U.S. DEPARTMENT OF
ENERGY

Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

# Critical Materials Rare Earths Supply Chain: A Situational White Paper

April 2020

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The DOE Office of Energy Efficiency and Renewable Energy (EERE) Advanced Manufacturing Office (AMO) partners with industry, small business, universities, and other stakeholders to identify and invest in emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance the global competitiveness of the United States.

## Disclaimer

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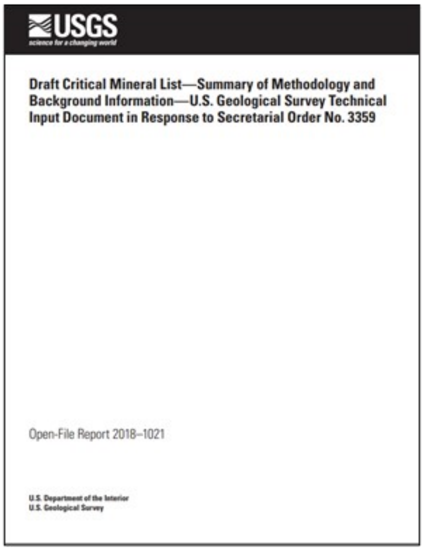
# Introduction

The assured supply of critical materials and the resiliency of their supply chains are essential to the economic prosperity and national defense of the United States. The manufacturing and deployment of these goods provides employment for American workers and contributes to U.S. economic growth. The United States is dependent on foreign sources of critical materials. Building on a determination methodology[1] (see Figure 1), of the 35 minerals or mineral material groups identified as critical in the list[2] published in the Federal Register by the Secretary of the Interior, the nation is 100% net import reliant for 14[3] and is more than 50% import-reliant for 17 of the remaining 29 mineral commodities.[4] This import dependence is a problem when it puts supply chains and U.S. companies and material users at risk. Many foreign sources of critical materials are concentrated in just one or two countries. For example, 60% of the world's cobalt is mined in the Democratic of Congo, and 80% of that supply is processed in China.[5] The dependency of the nation on foreign sources of critical materials creates a strategic vulnerability for both our economy and our military with respect to adverse foreign government actions, natural disasters, and other events that could disrupt supply.

**Figure 1. Methodology for Critical Mineral Determination**



USGS

science for a changing world

Draft Critical Mineral List—Summary of Methodology and Background Information—U.S. Geological Survey Technical Input Document in Response to Secretarial Order No. 3359

Open-File Report 2018–1021

U.S. Department of the Interior
U.S. Geological Survey

To address this problem and reduce the Nation's vulnerability to disruptions in the supply of critical minerals, President Donald J. Trump issued Executive Order (EO) 13817, *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals*,[6] on December 20, 2017. The EO directs the Secretary of Commerce, in coordination with heads of selected executive branch agencies and offices, to submit a report to the President that includes:

I. a strategy to reduce the Nation's reliance on critical minerals;

**Critical Mineral***

i. A non-fuel mineral or mineral material essential to the economic and national security of the United States;
ii. the supply chain of which is vulnerable to disruption; and
iii. that serves an essential function in the manufacturing of a product, the absence of which would have significant consequences for our economy or our national security.

* Definition in EO 13817.[6]

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[1] Fortier et al. *Draft Critical Mineral List—Summary of Methodology and Background Information—U.S. Geological Survey Technical Input Document in Response to Secretarial Order No. 3359*. U.S. Geological Survey. 2018. Available online at: https://pubs.usgs.gov/of/2018/1021/ofr20181021.pdf.

[2] Aluminum (bauxite), antimony, arsenic, barite, beryllium, bismuth, cesium, chromium, cobalt, fluorspar, gallium, germanium, graphite (natural), hafnium, helium, indium, lithium, magnesium, manganese, niobium, platinum group metals, potash, rare earth elements group, rhenium, rubidium, scandium, strontium, tantalum, tellurium, tin, titanium, tungsten, uranium, vanadium, and zirconium.

[3] *Mineral Commodity Summaries 2020*. U.S. Geological Survey. 2020. Available online at: https://pubs.er.usgs.gov/publication/mcs2020.

[4] Final List of Critical Minerals 2018, U.S. Department of the Interior. 83 Fed. Reg. 23295; 2018. Available online at: https://www.federalregister.gov/documents/2018/05/18/2018-10667/final-list-of-critical-minerals-2018.

[5] Supra 3. *Mineral Commodity Summaries 2020*. U.S. Geological Survey. 2020.

[6] Executive Order 13817. Executive Office of the President. December 2017. Available online at: https://www.whitehouse.gov/presidential-actions/presidential-executive-order-federal-strategy-ensure-secure-reliable-supplies-critical-minerals/.

