options are *only* available to agencies outside of DoD, for example, the U.S. Treasury Department (e.g., CFIUS, WTO petitions), U.S. Department of the Interior (e.g., geological surveys), the executive branch (e.g., sanctions), and Congress (e.g., sanctions, subsidies).

However, not every policy option is created equal. Each policy is unique in the time needed for it to take effect, or its *time to impact*. A policy's time to impact determines whether the policy can be effective in a reactive posture, i.e., after disruption has taken place. If developing a mine takes a decade or longer and the DIB's time to survive is less than a year, it would not make sense to focus efforts on developing new production. Likewise, if processing capacity takes years to expand, the action will not adequately support the DIB within the needed time frame. Alternatively, if an option such as releasing stockpiles takes a few weeks, that is a viable policy. Although it is unknown if or when a disruption scenario will take place, it would be prudent to take a proactive stance by implementing the policies that take the longest well before a disruption occurs; the DoD's investments in the domestic REO supply chain and the executive and legislative branches' policy actions in the LIB supply chain mirror this proactive stance. Some policy options could work to increase the DIB's time to survive or decrease the time to recover and thereby increase the number of viable reactive policies with an appropriate time to impact.

Finally, our workshop participants noted that the type of reactive policy option needed may differ depending on the root cause of the disruption. For example, if the root cause was not deliberately malevolent, it would make no sense to sanction the nation where the disruption originated.

Past Use of Policy Options

Among proactive policies used by DoD in the past, some progress has been made with respect to their advocacy and adoption, but gaps remain. These include stockpiling and use of DPA Title III and RDT&E funding. The quantity of stockpiled REO material is uncertain; however, DoD has made plans to stockpile several metric tons of REEs and rare earth magnet blocks in fiscal year 2022.[75] As stated earlier, DoD awarded a DPA Title III technology investment agreement to Lynas Rare Earths to aid in establishing a domestic processing capability.[76]

However, the ongoing COVID-19 pandemic has delayed this effort. Various RDT&E efforts are underway to support alternative sourcing of REOs and recycling of components that use REOs.[77] Generally, less-effective substitutes for REOs are available if spare rare earth components are in demand; however, they may affect component and platform performance and, hence, the availability of a capability.

Two reactive policies have been used previously—one effective but lengthy, the other ineffective. As shown earlier, the WTO process effectively required three years to remove Chinese export quotas on REOs, while the use of CFIUS to control the offshoring of rare earth magnet technology failed to retain U.S. production capacity.

Cooperation between the United States and other nations is underway, especially in Australia, Canada, and Europe, as U.S. allies and partners move to reduce their dependence on China as well, but these actions are only just beginning to have results.

Future Considerations for Policy Options

We identified several factors worth considering when developing proactive or reactive policy. Reactive and proactive policy options for critical materials should be applicable across materials, i.e., policy options to reduce supply chain risk in REOs can be applicable to LIB materials but should be tailored accordingly, depending on the geographic location of raw materials and processing capacity. For example, stockpiling rare earth magnets is useful when the U.S. production capacity for these components is nonexistent and when the U.S. DIB can leverage those stockpiled components; however, stockpiling REOs would not be as useful in a supply disruption because, currently, these stocks would have to be exported (most likely to China or Japan) before they could be used as feedstock for magnet production.[78] Similarly, stockpiling materials such as lithium-metal oxides or anode and cathode sheets could serve as feedstock for domestic LIB manufacturers, but stockpiling lithium carbonate equivalents or metal sulfates may be less useful because there is less processing capacity to turn these feedstock chemicals into battery grade lithium-metal oxides. As efforts to strengthen the resiliency of the critical material supply chains take effect, policies such as stockpiling should be adjusted to account for the new industrial environment, capability, and capacity.

We also found a potential need for a reactive cross-agency working group to plan for disruption scenarios because of the interdependence of DoD options on other branches of government and deficiencies in reactive policies implemented thus far. Such cross-agency collaborations are already underway for proactive policies with USGS, DoE, and other agencies; collaborating on reactive policies is a logical step forward. Such an effort might include

- planning for coordinated reactive actions, such as WTO complaint filings, sanctions, or other economics measures
- supporting proactive actions to mitigate hazards to externalities, such as consumer groups and domestic and foreign industry;[79] and U.S. allies, partners, and international agreement participants.

