United States Government Accountability Office

Report to the Ranking Member, Subcommittee on Interior, Environment, and Related Agencies, Senate Committee on Appropriations

June 2022

CRITICAL MINERALS

Building on Federal Efforts to Advance Recovery and Substitution Could Help Address Supply Risks

GAO-22-104824

GAO Highlights

Highlights of GAO-22-104824, a report to the Ranking Member, Subcommittee on Interior, Environment, and Related Agencies, Senate Committee on Appropriations

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Building on Federal Efforts to Advance Recovery and Substitution Could Help Address Supply Risks

Why GAO Did This Study

The U.S. is heavily reliant on imports of many minerals, such as cobalt and lithium, which are essential for manufacturing advanced technologies (see figure). Supply chains for many of these minerals are also vulnerable to various risks, such as foreign government actions. In 2018, Interior designated 35 minerals and mineral groups whose supply chains are vulnerable to disruption as essential to our nation's economic and national security. GAO was asked to review federal efforts to advance critical minerals recovery and substitution.

This report (1) identifies key challenges affecting efforts to advance critical minerals recovery and substitution in the U.S., and (2) examines the extent to which federal agencies have taken actions to advance recovery and substitution. GAO reviewed laws and agency documents and interviewed officials and staff on the CMS, including the Departments of Commerce, Defense, Energy, and the Interior, EPA, the National Economic Council, and OSTP. GAO also interviewed a nongeneralizable sample of seven nonfederal stakeholders such as academic researchers and industry, selected for their relevant expertise.

What GAO Recommends

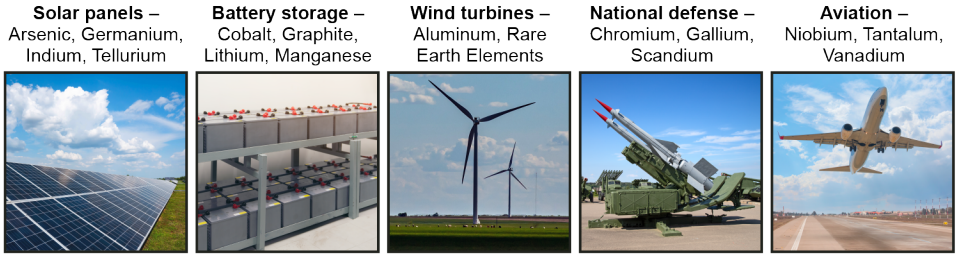
GAO recommends that DOE, Interior, and OSTP work together to update the national strategy to address recent developments and more fully incorporate characteristics of effective national strategies. DOE concurred with the recommendation, OSTP took no position, and Interior thought it should be directed to OSTP. GAO maintains the recommendation is warranted as outlined in the report.

View GAO-22-104824. For more information, contact J. Alfredo Gómez at (202) 512-3841 or gomezj@gao.gov.

What GAO Found

Based on GAO's analysis of the views of six federal agencies and seven nonfederal stakeholders, five cross-cutting challenges constrain efforts to advance critical minerals recovery (i.e., recycling and use of nontraditional sources) and substitution (i.e., developing alternatives) in the U.S. These challenges include (1) limited data and analytical tools to support decision-making, (2) limited research and development, (3) limited domestic infrastructure and capacity, (4) potential adverse effects on the environment and worker safety, and (5) limited economic viability of recovery and substitution methods. Federal agencies have taken some steps that may help address these challenges. For example, the Environmental Protection Agency (EPA) issued guidance for protecting worker safety during electronic waste recycling.

Examples of Critical Minerals Used in Advanced Technologies



Source: GAO analysis of agency documents; Photos: Stockadrik/tongpatong/Rawf8/swisshippo/muratart/stock.adobe.com. I GAO-22-104824

In 2019, the Department of Commerce, in coordination with the Critical Minerals Subcommittee (CMS)—an interagency group co-chaired by the Departments of Energy (DOE) and the Interior and the Office of Science and Technology Policy (OSTP)—issued a national strategy for ensuring secure and reliable supplies of critical minerals. Federal agencies have taken specific actions recommended by the strategy. For example, DOE is developing a research and development roadmap to guide federal efforts to advance critical minerals recovery and substitution.

However, the national strategy does not incorporate certain characteristics of effective national strategies identified in prior GAO work. Specifically, the strategy does not fully address (1) what the strategy intends to achieve, how results will be achieved, or performance measures to gauge results; (2) what the strategy will cost; and (3) how federal agencies will implement it. For example, the strategy does not identify how agencies will implement the activities necessary to complete the roadmap or how they will integrate these activities into existing programs. Furthermore, the strategy does not address newly enacted statutory requirements or recent agency efforts, such as recommendations from a 2021 White House report that assessed risks to critical mineral supply chains. Updating the strategy to address recent developments and better incorporate characteristics of effective national strategies would provide greater assurance of the strategy's usefulness to congressional and agency decision makers. Such an update would also better ensure accountability for the strategy's implementation.

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Abbreviations

CMS	Critical Minerals Subcommittee
DOD	Department of Defense
DOE	Department of Energy
EPA	Environmental Protection Agency
NEC	National Economic Council
NSF	National Science Foundation
OSTP	Office of Science and Technology Policy
REE	rare earth element
USGS	U.S. Geological Survey

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June 16, 2022

The Honorable Lisa Murkowski
Ranking Member
Subcommittee on Interior, Environment, and Related Agencies
Committee on Appropriations
United States Senate

Dear Ms. Murkowski:

Certain minerals and mineral groups are essential to the manufacturing of advanced technologies across a range of industrial sectors in the U.S. and play an important role in developing defense applications for our nation's security.[1] For example, gallium is used in satellite communications, spacecraft power generation, and radar missile defense. Minerals vary widely in many respects, such as how they are used, supply sources, projected demand, and the availability and accessibility of substitute materials. A recent multi-agency report projects the demand for numerous important minerals will surge over the next 2 decades. According to the report, this surge will stem from countries' efforts to eliminate net carbon emissions by 2050.[2] For example, as demand for clean energy technologies increases, the demand for certain minerals is expected to grow substantially because they serve as the building blocks for many clean energy technologies such as advanced battery storage and wind turbines.[3]

The U.S. is heavily reliant on imports of many minerals, and supply chains are vulnerable to various risks, including natural disasters and

[1]Minerals—naturally occurring inorganic solids such as salt and certain metals—typically are mined from the ground. Mineral groups include the rare earth elements (REE) group, which consists of 17 elements such as yttrium and scandium, and the platinum group metals, which consists of different types of platinum.

[2]The White House, Department of Commerce, Department of Energy, Department of Defense, Department of Health and Human Services, *Building Resilient Supply Chains, Revitalizing American Manufacturing, and Fostering Broad-Based Growth* (Washington, D.C.: June 2021).

[3]International Energy Agency, *The Role of Critical Minerals in Clean Energy Transitions* (May 2021). For example, lithium, manganese, and cobalt are used in advanced battery storage, and REEs are used in wind turbines.

foreign government policies such as market-distorting trade actions.[4] The federal government has taken steps to assess the ability of domestic industries to address disruptions to mineral supplies. For example, in April 2016, the National Science and Technology Council, a cabinet-level council that coordinates science and technology policy across the federal government, reestablished the Critical Minerals Subcommittee (CMS).[5] According to its charter, CMS seeks to facilitate a strong, coordinated effort across federal agencies to identify and address important policy implications arising from critical and strategic mineral supply issues.[6]

In December 2017, the President issued Executive Order 13817, *A Federal Strategy To Ensure Secure and Reliable Supplies of Critical Minerals*.[7] In response to this executive order, in May 2018, the Secretary of the Interior designated 35 minerals and mineral groups whose supply chains are vulnerable to disruption as essential to our nation's economic

[4]For example, according to the Department of the Interior's U.S. Geological Survey (USGS), China accounted for 80 percent of global REE production between 2016 and 2019. In 2010, China sharply reduced REE exports to Japan over a maritime incident between the two countries, resulting in disruptions to global supply chains. In March 2012, the U.S., Japan, and the European Union requested consultations with China regarding China's restrictions on the export of REEs and other minerals. In March 2014, a World Trade Organization dispute panel found that China's REE restrictions were inconsistent with certain treaty obligations. In May 2015, China announced that it removed the restrictions.

[5]CMS is an interagency group co-chaired by the Executive Office of the President's Office of Science and Technology Policy (OSTP), Department of Energy (DOE), and Interior.

[6]The Subcommittee on Critical and Strategic Mineral Supply Chains was chartered in 2010 and subsequently renamed CMS. The federal departments and agencies represented on CMS are the Central Intelligence Agency; the Departments of Agriculture, Commerce, Defense, Education, Energy, Homeland Security, Interior, Justice, Labor, State, and Treasury; the Environmental Protection Agency; the National Aeronautics and Space Administration; and the National Science Foundation. The entities in the Executive Office of the President represented on CMS are the Council on Environmental Quality, National Economic Council, National Security Council, Office of Management and Budget, OSTP, and the Office of the U.S. Trade Representative. OSTP advises the President and others within the Executive Office of the President on scientific, engineering, and technological issues related to the economy, the environment, and human health, as well as foreign relations, national security, and homeland security.

[7]82 Fed. Reg. 60835 (Dec. 26, 2017). Among other things, Executive Order 13817 directed the Secretary of the Interior, in coordination and consultation with others, to publish a list of critical minerals within 60 days. In addition, the order directed the Secretary of Commerce, in coordination with others, to submit a report to the President that, among other things, includes a strategy to reduce the nation's reliance on critical minerals and an assessment of progress toward developing critical minerals recycling and reprocessing technologies as well as technological alternatives to critical minerals.

and national security. In this report, we refer to these 35 minerals and mineral groups as critical minerals. Also, in response to Executive Order 13817, in June 2019, the Department of Commerce, in coordination with CMS, issued a national strategy to address critical minerals supply chain risks.[8] Throughout this report, we refer to this as the national strategy.

The national strategy recommended specific actions that federal agencies represented on CMS should take to address critical minerals supply chain risks by reducing the demand for and increasing the supply of critical minerals, such as by expanding and expediting domestic mining. However, efforts to secure domestic supplies of certain critical minerals through traditional mining activities can pose risks to human health and the environment. In July 2021, we reported on examples of mining that by their very nature disturb the land and create the potential for costly and long-lasting hazards to human health and the environment.[9] The national strategy also outlined actions that federal agencies should take to diversify and expand critical mineral supplies outside of traditional mining. These actions include promoting the efficient use, reuse, and recycling of critical minerals; recovering critical minerals from mining and other waste streams; and developing alternatives for certain critical minerals by using more abundant, or more readily accessible, and less costly materials. For the purposes of this report, we refer to such efforts to diversify and expand critical mineral supplies as actions to advance critical minerals recovery and substitution.[10]

The Energy Act of 2020 established several requirements regarding critical minerals recycling and reuse, which are key recovery and substitution activities.[11] For example, the act requires the President, through the Executive Office of the President, to coordinate departments

[8]Department of Commerce, *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals* (June 2019).

[9]See GAO, *Federal Land Management: Key Differences and Stakeholder Views of the Federal Systems Used to Manage Hardrock Mining*, GAO-21-299 (Washington, D.C.: July 21, 2021). We reported that surface and groundwater contamination due to the release of cyanide, acid, and metals from a closed mine on federal land in Montana resulted in a $33 million liability for long-term water treatment costs, including the possibility of water treatment in perpetuity.

[10]Primary raw material extraction, such as traditional mining and seabed extraction, falls outside the scope of our review.

[11]Consolidated Appropriations Act, 2021, Pub. L. No. 116-260, div. Z, 134 Stat. 1182, 2418-2615 (2020).

and agencies to, among other things, promote the efficient production, use, and recycling of critical minerals. More recently, the Infrastructure Investment and Jobs Act established additional requirements and made appropriations to federal agencies for certain critical minerals recovery and substitution efforts.[12]

In 2016, we reported on federal efforts to identify and strategically plan for critical materials issues related to the supply of certain metals, minerals, and other critical raw materials important to advanced technologies.[13] We found that, among other things, Commerce did not have a process to engage with stakeholders to continually identify and assess critical materials needs across certain industrial sectors.[14]

You asked us to examine federal efforts to advance critical minerals recovery and substitution in the U.S. This report (1) identifies key challenges affecting efforts to advance critical minerals recovery and substitution in the U.S., and (2) examines the extent to which federal agencies have taken actions to advance critical minerals recovery and substitution in the U.S.

To identify key challenges affecting efforts to advance critical minerals recovery and substitution in the U.S., we obtained and analyzed the views of key federal and selected nonfederal stakeholders. We identified six federal agencies and offices based on their involvement in critical

[12]Pub. L. No. 117-58, 135 Stat. 429 (2021). For example, the law requires the Secretary of Energy to establish a battery manufacturing and recycling grant program and appropriates $3 billion for the program.

[13]GAO, *Advanced Technologies: Strengthened Federal Approach Needed to Help Identify and Mitigate Supply Risks for Critical Raw Materials*, GAO-16-699 (Washington, D.C.: Sept. 7, 2016). In this report, a critical material was defined as one that is subject to supply risks, such as a single source of production or geopolitical unrest; has limited substitutability; and has an end use that is important to U.S. economic or national security interests.

[14]GAO-16-699. OSTP has taken actions to fully implement our recommendations related to working with agencies on the National Science and Technology Council's Committee on Environment, Natural Resources, and Sustainability, Subcommittee on Critical and Strategic Mineral Supply Chains (subsequently renamed CMS) to (1) agree on and clearly define roles and responsibilities; (2) develop joint strategies; (3) develop mechanisms to monitor, evaluate, and report on the progress of agencies' efforts; and (4) examine approaches other countries or regions are taking to identify lessons learned. As of April 2022, Commerce had not yet taken actions to implement our recommendation related to engagement with industry, and OSTP had not yet fully taken actions to implement our recommendation to take the steps necessary to include potentially critical materials beyond minerals, such as developing a plan or strategy prioritizing additional materials for which actions are needed to address data limitations.

minerals recovery and substitution activities identified in the national strategy or their leadership roles in CMS. We reviewed agency reports and conducted semi-structured interviews with officials and staff from Commerce and the Department of Defense (DOD), Department of Energy (DOE), Environmental Protection Agency (EPA), Department of the Interior, and Office of Science and Technology Policy (OSTP), to obtain information about the key challenges they face in efforts to advance critical minerals recovery and substitution. Additionally, we identified nonfederal stakeholders based on their knowledge and expertise about critical minerals recovery and substitution efforts—including representatives from academia, industry, nonprofit organizations, and a trade association—through our prior work and by asking these stakeholders to refer us to other nonfederal stakeholders.

