An Overview of Rare Earth Elements and Related Issues for Congress

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SUMMARY

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Congress is considering legislative changes that could address U.S. access to rare earth elements. Rare earth elements (REE), a group of 17 elements included in the list of critical minerals pursuant to Executive Order 13817, are used in many components and products in various sectors. Examples of sectors in which REE are commonly used include petrochemicals, metals and alloys, glass and ceramics, and electronics. Examples of components and products that contain REE include catalysts (e.g., oil refineries, automobiles), permanent magnets (e.g., cell phones, wind turbines, electric vehicle motors), fiber optics (e.g., signal amplifiers, lasers), and lighting/displays (e.g., fluorescent lights, cell phone and computer displays). Many components and products containing REE are used for defense applications.

China is currently the global leader in REE mining, refining, and component manufacturing. From 2015 through 2018, the United States imported 80% of REE compounds and metals from China; much of the imports from other countries were derived from Chinese REE inputs. Between 2010 and 2014, China imposed export restrictions on REE. The supply shock resulted in dramatic increases in prices and concern over securing access to REE, which led to increased global exploration for economical REE deposits. Some known domestic REE deposits include those located at Mountain Pass, CA; Bokan Mountain, AK; Bear Lodge, WY; Round Top, TX; and Elk Creek, NE.

Privately and federally funded research is seeking to lower REE extraction costs. Lower costs and improved extraction processes or technologies could make previously uneconomical deposits of REE available for extraction. Similarly, ongoing research is seeking means of extracting or reusing REE in components and products containing them. Lowering the costs to extract REE from other minerals, mining waste, and recycled products could potentially create economically viable sources of REE.

Typically 60% of REE consumed domestically is used in catalysts (e.g., oil refineries, automobiles); the remainder is typically divided (around 10% each) among metallurgical applications and alloys, ceramics and glass, polishing, and other uses. Prices vary greatly among REEs; two examples from 2018 include $455 per kilogram of terbium oxide and $2 per kilogram of lanthanum oxide. Price trends for REE appear to have stabilized after China lifted its export restrictions.

A range of legislation to increase U.S. access to REE has been introduced in the 116th Congress. The Senate considered a major energy and minerals bill, S. 2657, in 2020. A Senate cloture motion on S. 2657 did not pass in March. The House considered a major energy and minerals bill, H.R. 4447, which was passed in the House in September. Both bills would (among other provisions) authorize funds to research the extraction of REE from coal and coal byproducts (formalizing an ongoing research program at the National Energy Technology Laboratory). S. 2657 and H.R. 4447 would direct the U.S. Department of Energy (DOE) to research REE extraction via a consortium. H.R. 4447 contains provisions directing DOE to create a research program related to recycling critical minerals from energy storage systems. Three other bills, S. 3694, S. 4537, and H.R. 7812, would direct the U.S. Department of Defense (DOD) to establish a grant program to encourage the domestic development of critical minerals, among other provisions. These bills would authorize $50 million per year for four years.

Four bills, S. 3694, S. 4537, H.R. 7812, and H.R. 8143, would create tax incentives for firms investing in domestic REE extraction and consumption. The incentives would include 100% expensing (immediate tax deduction) for qualified property involved in extracting critical minerals and metals from deposits in the United States; a special allowance (100% depreciation deduction) for nonresidential real property; and a 200% cost deduction for the purchase of critical minerals and metals extracted within the United States.

Two bills, S. 2093 and H.R. 4410, would create a federally chartered cooperative and a federally chartered corporation to mitigate potentially high costs associated with extracting REE from minerals that may be found with radioactive elements (typically thorium and uranium). The cooperative would accept REE material from domestic and international partners for processing into salable products. The corporation would accept any related materials containing uranium or thorium from the cooperative for storage and potential sale. The federally chartered cooperative and corporation would be privately funded.

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Introduction

The rare earth elements (REE) are a commonly recognized group of 17 elements included in the list of critical minerals identified by the U.S. Geological Survey (USGS) pursuant to Executive Order 13817.[1] Although domestic resources exist for some REE, the United States is currently reliant on imports. In 2019, the United States imported 100% of rare earth metals and compounds it consumed, even though it exported some domestically mined rare earth element concentrate for further processing (due in part to a lack of domestic processing facilities).[2]

As the United States currently imports all rare earth metals and compounds, an ongoing concern for many is maintaining unrestricted access to these supplies. REE are used in many products and sectors; examples of products containing REE include metal alloys, catalysts, magnets, motors, and electronic displays. More information on the consumption of REE in representative sectors and products is presented in the section "Demand for Rare Earth Elements" below.

This report provides an overview of REE, with a focus on domestic mineral resources and the potential for transforming REE sources (e.g., minerals, ores, concentrate, compounds) into inputs for other products. The United States has known deposits of REE, and one has been mined intermittently over several decades. While some deposits offer additional potential supply options, the United States currently does not have commercial-scale REE extraction capabilities. Ongoing research aims to lower the cost of extracting REE from mineral deposits and from recycled materials. Congress has shown interest in securing and enhancing the domestic supply of rare earth elements and critical minerals through proposed legislation.

Critical Minerals and Rare Earth Elements Defined

Many discussions of critical minerals employ the definition stated in, and the resulting list pursuant to, Executive Order (E.O.) 13817. The E.O. defines a *critical mineral* to be

> (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.[3]

The E.O. directs the Secretary of the Interior, who in turn directs the USGS, to work with other federal agencies to produce a list of critical minerals (and to update the list periodically). The Department of the Interior (DOI) accepted the final list from USGS, which includes the REE as critical minerals.[4]

Seventeen elements are commonly considered to be REE, 15 within the lanthanoid group of elements, as well as yttrium and scandium. REE are often discussed or categorized as light REE (LREE) or heavy REE (HREE). LREE include lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), and gadolinium (Gd).

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[1] Department of the Interior, "Final List of Critical Minerals 2018," 83 *Federal Register* 23295, 2018.

[2] U.S. Geological Survey, *Mineral Commodity Summaries*, 2020, pp. 132-133.

[3] Executive Order 13817, "A Federal Strategy to Ensure Secure and Reliable Supplies," 82 *Federal Register* 60835 (2017).

[4] The full list is 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, the rare earth elements group, rhenium, rubidium, scandium, strontium, tantalum, tellurium, tin, titanium, tungsten, uranium, vanadium, and zirconium.

HREE include terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu). Yttrium (Y) is generally considered a HREE, due to its similar chemical and physical properties. Scandium (Sc) is not included in either subcategory. Promethium is sometimes excluded from these subcategories because it does not occur in nature.[5]

Supply of Rare Earth Elements

REE are found in a variety of minerals, but not all are equally suitable for economic development.[6] While more abundant than many other elements, REE are generally found in concentrations below what is economically viable for extraction at current prices using available technology. Increasing the domestic supply of REE could be achieved by locating additional geologic reserves,[7] lowering the costs of extracting REE from the ores (or minerals) in which they are found, enhancing technologies to produce REE by recycling, and increasing the substitutability among REE for a given use.