What Should Be the Aim of Policy Options?

The White House's 100-day supply chain report includes several recommendations to strengthen responsibly sourced supplies for key minerals; we will not reproduce those recommendations here. Instead, we highlight the aims of policies that would best prevent or mitigate effects of a disruption.

Diversifying the supply chain is paramount. The point in the supply chain on which to focus efforts varies from material to material, but whether using incentives to build domestic capacity or investing in allies, partners, and neutral parties, the primary aim of proactive policies should be to divert market share from China's SOEs and private industry. Efforts should also aim to co-locate the upstream and downstream sectors to better use industrial efficiencies.

Reactive policies should aim to reduce the DIB's time to recover and increase its time to survive. This is likely to require DoD to leverage support from agencies outside the department and from industry.

Both proactive and reactive policy options with the longest time to impact should be implemented sooner rather than later to realize benefits. Policies, planning, and coordination should also aim to reduce the time to impact for proactive and reactive policies. Finally, both proactive and reactive policies should leverage U.S. ally and partner capabilities, or build relationships with neutral countries, wherever possible. Working with nontraditional partners will be necessary as these countries have geographic access to critical materials and extraction capacity that the U.S. and its allies and partners do not.

What Other Policy Options Make Sense?

Additional policy options exist, ranging from forming new partnerships to monitoring critical material markets. Additional policy options could include expanding domestic mining of sources not currently being fully used but showing potential for further development, e.g., Alaska's REO deposits. Expanding the definition of *domestic sources* to include more U.S. allies and partners could also alleviate some of the difficulty companies have while trying to responsibly source their inputs to stay in compliance with DoD policies.

Preferred supply agreements with U.S. allies and partners (e.g., Japan, South Korea, Australia, Finland, Estonia) are an opportunity to align critical material strategies. Encouraging the development of new mining activities or processing capacity in new countries (e.g., Indonesia, India, Chile, Argentina, Bolivia, Vietnam, the Philippines, Brazil, Cuba, Papua New Guinea, Madagascar, and Mozambique) would help diversify the upstream supply chain as well.

Increasing domestic demand could be hastened if DoD would procure products that rely on REO-dependent components and LIBs. These products could include EVs, autonomous systems, munitions, satellites, and more, and could also include increasing the number of spares procured. Increased demand and increasing the number of development projects for these materials and components has the added benefit of increasing the likelihood of retaining a proficient engineering workforce.

Stockpiling should take a flexible posture to react to the efforts to build up domestic capacity and fill needed gaps. For example, as more capacity for battery-active materials, anodes, and cathodes comes online, DLA could switch to stockpiling chemicals such as lithium carbonate, lithium hydroxide, and metal sulfates, which are further upstream in the supply chain. This would allow recipients to procure only those precursor materials needed to produce active materials instead of being limited to the active material currently stockpiled, but this would require close and constant monitoring of the domestic market for red flags of hazards.

Finally, Chinese disinformation campaigns should be expected in other critical material supply chains. The extraction sector should work with cybersecurity experts and the U.S. intelligence community to educate their executives and local governments about risks. Businesses should communicate their plans—and any influence operations underway—to local communities to build trust and situational awareness for residents and officials. The intelligence community should educate policymakers, U.S. allies and partners, and the public about the extent of Chinese interference in critical material supply chains.

China's control over critical material supply chains allows it to use threats of economic coercion to influence policymakers around the globe. While foreign dependencies may limit decisionmakers' ability to respond to geopolitical actions, it does not prevent them from investing to diversify supply chains and reduce the risk of supply disruption. However, the successful implementation of policy actions depends on timing: the DIB's time to survive and time to recover, the policy action's time to impact, and the time needed to close the production-demand gap. The United States is in a position to cultivate proactive polices to mitigate risks of supply chain disruption before it occurs and develop reactive policies to navigate uncertainties after the fact. But policies take time to implement. If history has taught us anything, it has taught us that, in a quickly evolving technological world, timing is critical, and the time to act is now.

