GAO

United States Government Accountability Office

Report to Congressional Addressees

July 2024

TECHNOLOGY ASSESSMENT

Critical Minerals

Status, Challenges, and Policy Options for Recovery from Nontraditional Sources

GAO-24-106395

The cover image displays the list of 50 critical minerals identified by the U.S. Geological Survey (USGS) within the form of a representative ore.

Cover sources: USGS, Mineral Commodities Summaries 2023, Graphic Gurus(topographic pattern)/Rushi(rock outline)/stock.adobe.com; and GAO (composite). | GAO-24-106395

Highlights of GAO-24-106395, a report to congressional addressees

July 2024

Why GAO did this study

Critical minerals are essential for technologies used across the economy, including in energy, defense, health care, and electronics. But the U.S. supply is highly dependent on foreign countries. One strategy for increasing and diversifying the domestic supply of critical minerals is by recovering them from nontraditional sources.

This technology assessment discusses (1) the benefits of recovering critical minerals from nontraditional sources; (2) the status of available technologies to use on mining wastes, coal wastes, and geothermal and other brines; (3) the challenges of recovery from nontraditional sources; and (4) options policymakers could consider to help address the challenges.

In conducting this assessment, GAO interviewed officials from the federal government, academia, private industry, and nongovernmental organizations; convened a meeting of 15 experts with assistance from the National Academies of Sciences, Engineering, and Medicine; analyzed patent data from the U.S. Patent and Trademark Office; and reviewed relevant laws, government reports, and academic literature. GAO is identifying policy options in this report (see next page).

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What GAO found

The U.S. is highly dependent on foreign countries, including some adversaries, for its supply of critical minerals for manufacturing, such as rare earth elements for weapons systems and lithium for electric vehicle batteries. In addition to obtaining critical minerals from sources such as hardrock mines, it is possible to produce them from nontraditional sources found across the U.S. Such sources include mining wastes, water from existing mines, waste from coal-fired power plants, and saline groundwater (brine) from geothermal power plants. Domestic, nontraditional sources of minerals could increase the U.S. manufacturing and defense sectors' independence from foreign suppliers, reducing the need to open new mines, among other benefits.

Nontraditional sources of critical minerals

Coal-based sources | Hardrock mining wastes | Brines

Source: West Virginia University Water Research Institute (photo, coal-based sources); GAO (photos, hardrock mining wastes and brines). | GAO-24-106395

To recover minerals from coal and mining wastes, operators can generally repurpose mature technologies already used by the mining industry. However, we found that most of these projects are at the pilot scale. In contrast, direct lithium extraction from geothermal brines is closer to commercial-scale operation, with one such plant expected to be operational in 2025.

We identified several areas where challenges may arise in the recovery of critical minerals from nontraditional sources. Recent legislative and executive actions may help address characterization and permitting challenges. Remaining challenges are:

- **Liability.** Recovery operations on previously mined sites could result in operators being responsible for historical liabilities. There is little appetite in industry to take on this financial risk, according to experts.
- **Economics.** Due to factors such as high fixed costs and unstable prices potential recovery project operators may be uncertain that their investments will be financially viable.
- **Public engagement and tribal consultation.** Stakeholders and experts identified engagement with local communities, and when appropriate, government-to-government consultation with Tribal Nations as important steps to a successful critical mineral recovery project.

GAO identified three policy options that could help address the challenges or enhance the benefits of recovering critical minerals from nontraditional sources. The policy options are possible actions by policymakers—which may include Congress; federal agencies; and state, local, and tribal governments. In addition, policymakers could choose to maintain the status quo, whereby they would not take additional action beyond current efforts. See below for details of the policy options.

Policy Options to Help Address Challenges or Enhance Benefits of Recovering Critical Minerals from Nontraditional Sources

Policy Option	Opportunities	Considerations
Pilot Good Samaritan legislation (report p. 30) **Implementation approaches:** *Legislators could provide some liability protections for third parties recovering critical minerals from waste at previously mined sites.* *Legislators could provide protections for third parties but require a portion of profits generated be used for restoration activities.*	• Could encourage investment in domestic recovery operations. • Could expand the types of organizations interested in cleaning up previously mined sites.	• Disturbing previously mined sites may result in new environmental effects. • If financial assurances are not adequately set, federal or state taxpayers may become responsible for cleaning up additional environmental liabilities. • Requiring that a percentage of profits be used for restoration activities could affect industry interest in previously mined sites.
Subsidies (report p. 30) **Implementation approaches:** *The federal government could subsidize the development of specific nontraditional sources to meet defense or energy needs.* *Subsidies could be made available as tax credits for those pursuing nontraditional sources of critical minerals.*	• Properly tailored subsidies could catalyze technology development, demonstration, commercialization, and domestic production of critical minerals. • Subsidies could help offset some of the fixed costs associated with developing recovery and processing infrastructure.	• Taxpayer-funded subsidies do not guarantee that supported recovery operations would become profitable. • Once in place, subsidies can be difficult to end. • May result in reallocation of resources from other priorities.
Community benefit agreements (report p. 31) **Implementation approaches:** *To improve engagement with communities near nontraditional sources, permitting agencies could encourage operators to pursue agreements that outline how communities may benefit from projects that also incur costs in their communities.* *Companies could adopt policies that encourage or facilitate these agreements.*	• Negotiating specific community benefits from new recovery operations could create deeper acceptance of facilities that may have environmental effects. • New recovery operations could offer additional employment opportunities in economically depressed communities.	• Negotiating which stakeholders benefit, which do not, and who controls the agreement can be challenging. • It is difficult to predict who will be willing to engage in such agreements. • Such agreements may be time consuming to create. • Some provisions in these agreements may be difficult to enforce.
Status quo (report p. 31) **Implementation approach:** *Sustain current efforts.*	• Federal policymakers could observe and evaluate existing efforts, such as agency funding of characterization of nontraditional sources, which could limit risks and resources expended. • Continued private sector efforts, such as recovery of lithium from geothermal brines, could ultimately result in profitable recovery of minerals. • The private sector may also pursue other options to overcome critical mineral supply chain issues. For example, buyers may pursue substitutes, reducing the need for new sources.	• Current efforts may not address all the challenges described in this report. • Current efforts alone may delay or inhibit the development of nontraditional sources for critical minerals, which could result in forgone benefits such as increased independence from foreign suppliers.

Source: GAO. | GAO-24-106395

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Abbreviations

DOE	Department of Energy
EPA	Environmental Protection Agency
IWG	Interagency Working Group on Mining Laws, Regulations, and Permitting
USGS	U.S. Geological Survey
USPTO	U.S. Patent and Trademark Office

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July 31, 2024

Congressional Addressees

Critical minerals such as lithium, cobalt, and rare earth elements are essential for technologies used in many sectors of the economy, including energy, transportation, national defense, health care, and consumer electronics. These minerals are vulnerable to supply-chain disruptions for several reasons, including U.S. reliance on foreign sources, as well as the rapid growth in demand for critical minerals in the U.S. and abroad.

In addition to traditional sources for critical minerals, such as hardrock mines, several domestic waste sources at existing mining and industrial sites have the potential to be sources for some critical minerals. These nontraditional sources include mining wastes, water from existing mines, waste from coal-fired power plants, and groundwater that is already used for geothermal power or in the recovery of oil and gas.[1] Such sources are located throughout the U.S., and some are abundant. For example, the U.S. has 250 billion tons of coal reserves, 4 billion tons of coal waste, and 2 billion tons of coal ash, according to Department of Energy (DOE) estimates.[2] Recovering critical minerals from existing mining and industrial sites could bring additional benefits, such as reduced demand for additional mines, as well as increased employment in economically depressed communities. However, critical mineral recovery from nontraditional sources may also face liability and economic challenges.

We prepared this report under the authority of the Comptroller General to assist Congress with its oversight responsibilities given broad congressional interest in critical minerals. We examined (1) domestic nontraditional sources that could be used to recover critical minerals and the status of associated recovery technologies, (2) benefits and challenges associated with the recovery of critical minerals from nontraditional sources, and (3) policy options that could help enhance these benefits or mitigate these challenges. To address these objectives, we reviewed peer-reviewed articles and other reports, conducted a patent analysis, interviewed stakeholders, conducted site visits, and convened an expert meeting. See appendix I for a full discussion of our objectives, scope, methodology and see appendix II for a list of experts who participated in our meeting.

[1]For the purposes of this report, nontraditional sources refer to unconventional sources (e.g., coal and geothermal brines) and certain secondary sources (e.g., mining wastes, coal ash, and acid mine drainage). Recycling of critical minerals from post-consumer secondary sources is outside the scope of this report.

[2]U.S. Department of Energy, Funding Notice: Bipartisan Infrastructure Law: Front-End Engineering and Design Studies for Production of Critical Minerals and Materials from Coal-Based Resources, https://www.energy.gov/fecm/funding-notice-bipartisan-infrastructure-law-front-end-engineering-and-design-feed-studies, accessed June 11, 2024.

We conducted our work from November 2022 to July 2024 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

1 Background: Critical Minerals and Nontraditional Sources

In December 2017, the President issued Executive Order 13817, *A Federal Strategy to Ensure Secure and Reliable Supplies of Critical Minerals*. Pursuant to this order, the Secretary of the Interior identified critical minerals as (1) non-fuel minerals or mineral materials essential to the economic and national security of the U.S., (2) that had a supply chain vulnerable to disruption, and (3) that served an essential function in the manufacturing of a product, whose absence would have significant consequences for the U.S. economy or national security.[3] In response to this order, the U.S. Geological Survey (USGS) produced an initial list of critical minerals in 2018.

After the Energy Act of 2020 codified the definition of a critical mineral into law,[4] USGS released an updated list of critical minerals.[5] The act requires that the Secretary of the Interior review the critical minerals list at least every 3 years. There are currently 50 critical minerals. Figure 1 shows these minerals, along with details about their sources and uses.

[3]82 Fed. Reg. 60835 (Dec. 26, 2017); *see also* Exec. Order No. 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).

[4]Energy Act of 2020, Pub. L. No. 116-260, § 7002, 134 Stat. 2418, 2562 (codified at 30 U.S.C. § 1606).

[5]2022 Final List of Critical Minerals, 87 Fed. Reg. 10381 (Feb. 24, 2022).