During exploration for new deposits of REE, the grade of the deposit is commonly reported in percent terms of the total deposit that could be produced as rare earth oxide (REO). REE mineral deposits are typically discussed in terms of the quantity of recoverable REO (typically in tons or metric tons). Recoverable REO from a resource is typically the product of the quantity (e.g., tons) of the resource multiplied by the grade (percent) of the resource.

REO is a commonly traded form of refined REE. Some mine operations include the necessary facilities to extract REE from ores and produce REO on site. Other mine operations may produce REE concentrate, which results from subjecting the ore to a variety of physical and chemical refining processes; REE concentrate requires additional processing to become REO.

The grade, or concentration, of REE in its host mineral may not always be a useful indicator of economic viability. Some higher-grade deposits (e.g., ~8% REO at Mountain Pass, CA) may have characteristics that require expensive means of extraction or are technologically infeasible to produce. Alternatively, some lower-grade deposits (e.g., 0.05% in some Chinese clay deposits) may have characteristics that facilitate REE extraction, resulting in an economically viable deposit. Characteristics that affect economic viability include the type of deposit (e.g., vein, placer), the mineralogy (crystalline structure) of the REE minerals in the deposit, accessibility to

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[5] Bradley S. Van Gosen, Philip L. Verplanck, and Poul Emsbo, *Rare Earth Element Mineral Deposits in the United States*, U.S. Geological Survey, Circular 1454, 2019, pp. 1-2, https://doi.org/10.3133/cir1454.

[6] "REE-bearing minerals are diverse and often complex in composition. At least 245 individual REE-bearing minerals are recognized; they are mainly carbonates, fluorocarbonates, and hydroxylcarbonates.... Many of the world's significant REE deposits occur in carbonatites, which are carbonate igneous rocks. The REEs also have a strong genetic association with alkaline magmatism. The systematic geologic and chemical processes that explain these observations are not well understood. Economic or potentially economic REE deposits have been found in (a) carbonatites, (b) peralkaline igneous systems, (c) magmatic magnetite-hematite bodies, (d) iron oxide-copper-gold (IOCG) deposits, (e) xenotime-monazite accumulations in mafic gneiss, (f) ion-absorption clay deposits, and (g) monazite-xenotime-bearing placer deposits." Bradley S. Van Gosen, Philip L. Verplanck, Robert R. Seal II, Keith R. Long, and Joseph Gambogi, *Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply*, ed. Klaus J. Schulz, John H. DeYoung, Jr., Robert R. Seal II, Dwight C. Bradley (Reston, VA: U.S. Geological Survey, 2017), p. O1, https://doi.org/10.3133/pp1802O.

[7] Geologic deposits of minerals are commonly discussed as *reserves* or *resources*; different countries may define these terms differently. Reserves commonly denote mineral deposits that could be profitably produced using available technology, at current prices; sub-classifications can include marginal and sub-economic reserves. Resources commonly denote mineral deposits that could be currently or potentially produced economically; resource sub-classifications can include measured, indicated, and inferred (U.S. Geological Survey, *Mineral Commodity Summaries*, 2020, pp. 195-198).

and infrastructure available at the deposit, specific type of REE contained in the deposit, and presence of uranium or thorium in the deposit, which can increase production costs.[8]

Global Resources

From the 1960s until around 1985, the United States was the world's largest producer of REE, with all production originating from the Mountain Pass mine in California. Starting in the mid-1980s, China began REE mining and extraction operations and became the largest contributor to global REE production. By the 2010s, China was producing nearly 85% of the world's supply of REE and supplying 95% of processed REE.[9] China imposed export restrictions on REE between 2010 and 2014, resulting in dramatic increases in REE prices during those years.[10] These high prices led to increased global exploration for REE deposits. The 40 largest exploration projects indicate over 3,000 million metric tons (Mt) of inferred resources (at various grades) in more than 15 countries.[11]

In addition to various REE exploration projects globally, there were 10 active REE mining operations in 2017 (**Table 1**).

Table 1. Active REE Mines in 2017

Deposit Name	Location	Resource (Mt)	Grade (REO, %)
Mount Weld	Australia	23.9	7.9
Buena Norte	Brazil	na	na
Bayan Obo	China	800	6
Daluxiang (Dalucao)	China	15.2	5
Maoniuping	China	50.2	2.89
South China clay deposits	China	na	0.05 – 0.4
Weishan	China	na	na
Karnasurt Mountain	Russia	na	na
Mountain Pass	United States	16.7	7.98
Dong Pao	Vietnam	na	na

Source: Bradley S. Van Gosen, Philip L. Verplanck, Robert R. Seal II, Keith R. Long, and Joseph Gambogi, *Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply*, ed. Klaus J. Schulz, John H. DeYoung, Jr., Robert R. Seal II, Dwight C. Bradley (Reston, VA: U.S. Geological Survey, 2017), Table O3, p. O12, https://doi.org/10.3133/pp1802O.

8 Uranium and thorium may be considered "source material" by the U.S. Nuclear Regulatory Commission (NRC), which states, "Source material is licensed and regulated to ensure that the material is used for safe, commercial uses and is not used by adversaries." Processing of these ores requires a source material license, adding to the production costs of the REE (NRC, "*Source Material*," https://www.nrc.gov/materials/srcmaterial.html).

9 Bradley S. Van Gosen, Philip L. Verplanck, and Poul Emsbo, *Rare Earth Element Mineral Deposits in the United States*, U.S. Geological Survey, Circular 1454, 2019, p. 4, https://doi.org/10.3133/cir1454.

10 For background on this REE supply interruption, see CRS In Focus IF11259, *Trade Dispute with China and Rare Earth Elements*, by Wayne M. Morrison.

11 Bradley S. Van Gosen, Philip L. Verplanck, Robert R. Seal II, Keith R. Long, and Joseph Gambogi, *Critical Mineral Resources of the United States—Economic and Environmental Geology and Prospects for Future Supply*, ed. Klaus J. Schulz, John H. DeYoung, Jr., Robert R. Seal II, Dwight C. Bradley (Reston, VA: U.S. Geological Survey, 2017), Table O4, pp. O14-O15, https://doi.org/10.3133/pp1802O.

Notes: Ordered by Location and Deposit Name; Mt: million metric tons; REO: rare earth oxide; na: not available. Reported resource information may be out of date for some deposits.

The USGS estimates that in 2019 China produced 132,000 metric tons of REO and the United States produced 26,000 metric tons (REO equivalent) of ores and compounds; the estimated global total REO production was 210,000 metric tons.[12] In 2019, estimates of REO equivalent production in Australia and Myanmar were approximately 22,000 metric tons in each country; production in India, Madagascar, and Russia was estimated to be 3,000 metric tons or less for each country in the same year.[13] REO are the commonly traded form of REE to be used in components and products. REO result from the extraction and refining processes using REE ores and compounds (or concentrates) as inputs.

