Progress on Critical Materials Resilience

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INTRODUCTION

Demand for critical materials is growing quickly, driven by the energy transition. Here we focus on just two of those critical materials: rare earth elements (REEs) and lithium. Demand for REEs, important for electric vehicles (EVs), wind turbines, smartphones, high-performance magnets, and many other commercial and national security applications, is projected to double between 2021 and 2030.[1] And demand for lithium, important for batteries for EVs and grid storage, is projected to quadruple over the same time period.[2] China now dominates the extraction and processing of REEs and the processing of lithium and other critical minerals that will play a central role in the energy transition.[3]

The purpose of this report is to document the progress that is being made in expanding the extraction and processing of critical materials in the United States and in reliable partners, and in diversifying critical material supply chains. As discussed in our first case study on REEs, in 2010 China was responsible for more than 95 percent of global extraction.[4] Expansion of extraction in Australia, the United States, and elsewhere has since reduced China's share of rare earth extraction to about 60 percent.[5] Meanwhile, US extraction of rare earths has increased from zero to about 16 percent of global supply (see table 1).

TABLE 1 SHARES OF GLOBAL EXTRACTION OF RARE EARTH ELEMENTS

	2010	2022
China	95%	60%
United States	0%	16%

Processing of REEs is still heavily concentrated in China, with about an 85 percent market share.[6] But discernible progress toward increasing diversity in processing REEs is underway as well, with facilities being constructed in California and Texas for refining REEs, where initial shipments of refined products are planned for this year.

The story is similar for lithium, the subject of our second case study. Lithium is a key component of batteries for electric vehicles and short-duration grid storage applications. China holds about a 60 percent share of lithium processing, largely because Australia (the world's largest lithium miner) has traditionally sent its ore concentrate to China for processing into battery-grade lithium compounds. The first lithium processing facility in Australia opened in 2022, and Australia aims for 10 percent of the global market in lithium battery materials by 2024 and 20 percent by 2027. Work is underway in the United States, Australia, and South America to substantially expand lithium extraction and processing and reduce the global dependence on China.

There is a long way to go, and much work to be done, to assure a sufficient and reliable supply of critical materials for the energy transition and other important commercial and national security purposes. With a typical timescale for mining and processing projects on the order of sixteen years for permitting, construction, and commissioning, there is uncertainty whether supply will align with demand. Prices are likely to continue to be volatile. But discernible progress is being made.

We examine the interplay of market forces, government policies, and technology in promoting expansion of the supply of critical materials. Market forces at work include rising prices, increased capital investment, and growing demand from users of rare earth magnets and lithium battery materials. In addition, government policies have been adopted that aim to increase the supply by domestic producers and reliable partner nations of materials critical to the US economy and national security. Technology can play an important role in reducing environmental impact (by recycling water used in processing, for example) and making extraction and refining more efficient and less wasteful. And technology can potentially provide alternatives to critical materials for certain applications, opening up alternative paths to achieving energy transition goals. We identify evidence that market forces, government policy, and technology are beginning to have the desired effect of increasing supply and reducing dependence on China for critical minerals.

We focus on REEs and lithium, recognizing that many other materials will also play crucial roles, including copper and nickel. Many of our observations are likely to be applicable to those cases as well.

RECENT GOVERNMENT POLICIES TO SUPPORT A SECURE SUPPLY OF CRITICAL MATERIALS

In response to the growing demand for critical materials that are crucial for national security and for the energy transition, the federal government has taken a number of policy and program initiatives intended to increase supply, diversify supply chains, and reduce dependence on China for critical materials. A whole-of-government approach drawing upon the work of a broad range of agencies produced "A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals" in June 2019 and "Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth" in June 2021.[7] Based on the analysis and recommendations in these reports and comparable work by the International Energy Agency, new legislation has been enacted to enable government action to strengthen critical material supply chains.[8] The scope and scale of these government interventions represent a shift in US industrial policy from federal support of early stages of innovation to support for deployment of industrial facilities.

Highlights of the legislation establishing government policies and providing substantial funding to support resilient critical material supply chains are described below.

The Infrastructure Investment and Jobs Act (IIJA), signed into law in November 2021, provided $7.9 billion for initiatives related to critical materials.[9] They include the following:

- Grants for advanced battery material processing projects ($3 billion), for advanced battery manufacturing projects ($3 billion), and for battery recycling projects ($335 million).
- Enhanced geological mapping of domestic mineral resources ($320 million).[10]
- An Energy and Minerals Research Facility ($167 million).
- A project to demonstrate the feasibility of extracting and refining rare earth elements from wastes such as coal ash ($140 million).
- Steps to improve the permitting process for critical mineral mining on federal lands.

The Inflation Reduction Act (IRA), signed into law in August 2022, added further initiatives to support extraction and processing of critical materials.[11] These include the following:

- A tax credit of 10 percent of the cost of producing and refining critical minerals in the United States.