Figure 1: The 2022 U.S. list of critical minerals, percentage of the U.S. supply imported in 2022, industries in which each is used, and primary import source

Mineral	Percentage from foreign sources[a]	Key Industries: Aerospace	Key Industries: Defense	Key Industries: Energy	Key Industries: Telecommunications and electronics	Key Industries: Transportation (non-aerospace)	Primary Import Source (2018–2021)[b]
Arsenic	100%		●	●	●		China: 57%
Cesium	100%	●	●	●	●		N/A
Fluorspar	100%			●	●		Mexico: 66%
Gallium	100%	●	●	●	●		China: 35%
Graphite	100%	●	●	●	●	●	China: 35%
Indium	100%	●	●	●	●		Republic of Korea: 35%
Manganese	100%	●	●	●		●	Gabon: 67%
Niobium	100%	●	●	●			Brazil: 66%
Rubidium	100%	●	●	●	●		N/A
Tantalum	100%	●	●	●	●		China: 24%
Bismuth	96%		●	●	●		China: 65%
Rare Earth Elements (Cerium, Dysprosium, Erbium, Europium, Gadolinium, Holmium, Lanthanum, Lutetium, Neodymium, Praseodymium, Samarium, Scandium, Terbium, Thulium, Ytterbium, Yttrium)	>95%	●	●	●	●	●	China: 74%
Titanium	>95%	●	●	●			Japan: 89%
Antimony	83%		●	●	●	●	China: 63%
Chromium	83%	●	●	●			South Africa: 37%
Tin	77%		●		●		Peru: 25% (refined Tin)
Cobalt	76%	●	●	●	●	●	Norway: 22%
Zinc	76%		●	●			Canada: 66%
Barite	>75%			●			China: 38%
Tellurium	>75%		●	●	●		Canada: 52%
Platinum[c]	66%	●		●	●	●	South Africa: 24%
Nickel	56%	●	●	●			Canada: 45%
Aluminum	54%	●	●	●		●	Canada: 50%
Vanadium	54%	●	●	●			Canada: 31%
Germanium	>50%	●	●	●	●		China: 54%
Magnesium	>50%	●	●	●	●	●	Canada: 21%
Tungsten	>50%	●	●	●	●		China: 29%
Zirconium	<50%	●	●	●			China: 89% (Zirconium unwrought, including powder)
Palladium[c]	26%	●		●	●	●	Russia: 34%
Lithium	>25%	●	●	●	●	●	Argentina: 51%
Beryllium	<20%	●	●	●	●		Kazakhstan: 43%
Hafnium	—	●	●	●			Germany: 36%
Iridium[c]	—	●		●	●	●	—
Rhodium[c]	—	●		●	●	●	—
Ruthenium[c]	—	●		●	●	●	—

Source: U.S. Geological Survey (USGS), *Mineral Commodity Summaries 2023* (Reston, Virginia: 2023). | GAO-24-106395

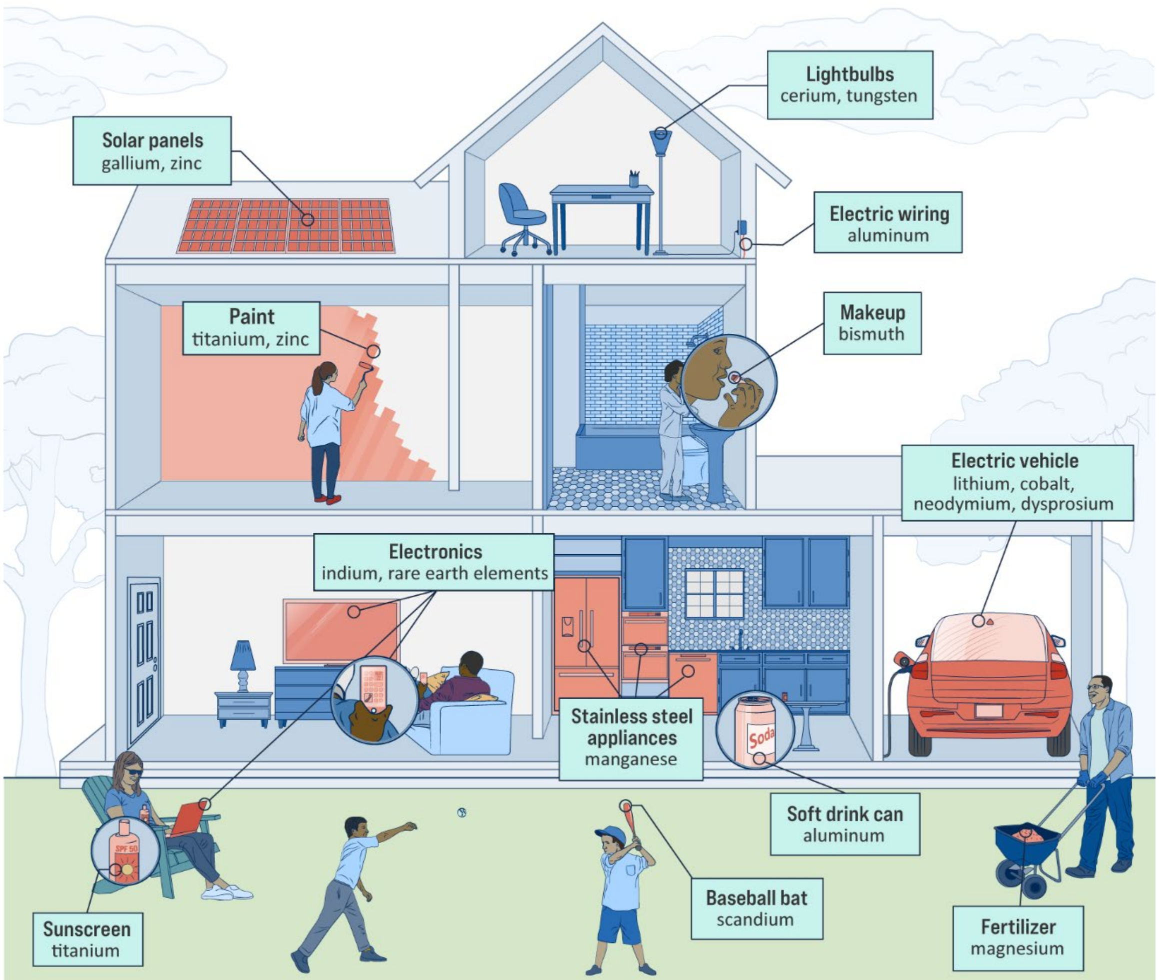
[a]U.S. net import reliance expressed as a percentage of apparent U.S. consumption in 2022, a metric developed and calculated by USGS using import data from the U.S. Census Bureau and consumption data from *USGS's Mineral Commodity Summaries 2023*.

[b]Import source percentage from 2018 through 2021, calculated by USGS using import data from the U.S. Census Bureau.

[c]This mineral is a part of the platinum group and the key industries shown are for the group.

Critical minerals are necessary inputs for products that the military, domestic infrastructure, and the broader economy depend upon. Such products include airplanes, computers, cell phones, electrical systems, and advanced electronics. Figure 2 depicts products used in everyday life that contain critical minerals.

Figure 2: Critical minerals used in everyday life



Source: GAO (analysis and illustrations). | GAO-24-106395

Critical minerals are largely acquired as by-products of other mining activity rather than sought directly by mining firms. For example, of the 50 critical minerals on the 2022 USGS list, only six are primary minerals sought in mining operations: aluminum, nickel, platinum, tin, titanium, and zinc. The 44 other critical minerals are largely recovered as by-products of 10 "host metals." See table 1 for the relationship between host metals and by-product minerals on the USGS critical minerals list.

Table 1: Host metals and byproduct minerals on the 2022 U.S. list of critical minerals

Host metals	By-product minerals on the 2022 U.S. list[a]
Aluminum	Gallium, vanadium
Copper[b]	Tellurium, cobalt, indium, bismuth, tin, zinc
Gold[b]	Antimony, zinc
Iron[b]	Neodymium, cerium, praseodymium, lanthanum, europium, vanadium, samarium, gadolinium, manganese, terbium, dysprosium, yttrium
Lead[b]	Antimony, bismuth, tellurium, zinc
Nickel	Palladium, cobalt, rhodium, iridium, platinum, ruthenium
Platinum	Ruthenium, rhodium, iridium, palladium, chromium, nickel, cobalt
Tin	Niobium, tungsten, antimony, indium, bismuth, tantalum, erbium, holmium, dysprosium, terbium, gadolinium, europium, samarium, neodymium, praseodymium, cerium, lanthanum, yttrium
Titanium	Zirconium, hafnium, yttrium, lanthanum, cerium, praseodymium, neodymium, samarium, europium, gadolinium, terbium, holmium, dysprosium, europium, thulium, ytterbium, lutetium
Zinc	Indium, germanium, gallium, tin

Source: GAO analysis of U.S. Geological Survey (USGS) data. | GAO-24-106395

[a]Minerals are listed in the order of percentage (most to least) of primary production that originates with the host metal.

[b]This metal is not on the 2022 USGS critical minerals list but its by-product minerals are.

In June 2019 the Department of Commerce issued a national strategy outlining actions that federal agencies should take to diversify and expand critical mineral supplies obtained from sources other than traditional mining.[6] We previously reported on federal efforts to advance recovery and substitution of critical minerals and recommended updating the national strategy.[7] This technology assessment addresses three nontraditional sources for critical minerals that may be available at mining and industrial sites throughout the U.S.:

- Mining wastes (for cobalt, lithium, and antimony, among others)
- Coal-based sources such as acid mine drainage (for rare earth elements)
- Geothermal and other brines (for lithium, manganese, and zinc).

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

[7]GAO, *Critical Minerals: Building on Efforts to Advance Recovery and Substitution Could Help Address Supply Risks*, GAO-22-104824 (Washington DC, June 16, 2022).

2 Benefits of Recovery from Nontraditional Sources

Our review identified three categories of benefits to recovering critical minerals from nontraditional sources: (1) domestic supply, (2) reuse of existing sites, and (3) community.