We reviewed reports produced by these nonfederal stakeholders, such as information about the environmental effects of certain mining and recovery processes, and we interviewed representatives of seven of these nonfederal stakeholders. We analyzed stakeholder views obtained from documentary and testimonial evidence to identify and categorize the key challenges these stakeholders identified. In addition, we obtained and analyzed information about federal activities that could help address the identified challenges.

To examine the extent to which federal agencies have taken actions to advance critical minerals recovery and substitution in the U.S., we identified relevant entities across the federal government—those mentioned above and the National Economic Council—based on their engagement in related interagency efforts through CMS. We reviewed federal laws, regulations, and agency documents—such as guidance, plans, and reports—and interviewed knowledgeable officials and staff to identify agency activities. We selected characteristics of effective national strategies identified in our prior work based on their applicability to the portions of the national strategy that address critical minerals recovery and substitution.[15] We compared the national strategy and related agency activities to these selected characteristics of effective national strategies. See appendix I for additional details on our scope and methodology.

[15]GAO, *Combating Terrorism: Evaluation of Selected Characteristics in National Strategies Related to Terrorism*, GAO-04-408T (Washington, D.C.: Feb. 3, 2004). National strategies are documents that are national in scope, cutting across levels of government and sectors of the economy and involving a large number of organizations and entities (i.e., federal, state, local, and private sectors).

We conducted this performance audit from February 2021 to June 2022, in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

Background

Critical Minerals List

Executive Order 13817 defines a critical mineral as a mineral (1) the Secretary of the Interior has identified as a non-fuel mineral or mineral material essential to the economic and national security of the U.S., (2) that has a supply chain vulnerable to disruption, (3) that serves an essential function in the manufacturing of a product, and (4) whose absence would have significant consequences for our economy or national security. The U.S. Geological Survey (USGS) used this definition to develop the list of 35 critical minerals that the Secretary of the Interior issued in 2018. Figure 1 shows this list of critical minerals, the percentage of the U.S. supply that comes from foreign sources, and the key industries in which each mineral is used.

Figure 1: Department of the Interior's 2018 Critical Minerals List, Percentage of the U.S. Supply Imported in 2020, and Key Industries in Which Each Is Used

Mineral	Percentage from foreign sources (2020)[a]	Key Industries: Aerospace	Defense	Energy	Telecommunications and electronics	Transportation (non-aerospace)	Notes
Arsenic	100%		●	●	●		Imported 58% from China[b]
Cesium		●	●	●	●		
Fluorspar				●	●		
Gallium		●	●	●	●		Imported 55% from China[b]
Graphite		●	●	●	●	●	
Indium		●	●	●	●		
Manganese		●	●	●		●	Used in battery storage, such as for electronic vehicles.
Niobium		●	●	●			
Rubidium		●	●	●	●		
Scandium		●	●	●	●	●	
Strontium		●	●	●	●	●	
Tantalum		●	●	●	●		
Rare Earth Elements		●	●	●	●	●	Imported 80% from China[b,c]
Platinum Group Metals	≤100%	●		●	●	●	Import reliance[d]
Vanadium	≥90%	●	●	●			
Tellurium			●	●	●		
Bismuth			●	●	●		Imported 69% from China[b]
Potash				●			
Antimony	>75%		●	●	●	●	Imported 63% from China[b]
Cobalt		●	●	●	●	●	Used in battery storage, such as for electronic vehicles.
Rhenium		●		●	●		
Barite	≥75%			●			Imported 47% from China[b]
Chromium		●	●	●			
Tin			●		●		
Germanium	>50%	●	●	●	●		Imported 58% from China[b]
Lithium		●	●	●	●	●	Used in battery storage, such as for electronic vehicles.
Tungsten		●	●	●	●		
Magnesium	<50%	●	●	●		●	
Zirconium	<25%	●	●	●			
Aluminum		●	●	●		●	
Beryllium		●	●	●	●		
Helium	0%				●		U.S. is a net exporter
Titanium		●	●	●			U.S. is a net exporter
Hafnium	Data not applicable	●	●	●			
Uranium		●	●	●			Used in nuclear energy and weapons

Source: Department of the Interior, *U.S. Geological Survey, Mineral Commodity Summaries 2021* (Reston, Virginia: 2021). | GAO-22-104824

Note: In 2018, the Secretary of the Interior designated 35 minerals and mineral groups as essential to the economic or national security of the U.S. The U.S. Geological Service (USGS) released an updated list of critical minerals in February 2022.

[a]U.S. net import reliance expressed as a percentage of apparent U.S. consumption, a metric developed and calculated by USGS using import data from the U.S. Census Bureau and consumption data from USGS' Mineral Commodity Summaries.

[b]Import source percentage from 2016 through 2019, calculated by USGS using import data from the U.S. Census Bureau.

[c]Rare earth elements include 17 elements: cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, praseodymium, promethium, neodymium, samarium, scandium, terbium, thulium, ytterbium, and yttrium. However, scandium is listed separately.

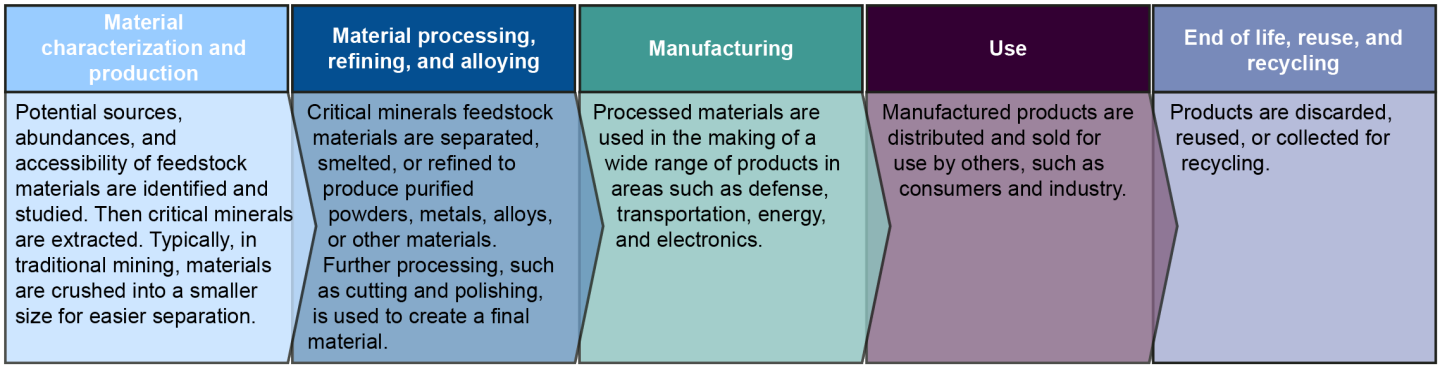
[d]Platinum group metal estimated import percentages for 2020 include iridium (100 percent), osmium (n/a), palladium (40 percent), platinum (79 percent), rhodium (100 percent), and ruthenium (100 percent).

According to a 2022 USGS report, the U.S. is import-reliant (i.e., imports are greater than 50 percent of annual consumption) on 29 of the 35 critical minerals.[16] Among these, the U.S. does not domestically produce 14 critical minerals and relies completely on imports to meet its demand for these minerals.

Opportunities for Critical Minerals Recovery and Substitution across Supply Chains

According to knowledgeable federal officials and nonfederal stakeholders we interviewed, the supply chains for critical minerals generally follow a linear path containing five key stages (see fig. 2).

Figure 2: Key Stages of Critical Minerals Supply Chains



Source: GAO analysis of stakeholder information. | GAO-22-104824

[16]Department of the Interior, U.S. Geological Survey, *Mineral Commodity Summaries 2022* (Reston, Virginia: 2022).

The national strategy states that all stages of critical minerals supply chains are important and can affect one another. For example, according to the national strategy, increasing the rate of mining for critical minerals without increasing corresponding processing and manufacturing capabilities will simply move the source of economic and national security risks further down the supply chains and may necessitate relying on foreign industries for these capabilities.

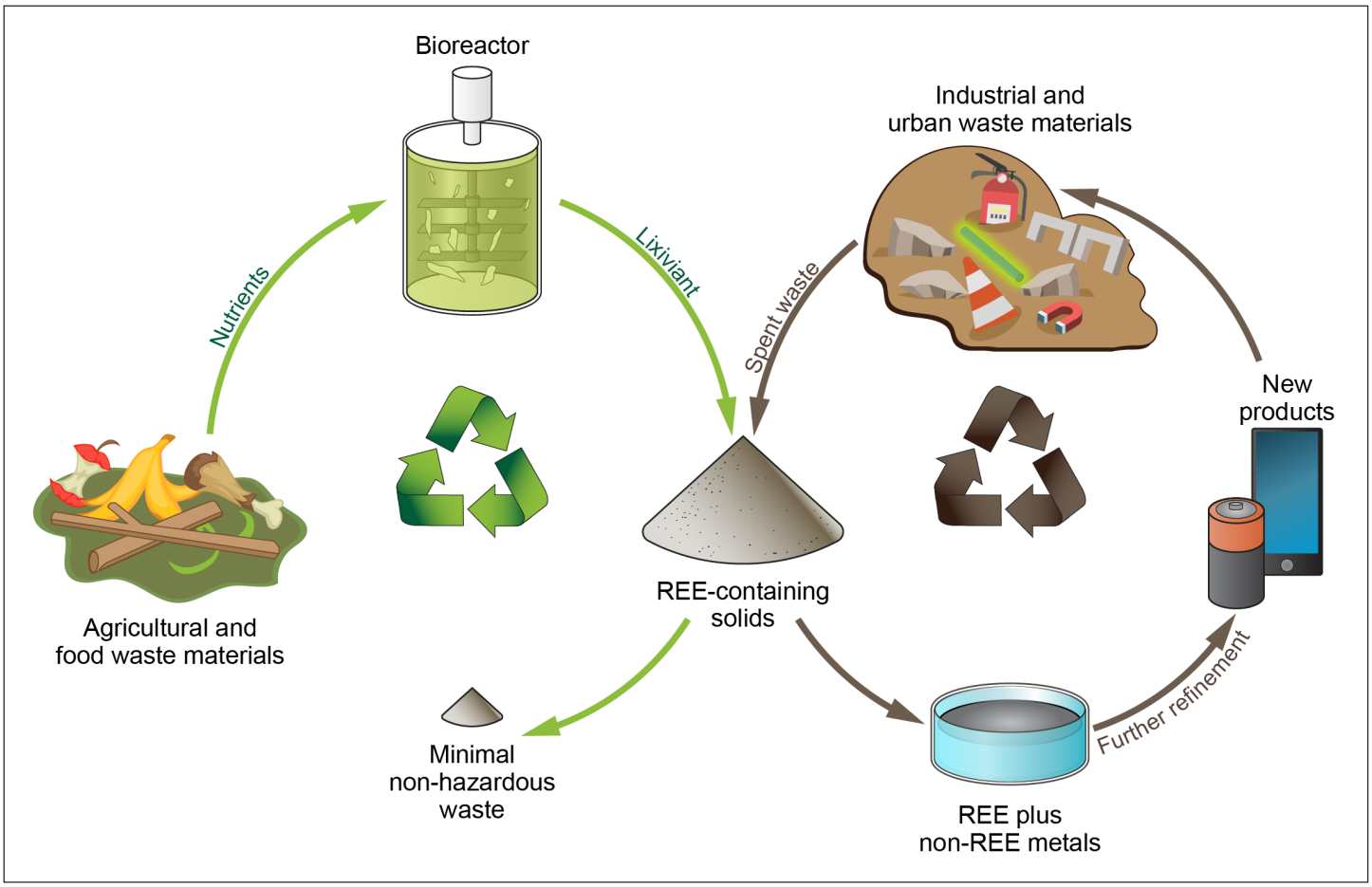
The national strategy also identifies opportunities to pursue recovery and substitution across critical mineral supply chains, including by (1) diversifying and expanding domestic sources of critical minerals; (2) more efficiently processing, manufacturing, and recycling critical minerals to minimize waste and increase supply;[17] and (3) developing alternatives to critical minerals.[18] For example, opportunities exist to diversify and expand domestic critical mineral sources using unconventional sources or secondary sources to derive critical minerals.[19] See figure 3 for an example of recovery from unconventional (i.e., agricultural and food waste) and secondary (i.e., industrial and urban waste) sources.

[17]According to the national strategy, efficiency can be achieved in a variety of ways, including (1) content reductions in products, (2) minimizing material waste during manufacturing, (3) reusing post-production waste, and (4) recycling at the end of a product's life.

[18]According to the national strategy, developing alternatives can include substituting critical minerals with abundant, less expensive, or more readily accessible replacements that could conserve critical minerals, reduce vulnerability to disruptions, and lower product costs.

[19]According to DOE officials we interviewed, unconventional sources are natural resources that require greater than industry standard levels of technology or investment to be recovered—such as rock and sediment sources (i.e., coal and coal measures, underclays, coal shale, mine tailings, garnet sands, sulfide mineral by-products, and brine). In addition, according to DOE officials, secondary sources are materials obtained from the recovery of waste products, such as (1) coal waste and industrial by-products (i.e., coal ash, flume dust, slurry, cakes, produced waters, acid mine drainage, acid solutions, and alloy residues); (2) mineral processing, extractive metallurgy, and manufacturing sources (i.e., mineral processing tailings, slag and furnace residue, hydrometallurgical leachates, and magnet swarf); and (3) end-of-life components and post-consumer waste such as computer hard disk drives and lithium-ion batteries.