- A consumer tax credit for the purchase of new EVs, the size of which depends on the fraction of critical battery materials extracted or processed in the United States or in a country that has a free trade agreement with the United States, or on whether critical battery materials were derived from recycling in North America (relevant countries with free trade agreements include Australia, Canada, Chile, and recently Japan).[12]

- In addition to existing Defense Production Act (DPA) appropriations, $500 million to strengthen the US supply chain for critical minerals. The Defense Department has in recent years used its authority to make four grants totaling $195 million to support development and deployment of light and heavy REE separation and refining facilities in California and Texas.[13] The new funding could expand this effort to support domestic processing of REEs through flexible multiyear spending.[14]

The federal government has traditionally supported research in university and government laboratories to advance the science and technology of mineral extraction and processing. This work continues, aiming to increase efficiency and reduce environmental impact and waste. Recent examples include $12 million in Department of Energy (DoE) support for research to develop technologies to extract large quantities of lithium (comparable to current total US demand) as a byproduct of geothermal energy production with a small environmental footprint and DoE funding of $70 million in projects to advance technologies and processes for recycling EV batteries and reuse of their critical materials.[15]

The new legislation gives the federal government a mandate to go beyond technology development to support deployment of industrial-scale facilities for extraction and processing of critical materials, backed by substantial new resources for grants and loans. Moving quickly to use this new authority, DoE has made a conditional commitment to a $700 million loan to support a new lithium project in western Nevada and is processing an application for a loan for another large new lithium project in northern Nevada, both of which will extract lithium and refine it on-site to produce battery-grade materials.[16] DoE has also made a conditional commitment to a $2 billion loan to support construction of a facility in Nevada to produce battery components from recycled materials and a $150 million grant to support construction of a lithium ore concentration facility in North Carolina, which will support reopening a lithium mine in North Carolina and a downstream processing facility in the southeastern United States as well.[17]

The US government has also taken the initiative to form, under the State Department, the Minerals Security Partnership, a group of like-minded countries aiming to work together to bolster critical mineral supply chains.[18] Australia, Canada, Finland, France, Germany, Japan, South Korea, Sweden, the United Kingdom, the United States, and the European Union have joined the Minerals Security Partnership. Objectives of the partnership include strengthened information sharing, increased investment in critical minerals, and development of recycling technologies.

CASE STUDY: RARE EARTH ELEMENTS AND APPLICATIONS

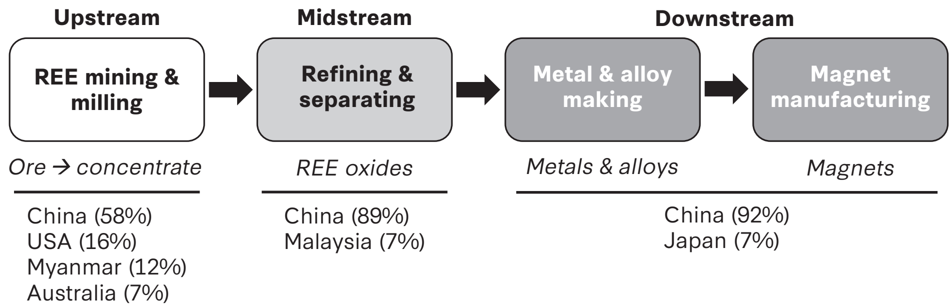
The rare earth elements (REEs) are a group of seventeen chemical elements—atomic numbers 57 (lanthanum) through 71 (lutetium) along with scandium and yttrium, several of which have important commercial and national security applications.[19] REEs are classified as either light or heavy depending on their atomic number. Light REEs, atomic numbers 21 and 57–63, notably including praseodymium (Pr) and neodymium (Nd), are typically more common and relatively easier to extract from ore. Heavy REEs, atomic numbers 39 and 64–71, notably including terbium (Tb) and dysprosium (Dy), are less abundant and more difficult and expensive to produce than light REEs.[20]

Traditional uses of REEs include fluorescent lighting and automotive exhaust catalysts. Looking forward, REEs will play an important role in the transition to lower-carbon energy systems. Demand for the many products underlying that transition is expected to grow, since electric motors, consumer electronics, and modern HVAC systems and appliances rely on compact, high-power magnets that use neodymium alloyed with iron and boron (NdFeB). For applications where magnets must operate at elevated temperatures, such as EVs and offshore wind turbines, dysprosium and terbium are added to the NdFeB magnets. A 2.5- or 3-megawatt wind turbine requires approximately 2,000 kilograms (approximately 4,400 pounds) of magnets, of which rare earth materials, including neodymium, praseodymium, dysprosium, and terbium, account for approximately 600 kg (approximately 1,320 lbs.).[21] An electric car contains approximately 5 kg (11 lbs.).[22] And on average an iPhone contains about a third of a gram of rare earth materials.[23]

There is significant variability in the supply and demand for the various REEs. Some markets are growing rapidly (EVs and wind turbines); others are stagnant (automotive catalysts and fluorescent lighting). The natural abundance of these elements also varies widely. The chemical similarity of REEs means they are often together in ore deposits—although their relative abundance can vary by factors of a hundred to a thousand. For example, rare earth ores tend to have relatively abundant cerium (Ce) and lanthanum (La), which have limited markets. Dysprosium, in high demand for high-performance motors and generators, is scarce. As a result, there is overproduction of some rare earths (cerium and lanthanum) and supply shortages for others (dysprosium). Market prices naturally reflect these supply-demand mismatches.[24]

Among many attempts to forecast REE consumption, the European Commission Joint Research Centre (JRC) has produced one analysis of the balance of future supply and demand for REEs for clean energy applications (neodymium, praseodymium, dysprosium, and terbium) for both high and low demand scenarios out to 2050. The most interesting finding of the JRC study is that the projected supply of dysprosium falls short of projected demand for clean energy uses alone in a high demand scenario. The study also notes that when all uses of rare earths are taken into account (for traditional applications as well as for clean energy), other rare earths could be in short supply as well. This suggests potentially stormy markets for dysprosium and a

FIGURE 1 Rare earth elements supply chain and market share (2022)



need to explore alternative technologies for substitutes for rare earths for clean energy and traditional uses.[25]