2.1 Domestic supply

Some critical minerals are mined in a single country or in a region that is vulnerable to geopolitical unrest. Critical minerals processing can also be limited to a small number of facilities in other countries. Increasing domestic recovery of critical minerals, including by pursuing nontraditional sources, could bring the following benefits:

- **Increased independence from foreign control.** Additional domestic sources could make the supply of critical minerals more reliable for the U.S. and its allies. In turn, this could help make the production of goods important to national security and the economy more reliable. In cases where a single country controls much of the supply of a particular mineral, export restrictions could prevent access for users in the U.S. For example, in August 2023, China unexpectedly restricted the export of gallium and germanium, metals used in military and energy technologies. In addition, in December 2023, China began requiring export permits for some graphite products that are key materials in batteries.
- **Price stability.** Changes to foreign trade policies can also cause rapid price increases. For example, in 2010, China increased its export restrictions on rare earth elements, and prices increased rapidly. In one case, from April 2010 to July 2011, the price of the rare earth element dysprosium rose from $250 per kilogram to $2,840 per kilogram.[8]

2.2 Reuse existing sites

Recovering critical minerals from nontraditional sources on existing sites may result in the following benefits:

- **Reduced traditional mining.** Recovering critical minerals from waste at an existing mine site may reduce demand for new mines, avoiding their negative effects on the environment, although these activities may result in other environmental effects. Additionally, newer techniques to access lithium in geothermal and other brines may require less land than conventional techniques (see ch. 4).
- **Leverage existing infrastructure.** Existing sites may already have some supporting infrastructure that can be leveraged for extracting critical minerals. For example, coal mines can add technology for extracting rare earth elements to the water infrastructure already in place to treat runoff (known as acid mine

[8]Dysprosium is magnetic and is used in data storage devices as well as electric vehicles. Dysprosium helps the magnets in motors preserve their magnetism at high temperatures and improves their resistance to corrosion.

drainage, see ch. 3). For geothermal brines, firms can pair mineral extraction with geothermal power production and may be able to access some of the low-carbon energy produced on the same site.[9]

- **Lower operational costs.** Some aspects of processing nontraditional sources can be less costly than traditional mining. For example, 40 to 60 percent of mineral processing costs are related to mining and material crushing, steps that may be unnecessary for some waste materials. In the case of brines, an operator—which could be a geothermal power plant or an oil and gas firm—is already pumping the brine to the surface, so the additional cost to access the source by an extraction firm may be minimal.

- **Additional revenue stream to offset reclamation activities.** Recovering critical minerals from waste could provide an additional source of revenue at a site. Firms could use some of this revenue to offset the cost of reclaiming land at current or legacy mine sites or improving water quality. For example, there is a firm recovering cobalt, nickel, and other materials from surface mine tailings at a Superfund site in Missouri. The original tailings had been left in unlined impoundments that did not fully prevent the release of toxic materials. After recovering the minerals of interest, the firm places the newly generated tailings in improved impoundments, which provides an environmental benefit.

2.3 Community

Efforts to reopen mines or pursue new business at an active mine or geothermal power plant can benefit local communities and industry. For example:

- **Local workforce development.** New activities to recover critical minerals from nontraditional sources may offer employment opportunities for local residents and opportunities for them to develop new skills. According to DOE officials, critical mineral recovery from coal-based sources could bring new jobs to regions where coal mines, which had been the basis for local economies, are closing.

- **Rebuilding trust.** Local stakeholders in some mining communities may not trust the mining industry or government regulators due to negative experiences they have had in the past. Experts said that operators considering re-opening a closed mine must prioritize building trust with the local community and address all historical and new concerns. Recovery from mine waste is a potential gateway to reestablish mining operations and develop positive relationships with nearby communities. For example, experts told us that any communication and transparency mechanisms operators put in place with stakeholders can create

[9]Geothermal power plants draw fluids from underground reservoirs to the surface to produce steam, which then drives turbines that generate electricity. Once the brine is pumped to the surface, an extraction facility can recover minerals before re-injecting it into the ground.

new opportunities to interact and exchange information and concerns.

Experts who participated in our meeting—along with experts from the Interagency Working Group on Mining Laws, Regulations, and Permitting (IWG)—noted that companies can formally promise benefits to communities hosting their operations.[10] For example, in 2022 the Fort McDermitt Paiute and Shoshone Tribe in Nevada signed a community benefit agreement with a lithium company that provided for, among other things, job training and construction of an 8,000-square-foot community center.

The resulting "community benefit agreements" are legally binding contracts between stakeholders of the community and mining companies. They can help shape local projects to improve residents' quality of life through provisions such as revenue sharing, employment and training opportunities, requirements for local business contracting or local infrastructure development, and impact monitoring programs. The process can also create channels of communication between the community and the company, according to an expert.

[10]Biden-Harris Administration Interagency Working Group on Mining Laws, Regulations, and Permitting, *Recommendations to Improve Mining on Public Lands,* (Washington, DC, Sept. 2023).

3 Mining and Coal Wastes

Wastes from mining activities—both hardrock and coal—and wastes from the use of coal generally are found in large quantities domestically and are currently being developed as nontraditional sources of critical minerals. These wastes historically were thought to have no value, but more recent scientific analysis has revealed that they can contain recoverable quantities of critical minerals. The technology needed to recover minerals from this waste is mature for other applications. Operators can generally repurpose technologies, such as chemical leaching, already used by the mining industry but may need to modify them. However, most of the projects we identified seeking to recover minerals from these sources have been at the pilot scale.[11]

3.1 Overview of mining and coal wastes

Wastes from hardrock and coal mining are one of the world's largest waste types. Mining waste refers to all material that is extracted from the ground and processed in varying stages that has low or no economic value at the original time of extraction. In addition, coal-fired power plants produce wastes that contain critical minerals. Coal-based sources—including waste from coal mining and the use of coal—are of particular interest as a nontraditional source of rare earth elements (see text box).

Rare earth elements

Of the 50 critical minerals on the U.S. Geological Survey's (USGS) 2022 list, 16 are considered rare earth elements: cerium, dysprosium, erbium, europium, gadolinium, holmium, lanthanum, lutetium, neodymium, praseodymium, samarium, scandium, terbium, thulium, ytterbium, and yttrium. Rare earth elements are relatively abundant in the earth's crust but are often found in low concentrations which makes recovering them difficult. According to USGS, there are an estimated 3.6 million tons of minable rare earth element resources in the U.S.

Rare earth elements are used in many technologies in a variety of sectors including defense, communications, and health care. They are also an essential part of the digital economy. For example, terbium is used in solid-state devices such as transistors, solar cells, and integrated circuits. Rare earth elements are a key component in permanent magnets which are used in certain clean energy technologies, including wind turbines and electric vehicle motors. Increasing adoption of these technologies is expected to increase the demand for these minerals in the coming decades.

Just one mine currently produces rare earth elements in the U.S. (in Mountain Pass, California), while about 70 percent of the world's rare earth elements ore supply comes from deposits in China. An even greater share of rare earth elements separation and processing occurs in China (around 90 percent).

Source: GAO analysis. | GAO-24-106395

These and other critical minerals have been successfully recovered from several types of mining wastes and coal-based sources:

- **Tailings** are a byproduct of hardrock or coal ore mineral processing. In hardrock mining, tailings are being produced at an increasing rate as advances in technology enable the use of large volumes of lower-grade ores.
- **Waste rock piles** contain the material removed to access an ore deposit. These

[11]Typically, the pilot scale includes testing of an engineering-scale prototype in a relevant environment. Successful technologies may then advance to demonstration of a full-scale or actual system prototype. Once a technology is proven to work at the demonstration scale, it is considered ready for commercialization.

piles can include metals such as zinc, iron, cadmium, copper, and lead that are locked within the rock in quantities that were not feasible to extract during past mining operations.

- **Acid mine drainage**, also called acid rock drainage**,** is runoff from underground and aboveground mine workings, waste rock, or tailings that contains sulfuric acid and dissolved metals, which forms through the chemical reaction of water with rocks that contain iron sulfide. Acid mine drainage can also contain rare earth elements and other critical minerals.

- **Coal fly ash**, or simply fly ash, is a waste product of coal-fired power plants—very fine, powdery material composed mostly of silica. Plants may dispose of it in landfills or sell it for use in concrete, cement, or structural fill. Fly ash also contains a high concentration of rare earth elements—in certain cases, even higher than what can be found in some of the rare earth element ores.