Appendix A: Policies or Actions to Prevent or Mitigate Effects of Supply Chain Disruptions

In Table A.1, we list the policies examined in this study to prevent or mitigate the effects of supply chain disruptions. For each policy option we list (1) a brief description; (2) which U.S. government entity is responsible for authorizing or conducting the option; (3) whether or not that entity operates under DoD and, thus, is an available option for DoD; (4) whether the option is proactive, reactive, or both; and (5) its time to impact. We define *time to impact* as an estimated time for the policy option to affect a supply chain, including the estimated time needed to execute the policy. These estimated times are based on our interviews with subject-matter experts.

TABLE A.1

Policies or Actions to Prevent or Mitigate Effects of Supply Chain Disruptions

Policy or Action	Description	Policy Owner(s)	Available to DoD	Proactive	Both	Reactive	Time to Impact
Mapping and quantifying resources	Search for and quantify additional mineral resources within U.S. and territories to identify reserves	USGS	—	X	—	—	Years to > 1 decade
New mining activities	Support development of reserves and construction of mines	USGS, private sector	—	X	—	—	> 1 decade
Stockpiling	Procure quantity of critical materials and hold for later use	DLA	X	X	—	—	Weeks to years
Stockpile release	Release materials or components when needed	DLA	X	—	—	X	Weeks to months
Preferred supply agreements	Work with allies and partners to establish trade agreements on preferred suppliers	Executive, DLA, DoS	X	—	X	—	Months to years
Economic retaliation	Enact sanctions and other policies aimed at deterring the continuation of disruption (e.g., design policies to poach knowledgeable personnel)	Executive, Federal legislature	—	—	—	X	Weeks to months
Implicit subsidies	Provide subsidies that preference sourcing materials outside China	Federal and state legislatures	—	X	—	—	Months to years
Explicit subsidies	Provide tax breaks, access to land, finance, and R&D tax credits	Federal and state legislatures	—	X	—	—	Months to years
Encourage foreign Investment	Incentivize foreign investment to increase domestic capability and capacity	Federal and state legislatures, DoD	X	X	—	—	Years
Prevent foreign acquisitions	Intervene in foreign acquisitions of U.S.-based companies to prevent transition of technology or production capabilities outside the U.S.	CFIUS	—	—	X	—	Weeks to months
Direct investment in company (foreign)	Provide loans, loan guarantees, equity, and insurance for foreign private sector–led development projects	DFC, USAID	—	—	X	—	Months to years

Table A.1—Continued

Policy or Action	Description	Policy Owner(s)	Available to DoD	Proactive	Both	Reactive	Time to Impact
Defense Production Act Title I	Use grants, loans, loan guarantees to purchase material, services, and facilities from U.S. companies	Executive, multiple federal agencies (e.g., DoD, DHS, DoE, FEMA, DoC)	X[a]	—	—	X	< Weeks
DPA Title III	Use grants, loans, loan guarantees for direct investment in domestic companies to support production capacity	Executive, multiple federal agencies (e.g., DoD, DHS, DoE, FEMA, DoC)	X[a]	—	X	—	Months to years
DPA Title VII	Use grants, loans, loan guarantees to coordinate private industry	Executive, multiple federal agencies (e.g., DoD, DHS, DoE, FEMA, DoC)	X[a]	—	X	—	Weeks to months
WTO petitions (with partners and allies)	Lobby WTO to induce compliance by defaulting country or collect countermeasures, such as obligations (fees)	Executive	—	—	—	X	Years to 1 decade
Waste and scrap recycling	Support organizations and efforts to set up recycling of components and scrap composed of critical materials	DoE, private sector, DLA	X	—	—	X	Months to years
Material or component substitutions	Use alternative materials or components to provide platforms and weapon systems with similar levels of performance (may or may not be feasible)	Private sector	—	—	—	X	Months
RDT&E funding for alternative sources, processes, and devices	Support fundamental research in academia and agencies (e.g., SBIR and STTR, alternative sources, substitutes, recycling processes, prototyping)	Various federal agencies (e.g., DoD, DoE, DARPA)	X	X	—	—	Unknown

NOTE: DARPA = Defense Advanced Research Projects Agency; DFC = U.S. International Development Finance Corporation; DHS = U.S. Department of Homeland Security; DoC = U.S. Department of Commerce; DoS = U.S. Department of State; FEMA = Federal Emergency Management Agency; USAID = U.S. Agency for International Development.