II. an assessment of progress toward developing critical minerals recycling and reprocessing technologies, and technological alternatives to critical minerals;

III. options for accessing and developing critical minerals through investment and trade with our allies and partners;

IV. a plan to improve the topographic, geologic, and geophysical mapping of the United States and make the resulting data and metadata electronically accessible, to the extent permitted by law and subject to appropriate limitations for purposes of privacy and security, to support private sector mineral exploration of critical minerals; and

V. recommendations to streamline permitting and review processes related to developing leases; enhancing access to critical mineral resources; and increasing discovery, production, and domestic refining of critical minerals.

The Department of Commerce (DOC) subsequently published the report to the President on June 4, 2019.[7]

## The Department of Energy's Role

The approach of the Department of Energy's (DOE) to address critical materials is in alignment with the Executive Order. Within DOE, research and development (R&D) investments are coordinated among the program offices agency-wide around three pillars to address supply chain disruption risks:

1. Diversifying supply of critical materials – including increasing domestic production, separations, and processing
2. Developing substitutes
3. Driving recycling, reuse, and more efficient use of critical materials.

Activities at DOE that support pillar 1, increasing domestic production of critical materials, are briefly highlighted here, but do not represent a complete list of DOE investments or activities.

1. The Department conducts on-going assessment of material criticality across a range of energy technologies based on importance to energy and potential for supply risk. These assessments inform R&D investments across DOE's program offices.
2. The Office of Energy Efficiency and Renewable Energy (EERE) has established the Critical Materials Institute, an Energy Innovation Hub managed by the Advanced Manufacturing Office (AMO), which carries out early-stage applied research to diversify supply, develop substitutes, and drive reuse and recycling of materials critical to clean energy technologies. EERE has also invested and continues to invest in the recovery of critical materials, such as lithium from geothermal brines (through the Geothermal Technologies Office and AMO).
3. The Office of Fossil Energy (FE) funds the National Energy Technology Laboratory (NETL) *Feasibility of Recovering Rare Earth Elements Program* focuses on developing technologies for the recovery of rare earth elements and critical minerals from coal and coal-based resources.

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[7] *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Materials*. U.S. Department of Commerce. June 2019. Available online at: https://www.commerce.gov/sites/default/files/2020-01/Critical_Minerals_Strategy_Final.pdf.

4. The Office of Science invests in fundamental research to advanced understanding of critical materials down to the atomic level. This enables the development of novel synthesis techniques that control properties at the atomic level to develop unique capabilities for the preparation, purification, processing, and fabrication of well-characterized materials.

## Strategic Response

Addressing vulnerabilities in the critical minerals supply chain through an increase in domestic exploration, production, substitutes, technological alternatives, recycling, reprocessing, industry incentives, and R&D investments would help reduce our Nation's reliance on imports, preserve our leadership in technological innovation, support job creation, and improve our national security and balance of trade. In response to EO 13817, *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals* was published by the Department of Commerce (DOC), in coordination with Federal agencies including the DOE, on June 4, 2019.

The National Science & Technology Council (NSTC) Subcommittee on Critical Minerals (CMS) is the interagency body that will coordinate implementation of the Federal Strategy. An organizing principle of this strategy is to address the full supply chain of critical minerals, which spans from securement of raw materials to end-uses in both civilian and defense applications. The strategy is organized around six Calls to Action, supported by 24 goals with corresponding specific agency level recommendations that will be pursued over the next five years. DOE has key activities in the bolded Calls to Action below.

1. ***Advance Transformational Research, Development and Deployment across Critical Mineral Supply Chains*****:** Assesses progress toward developing critical minerals recycling and reprocessing technologies, technological alternatives to critical minerals, source diversification, and improving processes for critical mineral extraction, separation, purification, and alloying.

2. ***Strengthen America's Critical Mineral Supply Chains and Defense Industrial Base*****:** Discusses ways to improve critical mineral supply chains, which could help reduce risks to U.S. supply by increasing domestic critical mineral resource development, building robust downstream manufacturing capabilities, and ensuring sufficient productive capacity.

3. *Enhance International Trade and Cooperation related to Critical Minerals*: Identifies options for accessing and developing critical minerals through investment and trade with America's allies, discusses areas for international collaboration and cooperation, and ensures robust enforcement of U.S. trade laws and international agreements that help address adverse impacts of market-distorting foreign trade conduct.

4. ***Improve Understanding of Domestic Critical Mineral Resources***: Provides a plan to improve the topographic, geologic, and geophysical mapping of the U.S., support mineral information collection, and conduct critical mineral resource assessments.

5. *Improve Access to Domestic Critical Mineral Resources on Federal Lands and Federal Permitting Timeframes*: Summarizes recommendations to streamline permitting and review processes related to developing mining claims or leases and enhancing access to domestic critical mineral resources;

6. ***Grow the American Critical Minerals Workforce*****:** Discusses the activities needed to develop and maintain a strong domestic workforce to foster a robust domestic industrial base.