Global rare earth production amounted to 240,000 kg (approximately 530,000 lbs.) in 2020.[26] According to the International Renewable Energy Agency (IRENA), about one-third of all REEs were used in permanent magnets. Within that one-third share, 15 percent of permanent magnets went into EVs (representing around 6,000 to 9,000 kg of neodymium consumption, or approximately 13,200 to 19,800 lbs.), and 10 percent went toward wind turbines (4,000 kg neodymium, or approximately 8,800 lbs., notably for offshore turbines or, in China, in onshore turbines). This ratio of production to consumption is expected to change over the coming decade, however, as global wind turbine production may approximately double from current levels while EV manufacturing could grow by ten times.[27]

Rare earth production flows through a supply chain that starts with mining and ore concentration, followed by separation of the ore into individual elements in oxide form, refining into metals, production of magnet alloys, and finally manufacturing magnets from the alloys (figure 1). China (58 percent), the United States (16 percent), Myanmar, and Australia dominate rare earth ore mining, with significant expansion underway in Australia and Canada. China (89 percent) and Malaysia (7 percent) account for the vast majority of separation of REEs, while 90 percent of refining of rare earths into metal is done in China, with 8 percent in Southeast Asia (Thailand, Vietnam, and Laos). Magnet alloy manufacturing is primarily in China as well (92 percent), with some in Japan (7 percent).[28] As countries shift toward greater electrification of their economies, the United States and other global economies increasingly see it within their economic and security interests to diversify the REE supply chain.

Canada, in particular, has adopted an aggressive critical minerals strategy from exploration to mining, processing, manufacturing finished products, and recycling, and it is investing along the entire critical materials supply chain.[29] Rare earths are a priority, as Canada has some of the world's largest and highest quality deposits of rare earth ores.[30] With a number of REE extraction, processing, and refining projects underway by private companies with government support—and the growing demand for these minerals and products from its neighbor—Canada sees an opportunity to become a significant global supplier of REEs as a complement to its other strengths in mining and energy extraction.

RESTORING A RARE EARTH ELEMENT SUPPLY CHAIN IN THE UNITED STATES

Mountain Pass in California is the only active REE mine in the United States. As one of the world's richest REE deposits, Mountain Pass has a 7 percent average rare earth content as compared with 0.1 to 4 percent for most global deposits. The Mountain Pass mine produces rare earth ore concentrate, which is now sold to and processed in China. However, a facility is now being commissioned at Mountain Pass to process rare earth concentrate on-site into various rare earth products, including lanthanum, cerium, and neodymium-praseodymium (a key component of high-performance magnets).[31]

Production of REEs at Mountain Pass began in the 1950s. In the 1980s, Molybdenum Corporation of America operated the mine, which was then the world's dominant producer of REEs.[32] An Indianapolis-based company, Magnequench, a subsidiary of General Motors (GM), led the downstream manufacturing of REE magnets, with important commercial and defense applications.[33] The domestic REE industry grew rapidly between the 1970s and early 1990s—the United States led in REE technology patents and was at the forefront of REE ore processing and magnet production.

In 1998 the Environmental Protection Agency reported leaking of low-level radioactive waste at Mountain Pass.[34] Molycorp paid substantial fines, ceased processing operations in 1998, and closed the mine in 2002. China, as a result, became the world's supplier of REEs. Magnequench, which held important rare earth magnet patents and production processes, was sold to an investment consortium consisting of two China-based state-owned enterprises, and downstream magnet manufacturing operations were relocated to China.[35]

In 2010 China reduced REE exports anticipating domestic demand growth—a move interpreted by Japan and others at the time as being in response to a geopolitical flare-up over the disputed Senkaku Islands—leading to a spike in global REE prices.[36] Sensing an opportunity to capitalize on reduced REE exports from China, Molycorp tried to revive REE production at Mountain Pass. The company invested $1.7 billion to modernize the site and resume operations as a major supplier, but as a result of business miscalculations and operating deficiencies, Molycorp filed for bankruptcy in 2015.[37]

In 2017 MP Materials purchased the Mountain Pass mine at auction for $20.5 million—a remarkable bargain.[38] The company restarted the operations from cold-idle status within less than a year of purchase. This was made possible by a technical services/offtake agreement with a company in China, which provided technical services necessary to begin operations at Mountain Pass: MP Materials would produce and sell the rare earth ore concentrate to China for processing, and China would market the products to customers.

With the profits earned by selling rare earth concentrate to China, MP Materials was able to develop facilities and technologies to process rare earth concentrate at Mountain Pass. MP Materials has successfully installed refining technologies to separate and purify light and heavy REEs. In parallel, MP Materials is constructing a magnet manufacturing facility at Fort Worth, Texas.[39] Once completed, the magnet production facility in Texas will use REEs from Mountain Pass and produce up to 1,000,000 kg (approximately 2,200,000 lbs.) of NdFeB magnets annually, supporting US defense activities and the production of 500,000 EV traction motors. This restoration of a rare earth supply chain in the United States is supported by $700 million in venture capital through MP Materials, $10 million and $35 million Department of Defense contracts to build facilities at Mountain Pass to process light and heavy REEs, and a contract with GM to supply rare earth materials and finished magnets for electric motors in GM electric vehicles.[40] Initial deliveries to GM are planned to begin in late 2023.[41]

In order to meet California's strict environmental standards, MP Materials designed a state-of-the-art facility with sustainable mining and processing practices. Efforts to minimize the environmental footprint include recycling water from the ore concentration process, leaving only solid waste materials deposited into a lined impoundment, combined with a facility to consume waste brine and separate key reagents.