[a] Policy is available to DoD but requires executive approval.

Appendix B: Organizations Interviewed

We conducted structured interviews with different groups of various stakeholders between June 2021 and January 2022 from the following organizations:

- Ames National Laboratory
- Benchmark Minerals Intelligence
- Critical Materials Institute-Colorado School of Mines
- Defense Logistics Agency-Strategic Materials
- Defense Production Act Office
- Department of Energy
- Piedmont Lithium
- National Energy Technology Laboratory
- Redwood Materials
- University of Pennsylvania.

The interviews took place primarily over the phone or via email. The interviews were not for attribution, so no names are provided. We asked questions about the state of REE and LIB supply chains, risk and consequences of a disruption, and potential policies available to mitigate the risk.

Notes

1 We conducted structured interviews with different groups between June 2021 and January 2022. These interviews took place primarily over the phone or via email. The interviews were not for attribution, so no names are provided. We asked questions centered around the state of REE and LIB supply chains, risk and consequences of a disruption, and potential policies available to mitigate the risk.

2 The "Day After . . ." method, developed by RAND, provides participants with the opportunity to discuss reactive measures the day after an undesirable event, followed by a discussion of possible proactive measures to prevent the event from happening or mitigate its effects.

3 Kim et al., *The Role of Critical Minerals in Clean Energy Transitions*.

4 Lee and Bazilian, "The US Is Worried About Its Critical Minerals Supply Chains—Essential for Electric Vehicles, Wind Power and the Nation's Defense."

5 "[D]ependency of the United States on foreign sources creates a strategic vulnerability for both its economy and military to adverse foreign government action, natural disaster, and other events that can disrupt supply of these key minerals" (Executive Order 13817, "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals").

6 The 2018 National Defense Strategy includes in its strategic approach to "expand the competitive space" the line of effort to "build a more lethal force." Under this line of effort is an emphasis to "prioritize preparedness for war" and "modernize key capabilities." See DoD, *Summary of the 2018 National Defense Strategy of the United States: Sharpening the American Military's Competitive Edge*.

7 In July 2022, U.S. Energy Secretary Jennifer Granholm said the U.S. government "is concerned that supplies of critical minerals . . . could be subject to weaponisation as oil and gas have been amid the Ukraine conflict" (Paul, "U.S. Says It Is Concerned Critical Minerals Vulnerable to Manipulation").

8 Liang Quan [梁泉], "Deng Xiaoping Southern Tour: 'China Has Oil, China Has Rare Earth'" ["邓小平南巡时指出：'中东有石油，中国有稀土中广网'"].

9 Onstad, "Europe Urged to Launch Fund to Spur Rare Earth Magnet Output."

10 EU, "Communication from the Commission: A New Industrial Strategy for Europe."

11 ERMA, "Ensuring Access to the Raw Materials for the European Green Deal."

12 White House, "Executive Order on America's Supply Chains"; White House, "Fact Sheet: Securing a Made in America Supply Chain for Critical Minerals."

13 White House, "Memorandum on Presidential Determination Pursuant to Section 303 of the Defense Production Act of 1950, as Amended"; Bertuca, "DOD Makes Rare Earth Award."

14 EVs use six times more minerals in their production than gas-powered vehicles (Kim et al., *The Role of Critical Minerals in*

Clean Energy Transitions, p. 89; "Lithium Needs a Rio Tinto to Get to 2.2m Tonnes Demand by 2030."

15 For reference, the U.S. EV market alone is projected to reach $50 billion by 2025, making DoD's share of demand for LIBs less than one-half a percent. See White House, *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth: 100-Day Reviews Under Executive Order 14017*, p. 90.

16 White House, *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth: 100-Day Reviews Under Executive Order 14017*, p. 115.

17 These deposits include lithium brines (South America) and ore (Australia) along with nickel (Indonesia) and cobalt (Democratic Republic of Congo) ores. However, China controls 79 percent of graphite production; graphite comprises approximately a third of each LIB. See U.S. Geological Survey (USGS), *Mineral Commodity Summaries 2022*.