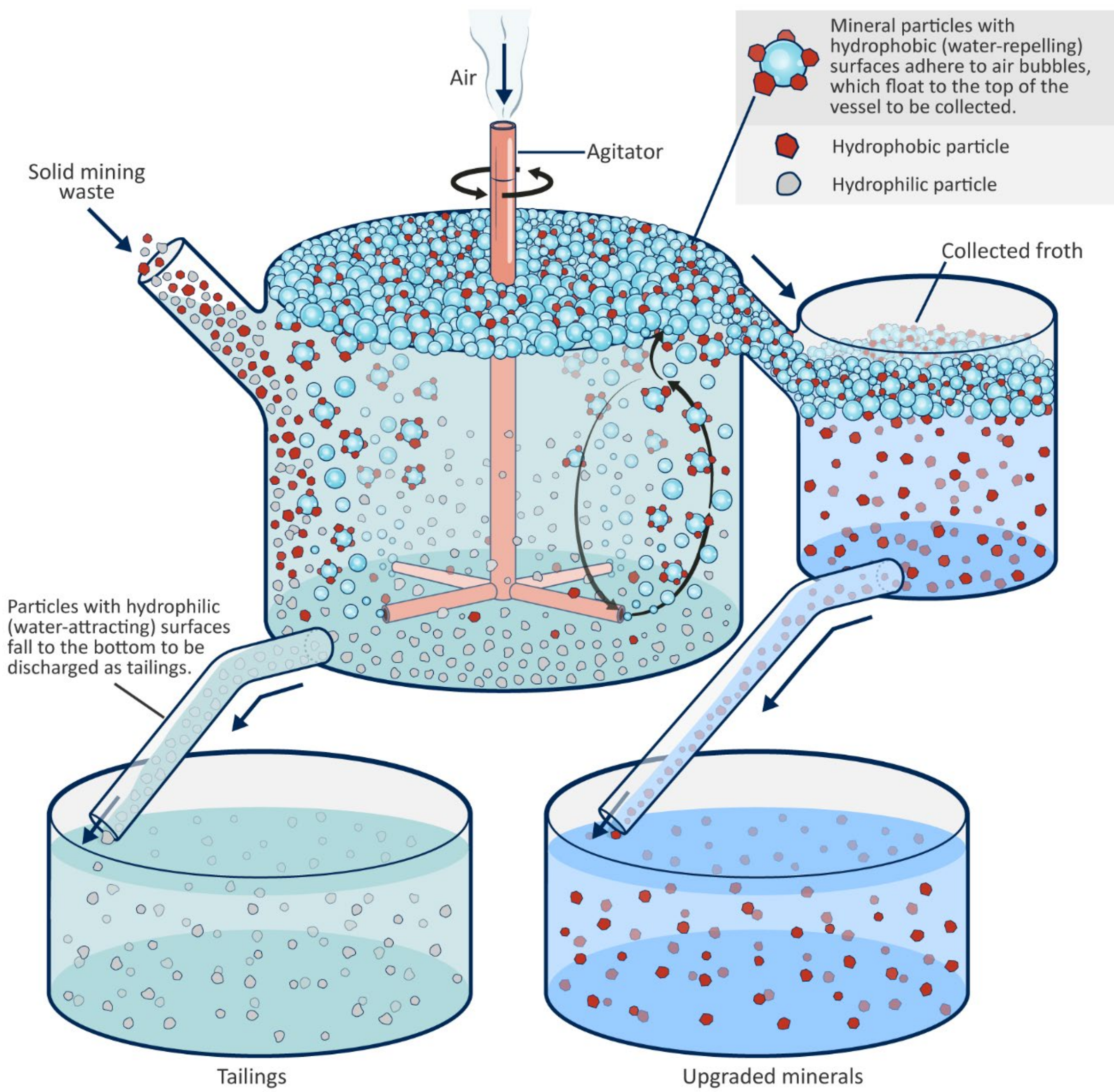
3.2 Recovery technologies and status

Several established technologies are available for recovering critical minerals from mining and coal wastes. These technologies have been developed for use in traditional hardrock and coal mining but may require modification to be used on waste sources.

Examples of such technologies include the following:

- **Froth flotation** injects air into a mixture of water, chemicals, and mineral particles, generating bubbles that attach to hydrophobic (water-repelling) particles and lift them to the surface (see fig. 3).

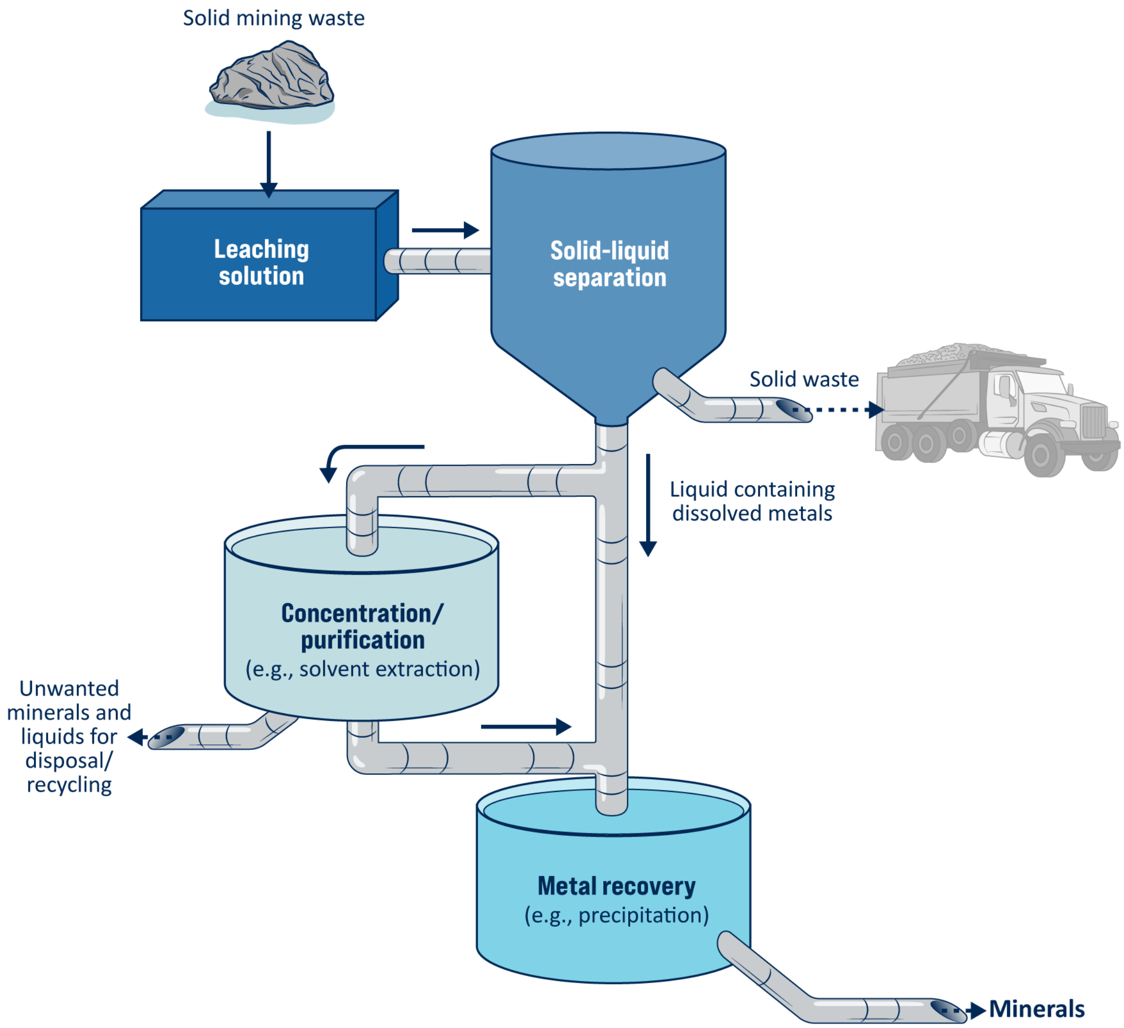
Figure 3: Froth flotation



Source: GAO (analysis and illustrations). | GAO-24-106395

- **Hydrometallurgy with chemical leaching** uses acids, or other chemicals, to extract specific metals while leaving other materials behind (see fig. 4).
- **Bioleaching** is a type of hydrometallurgy that uses microorganisms, such as bacteria and fungi, to extract metals.

Figure 4: Hydrometallurgy with chemical leaching



Source: GAO (analysis and illustrations). | GAO-24-106395

3.2.1 Recovery from hardrock mining wastes

Based on our stakeholder interviews, literature review, and expert meeting, we found that only a few small-scale pilot or demonstration projects have recovered critical minerals from hardrock mining wastes.[12] One such project, piloted by a mining company in Southern California successfully extracted lithium from its waste piles at a borate mine, according to company officials. Officials from this mining company told us that they considered scaling the project up to commercial scale, but at this time, the energy intensity of the process they piloted conflicts with a broader company goal of reducing carbon emissions.

Our analysis of patent filings suggests that inventors are exploring technology development that applies to critical mineral recovery from hardrock mining wastes. We identified 311 U.S. patents granted between 2010 and 2023 related to critical mineral recovery from hardrock mining wastes. Of these, 75 were filed by entities within the U.S., followed by 60 in Japan, and 32 in Canada.[13]

3.2.2 Recovery from coal-based wastes

DOE's Office of Fossil Energy has been conducting and funding research and pilot facilities for the recovery of critical minerals from coal mines and other domestic coal-based sources since 2014. We identified several small-scale projects producing critical minerals from coal-based wastes, although these projects were also at the pilot scale. For example, a firm in Pennsylvania produced rare earth oxides from fly ash at a pilot facility (fig. 5). In February 2024, DOE awarded this firm almost $8 million to design a strategy for producing rare earth compounds from coal ash at a power plant in Georgia.[14]

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[12]Information on such projects may not always be publicly available. For example, an official from the Bureau of Land Management provided an example of a copper mine that had been recovering minerals from waste for years, though they did not know whether the resulting products included critical minerals.

[13]Of the 311 patents we identified in our analysis, 15 did not indicate the filing entity's country of origin.

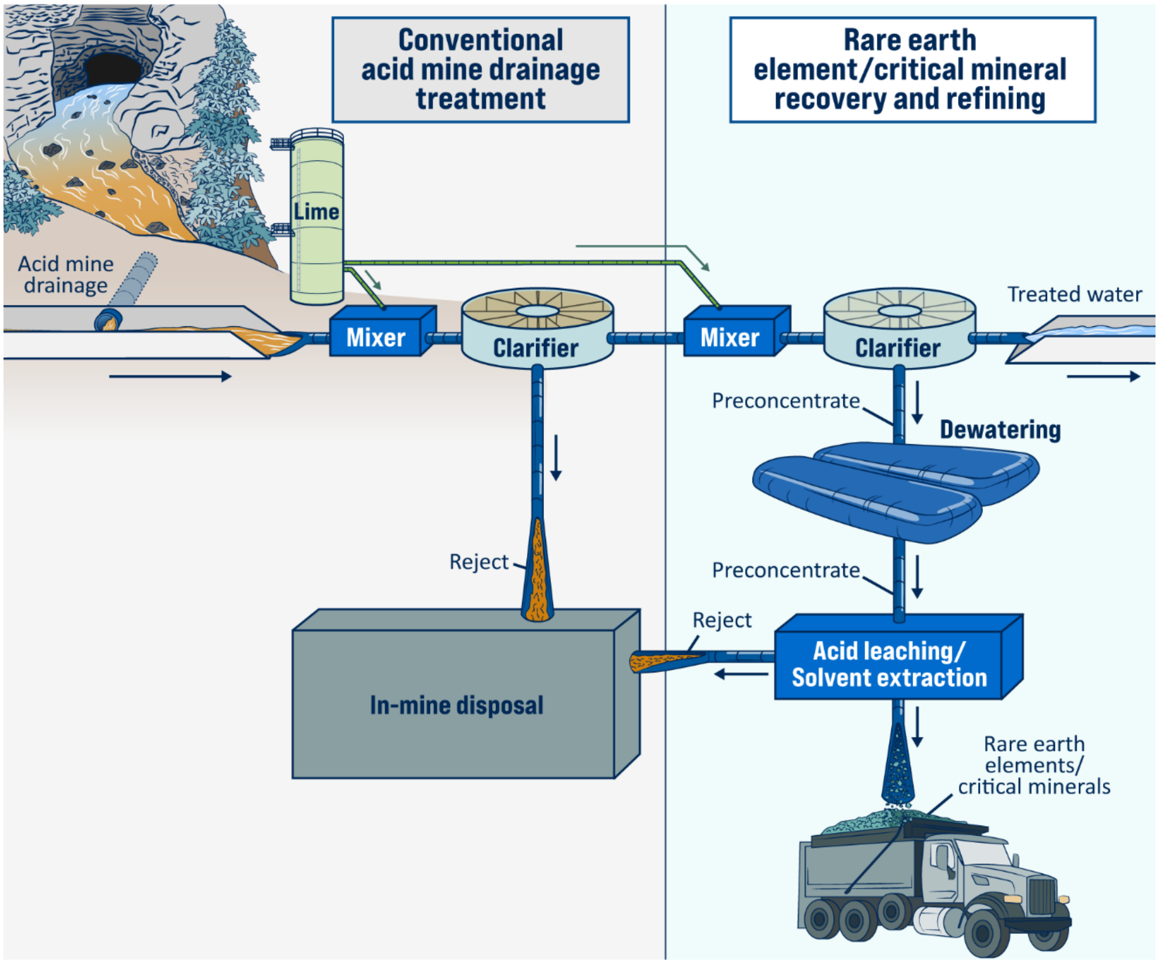
[14]National Energy Technology Laboratory, Department of Energy, "DOE Awards $17M to Conduct FEED Studies for the Production of Rare Earth Elements, Critical Minerals" (Feb. 15, 2024), accessed May 28, 2024, https://netl.doe.gov/node/13332.