Domestic Resources

The global REE supply shock related to Chinese export restrictions between 2010 and 2014 contributed to efforts to identify domestic REE resources. In addition to ongoing private exploration efforts, the USGS began implementation of the Earth Mapping Resources Initiative (Earth MRI) in 2019, which "is planned as a partnership between the U.S. Geological Survey (USGS), the Association of American State Geologists (AASG), and other Federal, State, and private-sector organizations."[14] The first steps of Earth MRI are to:

> forge cost-shared cooperative agreements between the USGS and State geological surveys; establish contracts with private industry to conduct geophysical and lidar surveys; offer partnership opportunities for collecting lidar data; and complete a preliminary national-scale data inventory of geologic framework and minerals data.[15]

Some U.S. deposits that contain or may contain economically recoverable quantities of REE are indicated below, followed by a list of additional locations where recoverable quantities of REE may be found.

Mountain Pass, CA

In a 2019 report the USGS states that the Mountain Pass deposit "produced most of the REEs mined in the United States since the late 1960s and contains proven and probable reserves totaling 18.4 million metric tons of carbonatite ore averaging 7.98 percent rare earth oxide (REO) using a cutoff grade of 5 percent REO."[16] The Mountain Pass mine produced all of the domestically mined REE in 2019, which was exported for processing.[17] One report indicates that MP Materials, the company operating the Mountain Pass mine, is planning to install the necessary equipment to process its rare earth concentrate into REO; it reportedly exports its rare earth

[12] U.S. Geological Survey, *Mineral Commodity Summaries*, 2020, p. 133.

[13] U.S. Geological Survey, *Mineral Commodity Summaries*, 2020, p. 134.

[14] Warren C. Day, *The Earth Mapping Resources Initiative (Earth MRI): Mapping the Nation's Critical Mineral Resources*, U.S. Geological Survey, Fact Sheet 2019–3007, 2019, p. 1, https://doi.org/10.3133/fs20193007.

[15] Ibid.

[16] Bradley S. Van Gosen, Philip L. Verplanck, and Poul Emsbo, *Rare Earth Element Mineral Deposits in the United States*, U.S. Geological Survey, Circular 1454, 2019, p. 9, https://doi.org/10.3133/cir1454.

[17] U.S. Geological Survey, *Mineral Commodity Summaries*, 2020, p. 133.

concentrate to Asia for processing.[18] MP Materials indicates that its facilities consist "of fully integrated and co-located mining and processing capabilities."[19]

Bokan Mountain, AK

The Bokan Mountain deposit is located on federal lands in southern Alaska on Prince of Wales Island. The surface land is managed by the U.S. Forest Service (FS), and the subsurface mineral estate is managed by the Bureau of Land Management (BLM). Bokan Mountain lies within the Tongass National Forest and is the site of the closed Ross Adams uranium mine; uranium, in varying concentrations, is found in and around areas of the REE deposit.

Ucore, a Canadian company, has acquired 512 mining claims covering almost 15 square miles of the mountain.[20] Ucore filed a proposed plan of operations with FS in 2012,[21] which includes a proposed underground mining operation that aims to produce 375 metric tons of REE concentrate per day, for a mine life of 11 years, from an estimated resource of 5.2 Mt.[22] Ucore's initial exploration of the mineral resource indicates a LREE grade of 0.394% and a HREE grade of 0.259%, which it states is the highest grade of any HREE deposit in the United States.[23] After additional analysis, Ucore updated its LREE and HREE resource findings, indicating that six additional critical minerals may also be recoverable from its planned mining operation (including beryllium, hafnium, niobium, titanium, vanadium and zirconium).[24] Ucore states that it is focused on commercializing its proprietary solvent extraction technology, which it would employ at a location in Ketchikan, AK, near the Bokan Mountain mine.[25]

Bear Lodge, WY

The Bear Lodge deposit is located near the town of Sundance, WY, on federal land managed by the FS. Rare Element Resources Ltd. (RER) owns the interests in 499 mining claims and 640 acres that it intends to develop into the Bear Lodge Critical Rare Earth Project.[26] The Bear Lodge deposit is estimated to contain 18 Mt of ore at a grade of 3.05% REO, representing approximately 549,000 tons of REO over the expected 38-year life of the mine.[27] In 2016, FS suspended RER's application process at RER's request, which was in the process of preparing a Draft

[18] NS Energy, "Mountain Pass Rare Earth Mine," https://www.nsenergybusiness.com/projects/mountain-pass-rare-earth-mine/.

[19] MP Materials, "Our Facility," https://www.mpmaterials.com/what-we-do/#our-facility.

[20] Tetra Tech, *Preliminary Economic Assessment Bokan Mountain Rare Earth Element Project*, Document No. 1196000100-REP-R0001-02, 2013, p. 4-4, https://www.ucore.com/s/NI-43-101-Preliminary-Economic-Assessment-PEA-Technical-Report-for-Bokan-Mountain-Heavy-REE-Project.

[21] U.S. Forest Service, *Environmental Assessment, Ucore Bokan Mountain Mining Plan of Operations*, June 2013, https://www.fs.usda.gov/nfs/11558/www/nepa/85247_FSPLT3_1447554.pdf.

[22] Ibid., p. 1-2.

[23] Ibid., p. 1-5, and Ucore, "Home," https://www.ucore.com/.

[24] Newsfile, "Ucore Increases Bokan Mineral Resource with Critical Co-Products," October 15, 2019, https://www.newsfilecorp.com/release/48774/Ucore-Increases-Bokan-Mineral-Resource-with-Critical-CoProducts.

[25] Ibid. and Ucore, "Home," https://www.ucore.com/.

[26] Rare Element Resources Ltd. (RER), "Rare Element Resources Ltd.," https://www.rareelementresources.com/company.

[27] Roche Engineering, Inc., *Bear Lodge Project Canadian NI 43-101 Prefeasibility Study Report on the Mineral Reserves and Development of Bull Hill Mine, Wyoming*, 2014, p. 1-2, https://www.rareelementresources.com/bear-lodge-project/project-related-studies-reports/2015/08/24/ni-43-101-technical-report-on-positive-pre-feasibility-results-for-bear-lodge-project.

Environmental Impact Statement (DEIS).[28] RER would use crushing, screening, and gravity separation at the mine site, and then truck the upgraded REE material to its planned processing plant in Upton, WY, for extraction and separation into REO using its proprietary technology.[29]

Round Top, TX

The Round Top deposit is located on state lands in Hudspeth County, TX. The Texas Mineral Resources Corporation (TMRC) holds state leases on 950 acres encompassing the deposit.[30] Exploration of the Round Top deposit indicates combined measured and indicated resources to include 304,000 metric tons of recoverable REO; other elements in the deposit that might be recovered include niobium, hafnium, tantalum, tin, uranium and thorium.[31] TMRC is pursuing an initial 20-year mining and on-site extraction operation that aims to produce 2,212 metric tons per year of REO (70% HREE) and 8,956 metric tons per year of lithium carbonate, among other products.[32]

Elk Creek, NE

The Elk Creek deposit is located in Johnson County, NE, under privately owned land. NioCorp has retained 100% of the mineral and/or surface rights to 4,038 acres of the deposit.[33] The Elk Creek deposit contains the REE scandium, and the critical minerals niobium and titanium, among other elements. If sufficient funds become available, NioCorp plans to pursue mining and extraction of these three elements over an estimated mine life of 36 years, estimating an average annual production of 95 metric tons of scandium trioxide; 7,220 metric tons of ferroniobium; and 11,642 metric tons of titanium dioxide.[34]

Other Domestic Deposits

The USGS indicates other deposits or regions that could contain economical quantities of REE,[35] including

- Iron ore mining tailings piles in Mineville, NY, estimated to contain 9 million tons of REE tailings;

[28] U.S. Forest Service, "Bear Lodge Project—Rare Earth Mine—Suspended," press release, January 22, 2016, https://www.fs.usda.gov/project/?project=37875.