DOE is the lead for Call to Action 1 of the Federal Strategy. As such DOE implementation will achieve the following goals, in coordination with broad Federal agency input[8], which support the Calls to Action above:

- Develop a roadmap that identifies key R&D needs and coordinates on-going activities for source diversification, more efficient use, recycling, and substitution for critical minerals; as well as cross-cutting mining science, data science techniques, materials science, manufacturing science and engineering, computational modeling, and environmental health and safety R&D. *(**DOE**, DOC [NIST, NOAA], DOD, and EPA; 2-4 years)*

- Complete technical and economic feasibility studies of the production of critical minerals and related manufactured materials from secondary and unconventional sources (including coal-based resources, mine tailings, smelter slag, waste streams, end-of-life products, and seawater deposits). *(**DOE**, DOC (NOAA), DOD, DOI [(USGS)], and EPA; 1-2 years)*

- Provide private industry and other external stakeholders' access to computing capabilities, testing, and validation support facilities by lowering barriers to engage with government and academic laboratories, institutes, and organizations. *(**DOE**, DOC [NOAA], DOD, and DOI [USGS]; 2-4 years)*

- Identify potential significant secondary and unconventional sources of critical minerals, as well as the technological developments needed to improve domestic recovery capability. Provide a periodic status update to the CMS. (***DOE**, DOD, DOI [USGS], and EPA; ongoing*)

To implement the Federal Strategy, DOE's Offices of EERE and FE hosted a *Critical Minerals Rare Earths Supply Chain Roundtable and Workshop* at the Colorado School of Mines in Golden, Colorado on October 31 and November 1, 2019. Stakeholders from across the U.S. rare earths supply chain including industry, academia, Federal government, and national labs were convened to discuss the challenges and opportunities to strengthen the rare earths supply chain. A limited number of international participants representing Canada, Australia, and Japan also attended. This stakeholder discussion aimed to identify the potential for increased international collaboration and inform a research and developed (R&D) critical materials roadmap, as part of execution of the Federal Strategy.

The focus of this meeting was on the up-to-midstream rare earths supply chain (Figure 3), spanning extraction and concentration of rare earths from conventional and unconventional sources, separation into rare earth oxides, and conversion to metals and alloys. Discussion also included manufacturing of neodymium-iron-boron (NdFeB) magnets. A report out of the meeting is included below, supported by a technology assessment to examine the state of the industry.

# Key Takeaways

With 88 total attendees across the two-day meeting, the meeting highlighted the importance of convening stakeholders across the rare earth supply chain – and the need for continued dialogue.

- A key need is to have more engagement with the demand side of the supply chain – separation and processing capabilities domestically and in allied countries for those producing concentrates and magnet and motor manufacturers, and original equipment manufacturers (OEMs) for those producing rare earth oxides, metals and alloys.

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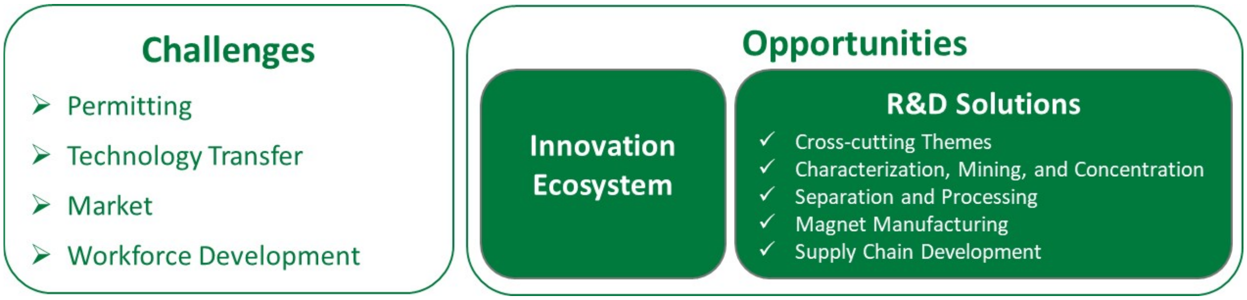
[8] Other key coordinating agencies for Action 1 encompass the Department of Commerce (DOC) including the National Institute of Standards and Technology (NIST) and National Oceanic and Atmospheric Administration (NOAA); the Department of Defense (DOD), the Department of the Interior (DOI) including the United States Geological Survey (USGS), and the Environmental Protection Agency (EPA).

- Participants also agreed that R&D should address the full supply chain, aligning well with DOE's critical materials pillars: (1) diversifying supply – including increasing domestic production, separations, and processing, (2) developing substitutes, and (3) driving reuse and recycling.
- Another key theme was that while R&D is necessary, it is not sufficient. International cooperation, policy, and investment are all levers the U.S. government can consider using to address challenges in the rare earths supply chain.