18 Kim et al., *The Role of Critical Minerals in Clean Energy Transitions*, p. 13.

19 Spherical graphite is processed natural graphite that is mined, of which China controls about 79 percent of global extraction. See USGS, *Mineral Commodity Summaries 2022*. The share of battery anodes using spherical graphite is about 35 percent, and synthetic graphite makes up about 60 percent. Most anodes use a blend of both. See Miller, "Graphite Special Report."

20 As of 2018. See Northern Graphite Corporation, "Visualizing the Graphite Supply Problem."

21 Chung, Elgqvist, and Santhanagopalan, *Automotive Lithium-Ion Battery (LIB) Supply Chain and U.S. Competitiveness Considerations*.

22 Moores, Simon [@sdmoores], "China's foresight and investment = EV supply chain domination . . ."; White House, *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth: 100-Day Reviews Under Executive Order 14017*, p. 117.

23 In response to Chinese market share, sizeable funding has been allocated by the U.S. government to help develop a domestic LIB supply chain: The Bipartisan Infrastructure Bill allocates $3.16 billion to develop manufacturing facilities, technology demonstrations, and battery recycling. The U.S. Department of Energy (DoE) has also committed $60 million of the bill's funding to research second-life applications of EV battery packs and pack recycling. See DoE, "Biden Administration Announces $3.16 Billion from Bipartisan Infrastructure Law to Boost Domestic Battery Manufacturing and Supply Chains."

24 Wübbeke, "Rare Earth Elements in China: Policies and Narratives of Reinventing an Industry."

25 A *mineral resource* is an estimate of the total amount of that mineral in the earth's crust whereas a *reserve* is the portion of that resource that is capable of being economically mined at present.

26 USGS, *Mineral Commodity Summaries 2022*.

27 White House, *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth: 100-Day Reviews Under Executive Order 14017*.

28 Light REEs consist of scandium, lanthanum, cerium, neodymium, promethium, and samarium. Heavy REEs consist of europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, and yttrium. Samarium, europium, and gadolinium are sometimes referred to as *medium rare earth elements*.

29 Executive Order 13953, "Addressing the Threat to the Domestic Supply Chain from Reliance on Critical Minerals from Foreign Adversaries and Supporting the Domestic Mining and Processing Industries."

30 Montague, "U.S. Companies Vie for Funds in Race to Build Rare Earths Industry."

31 Su, "The Hidden Costs of China's Rare-Earth Trade."

32 Heavy REEs are also relied on for phosphors used in light-emitting diodes, night vision, and similar displays.

33 Smith et al., *Rare Earth Permanent Magnets: Supply Chain Deep Dive Assessment*.

34 U.S. Government Accountability Office, *Rare Earth Materials: Developing a Comprehensive Approach Could Help DOD Better Manage National Security Risks in the Supply Chain*.

35 Argus Consulting Services, "Argus Rare Earths Monthly Outlook."

36 Zhou and Brooke, "China Merges Three Rare Earths State-Owned Entities to Increase Pricing Power and Efficiency."

37 See CFIUS, "USW's Gerard Calls for Moratorium on CFIUS Approvals, Comprehensive Review of Process; Letter to President Bush Cites Ports Controversy, Transfer of Magnequench 'Smart-Bomb' Technology to China"; Wheeler, "Missile Technology Sent to China," p. 26.

38 The use of export quotas artificially restricts the quantity of materials available outside China, which increases material prices outside China. Effectively, a two-tier pricing scheme evolves, which puts domestic companies at an advantage over foreign competitors. It incentivizes foreign companies to relocate to China to take advantage of lower prices for materials or downstream components. This has been an effective method to induce technology transfer from abroad. See Wu, "China's Export Restrictions and the Limits of WTO Law." Similar quotas have been used in the LIB materials supply chain as identified by the RAND research team.

39 Wu, "China's Export Restrictions and the Limits of WTO Law."

40 Currently, vacancies on the WTO board limit the WTO process; complaints can be filed and a ruling declared, but rulings cannot be appealed.