[29] RER, "Proposed Operations," https://www.rareelementresources.com/bear-lodge-project/proposed-operations.

[30] Texas Mineral Resources Corporation (TMRC), "Rare Earths—Round Top," http://tmrcorp.com/projects/rare_earths/ . TMRC and USA Rare Earth, LLC, entered into a joint venture in November 2018 (TMRC, "TMRC Secures Development and Funding Partner for Round Top Rare Earth Project," usarareearth.com/wp-content/uploads/2019/08/TMRC_USA-Rare-Earth-Press-Release-Nov-20-2018.pdf).

[31] Gustavson Associates, *Amended NI 43-101 Preliminary Economic Assessment Round Top Project Sierra Blanca, Texas*, 2014, p. 13, http://tmrcorp.com/_resources/reports/Amended_TRER_NI43-101_PEA_FINAL_28April2014.pdf.

[32] TMRC and USA Rare Earth, "Texas Mineral Resources and USA Rare Earth Report Significantly Upgraded Resource and Confirm Prior Potential Economics in Updated Round Top Preliminary Economic Assessment," http://usarareearth.com/wp-content/uploads/2019/08/2019-PEA-Draft-Press-Release-FINAL.pdf.

[33] Nordmin Engineering Ltd., *NI 43-101 Technical Report Feasibility Study, Elk Creek Superalloy Materials Project, Nebraska*, Project # 18000-01, 2019, pp. 31-32, http://www.niocorp.com/wp-content/uploads/180001_FINAL_43-101_FS_NioCorp_AS_FILED.pdf.

[34] NioCorp., "Overview of the Elk Creek Project," http://www.niocorp.com/elk-creek-project/.

[35] Bradley S. Van Gosen, Philip L. Verplanck, and Poul Emsbo, *Rare Earth Element Mineral Deposits in the United States*, U.S. Geological Survey, Circular 1454, 2019, pp. 11-12, https://doi.org/10.3133/cir1454. For more examples, see Table 1 in Jane M. Hammarstrom and Connie L. Dicken, *Focus Areas for Data Acquisition for Potential Domestic Sources of Critical Minerals—Rare Earth Elements*, U.S. Geological Survey, Open-File Report 2019–1023, 2019, p. 3.

- Phosphorite deposits (belonging to the Upper Ordovician horizon) in seven states, including one measuring 2,000 square kilometers in Arkansas, estimated to contain 1.3 million metric tons of REE;
- The Lemhi Pass district along the Montana-Idaho border; and
- The Wet Mountains mineral district in Colorado.

Improving Extraction and Recycling to Increase Supply

In addition to new deposits of REE, changes to existing extraction and recycling technologies could increase the secondary supply of REE by allowing the use of otherwise unusable sources of REE. New extraction technologies or lower cost extraction technologies can allow lower-grade deposits to be mined economically (i.e., lower a mine's cut-off grade). Such technologies can also potentially be applied to new sources of REE, such as wastewater or recycled waste.

Extraction Technologies

Typical REE production follows processes common to the production of many metals. After the ore is mined, it is crushed and milled to a desired size. The milled product may be subjected to a variety of separation processes, including the use of surfactants, magnetics, and physical forces (e.g., concentrators, thickeners, cyclones). The concentrated ore is typically subjected to solvent extraction, commonly through acid leaching. Solvent extraction is the most common technology employed to produce REO, at various concentrations. One source states that 100% of current commercial separation is through solvent extraction.[36]

While solvent extraction is well understood, variations in mineralogy or chemical composition can result in an uneconomical process. If separation is not economically viable, the REE will be discarded as waste. The USGS notes:

> Unlike many traditional metal commodities hosted in relatively simple minerals (as examples, copper in chalcopyrite [CuFeS] or lead in galena [PbS]), most of the REEs are hosted by minerals that have complex chemical formulas, presenting more of a challenge to process and extract the REEs.[37]

One example of a low-grade REE deposit that is economically viable due in part to low-cost separation is the South China clay deposit. According to the USGS,

> Although these clay deposits typically contain modest REE concentrations (approximately 0.03 to 0.2 percent REEs), they have become economically viable deposits, because (1) they are referentially enriched in the high-value HREEs; (2) the REEs are easily extracted from the clays with weak acids; and (3) mining costs are low.[38]

In addition to exploring and developing REE deposits, some REE mining companies are researching extraction technologies. Innovation Metals Corp. (IMC), a wholly owned subsidiary of Ucore (the company pursing development of the Bokan Mountain deposit), developed an enhanced solvent extraction technology, RapidSX, which it expects to provide significant technical and economic efficiency for producing commercial-grade REO.[39] To help fund the

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[36] Ucore, "RapidSX," https://www.ucore.com/rapidsx.

[37] Bradley S. Van Gosen, Philip L. Verplanck, and Poul Emsbo, *Rare Earth Element Mineral Deposits in the United States*, U.S. Geological Survey, Circular 1454, 2019, p. 13, https://doi.org/10.3133/cir1454.

[38] Ibid.

[39] Newsfile, "Ucore Announces Technical Services Agreement with Innovation Metals Corp. for RapidSX(TM) Rare

development of RapidSX, IMC received $1.8 million in assistance from the U.S. Department of Defense's (DOD's) Army Research Laboratory.[40]

Ongoing research, supported by federal and private funds, is testing alternatives to solvent extraction. A recent study notes that research on REE extraction from secondary resources in aqueous solutions commonly focuses on "several techniques, including ion exchange, bio-sorption, adsorption, solvent extraction, and precipitation."[41] In addition to critiquing these techniques, the study proposes electrodialysis as an alternative to solvent extraction, and reports successful application of the technology to the separation of scandium in a laboratory setting. However, successful application in the laboratory does not ensure economic viability for the process for an actual REE deposit.