Figure 2. Summary of Supply Chain Challenges and Opportunities



# Status of the Industry

## Background

Rare earth elements[9] (REEs) are comprised of the lanthanides,[10] scandium, and yttrium. The REEs are classified as "light" and "heavy" based on atomic number.[11]

> **Light REEs (LREEs):** lanthanum through gadolinium (atomic numbers 57 through 64)
>
> **Heavy REEs (HREEs):** terbium through lutetium (atomic numbers 65 through 71) and yttrium (atomic number 39), which has similar chemical and physical attributes with the other heavy REEs

Figure 3. Rare Earth Oxides

Clockwise from top center: praseodymium, cerium, lanthanum, neodymium, samarium, and gadolinium.

Credit: Peggy Greb, U.S. Department of Agriculture. Agricultural Research Service.

Neodymium and praseodymium (LREEs) are key critical materials in the manufacturing of neodymium-iron-boron (NdFeB) magnets. NdFeB magnets have the highest magnetic strength (energy product) among commercially available magnets and enable high energy density and high energy efficiency in energy technologies. Dysprosium and terbium (HREEs) are key critical materials often added to the NdFeB alloy to increase the operating temperature of the magnets. HREEs tend to be less abundant and more

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[9] The rare earth elements consist of the lanthanide series (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium) as well as scandium and yttrium.

[10] Lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, and lutetium.

[11] *Critical Mineral Resources of the United States – Economic and Environmental Geology and Prospects for Future Supply*. U.S. Geological Survey. 2017. Available online at: https://pubs.er.usgs.gov/publication/pp1802.

expensive than LREEs. The deployment of energy technologies such as wind turbines and electric vehicles (EVs) could lead to imbalances of supply and demand for these key materials.

A technology assessment has been performed to examine the state of the industry for these key materials, including the current landscape, barriers, and the potential of key technologies, and updated to reflect input from stakeholders at the *Critical Minerals Rare Earths Supply Chain Roundtable and Workshop*.

## Mining

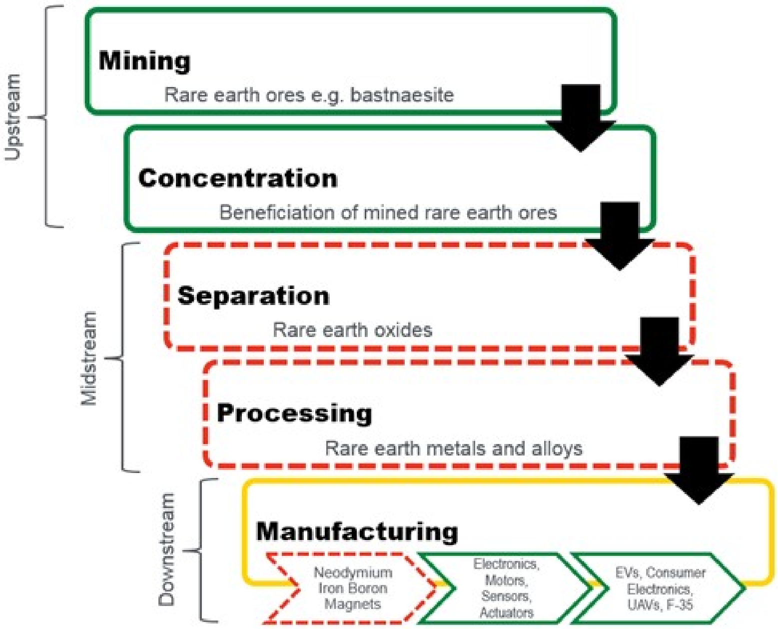
REEs are found combined in mineral deposits such as bastnaesite and monazite, the world's two largest sources of REEs. Bastnaesite, a carbonate-fluoride mineral, typically contains cerium, lanthanum, neodymium, and praseodymium. Monazite, a phosphate mineral, typically contains cerium, lanthanum, neodymium and samarium.

REE-containing mineral deposits have been identified in 19 states in the U.S.[12] REEs are not "rare" in the sense that they are commonly found in the Earth's crust. However, economic, mineable concentrations of REEs are less common.

Currently, there is only one active REE mine in the U.S. at Mountain Pass, CA, operated by MP Materials. The bastnaesite ore contains primarily LREEs by weight. The Bear Lodge Mountains in Wyoming and the Bokan Mountain in Alaska are two REE deposits, containing both bastnaesite and monazite minerals, that are being developed by the Rare Element Resources and Ucore Rare Metals respectively. Both deposits have significant concentrations of HREEs. The Ucore Rare Metals project in Alaska is slated to come online in the next three to four years.

Figure 4. Rare Earth Element Supply Chain for Neodymium Iron Boron Magnets

Gaps in the domestic supply chain are shown in red.