Figure 3: Recovering Rare Earth Elements (REE) Using Unconventional and Secondary Sources



Source: © 2019 American Chemical Society. | GAO-22-104824

Note: See https://doi.org/10.1021/acssuschemeng.9b02584. Further permission related to the material excerpted should be directed to the American Chemical Society. Leaching is a process that uses a lixiviant—a liquid medium used to selectively extract metals from a source. Bioleaching uses a lixiviant produced from microbial activity.

Potential Benefits of Critical Minerals Recovery and Substitution Activities

According to a 2021 DOE report, the U.S. does not have sufficient domestic resources from known traditional mining sources to meet expected demand for certain critical materials such as cobalt and

gallium.[20] Preliminary studies suggest that unconventional and secondary sources, such as coal waste and end-of-life batteries, have the potential to provide significant amounts of cobalt, but more analysis is needed to fully quantify and understand the cost-competitiveness and life-cycle implications of such sources.[21] Supply constraints can also be addressed through identifying new sources of critical minerals from mining waste, improved material stewardship, including more efficient use of critical minerals, extending the product life to reduce demand, improving reuse and recycling, partnering with international partners to secure supply chains, or developing substitutes.

According to the national strategy, critical minerals recovery and substitution efforts can help improve domestic capacity, offset growing consumer demands, and mitigate foreign dependencies. Furthermore, according to the national strategy, these efforts to advance critical minerals recovery and substitution can help (1) create new domestic businesses, such as recycling firms and permanent magnet start-ups; (2) revitalize ailing industries and their communities by harnessing the value of by-products and waste streams; and (3) increase the competitiveness of existing companies via technological spillover developed from federal research and development, through which new technologies or innovations are adapted to other industries or processes. These efforts also help promote greater resource sustainability through a more circular economy—an approach EPA advocates. This approach emphasizes the need to eliminate waste and pollution through improved design of products for durability, reuse, remanufacturing, and recycling to keep

[20]Department of Energy, *Critical Minerals and Materials: U.S. Department of Energy's Strategy to Support Domestic Critical Mineral and Material Supply Chains (FY2021-2031)* (January 2021).

[21]Pennsylvania State University, Center for Critical Minerals, *Secondary Cobalt and Manganese Resources in Pennsylvania: Quantities, Linkage with Mine Reclamation, and Preliminary Flowsheet Evaluation for the U.S. Domestic Lithium-Ion Battery Supply Chain,* prepared at the request of Leonardo Technologies, Inc. (LTI) of Bannock, OH (under the U.S. Department of Energy (DOE) Agreement Number DE- FE0022594) (Nov. 17, 2021); and Department of Energy, *Federal Consortium for Advanced Batteries (FCAB), Executive Summary: National Blueprint on Lithium Batteries 2021-2030* (June 2021).

materials in use in perpetuity.[22] EPA officials stated that progress towards a more circular economy for critical minerals could help mitigate supply chain vulnerabilities and reduce harms to the environment that may occur at the end-of-life of products.

Five Cross-Cutting Challenges Constrain Efforts to Advance Critical Minerals Recovery and Substitution in the U.S.

Based on our analysis of stakeholder views, we identified five cross-cutting challenges that constrain efforts to advance critical minerals recovery and substitution in the U.S.[23] These challenges are (1) limited data, information, and analytical tools to support decision-making; (2) limited scientific research and technology development; (3) limited domestic infrastructure and capacity; (4) potential adverse effects on the environment and worker safety; and (5) limited economic viability of recovery and substitution methods. Officials we interviewed from relevant federal agencies provided examples of actions they are taking that could help address these challenges.[24]

Limited Data, Information, and Analytical Tools to Support Decision-Making

According to our analysis of stakeholder views, federal agencies have limited data, information, and analytical tools to support decision-making about policies, programs, and initiatives to advance critical minerals recovery and substitution. Stakeholders we interviewed stated that some of the factors that contribute to limited data, information, and analytical tools include the following:

- **Data and information complexity.** According to Commerce and DOE officials, the complexity of critical supply chains makes it difficult to collect data and information necessary for recovery and substitution efforts. For example, Commerce officials stated that it is difficult to trace the use and concentration of critical minerals in products throughout the economy. This is because goods and products vary in how they are configured, such as the extent to which they contain

[22]For the purposes of the Save Our Seas 2.0. Act, the act defines circular economy as an economy that uses a systems-focused approach and involves industrial processes and economic activities that (1) are restorative or regenerative by design; (2) enable resources used in such processes and activities to maintain their highest values for as long as possible; and (3) aim for the elimination of waste through the superior design of materials, products, and systems (including business models). Pub. L. No. 116-224, § 2(1), 134 Stat. 1072, 1073 (2020) (*codified at* 33 U.S.C. § 4201(1)).

[23]We obtained these views by interviewing selected federal and nonfederal stakeholders about (1) the key challenges to advancing critical mineral recovery and substitution throughout the critical minerals supply chain stages, and (2) the steps they have taken to address those challenges.

[24]The actions that federal agencies are taking that were recommended in the 2019 national strategy are discussed later in this report.

critical minerals. These variations in how products are configured also make it difficult for federal agencies to identify potential pathways for critical minerals recovery and substitution, according to Commerce officials. DOE officials stated that there is a wide variety of potential sources of critical minerals, including traditional mining, as well as unconventional and secondary sources. According to these officials, each potential source may contain numerous critical minerals that need to be characterized and catalogued, which makes it difficult to establish priorities for recovery and substitution efforts.

- **Restrictions on sharing and accessing data and information.** Federal agency officials stated that private businesses are not required to submit data to the federal government about how they produce or use critical minerals, thereby hindering federal data collection efforts. For example, USGS relies on voluntarily submitted, proprietary data from businesses—such as mining companies and manufacturers—to analyze, publish, and share data and information about critical minerals. These data include information on domestic production, use, and recycling. As a result, USGS officials we interviewed said they do not have sufficient information about the amount of critical minerals that are currently recycled or the extent to which supply chain risks could be reduced through increased recovery and substitution efforts. In addition, Interior officials we interviewed told us that federal agencies do not have enough data and information to support their decision-making needs regarding critical minerals recovery and substitution because of restrictions that limit federal agencies' ability to share proprietary data and information with each other. Finally, according to DOE and Commerce officials, the federal government does not currently have a central database for federal agencies to share data and information on critical minerals with each other.
- **Outdated analytical models.** According to a recent federal report, in some cases, analytical tools for evaluating the costs and benefits of critical mineral recovery and substitution policies and programs rely on outdated or incomplete data. For example, according to the federal report, economic analysis tools used to assess data and information

on critical minerals are often based on outdated or incomplete data.[25] The report stated that advancements of these tools are needed.

Federal officials we interviewed described actions their agencies are taking to improve data and information to support decision-making. For example, Commerce officials stated that the department is establishing a new program to, among other things, promote a circular economy that will collect information on critical minerals recovery. As part of this effort, to set priorities for facilitating the reuse, repair, and recycling of electronic products, Commerce engaged stakeholders from the private sector, government, national laboratories, academia, and non-governmental organizations. Commerce held a virtual workshop with these stakeholders to identify information about (1) product evolution; (2) circular economy metrics, frameworks, and tools; and (3) infrastructure and workforce. In addition, EPA officials we interviewed stated that EPA publishes annual reports that provide data on the amount of electronic waste generated, recycled, and disposed, and it plans to add critical minerals to the list of materials that it analyzes.

Limited Scientific Research and Technology Development

According to our analysis of stakeholder views, limited scientific research and technology development constrains efforts to advance critical minerals recovery and substitution. For example, USGS officials stated that more research is needed to address the potential performance challenges and cost implications of using substitute materials in manufactured products. Stakeholders we interviewed stated that factors contributing to limited scientific research and technology development include the following:

- **Limited industry investment.** USGS officials stated that unconventional resource recovery of critical minerals requires significant scientific research to bring new materials into markets. However, according to representatives of nonfederal stakeholders we interviewed, science and technology gaps exist for developing cleaner, cost-competitive methods of obtaining critical minerals from unconventional and secondary sources and developing substitutes

[25]National Institute of Standards and Technology, *Circular Economy in the High-Tech World* (Gaithersburg, MD: September 2021). According to this report, multiple frameworks and system-level assessment tools have been developed utilizing a diverse range of metrics to evaluate sustainability performance (i.e., social, environmental, and economic impacts) of high-tech products or materials therein, such as life-cycle assessment, techno-economic analysis, material flow analysis, and risk modeling frameworks of critical mineral commodities. However, to date, these tools have largely focused on materials and material loops and are often based on outdated or incomplete data.

because industry does not have financial incentives to conduct basic scientific research. According to officials from federal agencies we interviewed, since future profit potentials are unknown, businesses tend to avoid investments in basic research and development, such as pilot and demonstration research projects that are needed to help mature new technologies for adoption by industry. For example, DOD officials stated that academic researchers have developed technologies for critical minerals recovery and substitution, but they lack funding from industry investors to develop and implement related projects.

In addition, DOE's research, development, demonstration, and commercial application programs generally require cost-sharing from 20 to 50 percent, depending on the activity. DOE officials we interviewed told us that cost-sharing agreements can create financial disincentives for private businesses to pursue public-private partnerships. DOE officials stated that, as a result, research and development projects are mostly conducted by national laboratories, rather than industry. However, according to these officials, such research and development projects are not enough to support critical minerals recovery and substitution efforts.

- **Workforce development issues.** The national strategy states that U.S. critical minerals supply chains face workforce challenges, including retiring and aging personnel and faculty, public perceptions about the nature of mining and mineral processing, and foreign competition for U.S. talent. In addition, Interior officials we interviewed stated that there is limited expertise in the workforce to fill highly technical expert positions related to critical minerals recovery and substitution, such as geologists and other scientists. Interior officials said that universities are not producing enough of these highly technical experts because of declining interests in these fields.

Federal officials we interviewed identified actions agencies are taking that could help address these research and development gaps. For example, DOE officials stated that the agency provides funding to national laboratories, universities, private businesses, and nonprofit research organizations to conduct critical research and development projects, demonstrate the viability of new technologies, and develop strategies to assess and use regional critical mineral-related resources, such as the region's workforce. In addition, DOE's Critical Materials Institute is engaging with industry partners to fill gaps in early-stage research prior to

industry entering into any cost-sharing commitments.[26] Finally, DOD provides grants and contracts to small businesses for research related to the processing and recovery of materials, including critical minerals. According to DOD officials, this research aims to encourage domestic production of materials used in defense applications.

Limited Domestic Infrastructure and Capacity

According to our analysis of stakeholder views, there is limited domestic infrastructure and capacity to recover critical minerals from unconventional and secondary sources. For example, according to an EPA report, limited infrastructure for collecting end-of-life materials reduces the potential amount of materials that could be potentially recycled.[27] Stakeholders we interviewed identified factors related to limited infrastructure and capacity, including the following:

- **Limited collection of recyclable materials.** DOE officials stated that most critical minerals, such as rare earth elements (REE), are not collected for recycling on a large scale, in part because of variations in recycling programs. In 2020, we reported that at least 23 states have extended producer responsibility laws for electronic waste.[28] According to DOE officials we interviewed, these laws vary on what is required, making collection and participation inconsistent and increasing the costs for manufacturers to comply. For example, California, Oregon, and Washington have state laws establishing or requiring establishment of recycling programs for various electronic products that can include several different critical minerals such as lithium, while Idaho does not have a state law requiring such a

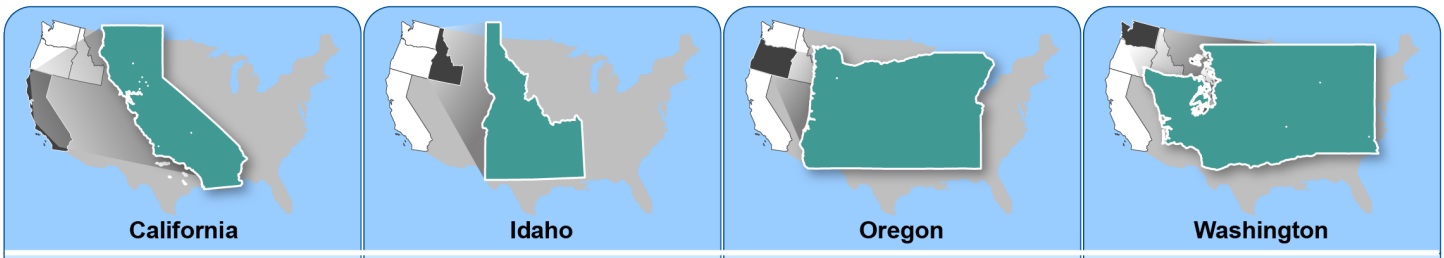
[26]The Critical Materials Institute is a DOE Innovation Hub—an integrated research center that combines basic and applied research with engineering to accelerate scientific discovery and address critical energy issues. This institute focuses on technologies that make better use of materials and eliminate the need for materials that are subject to supply disruption, including critical minerals and REEs.

[27]Environmental Protection Agency, *Status Report: Framework for Advancing the U.S. Recycling System* (July 2019).

[28]GAO, *Recycling: Building On Existing Federal Efforts Could Help Address Cross-Cutting Challenges,* GAO-21-87 (Washington, D.C.: Dec. 18, 2020). With extended producer responsibility, manufacturers generally develop product stewardship programs and associated fees to offset the cost of postconsumer management or end-of-life disposal of their products, which generally include recycling these products. Under these systems, businesses often work with a specific nonprofit organization to collect the fees and manage the recycling or disposal of the products.

program.[29] See figure 4 for information about selected state electronic waste recycling laws. Moreover, according to an EPA report, U.S. recyclable collection infrastructure is outdated.[30] For instance, manufacturers of new products and materials may not always design their products with end-of-life management in mind, which leads to products that are not designed to facilitate recycling. As a result, the recycling industry's ability to collect and recycle products is expensive and difficult. According to the national strategy, improving the national recycling and materials recovery infrastructure will help create more secure domestic supplies of critical minerals.