Figure 5: A pilot-scale facility in Pennsylvania for rare earth element extraction from coal ash

Source: Winner Water Services, Inc. | GAO-24-106395

Another project, conducted by West Virginia University, integrated a recovery technology for rare earth elements into an acid mine drainage treatment facility (fig. 6). This pilot facility was designed to treat up to 500 gallons of water per minute. With this volume of water, the project officials estimated that the facility would produce 1 metric ton of rare earth elements, cobalt, and nickel annually. This project group received a grant from the Department of Defense to recover critical minerals using the piloted technology at a copper mine in Montana.

Figure 6: Rare earth element recovery integrated into an acid mine drainage treatment facility



Source: GAO adaptation of a West Virginia University Water Research Institute diagram, U.S. patent number US10954582B2; GAO (illustrations). | GAO-24-106395

We identified other coal-based recovery projects that were in the developmental stage. One such project is examining the use of an acoustic technology to fracture fly ash into low- and high-carbon fractions. The high-carbon fraction may be turned into a feedstock for extracting critical minerals, while the low-carbon fraction may be used in cement and concrete as a commercial by-product, according to a project official we interviewed.

In addition to these projects, we analyzed patent filings and identified 76 U.S. patents granted between 2010 and 2023 on technologies for recovering critical minerals from coal-based sources. Of these, 38 were filed by entities within the U.S., nine by entities in China, and six by entities in Australia.[15]

[15]Of the 76 patents we identified in our analysis, five did not indicate the filing entity's country of origin.

4 Geothermal and Other Brines

Various types of highly saline waters, known as brines, already provide a large share of lithium production worldwide, primarily in South America.[16] But the conventional recovery process for producing lithium from brines, called evaporative concentration, uses large land areas and large amounts of water. Newer technologies have the potential to use less land and water and extract lithium, along with other minerals, from a wider range of brine sources.

These technologies are advancing from the demonstration to commercial stage and for one type of brine appear to be more mature than technologies for recovery from mining and coal wastes. Lithium is the main critical mineral currently being recovered, and a single region—California's Salton Sea—is by far the largest known source of lithium in geothermal brines in the U.S.

4.1 Overview of geothermal and other brines

Brine refers to water with a high concentration of salt (typically from 3.5 to 26 percent). Brines occur naturally in a variety of forms such as seawater, salt lakes, or in underground formations. They can contain multiple critical minerals, including manganese, zinc, lithium, and rare earth elements, though concentrations may be too low to recover economically due to limitations in current recovery technology. The growing demand for lithium for batteries is driving commercial interest in recovery from brines (see text box).

Growing demand for lithium

The demand for lithium is growing primarily for rechargeable batteries used in electric vehicles, portable electronic devices, electricity storage, and other applications. Demand increased by 41 percent from 2021 to 2022, according to the U.S. Geological Survey (USGS). A 2020 World Bank report estimated that lithium demand from energy technologies will increase by 488 percent from 2018 to 2050,[a] although other projections vary.

[a]Kirsten Hund, Daniele La Porta, Thao P. Fabregas, Tim Laing, and John Drexhage, World Bank Group, "Minerals for climate action: The mineral intensity of the clean energy transition." (2020).

Source: GAO analysis of USGS and World Bank reports. | GAO-24-106395

The economic viability of lithium extraction depends in part on lithium concentration in the source. Ocean water, for example, typically has around 0.2 milligrams (mg) of lithium per liter, making recovery relatively costly. By contrast, salt lakes and underground brines range from 100 to 1,000 mg per liter, increasing the likelihood of economic viability.

There are three main types of critical mineral-containing brine deposits:

- **Continental brines**, which are found in underground reservoirs within salt lakes or salt flats, may have the highest lithium concentrations along with other critical minerals. They are typically found in dry climates and are already a conventional source of lithium. Most are found in South America and China. For example, the Salar de Atacama in

[16]Excluding domestic U.S. production, Chile and Argentina provided 33 percent of the global supply of lithium in 2020. The other main source of lithium is hardrock deposits in Australia and China.

Chile has a lithium concentration of 1,570 mg per liter. According to USGS, as of 2023 one continental brine field was producing lithium at a commercial scale in the U.S. The brine field is in Clayton Valley, Nevada and reports of its lithium concentration range from around 160 to 360 mg per liter.

- **Geothermal brines** generally have concentrations lower than the continental brines that are exploited for lithium production. Geothermal brines are found in rocky underground formations with high heat flows. A study of data on geothermal brines in the U.S. found that fewer than 1 percent of the samples had lithium concentrations greater than 20 mg per liter.[17] Companies with geothermal brine extraction activities are also considering recovering manganese, zinc, strontium, potassium, cesium, and rubidium, according to an expert.

- **Produced water**, sometimes referred to as oilfield brines, is wastewater released by wells during oil and gas extraction. It is a complex mixture that includes salt, minerals, and other substances. Typically, oil and gas firms reinject produced water into the ground without testing it for critical minerals. An Environmental Protection Agency (EPA) publication estimated a median lithium concentration from produced waters at 44 mg per liter.[18] Produced water is a potential source of lithium, as well as other critical minerals, such as rare earth elements and magnesium.

4.2 Recovery technologies and status

Brines are already a significant source of lithium, accounting for over half of worldwide lithium production, though newer technologies seek to improve the process and increase recovery from domestic sources. Extraction from brines provides a large share of lithium production worldwide, primarily from continental brines in South America.

In the conventional process—called evaporative concentration—brine is pumped to the surface and distributed to an evaporation pond. The brine remains in the pond for months or years until chemical impurities are precipitated out and much of the water evaporates, leaving a concentrated solution of lithium chloride, which is further refined to either lithium hydroxide or lithium carbonate. Once a facility is up and running, evaporative concentration is relatively inexpensive, but the process is time consuming as well as land- and water-intensive.[19] This process is mostly limited to use with continental

[17] Ghanashyam Neupane and Daniel S. Wendt; "Assessment of Mineral Resources in Geothermal Brines in the US;" *Proceedings, 42nd Workshop on Geothermal Reservoir Engineering; Stanford University, Stanford, California, February 13–15, 2017, SGP-TR-212.*

[18] EPA, *Technical Development Document for the Effluent Limitations Guidelines and Standards for the Oil and Gas Extraction Point Source Category*, EPA-820-R-16-003 (Washington, DC: June 2016).

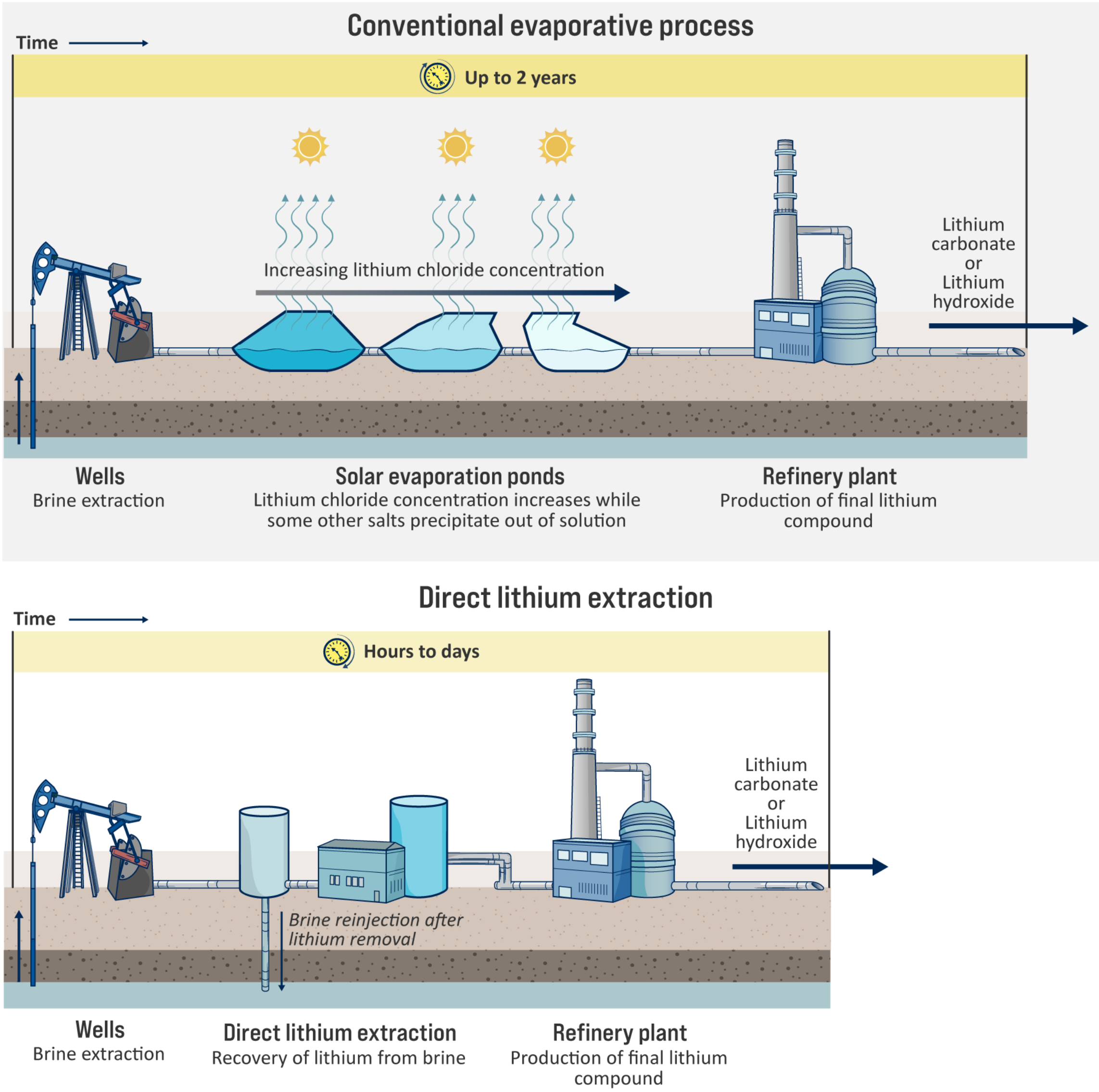
[19] According to a USGS official, an evaporative concentration facility requires a significant capital investment and takes 8 to 10 years to construct before the lengthy process of concentrating lithium can begin.