41 See Zhang, "The CCP's Information Campaign Targeting Rare Earths and Australian Company Lynas"; Mandiant Threat Intelligence, "Pro-PRC DRAGONBRIDGE Influence Campaign Targets Rare Earths Mining Companies in Attempt to Thwart Rivalry to PRC Market Dominance."

42 Zhang, "Pro-CCP Inauthentic Social Media Accounts Shift Focus to the Quad."

43 White House, "Executive Order on America's Supply Chains."

44 DoD, "DoD Awards $35 Million to MP Materials to Build U.S. Heavy Rare Earth Separation Capacity."

45 MP Materials, "MP Materials to Build U.S. Magnet Factory, Enters Long-Term Supply Agreement with General Motors."

46 Saywell, "USA Rare Earth Outlines Mine-to-Magnet Strategy."

47 Neo Performance Materials, "Energy Fuels and Neo Performance Materials Announce Contract Signing and Launch of Commercial Shipments of Rare Earth Product to Europe in Emerging U.S.-Based Rare Earth Supply Chain."

48 "Ucore, Innovation Metals' Rare Earths Processing Plant Expected in Q1 2022"; Lasley, "Rare Earths Project Reemerges in Wyoming."

49 Eggert et al., "Rare Earths: Market Disruption, Innovation, and Global Supply Chains."

50 Sustainable and environmentally friendly refining and separation facilities are challenging because these processes produce highly toxic, radioactive waste. Concerns over radioactivity and more-stringent environmental laws nearly forced all refineries to close when low-cost, China-sourced REEs started entering the market in the 1980s and 1990s.

51 While the Lynas plant located in Kuantan, Malaysia, processes some heavy REEs (principally samarium, europium, and gadolinium oxide), "[c]urrently, the most valuable product produced at the plant is praseodymium/neodymium, NdPr" (Kozak, "The 600 Pound Gorilla in the Room, Welcome, Lynas Rare Earths").

52 Bertuca, "DOD Makes Rare Earth Award."

53 Menon and Sharma, "Australia's Lynas Gets $120 mln Pentagon Contract for U.S. Rare Earths Project."

54 Nassar and Fortier, *Methodology and Technical Input for the 2021 Review and Revision of the US Critical Minerals List.*

55 Stone, "Pentagon to Boost Rare Earths and Lithium Stockpiles–Sources."

56 Two DoE laboratories are looking into these alternative methods. The Ames Laboratory is researching the recycling of neodymium iron boron (NdFeB) magnets to extract REEs, whereas the National Energy Technology Laboratory is producing mixed REO of high purity from coal and coal-based waste. One waste stream is acid mine drainage where the outflow of water from mining operations becomes acidic because of sulfur-bearing minerals encountering the flowing water. Over time this highly acidic water leaches REEs and other heavy metals from the surrounding minerals. Although this highly corrosive water from abandoned mines threatens natural habitats, the treatment and clean-up of acid-mine drainage allows for an easier recovery of REEs and other heavy metals. See Ames Laboratory, "Resilient NdFeB magnet recycling under COVID-19 pandemic"; National Energy Technology Laboratory, "NETL-Supported REE from Coal Ash Technology Development Attracts New Support from DOD."

57 Harrell, Rosenberg, and Saravalle, *China's Use of Coercive Economic Measures.*

58 Japan is an importer of processed and separated REOs to produce REE-based magnets and other components.

59 Hornby and Sanderson, "Rare Earths: Beijing Threatens a New Front in the Trade War"; Yu and Sevastopulo, "China Targets Rare Earth Export Curbs to Hobble US Defence Industry."

60 Hornby and Sanderson, "Rare Earths: Beijing Threatens a New Front in the Trade War."

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62 Silberglitt et al., *Critical Materials: Present Danger to U.S. Manufacturing*; RAND subject-matter experts, "Day After …" exercise with the authors, 2021. (For more details, see the section in this report titled "Expert Insights into Risk Mitigation and Policy Options.")

63 Caesars Report, *Medallion Resources: The Market's Interest in Rare-Earths Finally Revived.*

64 RAND subject-matter experts, "Day After …" exercise with the authors, 2021. (For more details, see the section in this report titled "Expert Insights into Risk Mitigation and Policy Options.")