Figure 4: Examples of State Laws Regarding Electronic Waste Recycling



California	Idaho	Oregon	Washington
Summary of state law: CA law requires consumers to pay recycling fees upon the purchase of a new or refurbished covered electronic device.	**Summary of state law:** ID does not have a state electronic waste recycling law.	**Summary of state law:** OR state law requires establishment of a statewide program for the collection, transportation, and recycling of covered electronic devices financed by manufacturers who do not establish their own recycling plan.	**Summary of state law:** WA law requires manufacturers to participate in a state system for the collection, transportation, and recycling of covered electronic products financed by manufacturers or establish their own system.
Covered electronic devices: Generally a video device containing a screen greater than 4 inches diagonally.	**Covered electronic devices:** Not applicable	**Covered electronic devices:** Generally includes computers, computer monitors with viewable areas greater than 4 inches diagonally, televisions, printers, and computer peripherals.	**Covered electronic devices:** Generally includes computers, computer monitors with viewable areas greater than 4 inches diagonally, and televisions with viewable areas greater than 4 inches diagonally.

Source: GAO analysis of state laws. | GAO-22-104824

- **Product variation.** According to EPA officials, products vary widely in how they are configured and the extent to which they contain critical minerals. This can exacerbate limitations in the nation's domestic recycling infrastructure and its capacity to recover critical minerals from certain materials. For example, older laptop and desktop

[29]Electronic products can include several different critical minerals such as germanium, graphite, and lithium.

[30]Environmental Protection Agency, *Advancing the U.S. Recycling System*.

computers use mechanical hard disk drives that contain REE magnets, while newer laptop and desktop computers use solid-state drives that do not.[31] See figure 5 for information about how products may vary in critical mineral content. According to an EPA report, this product variation makes it difficult and expensive to recover critical minerals through recycling.[32] In addition, EPA's report found that finished projects often are not designed for recycling, and different product configurations may limit recyclability. Furthermore, a nonfederal stakeholder we interviewed stated that some electronic equipment use glue or adhesives that make mechanical disassembly difficult or impossible.

Figure 5: Examples of Variations in Critical Mineral Product Content

Mechanical hard disk computer drive – uses rare earth element magnets.

Solid-state computer drive – does not use rare earth element magnets.

Source: rohane and Maksym Yemelyanov/stock.adobe.com. | GAO-22-104824

- **Limited domestic production from unconventional and secondary sources.** According to DOE officials, critical minerals processed from waste streams, such as coal wastes and byproducts, typically are not recovered for their value as critical mineral commodities. DOE officials we interviewed stated that this is largely

[31]A hard disk drive is a storage device that contains both magnetic and solid-state storage device components; the magnetic storage device is within the case and solid-state storage devices are on the external circuit board. A solid-state storage device appears to be identical to a magnetic hard disk drive; hybrid hard disk drives, however, can be identified by manufacturer and model number. Laptop hard disk drives manufactured in 2006 and later and Enterprise hard disk drives manufactured in 2013 and later are potentially hybrid disk drives. Hybrid drives require additional sanitation procedures beyond those outlined for typical magnetic hard disk drives, for disposal or recycling. National Security Agency, *Unclassified NSA/CSS Policy Manual 9-12 Storage Device Sanitization and Destruction Manual* (December 4, 2020).

[32]Environmental Protection Agency, *Advancing the U.S. Recycling System*.

because there are no domestic processing facilities to take them. These officials noted that there are currently no large-scale commercial operations in the U.S. that produce critical minerals from unconventional and secondary sources, even when such wastes are processed. For example, according to DOE officials, some coal ash waste is remediated or reclaimed, but the bulk of the materials within them are processed and sold for fertilizer or cement additives rather than used as sources of critical minerals.

- **Limited domestic recycling capacity.** According to nonfederal stakeholders we interviewed, the U.S. recycling industry collects materials domestically that may contain critical minerals, but then generally ships them to other countries for recycling.[33] Commerce officials, for example, stated that REE feedstocks or products containing REEs that are collected for recycling are generally sent to China for processing and do not return to the U.S. until they are turned into intermediate materials or goods. These materials and goods are then sold domestically as finished products.[34]
- **Data privacy concerns.** In 2020, we found that private businesses often do not voluntarily report recycling data due to concerns about privacy and competitiveness.[35] In addition, according to representatives of a nonprofit organization we interviewed, businesses are concerned about data being stolen from recycled electronic devices such as hard drives. As a result, according to these representatives, industry participation in voluntary electronic waste recycling programs is limited.
- **Limited domestic manufacturing capacity.** According to federal officials and our review of federal reports, domestic capacity for the middle stages of critical minerals supply chains, such as material processing, refining, and alloying and manufacturing, is lacking. For example, according to a USGS report, in 2021, the U.S. was the

[33]According to EPA officials, some electronic waste and scrap is exported for recycling and recovery of critical materials in other countries, but some recycling also occurs in the U.S. According to EPA officials, accurate data on U.S. exports of electronic scrap and waste are limited because there are no Harmonized System Codes from the Department of Commerce's International Trade Administration to track trade in this material. However, the World Customs Organization established new Harmonized System Nomenclature for electronic waste and scrap that took effect on January 1, 2022.

[34]Department of Energy, *Critical Minerals and Materials*. According to this report, the U.S. imports 80 percent of its REEs from China.

[35]GAO-21-87.

second largest producer of mined REEs in the world.[36] However, Commerce officials stated that these REE concentrates must be exported for processing into intermediate products used in the manufacture of components and products, which the U.S. then imports. In addition, a recent DOD report found that the U.S. industrial sector has limited capabilities to produce intermediate products, such as rare earth oxides and metals, or to refine alloys to produce magnets used in manufacturing.[37] Furthermore, according to a 2021 multi-agency report, the U.S. industrial sector capacity for certain REE permanent magnets is limited to the manufacturing stage of the supply chains.[38] According to the national strategy, strengthening the domestic manufacturing base will (1) improve the ability of the defense manufacturing sectors that use critical minerals to adapt to emerging mineral criticality issues, (2) reduce risks for U.S. businesses that rely on critical minerals, and (3) create a favorable U.S. business climate for production facilities at different stages of the supply chains. In turn, this will help reduce U.S. vulnerability to critical minerals supply disruptions.

DOE and EPA officials we interviewed said they are taking actions to increase domestic infrastructure and capacity. For example, EPA encourages all electronic recyclers to become certified by demonstrating to an accredited, independent third-party auditor that they meet specific standards to safely recycle and manage electronics.[39] DOE officials stated that DOE and EPA are working with stakeholders to develop sustainable-produced content standards for strategic and critical material-intensive industries. In addition, according to EPA and DOE officials, these agencies are developing incentives for product longevity and recyclability, and recycling and reuse of critical minerals. These officials

[36]U.S. Geological Survey, *Mineral Commodity Summaries 2022.*

[37]Department of Defense, *Strategic and Critical Minerals 2021 Report on Stockpile Requirements* (February 2021).

[38]The White House, et al., *Building Resilient Supply Chains*. According to the Department of Defense's *Strategic and Critical Minerals 2021 Report on Stockpile Requirements,* REE permanent magnets are used in motors and wind turbines, among other products.

[39]Currently, two accredited certification standards exist. Both programs offer a way to assess the environmental, worker health and safety, and security practices of entities managing used electronics. Both also require destruction of all data on used electronics. According to EPA's website, EPA recommends that businesses, large purchasers, and government agencies use certified electronics recyclers. Environmental Protection Agency, "Certified Electronic Recyclers," accessed February 15, 2022, https://www.epa.gov/smm-electronics/certified-electronics-recyclers.

stated that such incentives will be for use in an electronic waste sustainability label that is incorporated into the federal procurement process.

Potential Adverse Effects on the Environment and Worker Safety

According to our analysis of stakeholder views, critical minerals recovery efforts may have adverse effects on the environment and worker safety. For example, according to representatives from an academic institution we interviewed, different activities along the supply chains may pose risks to the environment or worker safety that should be considered when evaluating certain methods for critical minerals recovery and substitution. According to our analysis of stakeholder reports, the following activities related to obtaining critical minerals could have adverse effects on the environment and worker safety:

- **Responsible mining and recovery.** In 2021, we reported that the extraction of hardrock minerals such as platinum and aluminum creates the potential for public health, safety, and environmental hazards.[40] For example, acidic water draining from waste rock during traditional hardrock mining can carry heavy metals such as arsenic into nearby streams and pollute communities' water sources. According to a 2017 DOE report, extracting and processing rare earth elements through recovery from unconventional sources also could have adverse effects on the environment and human health.[41] For example, DOE noted significant adverse environmental effects from the extraction of REEs from coal, including increased energy consumption due to low concentrations of REEs, increased production of fine particulate dust from grinding and crushing operations, and production of large volumes of liquid and solid wastes.
- **Material processing.** According to a DOE report, industry's processing of critical minerals has adverse environmental effects. For example, in its 2017 report, DOE found several potential causes of adverse effects: (1) the toxic and caustic nature of chemicals required for extraction; (2) processing operations may produce high concentrations of radioactive materials; and (3) extracting REEs from

[40]GAO, *Hardrock Mining Management: Selected Countries, U.S. States, and Tribes Have Different Governance Structures but Primarily Use Leasing,* GAO-21-298 (Washington, D.C.: June 30, 2021). For a list of our previous work in this area, see the Related GAO Products page at the end of this report.

[41]Department of Energy, *Report on Rare Earth Elements from Coal and Coal Byproducts* (Washington, D.C.: January 2017).

existing waste piles could subject the owners of those waste piles to new waste management requirements.

- **Electronic waste recycling.** According to a 2021 EPA report on end-of-life lithium-ion battery fires, various waste management facilities in the U.S. experienced fires that were caused by recycling lithium metal or lithium-ion batteries.[42] In some of the waste management facilities, personnel or firefighters suffered injuries from fires, including chemical burns, smoke inhalation, and heat exhaustion. Furthermore, in 2020, we found that to recycle electronics, companies must separate electronics' valuable materials, such as REEs, from toxic materials such as lead.[43] According to EPA, unsafe handling of electronics waste may result in adverse effects to human health, worker safety, and the environment.

Federal officials we interviewed told us their agencies are taking actions that could help mitigate the potential adverse environmental and worker safety effects from critical minerals recovery efforts. For example, DOE officials stated that the Critical Materials Institute has developed technology to extract and process lithium from geothermal brines in a way that reduces environmental impacts.[44] In addition, EPA shares guidance on end-of-life disposal and information on recycling of electronic waste (e.g., solar panels and lithium-ion batteries containing critical minerals) through workshops and educational documents on its website for the public.[45] These educational documents include information on safety and sustainability challenges and solutions regarding end-of-life disposal and recycling.[46] For example, they stated that using electrical tape or bags to

[42]Environmental Protection Agency, *An Analysis of Lithium-ion Battery Fires in Waste Management and Recycling* (July 2021).

[43]GAO, *Consumer Electronics Recycling,* GAO 20-712SP (Washington, D.C.: August 2020).

[44]Geothermal brine is hot, salty water from thousands of feet underground that can be used to extract lithium and REEs. According to USGS officials, this technology has not yet been demonstrated to be economically viable.

[45]Environmental Protection Agency, "Electronics Donation and Recycling," accessed March 17, 2022, https://www.epa.gov/recycle/electronics-donation-and-recycling.

[46]Environmental Protection Agency, "Used Lithium-Ion Batteries," accessed February 15, 2022, https://www.epa.gov/recycle/used-lithium-ion-batteries; and "End-of-Life Solar Panels: Regulations and Management," accessed March 1, 2022, https://www.epa.gov/hw/end-life-solar-panels-regulations-and-management.

protect individual lithium-ion battery terminals for recycling and disposal can reduce the potential for fire hazards.

Limited Economic Viability of Recovery Methods

According to our analysis of stakeholder views, limited economic viability poses a challenge to efforts to advance critical minerals recovery and substitution. For example, according to nonfederal stakeholders we interviewed, critical minerals recovered from unconventional or secondary sources may not be as cost-effective as materials derived from traditional mining for use in manufacturing processes. Stakeholders we interviewed identified factors contributing to the limited economic viability of recovery and substitution efforts, including the following:

- **Competition with other materials.** According to a representative of an academic institution we interviewed, traditional mining for materials is generally more economically viable than critical minerals recovery and substitution because the latter efforts do not qualify for federal economic development benefits and tax incentives. For example, according to a federal report, the U.S. tax code contains a number of provisions that benefit the oil and gas sector.[47] According to the report, tax preferences for oil and gas reduce the after-tax cost of investing in oil and gas exploration and production, encouraging additional investment in this sector relative to other economic sectors. Furthermore, according to representatives of a separate academic institution that we interviewed, there are limited federal economic benefits incentivizing investment in research and development for new critical mineral recovery methods such as phyto-mining and bio-mining.[48] In addition, according to USGS officials, traditional mining is more economically viable because unconventional sources are often low-grade resources.
- **Transportation costs and options.** In 2020, we found that some localities stopped collecting a certain item for recycling because of high transportation costs and low market value.[49] According to a nonfederal stakeholder we interviewed, the cost of transporting materials is expensive, especially when such materials are collected in the U.S. and sent to other countries. For instance, according to a representative of a recycling industry trade association we interviewed, the price of shipping materials via trucks is determined by

[47]Congressional Research Service, *IN FOCUS Oil and Gas Tax Preferences* (April 2021).

[48]Phyto-mining is a type of agro-mining that uses plants. Bio-mining relies on microbes to extract minerals from mine waste.

[49]GAO-21-87.

weight, so trucking companies prioritize heavier materials that are more profitable than lighter cargo. According to this nonfederal stakeholder, other modes of transportation, such as ocean freight, rail, and barge, may also be expensive, limited, and unreliable. For example, weather, navigation issues, and high costs can affect transport of recyclable materials by barge. A nonfederal stakeholder we interviewed explained that difficulties with securing space to transport recyclable materials and ensuring that they are delivered on time and at competitive prices can sometimes disrupt supply chains.