## Concentration

Concentration or beneficiation is an extractive metallurgy process that upgrades the value of raw REE-containing mineral ores by removing gangue (low value) minerals, resulting in a higher-grade product (i.e., rare-earth concentrate). Physical beneficiation methods include gravity separation, magnetic separation,

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[12] Rare earth element mines, deposits, and occurrences. U.S. Geological Survey. Available online at: https://mrdata.usgs.gov/ree/.

electrostatic separation, desliming, and froth flotation. Froth flotation is widely deployed in industry for concentrating REEs.[13,14]

Beneficiation incurs significant costs in the REE supply chain due to the large volumes of ore processed, chemical reagent consumption, and poor recovery/purity. Choice of collector in froth flotation plays a large role in this. Fatty acids are typically used as a collector in bastnaesite flotation. They require high temperatures (increasing the energy intensity of the process) and result in poor selectivity of REEs.[15]

The mine at Mountain Pass produced an estimated 26,000 metric tons of bastnaesite concentrates in 2019.[16] These rare earth concentrates are exported for separation and processing. Southern Ionic Materials, LLC is producing and exporting concentrates from heavy minerals sands.[17,18]

## Separation & Processing

Separation refers to the process of separating individual REEs from one another in the mined concentrates in the form of rare earth oxides (REOs). Separation of REEs is chemically intensive because the REEs are very chemically similar to one another (close proximity on the periodic table). Thorium is removed at this stage, introducing both risk and cost associated with waste storage/disposal. Solvent extraction is this most common method of separation used in industry.[19] Processing refers to the conversion of REOs to rare earth metals, such as neodymium metal which can then be used to form alloys like NdFeB using metallurgical processes like sintering. Molten salt electrolysis is the conventional process for conversion to metals.

The United States currently lacks the domestic capability to separate REE concentrates into REOs and process them into rare earth metals at a commercial scale. MP Materials has announced it will begin developing its own separation and processing capability at Mountain Pass by the end of 2020.[20] Rare Element Resources has completed pilot-testing in Canada and Germany to validate its proprietary separation and processing technology. Ucore Rare Metals is developing a pilot plant to separate the HREEs and LREEs at Bokan Mountain.[21] USA Rare Earth has partnered with Texas Mineral Resources to open a pilot plant that will separate light and heavy REEs, in addition to other critical materials, in Wheat Ridge, Colorado. The ore being processed will come from the Round Top deposit in Texas.[22] Rare Earth Salts is currently operating a plant producing REOs.[23] Momentum Technologies also has the capability to produce REOs from a diverse set of feedstocks.

Currently, there are no commercial capabilities to separate and process HREEs outside of China. Blue Line Corporation has a memorandum of understanding (MOU) with Lynas Corporation, an Australian mining

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[13] A. Jordens et al. “A review of the beneficiation of rare earth element bearing minerals.” Minerals Engineering (2013), vol. 41, pages 97-114. Available online at: : https://ecotricity.co.nz/wp-content/uploads/2016/12/161207-Rare-Earth-mining-techniques-and-improvement.pdf.

[14] A. Golev et al. “Rare earths supply chains: Current status, constraints and opportunities.” Resources Policy (2014), vol. 41, pages 52-59. Available online at: https://doi.org/10.1016/j.resourpol.2014.03.004.

[15] Supra 3. *Mineral Commodity Summaries 2020*. U.S. Geological Survey. 2020.

[16] Ibid.

[17] Southern Ionic Materials product safety data sheet. February 2017. Available online at: http://www.southernionicsminerals.com/pdf/sds/Rare_Earth_Mineral_Sand.pdf.

[18] Southern Ionic Materials export license application. Available online at: https://www.nrc.gov/docs/ML1721/ML17215A492.pdf.

[19] F. Xie et al. “A critical review on solvent extraction of rare earths from aqueous solutions.” Minerals Engineering (2014), vol. 26, pages 10-28. Available online at: https://www.sciencedirect.com/science/article/pii/S0892687513003452.

[20] https://www.scmp.com/business/commodities/article/3011687/caught-between-trump-and-its-biggest-market-americas-sole-rare.

[21] https://ucore.com/ucore-announces-m3-plan-of-action-for-independent-u-s-hree-supply-chain.

[22] https://www.mining.com/pilot-rare-earths-processing-plant-first-one-outside-china-opens-in-texas/.

[23] https://physicstoday.scitation.org/doi/10.1063/PT.3.4040.

corporation, aiming to develop HREE separation and processing capacity in Texas.[24] Rare Element Resources is also developing separation and processing capabilities with proprietary technology.

Infinium Corporation reported to have the capability to convert REOs to metals.

## Magnet Manufacturing

Since 1995, the U.S. permanent magnet manufacturing sector has been reduced by half through industry consolidation, relocation, and closure. There are currently no large scale manufacturers of sintered NdFeB magnets in the United States. Gaps in the REEs supply chain pose a barrier to domestic manufacturing. Urban Mining Company, based in Texas, is now actively making bonded and sintered NdFeB magnets, but not at commercial scale. Electron Energy Company, which manufactures samarium cobalt magnets, actively stockpiles rare earth metals to prevent supply disruption – carrying between six to twelve months supply.

## Recycling

Currently, end-of-life products that contain REEs, including magnets, batteries and fluorescent light bulbs, are recycled in limited quantities.[25] Urban Mining Company has built its business model on magnet-to-magnet recycling. The Rare Earth Salts pilot plant processes fluorescent light bulbs. Momentum Technologies has licensed patented technology developed by the Critical Materials Institute, a DOE Energy Innovation Hub, to recovery REOs from magnet waste streams.