New technologies or new applications of existing technologies could allow otherwise uneconomical REE mineral formations or REE products to become economically viable. Coal, which can contain REE in concentrations similar to other deposits,[42] could potentially serve as a source of REE if extraction technologies prove to be viable. Coal products, such as fly ash from combusted coal or acid mine drainage from coal mines, could potentially become viable sources of REE if extraction technologies can be found to economically separate and concentrate the REE in these sources.[43]

Some ongoing federally funded research into the use of coal and coal products as sources of REE focuses on creating economically viable technologies to extract the REE from these sources. One example is the Feasibility of Recovering Rare Earth Elements program at the National Energy Technology Laboratory (NETL), whose objectives include "Recover REEs from coal and coal by-product streams," and "Advance existing and/or develop new, second-generation or transformational extraction and separation technologies."[44]

Recycling Technologies

Recycling products that contain REE represents a potential source of REE. As the number of products containing REE increases, the amount of REE potentially available from recycled products increases. However, recycling such products also poses separation and extraction challenges. For example, two common REE components (or powders) used in numerous products are magnets and phosphors. REE magnets are commonly used as components in hard disk drives (HDD), and REE phosphors are commonly used as fluorescent powders inside fluorescent light bulbs (FB). While HDD and FB are known to contain REE, they will not be available for recycling until the end of the products' lives, potentially resulting in unpredictable supplies of recyclable material. If the products enter the recycled waste stream, the REE components must be

Earth Element Separation Technology Testing," February 14, 2020, https://www.newsfilecorp.com/release/52447/Ucore-Announces-Technical-Services-Agreement-with-Innovation-Metals-Corp.-for-RapidSXTM-Rare-Earth-Element-Separation-Technology-Testing.

[40] Ibid.

[41] Changbai Li, Deepika L. Ramasamy, and Mika Sillanpää, et al., "Separation and concentration of rare earth elements from wastewater using electrodialysis technology," *Separation and Purification Technology*, vol. 254 (2021), pp. 1-7.

[42] Vladimir V. Seredin, Shifeng Dai, and Yuzhuang Sun, et al., "Coal Deposits as Promising Sources of Rare Metals for Alternative Power and Energy-Efficient Technologies," *Applied Geochemistry*, vol. 31 (2013), pp. 1-11.

[43] Clint Scott and Allan Kolker, *Rare Earth Elements in Coal and Coal Fly Ash*, U.S. Geological Survey, Fact Sheet 2019–3048, 2019, pp. 1-4, https://doi.org/10.3133/fs20193048.

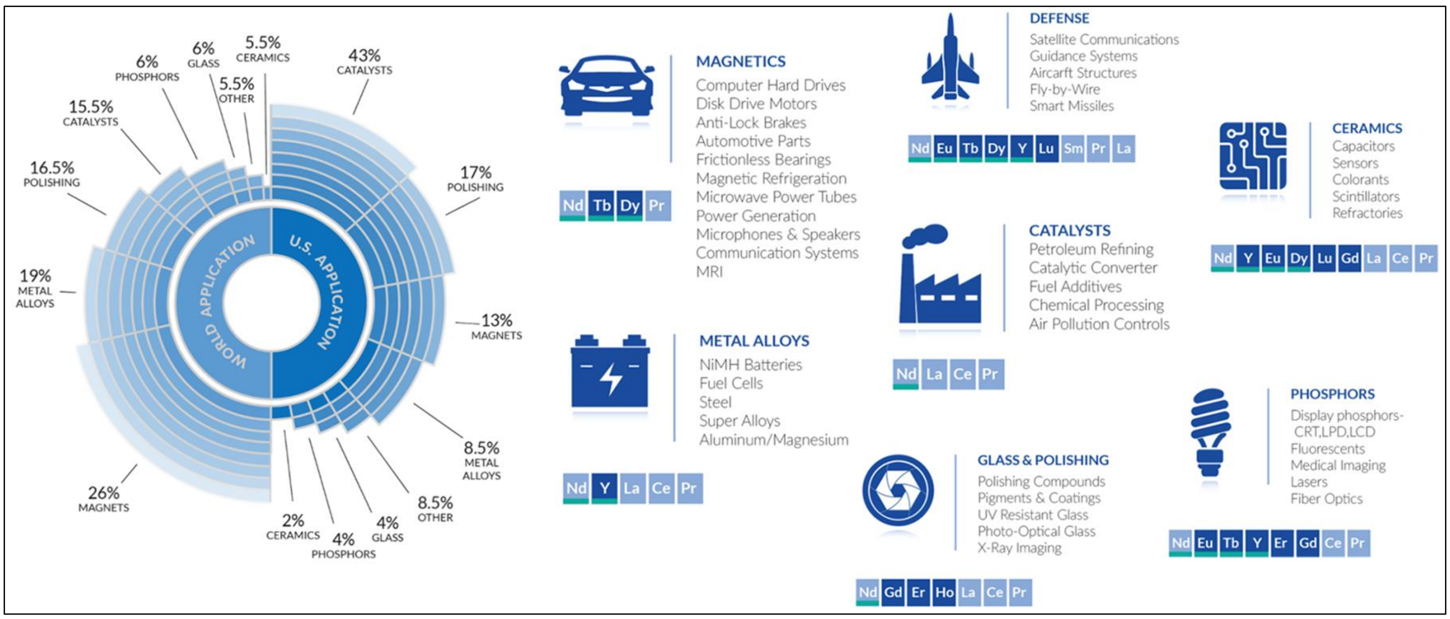
[44] NETL, "REE-CM Program," https://www.netl.doe.gov/coal/rare-earth-elements/program-overview/background.

able to be extracted from the products and processed economically. Research into these and other challenges is ongoing.[45]

Demand for Rare Earth Elements

REE are used in many components in many products; **Figure 1** provides examples of sectors and uses of REE globally and domestically. Examples of components and products that contain REE include catalysts (for use in oil refineries and automobiles), permanent magnets (for use in cell phones, wind turbines, and electric vehicle motors), fiber optics (for use in signal amplifiers and lasers), and lighting/displays (for use in fluorescent lights, cell phone screens, and computer displays). Although the United States exported some REE concentrate in 2019, it imported 100% of REE metals and compounds.[46] According to the USGS, "The estimated value of rare-earth compounds and metals imported by the United States in 2019 was $170 million."[47]

Figure 1. Global Demand and Domestic Consumption of REE



Source: National Energy Technology Laboratory (NETL), "REE-CM Program," https://www.netl.doe.gov/coal/rare-earth-elements/program-overview/background.

[45] For an example of research on recycling REE in fluorescent powders used in lighting, see Ajay B. Patil, Mohamed Tarik, and Rudolf P.W.J. Struis, et al., "Exploiting End-of-Life Lamps Fluorescent Powder E-waste as a Secondary Resource for Critical Rare Earth Metals," *Resources, Conservation, and Recycling*, vol. 164 (2021), pp. 1-8. For an example of research on recycling REE in HDD magnets, see S. T. Abrahami, Y. Xiao, and Y. Yang, "Rare-Earth Elements Recovery from Post-Consumer Hard-Disc Drives," *Mineral Processing and Extractive Metallurgy*, vol. 124, no. 2 (2015), pp. 106-115. For a life-cycle analysis of HDD, including technology options that do not require separation of REE from host materials, see Hongyue Jin, Kali Frost, and Ines Sousa, et al., "Life Cycle Assessment of Emerging Technologies on Value Recovery from Hard Disk Drives," *Resources, Conservation, and Recycling*, vol. 157 (2020), pp. 1-13.

[46] U.S. Geological Survey, *Mineral Commodity Summaries*, 2020, pp. 132-133.

[47] U.S. Geological Survey, *Mineral Commodity Summaries*, 2020, p. 132.