- **Critical mineral prices may not fully reflect environmental costs and benefits.** EPA officials we interviewed stated that critical mineral market prices do not reflect the environmental costs of producing different critical minerals. For example, according to federal and nonfederal stakeholders we interviewed, extracting critical minerals through traditional mining leads to environmental and social costs that are not accounted for in the prices for those commodities.[50] Furthermore, a nonfederal stakeholder we interviewed told us that critical minerals recovery efforts such as recycling are not considered cost-competitive because factors such as environmental costs and benefits are not considered in prices.

Federal officials we interviewed identified actions they are taking to improve the underlying economic viability of those materials. For example, DOE officials told us that for unconventional and secondary sources, DOE is integrating technologies and process design to reduce the costs of critical mineral production while maintaining environmental sustainability. In addition, according to DOE officials, DOE has a bio-mining program, and DOD has had several solicitations to advance bio-based approaches for critical minerals recovery. DOE officials told us that optimizations and innovations that reduce chemical usage and waste disposal, combined with co-production of critical minerals such as REEs, are improving the economics of domestic production from these unconventional and secondary sources that were once considered waste products.

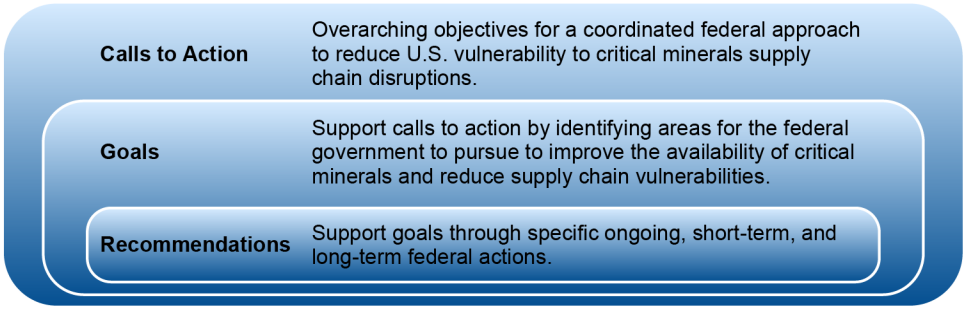
[50]In economic theory, social costs are private costs borne by individuals directly involved in a transaction together with the external costs borne by third parties not directly involved in the transaction.

Federal Agencies Have Taken Actions to Advance Recovery and Substitution, and Opportunities Exist to Improve the National Strategy

Federal Agencies Have Taken Actions Recommended in the National Strategy to Advance Critical Minerals Recovery and Substitution

As recommended by the national strategy, Commerce, DOD, DOE, and Interior have taken several actions to advance critical minerals recovery and substitution. The national strategy contains six calls to action, 24 goals, and 61 recommendations that describe specific steps the federal government should take to reduce critical minerals supply chain risks. Figure 6 shows the relationship among the 2019 national strategy's calls to action, goals, and recommendations.

Figure 6: Relationship among the Calls to Action, Goals, and Recommendations in the 2019 National Strategy for Critical Minerals



Source: GAO analysis of Department of Commerce, *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals* (June 2019). | GAO-22-104824

The national strategy broadly addresses critical minerals supply chain risks beyond those related to recovery and substitution. Three of the strategy's six calls to action include goals and recommendations that aim to advance critical minerals recovery and substitution through (1) advancing transformational research, development, and deployment across critical minerals supply chains; (2) strengthening America's critical minerals supply chains and defense industrial base; and (3) improving the

understanding of domestic critical mineral resources.[51] Progress towards these calls to action, goals, and recommendations could help agencies address the cross-cutting challenges constraining efforts to advance critical minerals recovery and substitution in the U.S.

Federal agencies have taken various actions to implement the recommendations associated with the three calls to action for advancing critical minerals recovery and substitution. According to our interviews with agency officials and our review of agency documents, DOE, DOD, and Interior have taken the following actions to advance transformational research, development, and deployment across critical minerals supply chains:

- **Creating a research and development roadmap.** The national strategy recommends that DOE—with assistance from agencies including DOD and EPA—(1) develop a roadmap that identifies key research and development needs; and (2) coordinate ongoing activities for source diversification and the more efficient use, recycling, and substitution of critical minerals by 2023.[52] According to DOE officials we interviewed, DOE has begun to develop a research and development roadmap. First, DOE officials told us that the agency is identifying its ongoing critical minerals research and development activities. For example, according to DOE officials we interviewed, DOE is conducting research and development—through public-private partnerships and the Critical Materials Institute—on fundamental science to discover new concepts and approaches to critical minerals recovery, such as reclamation and critical mineral production from unconventional and secondary sources. In addition, DOE awarded a total of $30 million in 3-year grants and awards to national laboratories and universities to support scientific research on critical minerals. DOE is also conducting research and development

[51]Other calls to action in the national strategy that do not include goals and recommendations that directly address areas to advance critical mineral recovery and substitution are to (1) enhance international trade and cooperation related to critical minerals, (2) improve access to domestic critical mineral resources on federal lands and reduce federal permitting time frames, and (3) grow the American critical minerals workforce.

[52]The national strategy states that the roadmap should also address cross-cutting mining science, data science techniques, materials science, manufacturing science and engineering, computational modeling, and environmental health and safety research and development.

on critical minerals substitution, such as alternatives to lithium-ion batteries and magnets with reduced or no critical REE content.

Second, DOE officials we interviewed told us that the agency is cataloguing ongoing critical minerals research and development efforts across other federal agencies. For example, DOD's Defense Logistics Agency contracted a private business to research the recovery of critical minerals from scrap lithium-ion batteries. Third, DOE held industry workshops to identify research and development opportunities and challenges. For example, through a recent workshop, DOE found that substituting critical minerals, such as cobalt, with nickel, could mitigate supply chain risks and advance the recycling of spent batteries.[53] According to DOE officials, DOE expects to meet the national strategy's 2023 deadline for developing the roadmap.

- **Conducting feasibility studies.** The national strategy recommends that DOE—with assistance from Commerce, DOD, EPA, and USGS––complete technical and economic feasibility studies of the production of critical minerals and related manufactured materials from secondary and unconventional sources such as coal-based resources, mine tailings, and end-of-life products. Federal agencies are taking actions to address this recommendation. For example, DOE conducted five small-scale pilots to demonstrate technical capabilities for producing critical minerals from unconventional and secondary sources (e.g., coal waste materials) and is conducting eight studies to facilitate the building of demonstration projects that could produce 1 to 3 metric tons of REEs per day. DOD is also conducting feasibility studies for recycling the agency's electric motor waste that contains REE magnets. In 2020, DOD awarded approximately $28.8 million to a private business for these studies to recycle REE magnets.[54] In addition, USGS has begun to develop a national mine waste inventory with the long-term goal of assessing the critical mineral resource potential associated with mine waste.

According to agency officials and our review of agency documents, Commerce, DOD, and DOE have taken the following actions to

[53]Department of Energy, Office of Energy Efficiency & Renewable Energy, *Office of Energy Efficiency and Renewable Energy Research and Development Battery Critical Materials Supply Chain Workshop* (Dec. 10-17, 2020).

[54]Department of Defense, Office of Inspector General, *Audit of the DoD Coronavirus Aid, Relief, and Economic Security Act Awards to the Defense Industrial Base*, DODIG-2021-081 (Alexandria, VA: May 20, 2021).

strengthen U.S. critical minerals supply chains and the defense industrial base:

- **Collaborating with industry.** The national strategy recommends that agencies, including DOD and DOE, convene industry and other nonfederal stakeholders from across critical minerals supply chains to, among other things, (1) improve the national recycling and materials recovery infrastructure to create more secure domestic supplies of critical minerals, (2) identify uses for secondary and unconventional sources of critical minerals, (3) improve product designs, and (4) explore technological and research and development needs to facilitate material recovery, by 2022. To address this recommendation, DOE held multiple workshops with nonfederal stakeholders and requested information related to challenges and opportunities across critical material battery supply chains, among other things. In addition, DOD officials told us that the agency is participating in a series of roundtable discussions organized by Commerce and DOE to connect U.S. industry with international partners for supply chain development, including critical minerals.
- **Incentivizing national defense innovations.** The national strategy also recommends that DOD evaluate and provide recommendations to incentivize U.S. industry to, among other things, develop innovations in material substitution and alternative approaches to processing and recycling, specific to national defense requirements. DOD has taken actions to address this recommendation. For example, DOD provided policy recommendations, including recommendations for critical minerals recovery, as part of a 2021 multi-agency report on critical mineral supply chains.[55] The review recommended that the federal government continue to provide research and development incentives to industry to develop, pilot, and deploy technologies that automate the removal of REE magnets from end-of-life items such as hard disk drives, cell phones, and other small devices.

According to agency officials and our review of agency documents, DOE and Interior have taken the following actions to improve the understanding of domestic critical mineral resources, according to agency officials and our review of agency documents:

- **Updating the critical minerals list.** The national strategy recommends that USGS—with the assistance of CMS—periodically

[55]The White House, et al., *Building Resilient Supply Chains*.

update the critical minerals list based on changes in mineral supply, demand, concentration of production, and current policy priorities. In addition, the Energy Act of 2020 requires the Secretary of the Interior, in consultation with others, to review the list of critical minerals as well as the methodology used to develop the list at least every 3 years and authorizes revisions to the methodology and the list.[56] In response to this requirement, in May 2021, Interior published an updated evaluation methodology as well as recommendations for updating the critical minerals list using this methodology.[57] In November 2021, USGS published in the *Federal Register* a draft list of 50 critical minerals; this list was finalized in February 2022.[58]

- **Assessing and identifying available resources.** The national strategy recommends that USGS—with assistance from DOE, EPA, and others—develop critical minerals resource assessment methods, characterize and map the critical mineral potential from unconventional and secondary sources, and provide a periodic status

[56]Consolidated Appropriations Act, 2021, Pub. L. No. 116-260, div. Z, § 7002(c), 134 Stat. 1182, 2564-2565 (2020) (*codified at* 30 U.S.C. § 1606(c)). The Secretary, acting through the Director of the U.S. Geological Survey, must publish a draft methodology for and list of critical minerals for public comment in the *Federal Register* and publish a final methodology and list in the *Federal Register* not later than 45 days after the close of the comment period on the draft methodology and list. 30 U.S.C. § 1606(c)(1).

[57]N.T. Nassar, and S.M. Fortier, *Methodology and Technical Input for the 2021 Review and Revision of the U.S. Critical Minerals List*, U.S. Geological Survey Open-File Report 2021-1045 (Reston, VA: U.S. Geological Survey, 2021). The updated methodology involved a quantitative assessment based on a risk modeling framework in which commodities with the greatest supply risk were those whose (1) global production was concentrated in countries that may become unable or unwilling to continue to supply to the U.S.; (2) U.S. consumption was predominately dependent on foreign supplies; and (3) U.S. consumption represented a large expenditure for U.S. manufacturing industries with low profitability, but who contributed greatly to the U.S. economy. In addition to the quantitative assessment, which focused on potential foreign supply disruptions, an evaluation of domestic supplies was also performed. Specifically, mineral commodities that had a single domestic producer along their raw material supply chains were identified as having a single point of failure and were automatically recommended for inclusion on the list.

[58]86 Fed. Reg. 62199 (Nov. 9, 2021); 87 Fed. Reg. 10381 (Feb. 24, 2022). The increase in the number of mineral commodities on the new list is largely the result of splitting the REEs and platinum group elements into individual entries rather than including them as mineral groups. In addition, the new list includes two commodities not on the 2018 list of critical minerals (nickel and zinc) and excludes four elements that were on the 2018 list (helium, potash, rhenium, and strontium). USGS used the definition of critical minerals in section 7002 of the Energy Act of 2020 to develop the new list. The section 7002 definition of critical minerals explicitly excludes fuel minerals, water, ice, snow, and common varieties of sand, gravel, stone, pumice, cinders, and clay.

update to CMS. Federal agencies are taking actions to address this recommendation. For example, according to USGS officials, USGS is (1) identifying natural resources by conducting critical mineral resource assessments; (2) conducting topographic, geophysical, and geological mapping of areas of the country with the potential to support efforts to conduct resource assessment; and (3) identifying methods to encourage the use of unconventional and secondary sources. DOE officials told us the agency is partnering with federal and nonfederal stakeholders in various coal-producing communities across the U.S. in an initiative to, among other things, develop strategies to produce and process critical minerals from unconventional and secondary sources.[59]

Opportunities Exist to Improve the National Strategy

In our previous work, we identified characteristics of effective national strategies, such as defining goals, identifying the resources and investments needed, and articulating how the strategy will be implemented.[60] We found that incorporating these characteristics into a national strategy enhances its usefulness to decision makers and better ensures accountability for its implementation. According to our analysis, the 2019 national strategy to address critical minerals supply chain risks partially addresses certain characteristics of effective national strategies identified in our prior work. For example, the national strategy describes various goals, assigns roles and responsibilities to specific agencies, and, in some cases, sets time frames for completing certain activities.

However, according to our analysis, the national strategy does not fully address certain characteristics of effective national strategies. Specifically, the national strategy does not fully (1) set goals, subordinate

[59]Department of Energy, National Energy Technology Laboratory, "Initiative to Create Jobs in Energy Communities Extracting Valuable Materials from Carbon Ore" (Aug.16, 2021), accessed February 14, 2022, https://netl.doe.gov/node/11045.