GOVERNMENT POLICY, MARKET FORCES, AND TECHNOLOGY

The restoration of Mountain Pass is an instructive example of how government policy, commercial markets, and technology can work together to expand domestic rare earth element infrastructure. Key elements of its progress to date include the following:

- As part of US government policy to support resilient critical material supply chains, the Department of Defense (DoD) awarded a DPA $10 million technology investment agreement to MP Materials in 2020 to add processing capabilities at Mountain Pass to refine its mixed rare earth ore concentrates into separated light REE products critical to numerous defense and commercial applications.[42] In 2022, DoD further awarded a DPA $35 million contract to design and build a processing and separation facility at Mountain Pass for heavy REEs for DoD and civilian applications.[43]

- Commercial support has played a major role. MP Materials has invested $700 million in venture capital to fully restore a REE supply chain in the United States. GM has supported this effort by entering into a long-term agreement for supply of US-sourced rare earth materials and finished magnets for EVs.[44] MP Materials' minority partner (8 percent) Shenghe Resources, a large China-based rare earths firm, has supported this effort by providing technical assistance and by purchasing the rare earth concentrates produced at the mine; these purchases financed the construction of processing and refining capabilities to complete the domestic supply chain.[45] In addition, MP Materials has recently entered into a contract with Japan's Sumitomo Corporation to sell neodymium and praseodymium produced at the Mountain Pass separation facilities for use in making magnets outside China.[46]

- Sustainable extraction and processing technologies introduced to minimize environmental impact avoid the problems that caused the previous owner to shut down the operation in 2002.

Today, Mountain Pass accounts for 16 percent of global production of REEs and is building out a complete domestic REE supply chain.

TECHNOLOGIES THAT COULD OFFER ALTERNATIVES TO RARE EARTH ELEMENTS

The importance of REEs in rapidly growing markets such as EVs and wind power generation motivates recent investments to strengthen REE supply chains. It is important, however, to temper this perceived opportunity with an assessment of the technology alternatives to employment of rare earths in system applications.

There are, for example, several alternatives to rare earth permanent magnet motors for EV applications and for permanent magnet generators in wind turbines. For both applications, induction motors and generators (which do not require any permanent magnets) are mature alternatives. Induction motors have been the most widely used motor since George Westinghouse and Nikola Tesla drove the development of AC electrical distribution and transmission in the late nineteenth century. High-performance induction motors were the primary traction motor in the original Tesla Roadster, though later models paired these permanent magnet–free induction motors with a permanent magnet motor. Permanent magnet motors, and rare earth (neodymium and dysprosium) permanent magnet motors in particular, are attractive in that they provide more torque in a compact, lightweight form. Even for EVs or hybrid-electric vehicles that only use permanent magnet motors (such as the Toyota Prius), engineers have been designing motors to minimize the total mass of those permanent magnet materials. Modern EV motors balance the torque generated by the permanent magnets with that generated by non-permanent magnetic materials such as iron (so-called internal synchronous reluctance motors). As modern EV motors move toward a smaller mass of those permanent magnets, it becomes feasible to consider replacing rare earth permanent magnets entirely with non–rare earth magnets; while these are larger, the smaller overall mass of modern motors means that the weight difference is less important. Indeed, in March 2022, Tesla announced that it would be moving away from rare earth permanent magnets in next-generation motors (likely moving to hard ferrite magnets, which are larger but abundant—and cheaper).[47]

Likewise, there are potential mature alternatives to permanent magnets for wind turbines. Older generations of wind turbines more commonly used induction machines (permanent magnet–free) paired with gearboxes in the nacelle to generate electricity. The industry has transitioned to the use of direct-drive generators using permanent magnets that can generate power even in low wind speeds as turbines increase in scale. Such technologies are expected to be particularly valuable in the growing offshore wind turbine market that values the size and weight advantages of rare earth permanent magnet generators, as well as reduced maintenance needs without a gearbox. Alternative direct-drive wind turbine generators include replacing the permanent magnets with electromagnets—so-called direct-drive electrically excited synchronous generators—using either heavier conventional electromagnets or lighter-weight superconducting electromagnets.[48] The availability of alternative motor and generator designs suggests that there is a price-performance trade-off that indicates a fairly elastic demand curve for rare earth permanent magnets.

TECHNOLOGIES THAT COULD OFFER ALTERNATIVES FOR SUPPLY OF RARE EARTH ELEMENTS FOR HIGH-PERFORMANCE APPLICATIONS

For applications that are most sensitive to the size, weight, and performance advantages of rare earth permanent magnet motors and generators, such as the F-35 joint strike fighter aircraft and other DoD applications, new options can be pursued, including development of alternative sources of scarce dysprosium and development of new materials for high-performance magnets that do not involve rare earths. New supplies of dysprosium could result from exploration outside of China for rare earth oxide deposits that are rich in dysprosium or recovery of REEs from tailings from coal mines, waste from phosphate fertilizer mining, and bauxite waste from aluminum mining.[49] While such waste sources may only contain small concentrations of dysprosium, an inexpensive separation and refining technology could nonetheless supply much of the demand for permanent magnet rare earths.