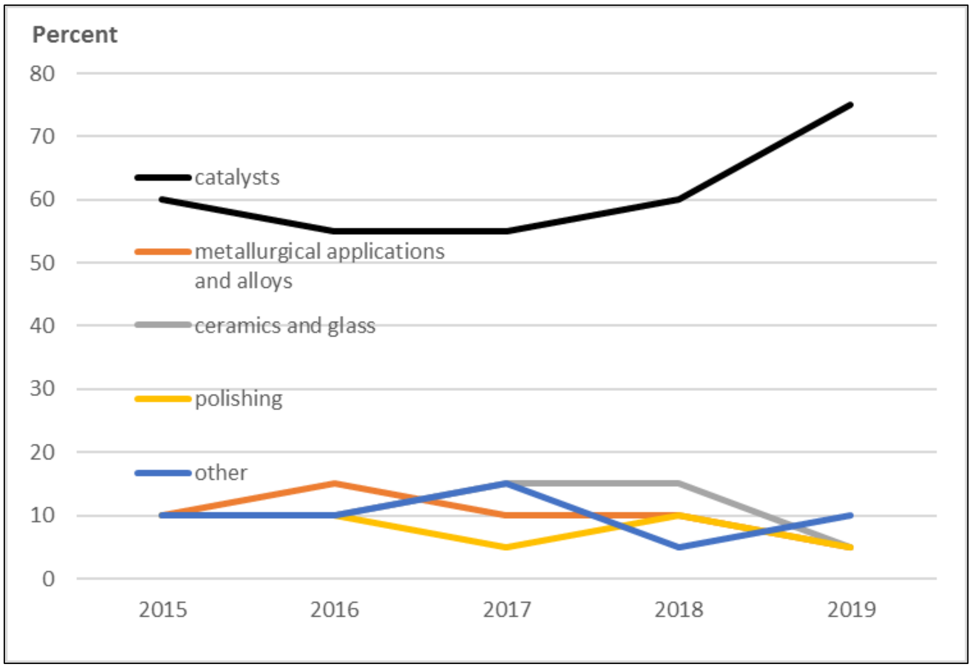
Notes: The figure provides examples of uses and sectors. Source and year of data is not given in original. Light-blue shaded elements are LREE; dark-blue shaded elements are HREE; green underscores denote "critical REE," as defined by NETL.

Domestic Consumption by Sector

Tracking domestic consumption and demand for REE poses challenges, due in part to the many components and products containing REE. For example, if a foreign-manufactured cell phone is imported, the REE contained in it (e.g., phosphors in the display, magnets in the speaker and motor) will not be included in domestic demand figures for REE. However, if such REE-containing components were manufactured in the United States and exported for inclusion in the cell phone (independent of its final sale location), the REE would be included as domestic consumption in the appropriate sector.[48]

Figure 2 shows, by sector, relative domestic REE consumption between 2015 and 2019 (the values for 2019 are estimates). Domestic REE use in catalysts consumed more than 50% of the total for each of the five years shown. Consumption in the other four sectors ranged from 5% to 15%.

Figure 2. Relative Domestic Consumption of REE by Sector



Source: U.S. Geological Survey, *Mineral Commodity Summaries*, 2020, p. 132.

Notes: Excludes scandium. Values for 2019 are estimates.

[48] According to the Bureau of Economic Analysis (BEA), in the U.S. Department of Commerce, "The end-use classification system for goods ... is based on the principal use rather than the physical characteristics of the merchandise" (*Concepts and Methods of the U.S. National Income and Product Accounts*, 2017, p. 8-7, available at https://www.bea.gov/sites/default/files/methodologies/nipa-handbook-all-chapters.pdf.). For more information on how commodities and products are classified for production, consumption, and trade, see the *North American Industry Classification System* (Executive Office of the President, Office of Management and Budget, 2017, available at https://www.census.gov/eos/www/naics/2017NAICS/2017_NAICS_Manual.pdf).

The trends shown in the figure can be interpreted differently. One view may be that the distribution of use of REE among these sectors is relatively stable, with the greatest change stemming from estimated data in 2019. Another view may highlight that consumption within a sector varies considerably, as the non-catalyst series frequently change ± 5% of the total from one year to the next (and the variation in the catalyst series is even greater). Excluding the estimated catalyst value for 2019, none of the series appears to have definitive positive or negative trends.

Demand for components and products containing REE can change for numerous reasons, some of which include large-scale changes in a given sector (e.g., increased demand for more electricity produced from wind turbines containing permanent magnets made with REE), changes in product technology (e.g., introduction of LED lights, which use less REE material than fluorescent lights), and price-induced substitution (e.g., in permanent magnets, where the higher cost of one REE results in the use of a lower-cost alternative, with an acceptable lower level of performance).

REE Prices

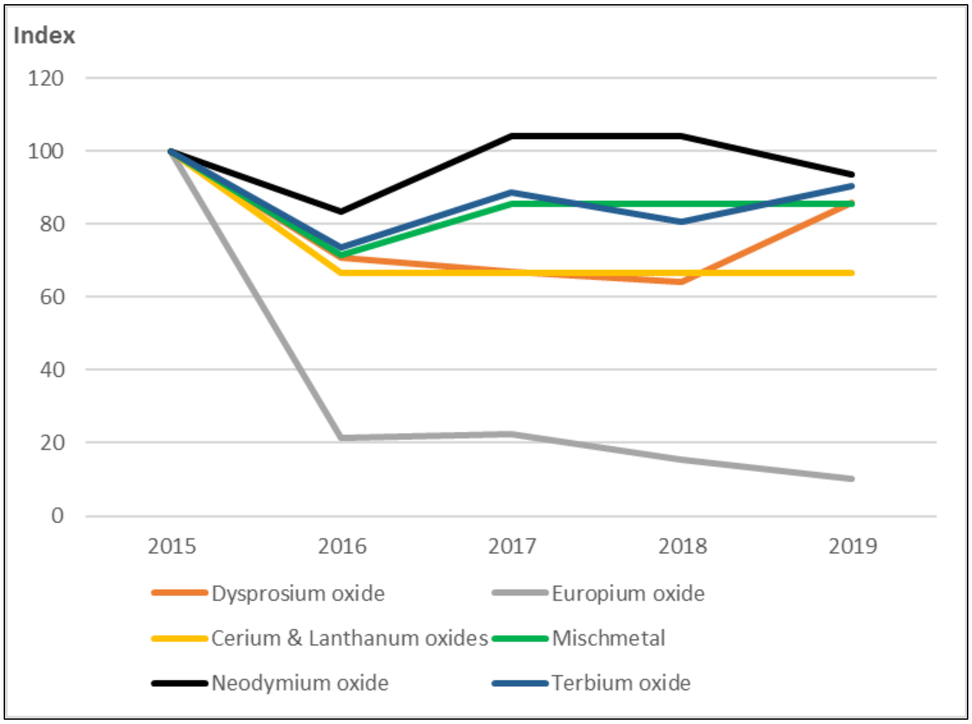
For commodities traded in markets, changes reflecting demand preferences, quantities demanded, and availability of supply are generally captured in movements in prices. Prices among different REOs vary considerably: in 2018 the price per kilogram of terbium oxide was $455, while the prices per kilogram for cerium and lanthanum oxides were $2.[49] To highlight recent price trends in REOs, **Figure 3** shows price indices for seven REOs between 2015 and 2019 (the price data underlying the 2019 values are estimates). The base year of the index is 2015; the index values are equivalent to percentage values. This presentation of the data highlights relative changes in each series. The higher relative values for 2015 capture the then-ongoing adjustments to the elimination of export restrictions that were still in place in 2014 in REO markets. The figure shows that relative prices continued to fall as China increased quantities of REO available for export.[50]

The price indices highlight what some may consider a return to a more stable REO market: from 2016 through 2019 prices fluctuated, but the changes do not appear to be market disrupting. These data could reflect greater supply of REE meeting growing demand; or the high demand for some REE during the supply disruptions may have led manufacturers to incorporate alternatives, thus freeing REE to be used by others.