[60]GAO-04-408T. GAO found that effective national strategies address (1) why the strategy was produced, the scope of its coverage, and the process by which it was developed; (2) the particular national problems and threats the strategy is directed toward; (3) what the strategy is trying to achieve, steps to achieve those results, as well as the priorities, milestones, and performance measures to gauge results; (4) what the strategy will cost, the sources and types of resources and investments needed, and where resources and investments should be targeted based on balancing risk reductions with costs; (5) who will be implementing the strategy, what their roles will be compared with others, and mechanisms for them to coordinate their efforts; and (6) how a national strategy relates to other strategies' goals, objectives, and activities and to subordinate levels of government and their plans to implement the strategy.

objectives, activities, and performance measures;[61] (2) identify the resources and investments needed and balance the risk reductions with cost;[62] and (3) articulate how federal agencies will implement the strategy and integrate the activities identified in the national strategy with existing programs and activities.[63] For example, the national strategy outlines specific actions for USGS to assess and identify available resources, but it does not outline priorities, milestones, and outcome-related performance measures to implement the recommended actions. In addition, the national strategy recommends that federal agencies collaborate with industry and other nonfederal stakeholders, but it does not identify the resources and investments necessary to implement the recommended activities. Furthermore, the national strategy recommends that federal agencies develop a research and development roadmap, which could help address the cross-cutting challenge related to limited scientific research and technology development. However, the strategy does not address how federal agencies will implement the activities necessary to complete the roadmap or how to integrate them into existing programs. See table 1 for our assessment of the extent to which the 2019 national strategy addresses selected characteristics of effective national strategies.

[61]GAO-04-408T. In our previous work, we found that the elements that should be included in the goals, subordinate objectives, activities, and performance measures characteristic are: overall results desired (i.e., “end-state”); hierarchy of strategic goals and subordinate objectives; specific activities to achieve results; priorities, milestones, and outcome-related performance measures; specific performance measures; process for monitoring and reporting on progress; and limitations on progress indicators.

[62]GAO-04-408T. In our previous work, we found that elements that should be included in the resources, investments, and risk management characteristic are: resources and investments associated with the strategy; types of resources required, such as budgetary, human capital, information technology, research and development, and contracts; sources of resources (e.g., federal, state, local, and private); economic principles, such as balancing benefits and costs; resource allocation mechanisms, such as grants, in-kind services, loans, or user fees; “tools of government” (e.g., mandates or incentives to spur action); importance of fiscal discipline; linkage to other resource documents (e.g., federal budget); and risk management principles.

[63]GAO-04-408T. In our previous work, we found that elements that should be included in the integration and implementation characteristic are: integration with other national strategies (horizontal); integration with relevant documents from implementing organizations (vertical); details on specific federal, state, local, or private strategies and plans; implementation guidance; and details on subordinate strategies and plans for implementation (e.g., human capital) and enterprise architecture.

Table 1: Extent to Which the 2019 National Strategy for Critical Minerals Addresses Selected Characteristics of Effective National Strategies

Characteristic	Description	Our assessment of the 2019 national strategy against the characteristics
Goals, subordinate objectives, activities, and performance measures	Addresses what the strategy is trying to achieve, steps to achieve those results, as well as the priorities, milestones, and performance measures to gauge results.	Partially addresses
Resources, investments, and risk management	Addresses what the strategy will cost, the sources and types of resources and investments needed, and where resources and investments should be targeted by balancing risk reductions and costs.	Does not address
Integration and Implementation	Addresses how a national strategy relates to other strategies' goals, objectives and activities, and how the strategy will be implemented.	Partially addresses

Legend: Possible outcomes include "fully addresses" (none of the selected characteristics met this possible outcome), "partially addresses," or "does not address."

Sources: GAO, Combating Terrorism: Evaluation of Selected Characteristics in National Strategies Related to Terrorism, GAO-04-408T (Washington, D.C.: Feb. 3, 2004); and GAO analysis of the Department of Commerce's A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals (June 2019). | GAO-22-104824

According to Commerce officials we interviewed, the national strategy, which Commerce prepared in coordination with CMS, does not fully address these three specific characteristics for various reasons related to how the national strategy was developed. For example, Commerce officials told us that the calls to action, goals, and recommendations in the national strategy were developed based on efforts to identify and reflect current agency capabilities and ongoing activities at the time the national strategy was being developed. Furthermore, Commerce officials stated that critical minerals supply chain risks are complex and involve numerous stakeholders, which made it difficult to provide additional specificity in this initial effort.

Since the release of the national strategy in 2019, federal agencies have been taking actions to implement executive orders and statutory provisions related to critical minerals recovery and substitution (see app. II for examples of these statutory provisions). For example, in February 2021, the President issued Executive Order 14017, America's Supply Chains, which directed the Secretary of Defense, in coordination with other federal agencies, to submit a report identifying the risks in the

supply chain for critical minerals and other materials and policy recommendations to address those risks.[64]

In June 2021, in response to Executive Order 14017, the White House issued a multi-agency report containing a 100-Day Review, conducted by DOD, of supply chain risks for critical minerals and materials.[65] The report included recommendations to the President for administrative and legislative actions to address supply chain vulnerabilities related to critical minerals. For example, the report recommended expanding sustainable domestic production and processing capacity, including recovery from secondary and unconventional sources and recycling. Executive branch efforts to implement the 100-Day Review recommendations are being co-led by the National Economic Council (NEC) and the National Security Council, in coordination with CMS, through a committee that convenes agencies, subject matter experts, and political stakeholders to inform decision-making.[66]

Executive Order 14017 also directed various federal agencies to conduct sector-specific supply chain assessments, which were published on February 24, 2022. For example, the executive order directed (1) DOD, in consultation with others, to report on supply chains for the defense industrial base and (2) DOE, in consultation with others, to report on supply chains for the energy sector industrial base. Each report was to, among other things, include specific policy recommendations for ensuring a resilient supply chain for specific industrial sectors. NEC, the National Security Council, and other components of the Executive Office of the President are to work together to implement the recommendations from these sectoral assessments. Figure 7 provides a timeline of selected

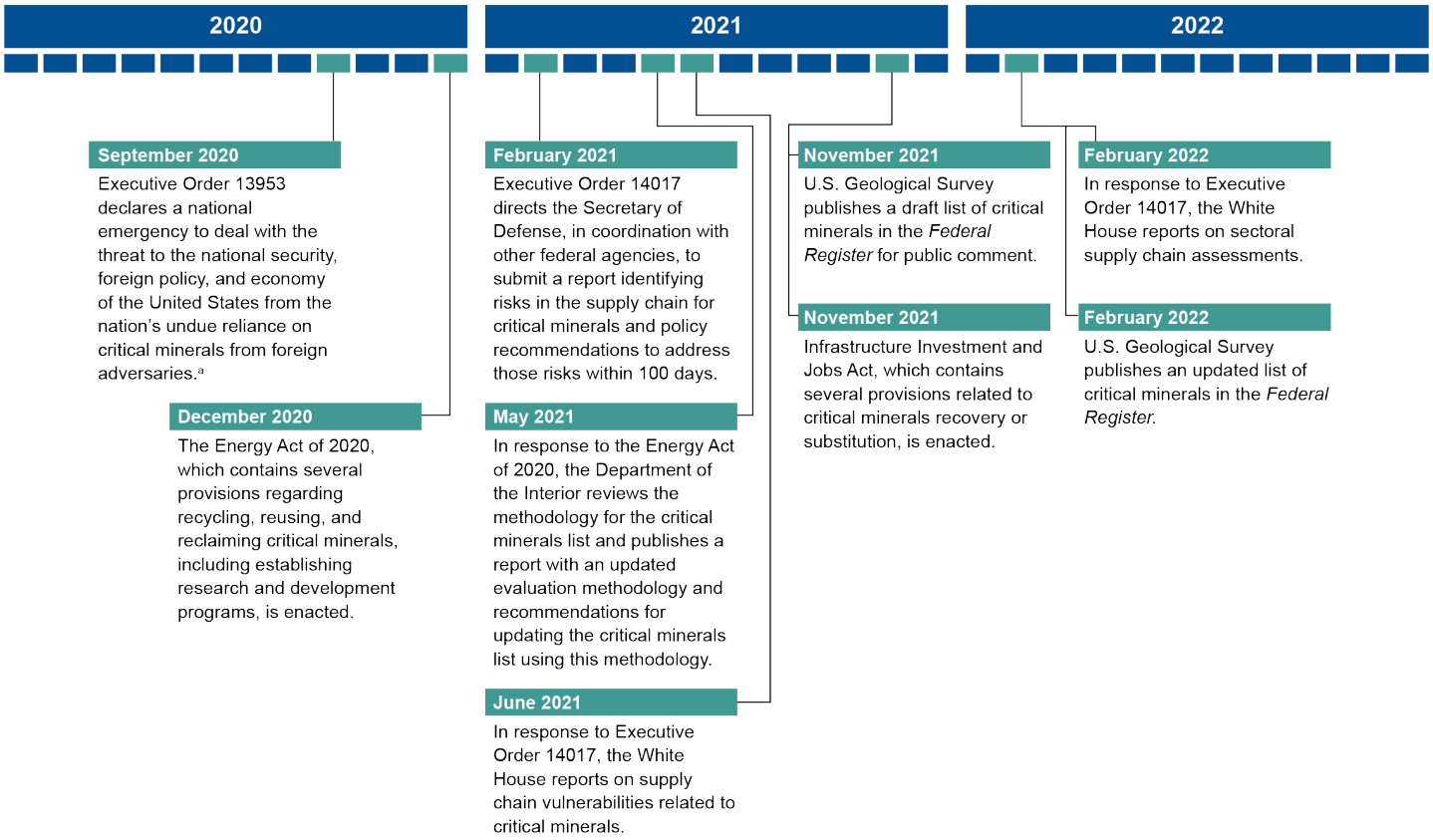
[64]86 Fed. Reg. 11849 (Mar. 1, 2021).

[65]The White House, et al., *Building Resilient Supply Chains*.

[66]For example, Commerce's review of semiconductor supply chains contained recommendations to address misaligned private market and public interest supply chain risks, including actions to increase public investment in research and development to advance sustainable technology. DOD's review of critical mineral and material supply chains included recommendations to (1) encourage industries to adopt design standards to make products more readily recyclable; and (2) establish a government-wide recycling program for reclaiming and recycling strategic and critical materials. DOE's review of high-capacity battery supply chain risks contained recommendations to increase the recovery of key critical minerals from recycled and unconventional sources as well as increase support for research and development into finding substitutes for certain critical minerals. In addition, the report recommended that DOE and EPA—with support from Commerce, Interior, and the Department of Transportation—develop sustainably produced content standards for strategic and critical material-intensive industries.

federal efforts to address executive orders and statutory requirements since 2020.

Figure 7: Key Federal Efforts to Address Executive Orders and Statutory Provisions Related to Critical Minerals Since 2020



Source: GAO analysis of agency documents and federal laws. | GAO-22-104824

[a]Executive Order 13953, *Addressing the Threat to the Domestic Supply Chain From Reliance on Critical Minerals From Foreign Adversaries and Supporting the Domestic Mining and Processing Industries*, 85 Fed. Reg. 62539 (Oct. 5, 2020).

According to USGS officials, CMS is evaluating the requirements in the recently enacted Energy Act of 2020, the Infrastructure Investment and Jobs Act, and appropriations acts to determine how to address the provisions related to critical minerals recovery and substitution.[67] In

[67]For example, the Infrastructure Investment and Jobs Act requires EPA to develop best practices for the collection of batteries to be recycled and voluntary battery labeling guidelines to promote battery recycling, and it appropriates $10 million and $15 million, respectively, for these activities.

particular, the Infrastructure Investment and Jobs Act authorizes CMS to develop, and update as necessary, a strategic plan to guide federal programs and activities to enhance scientific and technical capabilities across critical minerals supply chains. This includes providing a roadmap that (1) identifies key research and development needs, and (2) coordinates ongoing activities for source diversification, more efficient use, recycling, and substitution for critical minerals.[68] In addition, Office of Science and Technology Policy (OSTP) staff told us CMS was evaluating how to prioritize and implement the recommendations from the 100-Day Review of supply chains. The joint explanatory statement accompanying the Consolidated Appropriations Act, 2022, also directed appropriations to specific critical minerals recovery and substitution activities.[69] Furthermore, USGS's revised critical minerals list added new minerals to the list and removed others.

According to USGS officials we interviewed, as of January 2022, CMS had not made a decision about whether to update the national strategy. These officials told us that the timeline in which CMS will make a decision about updating the national strategy would be determined at a later date, based on agencies' priorities, plans, recent appropriations, and 100-Day Review recommendations. As of February 2022, according to OSTP staff, CMS was prioritizing its efforts based on the recommendations from the national strategy, the 100-Day Review, and other recent developments such as recently enacted requirements in the Infrastructure Investment and Jobs Act.

Updating the national strategy to more fully incorporate the characteristics of effective national strategies would provide DOE, Interior, and OSTP—the co-chairs of CMS—greater assurance of the strategy's usefulness to congressional and agency decision makers. Such updates could help in making resource and policy decisions, prioritizing federal efforts to address cross-cutting challenges, and better ensuring accountability for its implementation. For instance, including performance measures in the national strategy could better enable the CMS co-chairs to assess whether participating agencies are making progress toward reducing critical minerals supply chain risks. Furthermore, updating the national strategy to address recent developments would provide greater assurance that federal agencies are fully addressing executive orders and

[68]Pub. L. No. 117-58, § 40210(c)(3)(G)(i), 135 Stat. 429, 982 (2021) (*codified* at 42 U.S.C. § 18743(c)(3)(G)(i)).

[69]168 Cong. Rec. H1709, H2241 (Mar. 9, 2022).

recently enacted statutory requirements related to critical minerals recovery and substitution.

Conclusions

Certain minerals are critically important to U.S. economic prosperity and national security. However, the U.S. is heavily reliant on imports of many critical minerals, and supply chains are vulnerable to various risks. Federal agencies have taken actions to reduce vulnerabilities in the critical minerals supply chain by advancing recovery and substitution. More specifically, federal agencies are taking steps to implement the national strategy to ensure secure and reliable supplies of critical minerals, address recently enacted statutory requirements, and respond to recently issued executive orders.

However, the national strategy does not include these recently enacted statutory requirements and federal efforts, and it does not fully address certain characteristics of effective national strategies such as performance measures to gauge results, how federal agencies will implement the strategy, and the costs of doing so. Updating the strategy to address recent developments and better incorporate the characteristics of effective national strategies would provide greater assurance of the strategy's usefulness to congressional and agency decision makers and better ensure accountability for its implementation. Furthermore, updating the strategy could enhance CMS's efforts to address the cross-cutting challenges that currently constrain efforts to advance critical minerals recovery and substitution in the U.S.