65 Following the Diaoyu-Senkaku Island dispute in 2010, REO prices increased sixfold. Prices doubled during the onset of Chinese SOE consolidation in 2017, coinciding with the U.S.-China trade war.

66 Mandiant Threat Intelligence, "Pro-PRC DRAGONBRIDGE Influence Campaign Targets Rare Earths Mining Companies in Attempt to Thwart Rivalry to PRC Market Dominance."

67 As noted earlier, we conducted structured interviews with various stakeholders across academia, industry, and government. Interview questions centered around the state of REE and LIB supply chains, risk and consequences of a disruption, and potential policies available to mitigate the risk. RAND expertise was elicited from workshop participants (described in more detail below) and the RAND research team.

68 O'Connell, *Unraveling the Gordian Knot: Considering Supply Chain Resiliency.*

69 Goldfine, "Here's Every Company That Went Bankrupt During COVID-19."

70 Three instances of threats to restrict exports of rare earth products have occurred since 2010 as shown in Figure 2. Whether or not future threats escalate to an actual disruption is hard to predict, but such threats are usually in response to undesirable actions taken by other nations. Previous threats effectively equated to saber rattling, but with the advent of information operations aimed at deterring new mining and processing capacity in the United States and Canada, it is uncertain what other gray-zone tactics could be on the table in the future. Red flags like those listed in Table 1 may be helpful in determining risk, but further analysis is needed.

71 Meng et al., "Review of Lithium Production and Recovery from Minerals, Brines, and Lithium-Ion Batteries."

[72] Chinese lithium producer Tianqi made a $4.4 billion investment in Chile's SQM (Sociedad Química y Minera), the largest producer of lithium salts in the world. This was the single largest foreign investment from a Chinese company in 2018. See Mander, "China's Latin American Ambitions on Display in Chile."

[73] Nearly 90 percent of the world's lithium hydroxide production occurs in China. See Shanghai Metals Market, "Overview of China's Exports and Imports of Lithium Carbonate and Lithium Hydroxide in 2017–2021."

[74] The "Day After . . ." exercise consisted of two sessions. The first centered around a future global disruption of REE exports from China and the policy options available to DoD. Participants were presented with a set of identified policy options; asked to add to the list, if possible; and discuss how they might prevent or mitigate the impacts of the disruption to defense and aerospace original equipment manufacturers and the U.S. economy. The second session consisted of returning to the present for a similar discussion. The objective of this process was not to reach a consensus on a particular policy strategy but to ensure that the identified policies represented a range of credible DoD options that could prevent or mitigate disruption to U.S. supply chains; participants also discussed any limitations to their implementation. For more on the "Day After . . . " exercise methodology, see Molander et al., *The Day After . . . in Jerusalem: A Strategic Planning Exercise on the Path to Achieving Peace in the Middle East*.

[75] Defense Logistics Agency-Strategic Materials, "Annual Materials Plan for FY 2022."

[76] Bertuca, "DOD Makes Rare Earth Award."

[77] See Ames Laboratory, "Resilient NdFeB Magnet Recycling Under COVID-19 Pandemic"; National Energy Technology Laboratory, "NETL-Supported REE from Coal Ash Technology Development Attracts New Support from DOD."

[78] As the domestic supply chain grows to include REE processing capacity and magnet production capacity, a reevaluation of materials useful to stockpile will likely be needed to adapt to the changes in domestic manufacturing capability.

[79] Such industry includes mining, processing, and component/subcomponent manufacturing.

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About This Report

This report presents a short, exploratory analysis summarizing the state of critical material supply chains in two case studies and policies available to the U.S. Department of Defense to increase the resilience of these supply chains in the face of disruption. We conducted a "Day After . . ." exercise with a small group of RAND Corporation subject-matter experts in which participants reviewed and added to policy options collected by the authors while postulating responses to a plausible disruption scenario to the rare earth supply chain. We assessed the rare earth elements supply chain and extracted findings applicable to the supply chains of other critical materials—in this case, materials for lithium-ion batteries. During the exercise, we identified policy options as proactive or reactive, or both, to mitigate the impacts of a potential supply chain disruption.

This report should be of interest to the mining, mineral processing, and manufacturing sectors, as well as government, private sector, and nonprofit organizations involved with or concerned about these sectors.

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