Finally, new materials processing techniques have the potential to produce high-performance permanent magnets with even higher performance than today's rare earth–based permanent magnets.[50] Niron Magnetics, funded by DoE and with venture support from Volvo, Volta, and Western Digital, is exploring new crystal structures for iron-nitrogen permanent magnets, which have theoretical performance twice that of NdFeB. There are also emerging advanced alloys and material engineering approaches to realizing high-performance permanent magnets that replace dysprosium and terbium with the relatively abundant elements manganese (Mn), copper (Cu), zinc (Zn), and aluminum (Al) to stabilize the performance of permanent magnets at high temperatures.[51]

CASE STUDY: LITHIUM

Lithium is present in the earth's crust at 0.002–0.006 percent by weight. It is the thirty-third most abundant element in nature and is distributed widely in trace amounts in rocks, soils, and surface, ground, and sea waters. Because of its chemical reactivity, it is not found in elemental form but in rocks, clays, and brines. In 2020 four mineral operations in Australia, two brine operations each in Argentina and Chile, and two brine and one mineral operation in China accounted for about 95 percent of global lithium production.[52] One small brine operation in the United States supplied about 1 percent of world production. Lithium demand is growing dramatically, primarily for use in lithium-ion batteries for EVs and potentially for electric grid short-duration storage applications. Global production expanded at a 21 percent rate from 2020 to 2021.[53]

Lithium prices are volatile.[54] As an example, a Tesla Model S with an approximate 70 kWh battery contains the equivalent of 11.8 kg (26 lbs.) of pure lithium metal; the lithium alone in a battery pack in 2018 would have cost about $1,000, and three times that in 2022.[55] The International Energy Agency (IEA) projects that global demand for lithium between 2021 and 2030 will increase by four times for its Stated Policies Scenario (which assumes continuation of existing policies and measures and those under development) or by six times for its Announced Pledges Scenario (which is the extreme assumption that countries fully implement their national targets).[56] By 2030 lithium-ion batteries are expected to account for 95 percent of global lithium demand, with production volume expanding at an annual rate of 25 percent.[57]

The US Geological Survey (USGS) includes lithium on its critical materials list, which indicates US lithium imports are greater than 50 percent of consumption (even these imports do not include lithium embedded in finished goods imported into the United States, especially in lithium-ion batteries for EVs). Lithium clearly is expected to play a greatly expanded role in the forthcoming clean energy transition. Accordingly, governments and major commercial firms around the world are taking actions to facilitate a reliable supply and affordable cost.

One such way to ensure supply is through exploration for new mining resources and expansion of refining capacity for those mines. Australia is the world's largest source of lithium (52 percent), and its mines are being substantially expanded in response to rising demand. Until recently, Australia sent most of its lithium ore concentrate extracted from rocks to China for refining into battery materials. Largely for this reason, China, the third-largest source of lithium extraction (just 13 percent), controls 60 percent of the world's lithium refining capacity.[58] In an important step to reduce dependence on China for battery materials, the first refinery in Australia to process the output of its mines into battery-grade lithium hydroxide began operations in 2022. A second refinery is coming online as well, and further expansion of refining capacity in Australia is underway. Development of capacity to refine lithium has the strong support of the Australian government, which forecasts that Australia could capture 10 percent of the global market for lithium battery materials by 2024 and 20 percent by 2027.[59]

Chile, the second largest lithium source (25 percent), produces battery-grade lithium compounds by evaporation of brines in high, dry deserts. Chile is also substantially expanding production in response to projected demand and investing in technologies to more efficiently separate lithium from brines and reduce water consumption.[60] Similar but smaller brine operations in nearby Argentina are also growing. India and Africa are potential new sources of lithium.

TABLE 2 US, CANADIAN, AND UK FIRMS DEMONSTRATING NOVEL LITHIUM EXTRACTION TECHNOLOGIES

Firm	Direct lithium extraction technology employed
EnergyX (Puerto Rico)	Uses membranes, solvents, and adsorbents to directly capture lithium from brine.
Lilac Solutions (California)	Uses ion exchange technology to extract lithium from brines without the need for evaporation ponds.
Standard Lithium (British Columbia)	Uses solid ceramic crystalline adsorbent to selectively remove lithium from brines.
Controlled Thermal Resources (California)	Combines lithium recovery with geothermal energy.
Cornish Lithium (Cornwall)	Removes lithium from lithium-enriched granite.

While expanding existing mines that extract lithium from rocks, firms are also exploring new lithium extraction technologies. For example, both large and small enterprises are exploring new methods for directly extracting lithium from brines, with the potential to open up large new sources for lithium that cannot be exploited with existing technology, as shown in table 2. These new projects based on brine extraction have advantages of lower carbon dioxide emissions, lower water consumption, and less environmental disruption compared to hard rock extraction that relies on solid process crushing, roasting, and acid leaching.[61] However, brine production facilities are large and take several years to site and build; capacity from time to time may lag market demand.

While it is not possible to predict how soon these alternative technologies will be ready or their relative commercial viability, it is likely that one or more will be successful. The prospects for magnesium/lithium separation from salt lake brines seem particularly promising.[62] Research is also underway to develop technology to economically extract lithium from seawater.[63]

Finally, there is unmet potential in lithium recycling. Industry observers generally agree that recycling lithium from end-of-life lithium-ion batteries will expand greatly and become an extensive and profitable source for battery materials; recycling is likely to remain a minor contributor to the overall global supply chain for some time, however, given the rapid growth in the industry.

BUILDING A LITHIUM SUPPLY CHAIN IN THE UNITED STATES

Government support for lithium production has closely followed the government path for REEs discussed in the prior section. The final “Building Resilient Supply Chains” report released in June 2021 contains the study results of the departments of Commerce, Energy, Defense, and Health and Human Services in response to an executive order requesting a one-hundred-day study of America's supply chains. In this 250-page report, the Department of Defense, taking the lead role, devotes fifty pages to the challenges and recommendations to revive the domestic supply chain of critical materials needed by the domestic economy and national defense. The recommendations include sustainably reshoring supply chains, cooperating with allies and partners for alternative supply chains, and developing workforce capabilities.[64]

Because batteries have become—and will likely continue to be—the predominant use of lithium, US government policy and program proposals focus on developing lithium battery supply chains to accelerate the transition to EVs. To that end, in June 2021, DoE issued a National Blueprint for Lithium Batteries 2021–2030 with seven goals:[65]

- Secure US access to raw and refined materials for lithium batteries through domestic mining and processing ventures and cooperation with allies and partners.
- Increase domestic processing of critical battery materials.
- Establish an RDD&D program to develop advanced battery technologies that employ alternative critical materials.
- Expand US lithium battery manufacturing.
- Establish and support a domestic lithium battery recycling ecosystem.
- Support development of a trained battery supply chain workforce.
- Find new approaches to public-private partnerships to align private investments with the national blueprint.