Recommendation for Executive Action

The Secretary of Energy, the Secretary of the Interior, and the Director of the Office of Science and Technology Policy, in collaboration with the members of the Critical Minerals Subcommittee, should update the 2019 critical minerals national strategy as it relates to recovery and substitution. The update should address newly enacted statutory requirements and recent federal efforts and incorporate characteristics of effective national strategies, including (1) goals, subordinate objectives, activities, and performance measures; (2) resources, investments, and risk management; and (3) integration and implementation. (Recommendation 1)

Agency Comments and Our Evaluation

We provided a draft of this report to Commerce, DOD, DOE, EPA, Interior, the NEC, and OSTP for review and comment. In their comments, which are reproduced in appendix III and summarized below, DOE concurred with our recommendation. In their comments, which are reproduced in appendix IV and summarized below, Interior partially concurred with our recommendation. OSTP neither concurred nor

disagreed with our recommendation and provided comments in an email that are summarized below. DOE, EPA, and Interior also provided technical comments, which we incorporated, as appropriate. Commerce and DOD told us they had no comments on the draft report. NEC did not provide comments on the draft report.

In its written comments, DOE neither agreed nor disagreed with our recommendation, but in the email transmitting their comments, the agency said they agreed. The agency also stated that it regularly coordinates with federal, state, and local government offices, as well as industry and academia, to support efforts to make the U.S. less reliant upon imports for critical minerals. DOE also stated that it will support OSTP in making any updates to the national strategy deemed necessary by OSTP.

In its written comments, Interior stated that as the purpose and requirements of the national strategy are set by OSTP's National Science and Technology Council, USGS does not have a position on updating the national strategy or on the characteristics of such an update. Furthermore, USGS recommends that the report language be modified to direct the recommendation to OSTP, requiring consultation with the Secretaries of the Interior and Energy. However, we continue to believe that our recommendation is addressed to the appropriate entities responsible for updating the national strategy. The charter for the CMS lists OSTP, Interior, and DOE as its co-chairs. In addition, the national strategy itself states that CMS is the interagency coordinating body for critical minerals and that as part of its work, the CMS should be the entity that coordinates implementation of the national strategy. Furthermore, the national strategy states that the CMS should adaptively coordinate its implementation to reflect changes to the list of critical minerals and other emerging priorities and challenges.

In emailed comments, Senior Counsel at OSTP told us that they believe that the existing national strategy provides a useful framework for interagency collaboration and that the effort required to produce a new document would take time and attention away from executing the important work underway. Specifically, OSTP said that federal agencies are working closely together to address critical minerals issues across the entire supply chain through a number of Executive Office of the President-led mechanisms to implement the recommendations of the 100-day Review of supply chains and the sector-specific supply chain review reports, which were conducted in response to Executive Order 14017. OSTP said that federal agencies also are working to execute the

provisions of recent legislation, including the Energy Act of 2020 and the Infrastructure Investment and Jobs Act. We continue to believe in the importance of updating the current national strategy to be consistent with leading practices for effective national strategies. Updating the strategy also could enhance CMS's efforts to address the cross-cutting challenges that currently constrain efforts to advance critical minerals recovery and substitution in the U.S. Furthermore, updating the strategy will help to establish priorities, time frames, and performance measures, which would improve the strategy's usefulness to congressional and agency decision makers.

We are sending copies of this report to the appropriate congressional committees, the Administrator of EPA, the Director of the NEC, the Director of OSTP, the Secretary of Commerce, the Secretary of Defense, the Secretary of Energy, the Secretary of the Interior, and other interested parties. In addition, the report is available at no charge on the GAO website at http://www.gao.gov.

If you or your staff have any questions about this report, please contact me at (202) 512-3841 or gomezj@gao.gov. Contact points for our Offices of Congressional Relations and Public Affairs may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix V.

Sincerely yours,

J. Alfredo Gómez
Director, Natural Resources and Environment

Appendix I: Objectives, Scope, and Methodology

Our objectives were to (1) identify key challenges affecting efforts to advance critical minerals recovery and substitution in the U.S., and (2) examine the extent to which federal agencies have taken actions to advance critical minerals recovery and substitution in the U.S.

To identify key challenges affecting efforts to advance critical minerals recovery and substitution in the U.S., we obtained and analyzed the views of key federal and selected nonfederal stakeholders. The federal stakeholders include officials and staff from the Departments of Commerce, Defense, Energy, and the Interior; the Environmental Protection Agency (EPA); and the Office of Science and Technology Policy. We selected these six federal agencies and offices based on their participation in the Critical Minerals Subcommittee (CMS) and roles and responsibilities related to advancing critical minerals recovery and substitution outlined in the national strategy.[1]

The nonfederal stakeholders include academic researchers and representatives of industry, nonprofit organizations, and a trade association. Based on our prior work on hardrock mining, and by reviewing their participation in relevant congressional hearings, we identified a core group of three nonfederal stakeholders that were knowledgeable about critical minerals recovery and substitution efforts.[2] During our interviews with each of these stakeholders, we obtained recommendations for additional nonfederal stakeholders and selected four of these to interview. In total, we selected seven nonfederal stakeholders based on their knowledge and experience with critical minerals recovery and substitution efforts.

We conducted semi-structured interviews with these six federal agencies and offices and seven nonfederal stakeholders to obtain information about the stages of critical minerals supply chains, opportunities to increase supply or reduce demand for critical minerals, the key challenges facing stakeholders' efforts to advance critical minerals

[1]Department of Commerce, *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals* (June 2019).

[2]See GAO, *Federal Land Management: Key Differences and Stakeholder Views of the Federal Systems Used to Manage Hardrock Mining*, GAO-21-299 (Washington, D.C.: July 21, 2021); and *Hardrock Mining Management: Selected Countries, U.S. States, and Tribes Have Different Governance Structures but Primarily Use Leasing*, GAO-21-298 (Washington, D.C.: Dec. 18, 2020).

recovery and substitution, and illustrative examples of how these challenges affect certain stakeholders.

To corroborate testimonial information and provide contextual sophistication, we reviewed agency reports related to critical minerals recovery and substitution such as the EPA 2021 *National Recycling Strategy*.[3] We also reviewed reports produced by nonfederal stakeholders, such as recycling standards developed by nonprofit organizations, reports about environmental effects of certain mining and recovery processes from nonprofit organizations, and industry reports about renewable energy production. The views of these nonfederal stakeholders are not generalizable to all nonfederal stakeholders. However, the sample does contain stakeholders with a wide range of areas of expertise and viewpoints, and we sought to capture that range in our findings.

We analyzed stakeholder views to identify specific challenges affecting federal and nonfederal stakeholders' efforts to advance critical minerals recovery and substitution in the U.S. Based on these interviews, we developed a list of detailed challenges. We grouped similar items from this list into broader themes for reporting purposes. In grouping these items, we drew upon contextual information about the challenges, such as federal reports. We asked selected stakeholders to review our thematic groupings. We made changes to these groups, as appropriate, based on their feedback. For example, if all the stakeholders we interviewed agreed and there were no contrary opinions, we kept the original groups. We also kept the groups if one or more stakeholders stated that the group represented an important challenge and we did not receive any contrary views. Our final list included five cross-cutting challenges affecting multiple stakeholders or multiple stages of supply chains for critical minerals. In addition, we obtained information about illustrative examples of actions federal agencies are taking that could help to address these challenges. These actions were not explicitly recommended in the national strategy or linked to specific federal efforts to address its goals.

To examine the extent to which selected federal agencies have taken actions to advance critical minerals recovery and substitution in the U.S., we selected the six federal stakeholders noted above and added the

[3]U.S. Environmental Protection Agency, Office of Resource Conservation and Recovery, *National Recycling Strategy: Part One of a Series on Building a Circular Economy for All*, EPA 530-R-21-003 (Washington, D.C.: Nov. 15, 2021).

National Economic Council because of its role in coordinating related federal efforts. We reviewed the goals and recommendations from the national strategy and interviewed knowledgeable officials from these agencies and offices to identify agency activities related to advancing critical minerals recovery and substitution. We also reviewed federal laws, including the Energy Act of 2020 and the Infrastructure Investment and Jobs Act; regulations; and agency documents such as guidance, plans, reports, and budget requests.

In our prior work, we identified desirable characteristics of effective national strategies.[4] The national strategy broadly addressed critical minerals supply chain vulnerabilities, including activities that are not related to recovery and substitution. For example, the national strategy addresses barriers to international trade, ways to expedite time frames for permitting traditional mining on federal lands, and how to attract students to traditional mining engineering programs. In addition, CMS was established to address both critical minerals and strategic materials. Some of these activities and issues fall outside the scope of this review. We assessed the national strategy against the three desirable characteristics directly relevant to managing the progress of critical minerals recovery and substitution. These characteristics include: (1) goals, subordinate objectives, activities, and performance measures; (2) resources, investments, and risk management; and (3) integration and implementation.[5] We compared the 2019 national strategy to these selected characteristics and assessed the extent to which it incorporated these desirable characteristics.

We conducted this performance audit from February 2021 to June 2022, in accordance with generally accepted government auditing standards. Those standards require that we plan and perform the audit to obtain sufficient, appropriate evidence to provide a reasonable basis for our findings and conclusions based on our audit objectives. We believe that the evidence obtained provides a reasonable basis for our findings and conclusions based on our audit objectives.

[4]GAO, *Combating Terrorism: Evaluation of Selected Characteristics in National Strategies Related to Terrorism*, GAO-04-408T (Washington, D.C.: Feb. 3, 2004).

[5]The characteristics that we did not assess include (1) why the strategy was produced, the scope of its coverage, and the process by which it was developed; (2) the particular national problems and threats the strategy is directed toward; and (3) who will be implementing the strategy, what their roles will be compared with others, and mechanisms for them to coordinate their efforts.

Appendix II: Examples of Recently Enacted Statutory Requirements Related to Critical Minerals Recovery and Substitution

Table 2 shows selected requirements related to critical minerals recovery and substitution in the Energy Act of 2020, as amended.

Table 2: Selected Energy Act of 2020 Requirements, as Amended, Related to Critical Minerals Recovery and Substitution

Agencies	Act section (statutory citation)	Requirement	Statutory deadline
Department of Energy (DOE)	Section 3002(c), General Geothermal Systems Research and Development (42 U.S.C. § 17193(e))	Requires the Secretary of Energy to carry out a research and development initiative to provide financial assistance to demonstrate the coproduction of critical minerals from geothermal resources. Financial assistance provided by this initiative must improve the cost effectiveness of removing minerals from geothermal brines as part of the coproduction process, increase recovery rates of the targeted mineral commodity, decrease water use and other environmental impacts as determined by the Secretary, and demonstrate a path to commercial viability.	None
	Section 3201(b), Energy Storage System Research, Development, and Deployment Program (42 U.S.C. § 17232(b))	Requires the Secretary of Energy to establish an energy storage system program that focuses on research, development, and deployment of, among other things, cost-effective systems and methods for the sustainable and secure sourcing, reclamation, recycling, and disposal of energy storage systems, including critical minerals.	June 25, 2021
	Section 3201(e), Critical Material Recycling and Reuse Research, Development, and Demonstration Program (42 U.S.C. § 17231(q))	Requires the Secretary of Energy to establish a research, development, and demonstration program for critical material recycling and reuse of energy storage systems containing critical materials.	June 25, 2021
		Requires a report to relevant congressional committees summarizing the activities, findings, and progress of the program.	December 27, 2022, and every 3 years thereafter
	Section 7001, Rare Earths Elements, as amended (42 U.S.C. § 13344)	Requires the Secretary of Energy to conduct a program of research and development to, among other things, develop and assess advanced separation technologies for the extraction and recovery of rare earth elements and other critical minerals from coal and coal byproducts.	None
		Requires the Secretary to fund, through an agreement with an academic partner, the construction and build-out of a facility to demonstrate the commercial feasibility of a full-scale integrated rare earth element extraction and separation facility and refinery.	None
		Requires the Secretary to submit a report to relevant congressional committees evaluating the development of these separation technologies.	December 27, 2021, and annually thereafter while the facility with the academic partner remains in operation
	Section 7002(g), Recycling, Innovation, Efficiency, and Alternatives (30 U.S.C. § 1606(g))	Requires the Secretary of Energy to conduct a program of research, development, demonstration, and commercialization to, among other things, promote the efficient production, use, and recycling of critical materials, with special consideration for domestic critical materials, throughout the supply chain and ensure the long-term, secure, and sustainable supply of critical materials.	None

Agencies	Act section (statutory citation)	Requirement	Statutory deadline
		Requires the Secretary to submit a plan to Congress to carry out the program.	December 27, 2021
		Requires the Secretary of Energy to conduct a review of the program's activities to determine the achievement of technical milestones.	December 27, 2022
		Requires the Secretary of Energy to submit a report to Congress summarizing the activities, findings, and progress of the program.	December 27, 2022, and annually thereafter
		Requires the Secretary of Energy to establish and operate a Critical Materials Consortium for the purpose of supporting the program by providing, to the maximum extent practicable, a centralized entity for multidisciplinary, collaborative, critical materials research and development.	December 27, 2021
		Requires the Secretary of Energy to conduct a rigorous merit review to determine whether the Consortium helped the program achieve the technical milestones.	Not later than 5 years after the Consortium's establishment
	Section 7002(h), Critical Materials Supply Chain Research Facility (30 U.S.C. § 1606(h))	Requires the Secretary of Energy to support construction of a Critical Materials Supply Chain Research Facility.	None
Department of the Interior	Section 7002(j), Critical Minerals Analysis and Forecasting(30 U.S.C. § 1606(j))	Requires the Director of the U.S. Geologic Survey or a designee of the Secretary of the Interior, in consultation with the Energy Information Administration, academic institutions, and others, to include in the annually published Mineral Commodity Summaries a comprehensive review of past, and a comprehensive forecast of future, critical mineral production, consumption, and recycling patterns.	None
	Section 7002(k), Education and Workforce(30 U.S.C. § 1606(k))	Requires the Secretaries of the Interior and Labor to enter into an arrangement with the National Academy of Sciences and National Academy of Engineering to coordinate with the National Science Foundation on a study to, among other things, design an interdisciplinary program on critical minerals to improve the ability of the United States to increase domestic recycling of critical minerals.	None
		Requires the Secretary of the Interior to submit to Congress a description of the results of the study.	December 27, 2022
		Requires the Secretaries to jointly conduct a competitive grant program for institutes of higher education for grants to, among other things, fund startup costs for newly designated faculty positions in integrated critical mineral education, research, innovation, training, and workforce development programs.	None
DOE and Interior	Section 7002(i), Critical Materials Research Database and Information Portal (30 U.S.C. § 1606(i))	Requires the Secretaries of Energy and the Interior, in consultation with the Director of the National Science Foundation, to establish and operate a Critical Materials Information Portal to collect, catalogue, disseminate, and archive information on critical materials.	None

Source: Pub. L. No. 116-260, div. Z, 134 Stat. 1182, 2418-2615 (2020), as amended by Pub. L. No. 117-58, 135 Stat. 429 (2021). | GAO-22-104824

Table 3 shows selected requirements related to critical minerals recovery and substitution in the Infrastructure Investment and Jobs Act.