# Challenges

## Permitting

Permitting is a large barrier to increasing production from primary sources. The complex regulatory landscape often leads to lengthy permitting timelines. This and lack of industrial policy can lead to long lead times for new and developing projects. The loss of the U.S. Bureau of Mines in 1996 was acknowledged as a significant barrier for the mining industry. The U.S. Forest Service (USFS) reported that its National Environmental Policy Act Regulation policies are being revised. The proposed rule was released for public comment on June 13, 2019; the comments are currently being reviewed before the development of the final rule. USFS is also revisiting Locatable Mineral regulations and is currently working through that process. The Federal Permitting Improvement Steering Council (FPISC) is also considering the potential inclusion of critical minerals as part of Title 41 of the Fixing America's Surface Transportation Act (FAST-41).[26] On January 15, 2020 the FPISC voted to include non-energy mining as an infrastructure covered under FAST-41, allowing FPISC to add mining projects for non-energy, saleable and critical minerals.[27]

## Technology Transfer

Scaling up and commercializing new technologies is a challenge. However, there are no test-bed or pilot-scale facilities to help validate, demonstrate and compare new technologies for a wide-range of feedstock inputs. Getting industry input is often a challenge for researchers at DOE national laboratories and in academia at early stages of discovery and development. Conversely, the hand-off of new technologies is difficult without sustained engagement between industry, academia and national laboratories to address scientific and technical

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[24] https://www.lynascorp.com/wp-content/uploads/2019/05/190520-Lynas-Blue-Line-MOU-for-Rare-Earths-Separation-in-the-USA-1931006.pdf.

[25] Supra 3. *Mineral Commodity Summaries 2020*. U.S. Geological Survey. 2020.

[26] Title 41 of the Fixing America's Surface Transportation Act (FAST Act), referred to as "FAST-41," created a new governance structure, set of procedures, and funding authorities to improve the Federal environmental review and authorization process for covered infrastructure projects. https://www.fs.fed.us/specialuses/special_FAST-41.shtml.

[27] https://www.permits.performance.gov/sites/permits.dot.gov/files/2020-01/Mining%20Press%20Release%20OED.pdf.

challenges during scale up. Generally, achieving and maintaining cost-competitiveness for new processes is a challenge.

Obtaining intellectual property rights for manufacturing is another barrier. Historically, NdFeB magnets were independently invented in Japan (Sumitomo Special Metals Corporation) and the United States (General Motors Corporation). Japanese inventors won the rights to sintered (fully dense) NdFeB magnets and American inventors won the rights to bonded and hot pressed (in which magnet particles are dispersed in a binder) NdFeB magnets. Sumitomo Special Metals Corporation merged with Hitachi Metals, Ltd and the division at General Motors became Magnequench, which was bought by Chinese investors and relocated to China. Major manufacturers of sintered NdFeB magnets worldwide, including China and Germany, currently license the right to manufacture and sell from Hitachi.[28] Three Chinese companies filed *inter partes* reviews of Hiatchi's U.S. Patent No. 6,461,565 in 2017, claiming the processes were unpatentable. The final decision in 2018 determined that these claims did not show "by a preponderance of the evidence" that the Patent was unpatentable.[29]

## Market

The market is volatile and uncertain, and there is a lack of transparency in the rare earths supply chain. Concerns about market manipulation exist internationally, as iterated by the participants from Australia, Canada, and Japan. When rare earth oxide prices are too low, new mining projects are not economical upstream. When rare earth metal prices are high, magnet manufacturers can be constrained. The REO market is about $3-5 billion, but translates into an order of magnitude larger in value-added market.

Another challenge is to connect those markets in a way that allows for new capabilities to be developed upstream. Low material price is a large impediment to developing both a domestic and international supply chain that is not dependent on China. For example, Molycorp Inc., the previous operator of the Mountain Pass mine, invested $1.6 billion in a separation and processing facility[30] in the $3-5 billion REO market,[31] and ultimately filed for bankruptcy in 2015. This example illustrates the difficulties of developing economically competitive processes. Additionally, Chinese policymakers imposed a 25 percent tariff on imported REE concentrates (effective June 1, 2019), more than doubling the previous duty.

Environmental stewardship is also a challenge for economical mining of REEs. Bastnaesite contains up to 0.3 weight percent thorium dioxide and 0.09 weight percent uranium dioxide. Monazite contains between zero to 20 weight percent thorium dioxide and zero to 16 weight percent uranium dioxide. These radioactive materials make waste disposal a significant environmental challenge and introduce risks for workers in mines and processing facilities if not managed properly.