[49] U.S. Geological Survey, *Mineral Commodity Summaries*, 2020, p. 132.

[50] For more information on the history of global REE prices, see Viviana Fernandez, *Resources Policy*, vol. 53 (2017), pp. 26-45.

Figure 3. Relative REO Price Changes



Source: CRS calculations using nominal price data from U.S. Geological Survey, *Mineral Commodity Summaries*, 2020, p. 132.

Notes: Cerium and Lanthanum oxide values are identical. See source for purity grade of each category. Mischmetal is an alloy of REE. Values for 2019 are estimates.

Policy Topics and Legislative Activity

Legislation has been introduced in the 116th Congress to address concerns related to the supply and demand of REE. The House and Senate have each held at least one hearing on critical minerals, including discussion of REE during the second session of this Congress.[51] This section discusses selected bills and policy options related to some of these bills, focusing on those that would have a direct impact on REE. This section does not discuss bills indirectly impacting REE through broad changes to large sectors (e.g., bills altering the proportion of electricity supplied from renewable resources, which often employ REE components). Some discussion of critical minerals is included, as the current definition of critical minerals includes REE. Congress has debated whether to increase exploration and development of critical mineral resources, including REE, on federal lands, but this report does not discuss that issue in detail.[52] This section does not consider uses of or increases in authorizations to the Defense Production Act, which can be used

[51] Two hearings include U.S. Congress, House Committee on Science, Space, and Technology, Subcommittee on Energy, *Research and Innovation to Address the Critical Materials Challenge*, 116th Cong., 2nd sess., December 10, 2019, and U.S. Congress, Senate Committee on Energy and Natural Resources, *Full Committee Hearing on the Impact of COVID-19 on Mineral Supply Chains*, 116th Cong., 2nd sess., June 24, 2020.

[52] For more information on these topics, including legislation proposed in the 116th Congress, see CRS Report R46278, *Policy Topics and Background Related to Mining on Federal Lands*, by Brandon S. Tracy.

to fund REE-related activities,[53] nor does it consider authorizations for the National Defense Stockpile to acquire certain REE compounds.[54] Some additional legislative options are discussed.

In addition to the stand-alone bills discussed in this section, two comprehensive energy and minerals bills in the 116th Congress address U.S. REE supply. S. 2657, the American Energy Innovation Act of 2020,[55] was considered by the Senate starting March 5, 2020. On March 9, a cloture motion on the bill did not pass on a 15-73 vote. The bill incorporates language from several energy and mineral bills reported by the Senate Committee on Energy and Natural Resources. H.R. 4447, the Clean Economy Jobs and Innovation Act, was passed by the House on September 24, 2020. The bill incorporates language from several energy and mineral bills introduced and/or reported by various House committees. Among other provisions, S. 2657 and H.R. 4447 would authorize programs related to the domestic supply of REE, discussed below.

REE from Coal and Coal Byproducts

The United States contains vast coal resources and coal waste associated with decades of coal mining and combustion. Coal contains some amounts of various REE, coal and coal byproducts represent a potentially economical source of REE. S. 2657 and H.R. 4447 would authorize the U.S. Department of Energy (DOE) to develop technologies for the extraction of REE from coal and coal byproducts. These bills would formally authorize a program, part of the Clean Coal and Carbon Management program in the National Energy Technology Laboratory, which was appropriated funds in FY2014 for similar purposes.[56] The Senate bill would authorize appropriations of $23 million per year from FY2021 through FY2027 to fund this program, while the House bill would authorize appropriations of approximately $25 million per year from FY2021 through FY2025. These bills include similar or identical text from S. 1052, S. 1317, S. 4324, S. 4775, and H.R. 3607.[57]

Policymakers could consider different policy options to address the supply of domestic REE and/or domestic coal/coal byproducts' production and use. Finding additional uses for domestic coal appeals to some, as falling demand for coal as a fuel source has had negative economic impacts on some coal mining-dependent communities; spurring demand for coal through REE could help these affected communities. Additionally, producing REE from acid mine drainage could potentially reduce the financial burden of mitigating the environmental damage associated with such drainage. Some argue that additional uses of coal may result in more coal being combusted, resulting in the release of additional carbon dioxide (i.e., greenhouse gas) emissions

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[53] The Urban Mining Company, which recycles REE magnets into new REE magnets, indicates that it has been awarded $28.8 million from the U.S. Department of Defense, through a Defense Production Act, Title III program (Colin Staub, "Rare Earth Recycler Draws $28 Million in Federal Funding," *E-Scrap News*, September 11, 2020, https://resource-recycling.com/e-scrap/2020/09/11/rare-earth-recycler-draws-28-million-in-federal-funding). For more information on the Defense Production Act, see CRS Report R43767, *The Defense Production Act of 1950: History, Authorities, and Considerations for Congress*, by Michael H. Cecire and Heidi M. Peters.

[54] S. 1790, the National Defense Authorization Act for Fiscal Year 2020, authorizes the use of up to $37,420,000 for the acquisition of five materials, including cerium and lanthanum compounds.

[55] The American Energy Innovation Act is a substitute amendment to S. 2657, the Advanced Geothermal Innovation Leadership (AGILE) Act of 2019, as reported by the committee. For more information on S. 2657, see CRS Report R46372, *Summary and Analysis of S. 2657, the American Energy Innovation Act*, coordinated by Brent D. Yacobucci.

[56] For background on the Senate bill, see S.Rept. 116-74, available at https://www.congress.gov/116/crpt/srpt74/CRPT-116srpt74.pdf.

[57] S. 1052, Rare Earth Element Advanced Coal Technologies Act; S. 1317, American Mineral Security Act; S. 4324, Restoring Critical Supply Chains and Intellectual Property Act; S. 4775, Delivering Immediate Relief to America's Families, Schools, and Small Businesses Act; and H.R. 3607, Fossil Energy Research and Development Act of 2019.

and other pollutants. Policymakers could consider funding non-coal research options related to exploiting higher quality deposits or other sources of REE. Others question the use of federal funds for research on activities that may have benefits limited to a few private entities.