brines and their relatively high concentration of lithium.

Direct lithium extraction is a relatively new process that does not use evaporation, is better suited to less-concentrated brines, and can be used in a wider range of climates (see fig. 7). Direct lithium extraction also could offer benefits over evaporative concentration in terms of land and water use, although further research is needed to fully compare the environmental effects of the two processes, according to the scientific literature. For example, experts told us the footprint of a geothermal lithium extraction plant is around 50 acres. As of 2021, the evaporation pond area of the Salar de Atacama project was around 8,000 acres. Direct lithium extraction could avoid the large amount of water lost to evaporation in the conventional process; however, a recent review study found that freshwater use varied in direct lithium extraction projects, with about a quarter of facilities requiring more water than the conventional process, based on those reports that provided data.[20] The authors concluded that quantifying freshwater consumption is an urgent priority. Other potential benefits of critical mineral recovery by direct lithium extraction include faster recovery (on the order of days rather than years) and increased lithium recovery efficiency.

[20]María L. Vera, et al, "Environmental impact of direct lithium extraction from brines," *Nature Reviews Earth & Environment*, vol. 4 (2023).

Figure 7: Conventional evaporative process compared to direct lithium extraction



Source: GAO (analysis and illustrations). | GAO-24-106395

Multiple technologies for direct lithium extraction are in various stages of development, the most advanced being sorbent-based technology.[21] With this technology, lithium ions adhere to the surface of the sorbent, which is usually composed of inorganic chemicals. These sorbents are promising in part because they are relatively selective for lithium, and because they are reusable over multiple cycles of lithium extraction.

[21]Other technologies for direct lithium extraction from brines fall into four general categories: concentration and precipitation-based, solvent-based, membrane-based, and electrochemical-based.

There are challenges to developing an effective direct lithium extraction technology, and deploying the process is expected to incur higher upfront costs than evaporative concentration, according to the literature. A key challenge to the development of several of the less advanced technologies is their ability to extract lithium while leaving other substances behind—such as iron, manganese, or silica. Additionally, each brine source can have distinct characteristics, such as different types of minerals at varying concentration levels, and thus may require a unique lithium extraction process.

4.2.1 Recovery from geothermal brines

Direct lithium extraction from geothermal brines is transitioning from the demonstration to the commercial scale. Inorganic sorbents are the most advanced technology. Private sector technology development is currently focused on ensuring that the sorbents and other necessary material can survive under geothermal conditions and last for thousands of cycles, according to an expert. In some cases, companies can pair direct lithium extraction with geothermal power production. This process involves pumping brine to the surface to produce electricity, at which point an extraction facility can also recover lithium before the brine is re-injected into the ground.

Geological surveys have shown the Salton Sea region of California to be the largest potential source of lithium from geothermal brines in the U.S. Only three geothermal fields in the U.S. have lithium concentrations greater than 10 mg per liter,[22] making extraction from these fields more economically viable than extraction from sources with lower concentrations. The Salton Sea region has a lithium concentration greater than 100 mg per liter and is estimated to have 4.1 million metric tons of lithium carbonate equivalent in the parts of the reservoir that are well-characterized, but could be as high as 18 million metric tons.[23] The next highest source of U.S.-based lithium in geothermal brines—the Roosevelt field in Utah—is estimated to contain 37,000 metric tons of lithium carbonate equivalent, according to one assessment.[24]

There are three companies operating in the Salton Sea region, in various stages of development for lithium extraction. The largest company owns 10 of the 11 geothermal power plants in the region but is moving most slowly on lithium extraction, according to an expert. The company currently has one small-scale demonstration plant for extracting lithium chloride and is building another plant to process that material into battery-grade lithium compounds. These small demonstration plants are processing geothermal brine at a rate of 100 gallons per minute. The company plans to eventually operate a commercial plant at

[22]Neupane and Wendt, “Assessment of Mineral Resources.”

[23]Lawrence Berkeley National Laboratory, *Characterizing the Geothermal Lithium Resource at the Salton Sea* (Nov. 22, 2023).

[24]Stuart Simmons, *Western USA Assessment of High Value Materials in Geothermal Fluids and Produced Fluids* (Mar. 18, 2019).

50,000 gallons per minute at full scale capacity, according to the same expert.

The other two companies are smaller and moving more quickly, according to this expert. One company we spoke with plans to break ground on a commercial plant in late 2024 or early 2025. It plans to produce 20,000 tons of a lithium compound per year, with production starting in 2027. The third company broke ground on a combined geothermal power plant and lithium extraction plant in early 2024. That company plans to produce 25,000 tons per year of the same compound. It previously conducted a pilot at one-15th that scale and claimed to achieve 94 to 97 percent recovery efficiency, according to the expert. It plans to start delivering lithium in 2025.

4.2.2 Recovery from produced waters

Critical mineral recovery efforts from produced waters from oil and gas wells are at the pilot scale. As with geothermal brines, sorbents are the most advanced and promising technology. Continued research could increase the selectivity of these technologies for specific minerals, according to an academic researcher.

Some experts we spoke with stated that the oil and gas industry is interested in pursuing critical mineral recovery from produced water, while other experts disagreed. Some states have taken steps to encourage recovery. For example, New Mexico passed legislation in 2019 that encourages the oil and gas industry to reuse, recycle, or treat produced water.[25] In addition, Oklahoma passed a law that clarified ownership rights of minerals extracted from produced waters, which could encourage recovery, according to experts.[26]

Our analysis of patent filings identified 141 U.S. patents granted between 2010 and 2023 related to the recovery of critical minerals from brines. Of these, 62 were filed by entities within the U.S, 16 by entities in China, and 11 by entities in South Korea.[27]

[25]Produced Water Act, N.M. Stat. Ann. §§ 70-13-1 to -5. The act defines produced water as a fluid that is an incidental byproduct from drilling or the production of oil and gas, and vests regulatory jurisdiction of produced water with the state. The act places responsibility and control of produced water with both the working interest owners and operator of the gas or oil well, unless transferred.

[26]Okla. Stat. tit. 52, § 86.7 (2023).

[27]Of the 141 patents we identified in our analysis, 16 did not indicate the filing entity's country of origin.

5 Challenges to Recovery from Nontraditional Sources

Though recovering critical minerals from nontraditional sources has numerous potential benefits, (described in chapter 2), we identified five challenges to recovering critical minerals from nontraditional sources: (1) characterization, (2) liability, (3) permitting; (4) economics, and (5) public engagement and Tribal consultation.

5.1 Characterization

Experts who participated in our meeting and other stakeholders we interviewed said that a lack of knowledge about the kinds of minerals present in nontraditional sources and their concentrations pose a foundational challenge to fully exploiting these sources. (The same is true for traditional mining.) Existing data on the amount of critical minerals in mining wastes and coal-based sources in the U.S. are limited. Because of this limitation, nontraditional sources may first require expensive and complex testing (i.e., characterization) to determine whether they are suitable for recovery projects, according to experts and stakeholders. A portion of funds received by the USGS in the Infrastructure Investment and Jobs Act is being used to inventory and characterize mine waste in cooperation with State Geological Surveys, which may mitigate some of this challenge, but USGS's program is still in its infancy.[28]

5.2 Liability

Experts with hardrock mining experience who participated in our meeting cited liability issues as a key challenge to recovering critical minerals from hardrock mining wastes, particularly at abandoned mine sites. We previously reported that concerns about liability—that is, being held legally responsible for addressing environmental contamination created by another party—are a factor that limits efforts to address certain hardrock mine hazards on nonfederal land.[29] There is also little appetite to recover critical minerals from hardrock mining waste without liability reform, according to experts from our meeting. Such recovery activities could be combined with reclamation activities at these sites. While there are currently at least two proposed or active projects of this type, liability reform could increase interest or the number of projects, according to an expert. Some of the experts and other stakeholders we interviewed noted the long history of congressional interest in passing Good Samaritan legislation to shield new operators from liabilities at abandoned

[28]Infrastructure Investment and Jobs Act, Pub. L. No. 117-58, § 40201, 135 Stat. 429, 958-59 (2021). Section 40201 establishes the "Earth Mapping Resources Initiative" within USGS, with the purpose of accelerating efforts to provide integrated topographic, geologic, geochemical, and geophysical mapping; accelerating the integration and consolidation of geospatial and resource data; and providing interpretation of subsurface and above-ground mineral resources data. According to the act, this initiative shall complete a modern map and data integration effort on the full range of minerals (including mine waste sites). The act provided USGS $320 million over five years to carry out this section.

[29]GAO, *Abandoned Hardrock Mines: Information on Number of Mines, Expenditures, and Factors That Limit Efforts to Address Hazards*, GAO-20-238 (Washington, DC: Mar. 5, 2020).

mine sites.[30] However, as of July 2024, such legislation had not been enacted.