Government programs aim to realize these goals by stimulating expansion of the domestic lithium extraction and processing infrastructure, with financial support from the 2021 IIJA and the 2022 IRA and using a range of mechanisms including direct grants, tax credits, and loan guarantees.

Under the framework of the 2021 IIJA, DoE in October 2022 announced a new initiative "to expand domestic manufacturing of batteries for EVs and the electrical grid and for materials and components currently imported from other countries" through $2.8 billion in public cost share.[66] In total, the 2021 IIJA funds twenty recipients across domestic battery materials processing, battery manufacturing, and recycling. Examples are shown in table 3.

This initiative requires significant cost sharing between the federal sponsor and the private recipient. Such cost sharing understandably is usually accompanied by granting intellectual property rights to the private sector recipient. Exclusive intellectual property (IP)

TABLE 3 INFRASTRUCTURE INVESTMENT AND JOBS ACT OF 2021 BATTERY SUPPLY CHAIN FUNDING RECIPIENTS

Project description	Location	Applicant	Federal cost ($millions)	Recipient cost ($millions)
Cathode chemistries by microwave processing	(undec.)	6K	$50.0	$57.4
US based Li ore concentration	NC	Albemarle	$149.7	$225.9
LiOH extraction from US sedimentary resources	NV	ABTC	$57.7	$57.7
Prelithiation anode manufacturing facility	(undec.)	App. Materials	$100.0	$124.0
Recycle lithium from spent Li-ion batteries	KY	Ascend Elements	$316.2	$316.2
Cathode active material manufacturing plant	KY	Ascend Elements	$164.4	$164.4
Upgrade Li-ion battery recycle facility	OH	Cirba Solutions	$75.0	$107.5
Li-ion battery separator manufacture	OR	ENTEK	$100.0	$1,240.0
Li Fe phosphate powder (LFP) production	MO	ICL	$197.3	$232.3
Manufacturing Li hexafluorophosphate (LiPF6)	LA	Koura/Orbia	$100.0	$306.6
Lithium extraction ion exchange technology	NV	Lilac	$50.0	$129.3
Lithium hydroxide domestic rock resource	TN	Piedmont Li	$141.7	$430.6
Silicon anode material for Li-ion batteries	WA	Sila	$100.0	$300.0
Total			**$1,602.0**	**$3,692.0**

Source: Department of Energy, "Bipartisan Infrastructure Law Battery: Materials Processing and Battery Manufacturing & Recycling Funding Opportunity Announcement, Factsheets," November 1, 2022, https://www.energy.gov/sites/default/files/2022-11/DOE%20BIL%20Battery%20FOA-2678%20Selectee%20Fact%20Sheets.pdf.

ownership can, however, arguably slow broad diffusion of a new technology that is otherwise a principal objective of such a clean energy initiative. Resolution of the cost sharing/IP conflict is not easy; the issue deserves more attention, and broad public/private partnership may help avoid the issue.

DoE has other support programs to implement the lithium battery provisions of the 2022 IRA. The DoE Loan Programs Office (LPO), for example, has made a provisional award of $2 billion to Redwood Materials of McCarran, Nevada, for a closed loop end-of-life lithium-ion battery recycling facility.[67] The LPO has also made a $2.5 billion award to Ultium, a joint venture between GM and LG Energy Solution, to manage three lithium-ion battery manufacturing facilities in Ohio, Tennessee, and Michigan.[68] And in 2023, LPO announced a conditional $700 million award to the Ioneer Rhyolite Ridge project in Nevada to finance on-site processing of lithium carbonate.[69] This plant will produce about 24,000,000 kg (approximately 53,000,000 lbs.) of lithium carbonate per year for domestic commercial and defense purposes.[70]

These are substantial US government initiatives, motivated to assure reliable US access to lithium battery materials and lithium batteries for commercial and national security purposes. The United States is not alone in renewed efforts to secure critical supply chains. Partners in the European Union, for example, have recently approved €3.2 billion in public cost-share, combined with €5 billion from private firms, to fund seventeen participants to scale up innovations in support of development of a European battery supply chain infrastructure. The projects are expected to be completed by 2031.[71]

GOVERNMENT POLICY, MARKET FORCES, AND TECHNOLOGY

An instructive example of how government policy, commercial markets, and technology can work together to expand domestic lithium infrastructure is the Lithium Americas Thacker Pass project in northern Nevada, which will exploit the largest known lithium resource in the United States. This project has the potential to extract lithium from clays with an annual volume equivalent to 15 percent of global 2021 lithium production and to process it on-site to produce battery-grade lithium carbonate on a scale sufficient to supply the needs for up to one million electric vehicles per year.[72] Key factors in the project's genesis include the following:

- Federal and state governments have supported this project by providing all necessary permits to begin construction, and DoE's Advanced Technology Vehicles Manufacturing Loan Program is (as of early 2023) processing an application to provide up to 75 percent of the capital costs of construction.

- GM, meanwhile, has provided substantial commercial support with an equity investment of $650 million in this project, in return for exclusive access to the lithium carbonate produced in an initial phase for the first ten years, with an option to extend for an additional five years. As a result of this transaction, GM has become the largest shareholder in the project's parent company, supplanting China's Ganfeng Lithium.