The rare earth balance problem continues to be an issue for U.S. miners. The rare earth balance problem is the balance (or imbalance) between the market demand and the abundance of naturally occurring REEs in mineral deposits. The rare earth balance problem could be in part solved by closing the loop on the supply chain through reuse and recycling, partially offsetting the need for primary production. Additionally, finding new uses for non-critical REEs like cerium and lanthanum that are currently in oversupply can drive overall demand for REE production and increase profitability of mining. For example, cerium and lanthanum (LREEs) make up about 75% of the bastnaesite mineral deposit at Mountain Pass, CA,[32] but were worth two orders of

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[28] https://www.waltbenecki.com/uploads/hitachi_in_the_news.pdf.

[29] https://portal.unifiedpatents.com/ptab/case/IPR2017-01312.

[30] https://capitalresearch.org/article/americas-rare-earth-ultimatum-part-2/.

[31] https://www.otcmarkets.com/ajax/showNewsReleaseDocumentById.pdf?id=27726.

[32] B. S. Van Gosen, P. L. Verplanck, and P. Emsbo. *Rare Earth Element Mineral Deposits in the United States*. Circular 1454, Version 1.1. U.S. Geological Survey. April 2019. Available online at: https://pubs.usgs.gov/circ/1454/circ1454.pdf.

magnitude less than HREEs, such as dysprosium and terbium, per kilogram on the rare earth oxide market in 2019.[33]

Collection of end-of-life magnets is the largest barrier to reuse, recycling and recovery. It is exacerbated by the lack of downstream manufacturers domestically. Lack of reuse and recycling capability domestically introduces the risk for end-of-life products to be exported for recycling and re-introduced into the domestic supply chain as value-added products.

## Workforce Development

A cross-cutting need for the supply chain is workforce development. To maintain a domestic edge of technological innovation, multidisciplinary teams will be needed that go beyond traditional scientist and engineering skills to include artificial intelligence (AI), automation, and machine learning. The greatest need was reported to be at the technician level, where industry is already anticipating multi-generational workforce gaps, and many pointed out that there are few mining programs at higher education institutions in the United States. This is in part due to the social perception around mining, which is another obstacle to the development of domestic resources. Re-establishment of domestic upstream capabilities is crucial to establishing a pipeline for educational workforce development.

# Opportunities

## Innovation Ecosystem

Criticality applies not just to materials, but also to broader systems they are a part of. To address strategic vulnerabilities, the entire supply chain needs to be considered. For example, increasing the rate of mining without increasing corresponding processing and manufacturing capabilities will simply move the source of economic and national security risk further down the supply chain and create dependence on foreign sources for these capabilities. An innovation ecosystem should be built around a supply chain framework that emphasizes the integrated, interconnected nature of the problem. Key areas for development include:

- Understanding the systems, networks, and evolution of materials flow to identify opportunities, including co-production and unconventional resources
- Strengthening and extending relationships to match producers and customers
- Sustained engagement with OEMs, labs, and academia throughout the process to scale up new technologies
- Establishing a pipeline of projects for private investment
- Establishing an advisory group or community that identifies challenges and opportunities on an ongoing basis, including bridging domestic and international foci
- Pursuing a multidisciplinary workforce including AI, automation, rapid prototyping

## R&D Solutions

### Cross-cutting Themes

R&D is well-positioned to address long-term solutions to the supply chain. Transformational innovation can be used to shift the paradigm in the industry. DOE and DOD, including the Defense Advanced Research Projects

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[33] Supra 3. *Mineral Commodity Summaries 2020*. U.S. Geological Survey. 2020.

Agency (DARPA) and the Air Force Research Lab, are all investing in developing technologies that have the potential to innovate the supply chain and reduce dependence on rare earths by substantially reducing or even eliminating their use in end-use technologies.

In order to reduce costs and maintain responsible environment stewardship, connectivity is needed across the supply chain. For example, modular process intensification can link feedstocks with processing by co-locating multiple stages of the supply chain. Modeling and analysis play an important role in validating such ideas. Techno-economic analysis (TEA), life-cycle analysis (LCA) and agent-based modeling were discussed as vital steps in the scale-up of new technologies. Cooperation through public-private partnerships is needed for such validation and verification, with test-beds and pilot-scale facilities as one avenue to demonstrate new technologies. For development of new processes, certification is needed.

### Characterization, Mining, and Concentration

There is a significant need for geological mapping, exploration, and characterization of both conventional and unconventional sources of rare earths. Unconventional sources include abandoned mines, coal, coal byproduct, acid mine drainage (landfilled and in-production), phosphate, iron tailings, red mud, beach sands, laterites, seawater and deep sea. Some specific characterization needs include dilute media like coal ash and understanding phosphate heterogeneity.

R&D opportunities to address this need include remote sensing, rapid characterization, big data, and Earth Mapping Resources Initiative (MRI). This represents an area where USGS and DOE could collaborate more closely in the short-term. Data needs are a challenge, but if collected could be leveraged for development of AI technologies. Test-beds were suggested as means to compare and scale up new technologies.