A factor associated with liabilities is the financial assurance that mining firms must demonstrate to operate on federal and nonfederal lands. The Bureau of Land Management and the U.S. Forest Service hold billions of dollars in financial assurances, such as bonds, for hardrock mining operations on federal land. States can also require financial assurance for mining operations on federal and nonfederal land. These financial assurances are designed to prevent taxpayers from assuming the financial burden of mine site reclamation if an operator is unable or unwilling to perform the reclamation themselves. Hardrock mining experts from our meeting noted the large amount of financial assurance that they may need to cover, in addition to potential historical liabilities, as an additional challenge to financing recovery projects.

5.3 Permitting

We identified three aspects of permitting that are challenging to recovering critical minerals from nontraditional sources. These include:

- **Permitting mining projects can be complex.** As the IWG noted in its September 2023 report, the path to securing the multiple permits and authorizations necessary to begin mineral development can be arduous, particularly if minerals are in sensitive areas. The specific permits and consultations required for a mining project are dependent on a number of factors, including location; type of operation; quantity and type of wastes, water, and air emissions generated; and methods of managing or disposing of wastes and waters. In addition, states generally regulate—either with sole jurisdiction or along with the federal government—mine plans, waste management, groundwater use and impacts, reclamation, surface water use, fish habitat, and tailings dam safety.

- **Operators perceive the permitting process to be lengthy.** From our interviews with stakeholders and experts at our meeting we heard that permitting can be lengthy. There is a perception among some stakeholders that permitting a mining project can take 7 to 10 years. However, recent analysis by the IWG and our own previous work indicates that permitting typically concludes in about half that time or less.[31] One reason for this perception could be individual examples of mines with exceptionally long permitting timelines, such as a mine plan in Idaho that took over 11 years to review and approve. Permitting

[30]In the absence of legislation, EPA has some administrative tools to reduce barriers to the cleanup of abandoned mine sits. In 2007, EPA published “Guiding Principles” for “Good Samaritans” interested in cleaning up abandoned hardrock mines. The agency’s administrative tools under its existing statutory authorities include comfort letters and administrative settlement agreements.

[31]Biden-Harris Administration Interagency Working Group on Mining Laws, Regulations, and Permitting, *Recommendations to Improve Mining on Public Lands,* (Washington, DC: Sept. 2023); GAO, *Hardrock Mining: BLM and Forest Service Have Taken Some Actions to Expedite the Mine Plan Review Process but Could Do More*, GAO-16-165 (Washington, DC: Jan. 21, 2016).

delays can result from the potential for litigation prompting additional or more extensive analyses and how prepared some mining firms are for their initial application, among other challenges. Despite perceptions that other nations process permits faster, the U.S. total process time has not been found to be any longer than any other nation's total process time according to the IWG's September 2023 report.

- **Resources for processing permits.** We previously reported that federal agencies that handle mine permitting lack staff, expertise, funding, infrastructure, and training to process permits quickly and consistently.[32] The IWG noted that these challenges persisted as of its September 2023 report.[33]

To address permitting challenges, the executive branch and the Congress have taken recent actions to improve permitting. In September 2023, the executive branch initiated rulemaking to include critical minerals refining, recycling, and beneficiation, to the mining sector regulations of Title 41 of Fixing America's Surface Transportation Act,[34] an initiative to improve the transparency and predictability of the federal environmental review and authorization process for certain covered infrastructure projects. This initiative's covered projects receive comprehensive permitting timetables and transparent, collaborative management of those timetables via a federal dashboard.

In 2022, Congress authorized new funds to accelerate permit review as a part of the Inflation Reduction Act of 2022.[35] The act provided more than $1 billion to support permitting across the federal government, including $350 million in funding over 9 years for the Federal Permitting Improvement Steering Council's Environmental Review Improvement Fund. In fiscal year 2023, this steering council's Executive Director approved approximately $165 million in funding transfers to federal agencies to help facilitate and improve the federal infrastructure permitting process. This influx of funding is providing additional permitting staff at federal agencies, improving information technology tools to increase permitting efficiency, and supporting early planning and stakeholder engagement, according to a press release from the council.[36]

[32]GAO, *Federal Land Management: Key Differences and Stakeholder Views of the Federal Systems Used to Manage Hardrock Mining*, GAO-21-299 (Washington, DC: July 21, 2021); GAO-16-165.

[33]Biden-Harris Administration's Interagency Working Group on Mining Laws, Regulations, and Permitting, *Recommendations to Improve Mining on Public Lands*.

[34]*Revising Scope of the Mining Sector of Projects That Are Eligible for Coverage Under Title 41 of the Fixing America's Surface Transportation Act*, 88 Fed. Reg. 65,350 (Sept. 22, 2023).

[35]An Act to provide for reconciliation pursuant to Title II of S. Con. Res. 14, Pub. L. No. 117-169, 136 Stat. 1818 (2022), commonly known as the Inflation Reduction Act of 2022.

[36]Federal Permitting Improvement Steering Council, "Permitting Council Recognizes Transformative Accomplishments in the Federal Permitting Process in Celebration of IRA Anniversary," accessed May 20, 2024, https://www.permits.performance.gov/fpisc-content/permitting-council-recognizes-transformative-accomplishments-federal-permitting.

5.4 Economics

Industry faces several challenges to making critical mineral recovery from nontraditional sources financially viable:

- **Fixed costs.** Some nontraditional sources may have low concentrations of critical minerals, and operators may therefore need to process large volumes of material, leading to larger plants and higher capital costs. Low concentrations also mean that large amounts are needed to recover enough material to achieve economies of scale—a decrease in marginal costs resulting from large-scale operations. Once critical minerals are extracted from a domestic source, infrastructure to further process them in the U.S. is limited, which could result in other costs such as transportation. One expert from our meeting noted that the company the expert helps lead is in the permitting process for a project to extract antimony from gold mine tailings, but the revenue from new gold mining at the site will also be necessary to sustain the overall operation.

- **Unstable prices.** Price instability is one reason investors may be reluctant to invest in domestic critical minerals recovery, according to industry officials we interviewed. Lack of domestic processing and manufacturing capabilities for critical materials could make the U.S. vulnerable to foreign government actions that affect pricing.[37] For example, the prices of some critical minerals are driven by international markets that can be volatile due to unexpected changes in trade policy that restrict supply. DOE officials told us that companies need guaranteed end users and steadier prices to be competitive with offshore monopolies and to withstand trade disputes. Dumping is also a risk when foreign producers control a large share of the market, which is true for many critical minerals. Dumping occurs when a foreign producer sells a product in the U.S. at a price below that producer's sales price in the country of origin or at a price lower than the cost of production. Price volatility may ultimately encourage buyers to consider substitutes for unpredictably priced critical minerals.

- **Legacy costs.** An additional barrier to recovery of critical minerals from nontraditional sources is the potential of inheriting legacy remediation costs**.** For example, Clean Water Act provisions require that cleanup meet and maintain water quality standards, which can require ongoing water treatment. Meeting and maintaining such standards can be difficult at some mines due to naturally occurring heavy metals in the area and continual drainage from the mine.

5.5 Public engagement and tribal consultation

Stakeholders and experts identified engagement with local communities and,

[37]Department of Commerce, *A Federal Strategy*.

when appropriate, consultation with Tribal Nations as an important step to a successful critical mineral recovery project, though current and past efforts have not always been adequate.[38] Because recovery of critical minerals from nontraditional sources is relatively nascent compared to traditional mining, the effects these projects will have on nearby populations is not yet fully understood. Often, these communities have experienced the negative effects of legacy mining activities or other polluting industries and thus may be skeptical when firms claim that recovery from nontraditional sources will benefit them.

We previously identified public engagement and tribal government consultation and consent as areas for improvement in the management of hardrock mining on federal lands, as did the IWG.[39] These same challenges are also relevant to recovery of critical minerals from nontraditional sources, according to stakeholders and experts:

- **Inadequate public engagement.** Early and meaningful public engagement is a key practice that should occur but often does not, according to an environmental advocacy organization we spoke with. The current National Environmental Policy Act process provides opportunities for public comment but does not require public engagement before or apart from these prescribed opportunities, though mining firms may do so voluntarily. Firms may have already expended significant resources developing plans for a particular site before they reach a permitting stage that requires public comment, leaving communities feeling as if they were not given a meaningful voice in decision making, according to the IWG. When firms do conduct community outreach, it may not always be accessible to the community. For example, a community leader told us that firms conducting recovery projects in the region typically did not provide information in Spanish.

- **Challenges to tribal consultation and engagement.** Tribes are sovereign nations and the federal government is required to consult with them before making certain decisions that affect tribal lands and interests.[40] The federal government's obligations to Tribes are not limited to mining operations that occur on tribal lands; such obligations also apply to off-reservation activities that occur on public lands that affect Indian treaty rights, cultural resources,

[38]For the purposes of this report, "Tribes" refers to federally recognized Indian Tribes. Tribes use a variety of terms when referring to themselves, such as band, pueblo, and Native village. Federally recognized Tribes have a government-to-government relationship with the U.S. and are eligible to receive certain protections, services, and benefits by virtue of their status as Indian Tribes. The Secretary of the Interior is required by law to annually publish a list of all Tribes recognized by the Secretary. As of January 8, 2024, there were 574 federally recognized Tribes in the contiguous U.S. and Alaska. 89 Fed. Reg. 944 (Jan. 8, 2024).

[39]GAO-21-299; Biden-Harris Administration's Interagency Working Group on Mining Laws, Regulations, and Permitting, *Recommendations to Improve Mining on Public Lands*.

[40]For more information on tribal consultation see GAO, *Tribal Consultation: Additional Federal Actions Needed for Infrastructure Projects*, GAO-19-22 (Washington, DC: Mar. 20, 2019).

or other interests.[41] The IWG identified at least three challenges to tribal consultation for hardrock mining projects, which could also be relevant to recovery of critical minerals from nontraditional sources: (1) Typically, significant resources have already been committed by the mining firm before tribal engagement occurs, making the Tribes feel that it is unlikely they will be able to change the plan, (2) the optimal location for a mine is dependent on characteristics of the mineral deposit, and federal permitting agencies have limited options—other than approve or deny—when a planned mine would interfere with a sacred site,[42] (3) Tribal governments may not have the technical expertise or not have sufficient time to fully evaluate highly technical mine plans and environmental studies.