- Various best-available advanced mining and processing technologies are used to minimize the environmental footprint, including by recycling water and reducing waste and emissions.

Construction of the mine and the processing facility is now underway, with production of lithium carbonate to begin in 2026. Government policies, market forces, and innovative technologies are combining to develop this substantial new domestic source of critical materials for batteries.

In sum, the lithium story is becoming clearer: identification of a potential lithium availability "crisis" due to explosive demand for electric vehicle deployment ignited a range of responses from both the US government and major private firms. It is not yet certain that prices, markets, and technologies will respond in a way that will make all anticipated uses affordable, but many signs point in the right direction. As with REEs, China has a strong position in the global lithium market, with about 60 percent of global production of refined lithium battery materials. And as with REEs, China also now holds strong positions in the intellectual property surrounding many battery-related production processes given its industrial progress in this area over the past decade.[73] This will be a new challenge for the United States and like-minded partners to navigate. At the same time, China's global power may face limitations going forward. China produces more EVs than any other country, and continued high growth for China's EV market is projected through 2040.[74] China's own massive domestic demand, combined with new supply-side efforts of the United States, Australia, Chile, and other countries, may help to constrain China's ability to increase its influence in the global lithium supply chain market.

ISSUES TO WATCH

Notwithstanding a promising start, the effort to produce critical materials on the necessary scale, with reliable partners, at affordable prices, has a long way to go. A number of factors will determine how successfully reliable supply will meet growing demand.

TIME

Demand for critical materials for the energy transition is already growing strongly and is projected to continue to rise over the next decade and beyond.[75] The positive trends we now see are the results of projects already underway. New mineral projects average sixteen years to develop.[76] Meeting future demand will require persistence and strong investment growth over an extended period of time.

INNOVATION

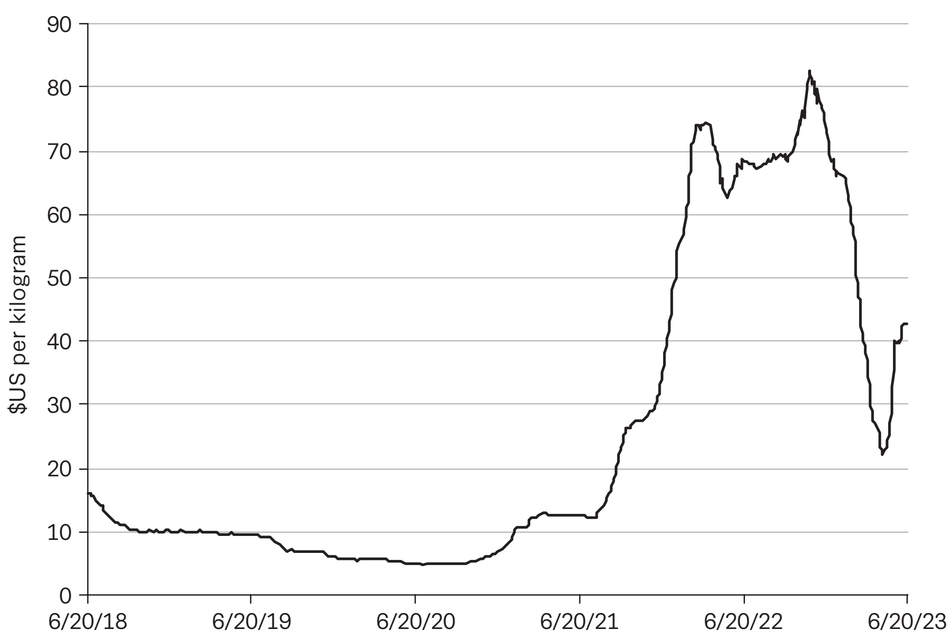
Advances in the technology of separating REEs without problematic solvents support the siting of processing operations in the United States and other countries with strong environmental standards.[77] Technological innovation could also in the future provide alternatives to REEs and lithium for certain applications. Other possibilities for innovation include extracting lithium from hot brines that are already being brought to the surface for geothermal energy production. If the science of extracting lithium from geothermal brines in a cost-competitive manner can be developed and demonstrated, the area near the Salton Sea in Southern California has the potential to produce lithium on a scale comparable to the current annual US demand with minimal environmental impact.[78]

Technological surprises are always possible. For example, there is much research activity directed to using sodium instead of lithium in batteries for EVs, especially in China.[79]

PRICES AND VOLATILITY

Low prices for critical materials support the production of affordable EVs, while high prices support investment in increased supply. The volatility of the spot price of lithium illustrated in figure 2 reflects in part fluctuations in production of EVs. Long-term contracts between lithium producers and manufacturers of EVs and batteries can increase predictability of price and supply and help to balance supply with demand.

FIGURE 2 Five years of lithium prices



Note: Lithium carbonate (minimum 99 percent purity) price in nominal US dollars (6/20/18 to 6/20/23, Shanghai daily spot market).

Source: Bloomberg, June 2023.