Table 3: Selected Provisions of the Infrastructure Investment and Jobs Act Related to Critical Minerals Recovery and Substitution

Agencies	Act section (statutory citation)	Requirement	Statutory deadline
Department of the Interior	Section 40201, Earth Mapping Resources Initiative (43 U.S.C. § 31l)	Establishes the Earth Mapping Resources Initiative within the U.S. Geological Survey (USGS) to complete an initial comprehensive national modern surface and subsurface mapping and data integration effort, with mapping and assessing critical minerals a priority.	November 15, 2031
	Section 40202, National Cooperative Geologic Mapping Program (43 U.S.C. § 31c(d)(4))	Requires USGS's National Cooperative Geologic Mapping Program to include an abandoned mine land and mine waste geologic mapping component to establish the geologic framework of abandoned mine land and other land containing mine waste. The priority for this effort is to map abandoned mine land and other land containing mine waste where multiple critical minerals, as defined by section 7002(a) of the Energy Act of 2020, and metal commodities are anticipated to be present.	None
Department of Energy (DOE)	Section 40207(b), Battery Material Processing Grants (42 U.S.C. § 18741(b))	Requires the Secretary of Energy to establish a Battery Material Processing Grant Program to, among other things, expand capabilities in advanced battery manufacturing and enhance the domestic processing capacity of minerals necessary for battery materials and advanced batteries.	May 14, 2022
DOE	Section 40207(c), Battery Manufacturing and Recycling Grants (42 U.S.C. § 18741(c))	Requires the Secretary of Energy to establish a battery manufacturing and recycling grant program to ensure that the U.S. has a viable domestic manufacturing and recycling capability to support and sustain a North American battery supply chain.	May 14, 2022
DOE	Section 40207(e), Lithium-Ion Battery Recycling Prize Competition (42 U.S.C. § 18741(e))	Requires the Secretary of Energy to continue to carry out the Lithium-Ion Battery Recycling Prize Competition.	None
DOE and Environmental Protection Agency (EPA)	Section 40207(f)(2), Battery Recycling Research, Development and Demonstration Grants (42 U.S.C. § 18741(f)(2))	Requires the Secretary of Energy, in coordination with the EPA Administrator, to award multiyear grants to eligible entities for research, development, and demonstration projects to create innovative and practical approaches to increase the reuse and recycling of batteries, including the extraction or recovery of critical minerals from batteries that are recycled; integration of increased quantities of recycled critical minerals in batteries and other products to develop markets for recycled battery materials and critical minerals; and addressing the cost-effectiveness and benefits of the reuse and recycling of batteries and critical minerals.	None

Agencies	Act section (statutory citation)	Requirement	Statutory deadline
DOE and EPA	Section 40207(f)(3),State and Local Programs (42 U.S.C. § 18741(f)(3))	Requires the Secretary of Energy, in coordination with the EPA Administrator, to establish a competitive grant program to award grants to states and units of local government to assist in the establishment or enhancement of state battery collection, recycling, and reprocessing programs.	None
DOE	Section 40207(f)(4), Retailers as Collection Points (42 U.S.C. § 18741(f)(4))	Requires the Secretary of Energy to award competitive grants to retailers that sell covered batteries or products containing batteries to establish and implement a system for the acceptance and collection of covered batteries and products for reuse, recycling, or proper disposal.	None
DOE and EPA	Section 40207(f)(5), Task Force on Producer Responsibility (42 U.S.C. § 18741(f)(5)	Requires the Secretary of Energy, in coordination with the EPA Administrator, to convene a task force to develop an extended battery producer responsibility framework to address, among other things, battery recycling goals, cost structures for mandatory recycling and outline regulatory pathways for effective recycling. The Secretary must submit a report to Congress describing the extended producer responsibility framework developed by the task force that includes the task force's recommendations on how best to implement a mandatory pay-in or other enforcement mechanism to ensure that battery producers and sellers are contributing to battery recycling and suggests regulatory pathways for effective recycling.	Report due not later than 1 year after the task force is convened
DOE	Section 40208, Electric Drive Vehicle Battery Recycling and Second-Life Applications Program (42 U.S.C. § 17231(k))	Requires the Secretary of Energy to carry out a research, development, and demonstration program of second-life applications for electric drive vehicle batteries that have been used to power electric drive vehicles and technologies and processes for final recycling and disposal of such batteries. The Secretary is required to award competitive, multiyear grants to eligible entities to, among other things, conduct research, development, testing and evaluation of solutions to increase the rate and productivity of electric drive vehicle battery recycling. The Secretary must publish the results of the projects carried out by the grants.	The first solicitation of applications for these grants was to be issued by February 13, 2022, and annually thereafter
		Requires the Secretary of Energy to conduct a study on viable market opportunities available for the recycling, second-use, and manufacturing of electric drive vehicle batteries in the U.S. and submit a report to relevant congressional committees on the results of the study.	November 15, 2022
DOE	Section 40209, Advanced Energy Manufacturing and Recycling Grant Program (42 U.S.C. § 18742)	Requires the Secretary of Energy to establish a program to award grants to eligible entities to carry out qualifying advanced energy projects. Qualifying advanced energy projects include projects that re-equip, expand, or establish a manufacturing or recycling facility for the production or recycling of advanced energy property (fuel cells, energy storage systems, electric or fuel cell vehicles, among other things) if they are located in certain areas and have a reasonable expectation of commercial viability, as determined by the Secretary.	May 14, 2022

Agencies	Act section (statutory citation)	Requirement	Statutory deadline
DOE and National Science Foundation (NSF)	Section 40210(b), Critical Minerals Mining and Recycling Research and Development (42 U.S.C. § 18743(b))	Requires the Secretary of Energy, in coordination with the Director of NSF, to issue awards to eligible entities to support basic research that will accelerate innovation to advance critical minerals mining, recycling, and reclamation strategies and technologies for the purposes of making better use of domestic resources and eliminating national reliance on minerals and mineral materials that are subject to supply disruptions.	None
Critical Minerals Subcommittee (CMS)	Section 40210(c), Critical Minerals Interagency Subcommittee (42 U.S.C. § 18743(c))	Requires the CMS of the National Science and Technology Council to coordinate federal science and technology efforts to ensure secure and reliable supplies of critical minerals to the U.S.	None
DOE, NSF, Interior, Department of Commerce	Section 40210(d), Grant Program for Processing of Critical Minerals and Development of Critical Minerals and Metals (42 U.S.C. § 18743(d))	Requires the Secretary of Energy, in consultation with the Director of the NSF, Secretary of the Interior, and Secretary of Commerce to establish a grant program to finance pilot projects for the processing or recycling of critical minerals, or the development of critical minerals and metals, in the U.S.	None
Energy Information Administration, Interior	Section 40415, Plan for the Modeling and Forecasting of Demand for Minerals Used in the Energy Sector (42 U.S.C. § 18775)	Requires the Administrator of the Energy Information Administration, in coordination with the Director of USGS, to develop a plan for the modeling and forecasting of demand for energy technologies—including for production, transmission, or storage purposes—that use minerals that are critical or could be designated as critical.	May 14, 2022
EPA	Section 70401(b), Best Practices for Collection of Batteries to be Recycled (42 U.S.C. § 6966c(b))	Requires the EPA Administrator to develop best practices that may be implemented by state, tribal, and local governments for collection of batteries to be recycled. Among other things, these best practices should optimize the value and use of material derived from recycling batteries. The Administrator must submit a report to Congress describing the best practices.	November 15, 2023, for the report to Congress
EPA	Section 70401(c), Voluntary Labeling Guidelines (42 U.S.C. § 6966c(c))	Establishes a program within EPA to develop voluntary labeling guidelines for batteries and other forms of communication materials for battery producers and consumers about the reuse and recycling of critical minerals from batteries.	None

Source: Pub. L. No. 117-58, 135 Stat. 429 (2021) | GAO-22-104824

Appendix III: Comments from the Department of Energy

Department of Energy
Washington, DC 20585

June 6, 2022

J. Alfredo Gomez
Director
Natural Resources and Environment
U.S. Government Accountability Office
441 G Street, NW
Washington, DC 20548

Dear Mr. Gomez:

The U.S. Department of Energy (DOE) appreciates the efforts of the U.S. Government Accountability Office (GAO) engagement team and the opportunity to provide comments on the GAO Draft Report, entitled: "*Critical Minerals: Building on Federal Efforts to Advance Recovery and Substitution Could Help Address Supply Risks.*" The draft report contains a recommendation for DOE to work with the Office of Science and Technology Policy (OSTP) and the Department of the Interior (Interior) to update the 2019 critical minerals strategy.

DOE regularly coordinates with Federal, state, and local government offices, as well as industry and academia, to support efforts to make the United States less reliant upon imports for critical minerals. Regarding the specific recommendation to update the 2019 critical minerals strategy, DOE will support OSTP in making any updates deemed necessary by OSTP.

GAO should direct any questions to John Wimer, Science & Technology Strategic Plans Programs, Acting Chief Research Officer, National Energy Technology Laboratory, at 304-285-4124.

Sincerely,

Brad Crabtree
Assistant Secretary
Fossil Energy and Carbon Management

Enclosure

Appendix IV: Comments from the Department of the Interior

United States Department of the Interior

OFFICE OF THE SECRETARY
Washington, DC 20240

J. Alfredo Gomez
Director, Natural Resources and Environment
U.S. Government Accountability Office
441 G Street, NW
Washington, DC 20548

Dear Mr. Gomez,

Thank you for providing the U.S. Geological Survey (USGS) an opportunity to review the draft Government Accountability Office (GAO) report titled *Critical Minerals Recovery, Building on Federal Efforts to Advance Recovery and Substitution Could Help Address Supply Risks (GAO-22-104824)*. The USGS partially concurs with the recommendation addressed to the heads of multiple agencies.

The GAO issued one recommendation to the Department as part of its overall findings. Below is the recommendation and the response to the specific recommendation.

Recommendation 1:

The Secretary of Energy, the Secretary of the Interior, and the Director of the Office of Science and Technology Policy, in collaboration with the members of Critical Minerals Subcommittee, should update the 2019 critical minerals national strategy, as it relates to recovery and substitution. The update should address newly enacted statutory requirements and recent federal efforts, and incorporate characteristics of effective national strategies including, (1) goals, subordinate objectives, and activities, and performance measures; (2) resources, investments, and risk management; and (3) integration and implementation.

USGS Response:

The USGS appreciates the GAO's review of Federal efforts to reduce supply risk for critical minerals by advancing recovery and substitution. As the purpose and requirements for the Federal Strategy are set by the Office of Science and Technology Policy's National Science and Technology Council, the USGS does not have a position on updating the strategy or the characteristics of such an update. In addition, the USGS recommends that the report language be modified to direct the recommendation to the Director of the Office of Science and Technology Policy, requiring consultation with the Secretaries of Interior and Energy.

If you should have any questions or need additional information, please contact Anne Barrett, Associate Director of the Office of Budget, Planning, and Integration at abarrett@usgs.gov.

Sincerely,

GARY GOLD Digitally signed by GARY GOLD
Date: 2022.05.17 16:10:34 -04'00'

for Tanya Trujillo
Assistant Secretary for Water and Science

Appendix V: GAO Contact and Staff Acknowledgments

GAO Contact

J. Alfredo Gómez, (202) 512-3841 or gomezj@gao.gov

Staff Acknowledgments:

In addition to the contact named above, Chad M. Gorman (Assistant Director); Joseph Capuano (Analyst-in-Charge); Kyle Abe; Darnita Akers; Kala Amos; Mark Braza; Lilia Chaidez; John Delicath; Chris Murray; Jeanette Soares; Sara Sullivan; Sarah Veale; and Sara Younes made key contributions to this report.

Related GAO Products

Science and Tech Spotlight: Deep-Sea Mining. GAO-22-105507. Washington, D.C.: December 15, 2021.

Science and Tech Spotlight: Advanced Plastic Recycling. GAO-21-105317. Washington, D.C.: September 14, 2021.

Federal Land Management: Key Differences and Stakeholder Views of the Federal Systems Used to Manage Hardrock Mining. GAO-21-299. Washington, D.C.: July 21, 2021.

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Recycling: Building on Existing Federal Efforts Could Help Address Cross-Cutting Challenges. GAO-21-87. Washington, D.C.: December 18, 2020.

Science and Tech Spotlight: Consumer Electronics Recycling. GAO-20-712SP. Washington, D.C.: August 31, 2020.

Advanced Manufacturing: Innovation Institutes Have Demonstrated Initial Accomplishments, but Challenges Remain in Measuring Performance and Ensuring Sustainability. GAO-19-409. Washington, D.C.: May 23, 2019.

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