Additional Critical Mineral and REE Research

Funding research to lower the costs of extracting REE from minerals and REE-containing components is a potential means of increasing domestic REE supply. S. 2657 and H.R. 4447 would authorize appropriations for and direct the DOE to promote the efficient production, use, and recycling of critical minerals throughout the supply chain. The proposed research program to achieve these goals is similar to those articulated for the Critical Materials Institute (CMI), which DOE established in FY2013 as one of its Energy Innovation Hubs. DOE did not request appropriations for CMI in FY2019, FY2020, or FY2021, stating "prior year appropriations will be used to conduct an orderly wind-down and termination of the existing institutes."[58] Congress appropriated $167 million in FY2019 and $199 million in FY2020 for Energy Efficiency and Renewable Energy-Research and Development (EERE-R&D) Consortia activities, which include those of CMI.[59] The House and Senate bills include similar or identical text from S. 1317, S. 4324, S. 4775, and H.R. 7061. H.R. 4447 would authorize appropriations of approximately $135 million per fiscal year from FY2021 through FY2025. S. 2657 would authorize appropriations of $50 million per fiscal year from FY2021 through FY2029 for these and related activities; a specific amount is not indicated for the critical minerals research program.

H.R. 4447 also contains provisions that would direct DOE to create a research program related to recycling critical minerals from energy storage systems. Three other bills, S. 3694, S. 4537, and H.R. 7812, would direct DOD to establish a grant program to encourage the domestic development of critical minerals, among other provisions.[60] These bills would authorize appropriations of $50 million per year for four years.

Additional legislative options exist to complement some provisions in these introduced bills. As research continues to investigate how recycled REE products and components may be introduced into the REE supply chain, one type of option to reduce the risks of unstable supplies of recycled materials could include a federal program encouraging recycling of REE products. A variety of recycling options and programs exist throughout the domestic economy, including private sector recycling companies and ordinances requiring separation of household recyclables. Another example includes state-level beverage container deposit programs (sometimes called "bottle bills"), which could serve as a model for recycling REE from discarded consumer products. The National Conference of State Legislatures describes these programs in the following manner.

> When a retailer buys beverages from a distributor, a deposit is paid to the distributor for each container purchased. The consumer pays the deposit to the retailer when buying the beverage, and receives a refund when the empty container is returned to a supermarket or other redemption center. The distributor then reimburses the retailer or redemption center the deposit amount for each container, plus an additional handling fee in most states.

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[58] U.S. Department of Energy (DOE), *FY2019 Congressional Budget Justification*, Volume 3 Part 2, 2018, p. 176, DOE, *Congressional Budget Request*, Volume 3 Part 2, 2019, p. 166, and DOE, *FY2021 Congressional Budget Request*, Volume 2, 2020, p. 250.

[59] DOE, *FY2021 Congressional Budget Request*, Volume 2, 2020, p. 251.

[60] S. 3694, ORE Act; S. 4537, RECOVERY Act; and H.R. 7812, ORE Act.

> Unredeemed deposits are either returned to the state, retained by distributors, or used for program administration.[61]

Such programs could be initiated at a state or federal level. Programs implemented at the state level could potentially benefit from tailoring programs to consumer behavior at a more granular scale. A federal program might have an advantage in coordinating a limited number of large manufacturers of REE products and an expected limited number of large REE extraction facilities using recycled products as inputs. Authorizing and funding such a program at the federal level could potentially mitigate problems experienced by some state container deposit programs, including payments for products whose sales pre-dated deposit assessments. A deposit and recycling program might require consideration of implementation aspects, such as collection and shipping of products containing REEs, handling of potentially toxic or unsafe products, and returning recycled REEs into commerce.

Tax Incentives for the Supply and Consumption of Domestic REE

Reducing taxes assessed on commercial activities is a potential means of stimulating investment. Investments in sectors with high initial costs, such as mines and ore refining operations, may be accelerated if tax incentives allow for earlier expected profitability. Among other provisions, S. 3694, S. 4537, H.R. 7812, and H.R. 8143 would provide tax incentives for domestic production and purchase of certain domestic critical minerals (defined in the legislation). The incentives would include full (100%) expensing (immediate deduction from taxable income) for qualified property involved in extracting critical minerals and metals from deposits in the United States; a special allowance (100% depreciation deduction) for nonresidential real property; and a cost deduction (200%) for the purchase of critical minerals and metals extracted within the United States.

Such tax incentives could potentially reduce net operating costs of firms producing and purchasing domestic REE minerals and products. As the Congressional Budget Office has not scored these bills, the potential impacts on federal revenue and the economy are not available. The legislation is silent on responding to changes in the supply and demand of critical minerals.

Additional legislative options exist to complement some provisions in these introduced bills. One option would include the imposition of a federal excise tax on some REE products. The excise tax or taxes could be applied generally to REE products from imported sources, or the tax could target products containing REE deemed critical for other uses. Congress could try to control the market-distorting effects of such taxes by varying the tax rate. For example, if the supply of erbium, which is commonly used in fiber optic amplifiers, becomes scarce, an excise tax could target uses of erbium in products other than fiber optic amplifiers. The increased costs would be expected to either reduce erbium demand in products other than fiber optic amplifiers or provide revenue that could be directed to the fiber optics sector to procure erbium or erbium substitutes from more expensive sources. Another option for the use of the revenue from such excise taxes includes offsetting the tax incentives included in these introduced bills. Managing excise taxes on multiple products or REE could prove challenging, especially on internationally traded commodities subject to supply and demand volatility.

[61] National Conference of State Legislatures, "State Beverage Container Deposit Laws," March 13, 2020, https://www.ncsl.org/research/environment-and-natural-resources/state-beverage-container-laws.aspx.

REE Cooperative and Corporation

Among other provisions, S. 2093 and H.R. 4410 would establish a federally chartered cooperative to process domestic and international sources of REE ores and materials containing thorium into products for sale. A federally chartered corporation would accept and store all radiological material (e.g., thorium) produced by the cooperative and sell any valuable materials, and could conduct research on new uses of such materials. The cooperative and corporation would be privately funded and operated.

The presence of thorium (or other radiological minerals) in REE deposits can add to overall costs of production, as the thorium becomes regulated source material during processing.[62] A cooperative/corporation could create a scale of operations that could overcome these additional costs that may render smaller operations unprofitable. In the absence of federal funding, it is not clear whether the federally chartered cooperative and corporation would be any more viable than a similar cooperative and corporation created by private sector entities.

These bills suggest that a federally chartered corporation could eliminate the higher costs a REE mining operation faces if the ore body contains thorium by taking ownership of thorium materials produced by cooperative members. It is unclear how a federally chartered cooperative could reduce the costs associated with the presence of thorium, as thorium materials would be expected to be regulated at the mine, where physical refining (e.g., crushing, sorting, floatation separation) can increase thorium concentrations to those regulated as source material. If the cooperative and corporation were to receive ore directly from the REE mine, they would likely face the higher costs associated with transportation of the ore and disposal of the tailings.

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Disclaimer

[62] Uranium and thorium ores may be considered source material by the U.S. Nuclear Regulatory Commission (NRC); processing of these ores requires a source material license, adding to the production costs of the REE (NRC, "Source Material," https://www.nrc.gov/materials/srcmaterial.html).