ENVIRONMENTAL AND SOCIAL ISSUES

Friction with the local community is a serious challenge to siting, construction, and operation of mineral extraction and processing projects. In our example of the Thacker Pass lithium mine and processing facility, the company committed to employ locally and work with local service providers and worked to establish a relationship with the largest nearby indigenous tribe, including by jointly conducting a cultural assessment of the site and by entering into a community benefits agreement with the tribe providing for workforce training and infrastructure development (a community center, a school, and highway improvements). Nevertheless, environmental groups, a local rancher, and other tribes brought multiple suits to block the project. These challenges were rejected by the court, and construction commenced in March 2022.[80] Research suggests that environmental and social challenges are a major risk to siting of new mineral projects and expansion of existing operations.[81] Recognition and mitigation of environmental and social risk are also necessary to attract investment in mineral projects.[82]

TRADE WITH ALLIES AND PARTNERS

Increasing the supply of critical materials on the necessary scale will require substantial expansion of extraction and processing by reliable allies and partners as well as the United States. The consumer tax credits of the Inflation Reduction Act favor EVs with battery materials extracted or processed in the United States and in countries with free trade agreements with the United States (importantly including Australia, Canada, and Chile). The recent rapid conclusion of a free trade agreement with Japan for lithium, nickel, cobalt, graphite, and manganese is a promising recognition of the importance of trade in critical materials with reliable partners.[83]

CHINA

China dominates the extraction and processing of critical materials for many reasons, greatly complicating the effort to diversify supply as demand grows. Factors underlying that dominance include the following:

- Some of China's resources have advantages in geology. A single mine near Baotou contains more than 40 percent of the total known REE reserves in the world, and it accounts for nearly half of global REE production. The REEs are a byproduct of iron ore mining operations, reducing costs.[84]

- The rest of the world has outsourced to China, with its more limited environmental controls, the key step of separation of REEs into individual elements, which traditionally uses large amounts of problematic solvents.

- With many years of operational experience, China's firms know how to tailor separation processes to the output of individual mines.

- At the top of the rare earth value chain—high-strength permanent magnets—China has a 95 percent market share, exploiting advantages in labor costs, materials costs, technology, and product range.[85]

- China's state-owned enterprises do not need to make a profit to survive.

OTHER CRITICAL MATERIALS

This essay has focused on REEs and lithium, but many of the issues and trade-offs apply to other materials crucial for the energy transition, including copper, nickel, and cobalt. As supply and demand grow, Africa will play an increasingly important role in the extraction and processing of a range of critical materials. Africa already produces more than two-thirds of the world's cobalt, bauxite, and platinum, and is becoming a supplier of lithium.[86] Sensing an opportunity, South Africa plans to host an African Critical Minerals Summit in October 2023 with global participation of key producers and users of mineral resources that underpin modern societies, aiming to attract diverse investment partners in mining, processing, and manufacturing products using African mineral resources, and to create sustainable jobs with an upskilled workforce.[87]

CONCLUSIONS AND RECOMMENDATIONS

This report has shown how a combination of market forces, government policy, and new technologies on both the supply and demand side are beginning to demonstrate measurable progress in increasing supply and reducing US dependence on China for rare earth elements and lithium, which together with other materials such as copper are set to become more central to our economy and national security in the coming decades.

But scale matters. This sector faces uncertainty in both growth in demand for these materials—e.g., the adoption rate of electric vehicles, or the use of lithium batteries versus alternate forms of electric grid energy storage, or the degree and pace of overall electrification within the United States, or China's own economy—and growth in supply, given the long lead times for extraction and processing projects. And many US allies and partners share our interest in not building a future energy economy that is entirely dependent on China and other problematic countries. Our energy and economic transition goals should continue to be informed by maintaining a balance of supply and demand so as to not drive new insecurities.

To that end, today's early progress should continue to be supported across each of these three realms—markets, policy, and technology—with a mind to sustaining that progress as the sector scales. Our recommendations to support such scaling include the following:

- To sustain market forces, prices for these commodities should continue to reflect global supply and demand—rather than being made subject to domestic price caps or floors—as prices convey information to investors and consumers. As global production capacity grows, attention should also be paid to below-cost dumping by incumbent mineral producers or processors that could disrupt fragile markets, a practice that contributed to today's dependence on China. To support such market transparency, Congress and relevant agencies should consider the adequacy and complementarity of existing USGS mineral commodity databases with the separate authorities for data collection and analysis of energy commodities and fuels that are afforded to the DoE's Energy Information Administration.

- Recent government policy has focused on subsidizing the supply and demand sides of diversified critical mineral supply chains through targeted domestic investments. Current negotiations over tax credit applicability with US partners show that like-minded nations also see this sector as an opportunity for new collaboration. US policy should prioritize diversification over protectionism. As we compete in that global marketplace, a scalable long-term domestic strategy will be one that sustains the competitiveness of doing business in the United States by finding suitable ways to reduce underlying costs in this sector. Capital (tax) efficiency, more certainty in timelines on permitting, coordination across agency reviews, flexibility in labor markets, and an appreciation for the national security benefits of critical technology domestic commerce within executive branch regulatory body decision making can all help. Minerals-oriented regulatory streamlining should be pursued by Congress as a package alongside similar reforms now being considered for other critical energy infrastructure.

- Finally, advancing technologies that increase efficiency, reduce impact on the environment, reduce waste, and promote recycling are crucial to attracting globally diversified supply chain investment at scale. These technologies support the competitiveness of US firms, yielding both private and public benefits. Federal tax policy can encourage continued private R&D investment, and the government should continue to fund the basic science that supports future technologies. Nuanced attention is needed on the matter of the IP underlying these capabilities and processes, protections for IP holders and for transfers of future IP, and treatment of IP generated under public-private partnerships in a way that balances private investment incentives with public interest.

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The United States faces a different threat landscape in this century than it did in the last. Strategies for meeting the international security challenges we face today need to address the many attributes of national power. Military strength is necessary but no longer sufficient. Effectively managing our national security problems will require cooperation with allies and partners, and recognition of the importance of diplomacy, economic strength, and science and technology. The GPS Initiative offers a fresh look, through a broad lens, to help navigate this emerging security landscape.

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