Foundational research for disruptive technologies are potential long-term solutions. These include microbes for selective uptake, geothermal brine extraction, seawater extraction, deep-sea mining, nano-filtration concentration of dilute resources for high resolution physical concentration, and chemical concentration (novel ion extraction resins, sorbents, ligands, selective leaching, automated particle sorting, and selective collectors for flotation).

Environmental considerations included membranes for water treatment, addressing effluent toxicity. To address management of radioactive materials found in some resources, new market opportunities could be developed or pursued for thorium. More generally, opportunities and challenges of co-production and by-production need to be further explored.

### Separation and Processing

In the short-term, solvent extraction is the industry standard for separation of beneficiated ore into rare earth oxides. Opportunities exist to improve efficiency and cost-competitiveness of solvent extraction. Process intensification is one possible route to achieve those goals. Alternative technologies with enhanced selectivity are long-term options for separation. These include laser ablation, ultrasound, synthetic biology, ion-exchange chromatography, novel ligands, and magnetic nanofluid separations.

For conversion to metals, short-term opportunities include cell efficiency and heat management. In the long-term ionic liquids, new electrolytes, and metallothermal reduction could be pursued. For conversion from metals to alloys, production costs are a larger concern than raw materials. New alloys like aluminum-scandium and magnesium-electron alloys could open up new market opportunities if production cost barriers can be overcome.

### Magnet Manufacturing

It was asserted that it is possible to be competitive with China in magnet manufacturing as the automotive and electronic industries have an international supply chain. Fundamental R&D needs include new materials discovery and new process discovery. Magnetic materials should be demonstrated in the range of 1 to 10 kilograms in order to assess manufacturability. Engagement with end-use designers could better inform material development. Magnetic properties are not the only figure of merit considered when designing a permanent magnet machine. In order to scale-up new process discoveries, simulation of virtual manufacturing could help enable new processes. Such simulation may warrant its own R&D development.

### Supply Chain Development

As noted above, modeling and analysis such as TEA, LCA and agent-based modeling are needed across the supply chain to evaluate the potential of new technologies and processes, including reuse and recycling of end-of-life products. Validated datasets are needed for such analysis. There is a need for R&D in the social sciences to understand public acceptance, risk analysis, decision analysis, and the market opportunity for mixed rare earth oxide recovery vs. elemental rare earth oxide recovery (e.g. neodymium/praseodymium oxide vs. neodymium oxide and praseodymium oxide). Upstream, resource map development is needed to better understand the potential of primary and unconventional production. Long-term, end-of-life wind turbines, photovoltaics, and electric vehicles could be leveraged to supply rare earths through reuse and recycling. Collection center analysis is needed to facilitate such an opportunity. This relates to the cross-cutting need to connect supplies with customers and form industrial networks.

Moving beyond R&D, commercial stockpiles and regulatory incentives were suggested as one possible way to stabilize the industry, although there was not consensus about whether either approach would be effective. Leveraging international collaboration with allied nations, such as members of the North Atlantic Treaty Organization (NATO), was suggested as a means to stand up an assured rare earth supply chain to reduce market uncertainty and volatility.

## Next Steps

As the part of the implementation of the Federal Strategy, a R&D roadmap will be developed. More engagement is needed to continue to identify opportunities and solutions to the many challenges in the rare earth supply chain. Specifically, stakeholder input is needed around metrics and technical targets for many of the R&D options discussed at the Workshop described above. DOE plans to continue this dialogue through future workshops.

## List of Acronyms

| | |
|---|---|
| AI | Artificial Intelligence |
| AMO | Advanced Manufacturing Office |
| CMS | Subcommittee on Critical Materials |
| DARPA | Defense Advanced Research Projects Agency |
| DOD | U.S. Department of Defense |
| DOE | U.S. Department of Energy |
| DOI | U.S. Department of the Interior |
| EERE | Energy Efficiency and Renewable Energy |
| EO | Executive Order |
| EPA | Environmental Protection Agency |
| EVs | Electric vehicles |
| FAST | Fixing America's Surface Transportation Act |
| FE | Fossil Energy |
| FPISC | Federal Permitting Improvement Steering Council |
| HREEs | High rare earth elements |
| LCA | Life-cycle analysis |
| LREEs | Light rare earth elements |
| MOU | Memorandum of Understanding |
| MRI | Mapping Resources Initiative |
| NATO | North Atlantic Treaty Organization |
| NdFeB | Neodymium-iron-boron |
| NETL | National Energy Technology Laboratory |
| NIST | National Institute of Standards and Technology |
| NOAA | National Oceanic and Atmospheric Administration |
| NSTC | National Science and Technology Council |
| OEMs | Original equipment manufacturers |
| R&D | Research and development |

| | |
|---|---|
| REE(s) | Rare earth element(s) |
| REOs | Rare earth oxides |
| TEA | Techno-economic analysis |
| U.S. | United States |
| USFS | United States Forest Service |
| USGS | United States Geological Survey |

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