[41]As described by the U.S. Constitution, treaties between the U.S. government and Indian Tribes are "the supreme law of the land." Treaties often described the boundaries of the Tribe's land ceded to the federal government and the boundaries of the lands reserved for habitation by the Tribe. Treaties also often discussed the tribe's rights reserved by the treaty, such as the right to hunt, fish, and gather on specified lands they ceded to the federal government. As a result of these treaties and other federal actions, many Tribes have ancestral lands they ceded to the federal government distant from where they are located today. These ancestral lands may include sites that have religious and cultural significance for the Tribe.

[42]The Mining Law of 1872 grants individuals a statutory right to explore, develop, and mine on certain Federal lands. According to one expert, those agencies that administer the law may only deny a plan in limited circumstances.

6 Policy Options

We identified three options, in addition to the status quo, that policymakers could consider to enhance the benefits or address the challenges of recovering critical minerals from nontraditional sources. This is not an exhaustive list of policy options, and the purpose is to provide policymakers with a broader base of information for decision-making. Potential users include legislative bodies, government agencies, academia, and industry.

6.1 Pilot Good Samaritan legislation

To encourage third-party investment in mining wastes as a source of critical minerals, Congress and state legislatures could enact pilot Good Samaritan legislation, to test providing some protections for new operators at previously mined sites from past environmental liabilities at those sites. Table 2 provides further details of this policy option.

Table 2: Policy option—Pilot Good Samaritan legislation

Implementation approach	Opportunities	Considerations
• Legislators could provide some liability protections for third parties recovering critical minerals from waste at previously mined sites. • Legislators could provide protections for third parties but require a portion of profits generated be used for restoration activities.	• Could encourage investment in domestic recovery operations. • Could expand the types of organizations interested in cleaning up previously mined sites.	• Disturbing previously mined sites may result in new environmental effects. • If financial assurances are not adequately set, federal or state taxpayers may become responsible for cleaning up additional environmental liabilities. • Requiring that a percentage of profits be used for restoration activities could affect industry interest in previously mined sites.

Source: GAO. | GAO-24-106395

6.2 Subsidies

To accelerate domestic recovery of critical minerals from nontraditional sources, federal and state governments could consider using subsidies. Experts who participated in our meeting noted that at several times in the past, the Department of Defense had used existing statutory provisions to ramp up domestic production of materials deemed critical to national defense.[43] Such subsidies could be revived or modified to address the nation's need for critical minerals. Table 3 provides further details of this policy option.

[43]The Defense Production Act authorizes several ways through which the President may incentivize domestic production of critical and strategic materials. Codified, in relevant part, at 50 U.S.C. § 4533.

Table 3: Policy option—Subsidies

Implementation approach	Opportunities	Considerations
• The federal government could subsidize the development of specific nontraditional sources to meet defense or energy needs. • Subsidies could be made available as tax credits for those pursuing nontraditional sources of critical minerals	• Properly tailored subsidies could catalyze technology development, demonstration, commercialization, and domestic production of critical minerals. • Subsidies could help offset some of the fixed costs associated with developing recovery and processing infrastructure.	• Taxpayer-funded subsidies do not guarantee that supported recovery operations would become profitable. • Once in place, subsidies can be difficult to end. • May result in reallocation of resources from other priorities.

Source: GAO. | GAO-24-106395

6.3 Community benefit agreements

To ensure that communities benefit from new mining activities, federal, state, local, and tribal policymakers could encourage the adoption of community benefit agreements. These agreements can address issues such as hiring preferences, the purchase of services and supplies from local vendors, infrastructure investments, and independent monitoring. Table 4 provides further details of this policy option.

Table 4: Policy option—Community benefit agreements

Implementation approach	Opportunities	Considerations
• To improve engagement with communities near nontraditional sources, permitting agencies could encourage operators to pursue agreements that outline how communities may benefit from projects that also incur costs in their communities. • Companies could adopt policies that encourage or facilitate these agreements	• Negotiating specific community benefits from new recovery operations could create deeper acceptance of facilities that may have environmental effects. • New recovery operations could offer additional employment opportunities in economically depressed communities.	• Negotiating which stakeholders benefit, which do not, and who controls the agreement can be challenging. • It is difficult to predict who will be willing to engage in such agreements. • Such agreements may be time consuming to create. • Some provisions in these agreements may be difficult to enforce.

Source: GAO. | GAO-24-106395

6.4 Maintain the status quo

As noted earlier, the Infrastructure Investment and Jobs Act contains provisions that could enhance the capacity of USGS to characterize nontraditional sources of critical minerals, and DOE has ongoing projects to evaluate the potential for recovering critical minerals from coal-based sources. In addition, the private sector is evaluating nontraditional sources for critical minerals. If policymakers find these efforts to be sufficient, or if they find other sources of critical minerals more suitable to their goals, they could choose not to take any new actions. Table 5 provides further details of this policy option.

Table 5: Policy option—Status quo

Implementation approach	Opportunities	Considerations
• Sustain current efforts.	• Federal policymakers could observe and evaluate existing efforts, such as agency funding of characterization of nontraditional sources, which could limit risks and resources expended. • Continued private sector efforts, such as recovery of lithium from geothermal brines, could ultimately result in profitable recovery of minerals. • The private sector may also pursue other options to overcome critical mineral supply chain issues. For example, buyers may pursue substitutes, reducing the need for new sources	• Current efforts may not address all the challenges described in this report. • Current efforts alone may delay or inhibit the development of nontraditional sources for critical minerals, which could result in forgone benefits such as increased independence from foreign suppliers.

Source: GAO. | GAO-24-106395

7 Agency and Expert Comments

We provided a draft of this report to the Department of Energy, the Environmental Protection Agency, and the Department of the Interior with a request for technical comments. We incorporated agency comments into this report as appropriate.

We also offered our expert meeting participants the opportunity to review and comment on the draft of this report, consistent with previous technology assessment methodologies. We sent the report to 12 of those experts for review and incorporated their comments as appropriate.

We are sending copies of this report to the appropriate congressional committees, the relevant federal agencies, and other interested parties. This report will be available at no charge on the GAO website at https://www.gao.gov.

If you or your staff members have any questions about this report, please contact Brian Bothwell at (202) 512-6888 or BothwellB@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 III.

Brian Bothwell, MS
Director,
Science, Technology Assessment, and Analytics

List of Addressees

The Honorable Gary C. Peters
Chair
The Honorable Rand Paul, M.D.
Ranking Member
Committee on Homeland Security and Governmental Affairs
United States Senate

The Honorable James Comer
Chair
Committee on Oversight and Accountability
House of Representatives

The Honorable Mike Simpson
Chair
The Honorable Chellie Pingree
Ranking Member
Subcommittee on Interior, Environment, and Related Agencies
Committee on Appropriations
House of Representatives

Appendix I: Objectives, Scope, and Methodology

We prepared this report under the authority of the Comptroller General to assist Congress with its oversight responsibilities given broad congressional interest in critical mineral recovery from nontraditional sources. We examined:

1. Domestic nontraditional sources that could be used to recover critical minerals and the status of associated recovery technologies.

2. Benefits and challenges of recovering of critical minerals from nontraditional sources.

3. Policy options that could help enhance these benefits or mitigate these challenges.

To conduct our work for all three objectives, we reviewed agency documents, federal regulations, federal statutes, and peer-reviewed literature; conducted site visits to observe technologies in use and obtain perspectives from private sector technology operators, developers, and others; and interviewed a variety of stakeholders, including agency officials, academic researchers, and representatives of industry organizations, private companies, and nongovernmental organizations. To further our assessment of recovery technologies, we identified relevant patent applications in the U.S. Patent and Trademark Office's (USPTO) PatentsView database that were granted from 2010 to 2023. We also conducted an expert meeting with the assistance of the National Academies of Sciences, Engineering, and Medicine to gather evidence and a range of perspectives about benefits and challenges of recovering of critical minerals from nontraditional sources and about potential policy options.[44]

Scope

The technologies we assessed included those that could diversify the domestic supply of critical minerals through recovery from nontraditional sources (i.e., not traditional hardrock mining). We considered the following three categories of nontraditional sources: mining wastes, coal-based sources, and geothermal and other brines. We excluded recycling of post-consumer products as a nontraditional source.

Literature search

For all three objectives, we reviewed relevant literature identified by agencies, experts, stakeholders, and our literature search. We worked with a GAO librarian to search a variety of databases, including EBSCO and Scopus using terms such as "critical mineral," "rare earth elements," "coal," and "geothermal brines." We further narrowed our search on the basis of our objectives and limited it to articles, reports, papers, and other materials published since 2018.[45] We selected for further review the references most relevant to our objectives and used

[44]This meeting of experts was planned and convened with the assistance of the National Academies to better ensure that a breadth of expertise was brought to bear in its preparation, however all final decisions regarding meeting substance and expert participation are the responsibility of GAO.

[45]Some articles identified as a result of our work were published before this date.

these references to identify and assess critical mineral recovery technologies. We identified additional literature and reports through our interviews and reviewed them as appropriate.

Interviews and expert meeting

We selected an appropriate number of interviewees to allow for a robust analysis for each of our three objectives and ensured the selection reflected an appropriate balance across sectors. Interviewees included officials (or representatives) from:

- three relevant federal agencies—the Department of Energy, the Department of the Interior, and the Environmental Protection Agency;
- five academic researchers or research groups;
- 10 private firms or industry organizations;
- one think tank; and
- three environmental advocacy or community groups.

Because this is a small sample of the stakeholders involved in critical mineral recovery technologies, the results of our interviews—though illustrative and representing important perspectives—are not generalizable.

We also convened an expert meeting to help us meet our objectives. To do so, we contracted with the National Academies to help develop a list of experts drawn from a range of stakeholder groups, including federal agencies, academia, industry, and nonprofits. The meeting was held virtually over 3 days with 15 experts. (See app. II for a list of these experts and their affiliations.)

We evaluated the experts for potential conflicts of interest, which we defined as any current financial or other interest that might conflict with the service of an individual because it could (1) impair objectivity or (2) create an unfair competitive advantage for any person or organization. We determined the 15 experts to be free of reported conflicts of interest, except those that were outside the scope of the forum or where the overall design of our meeting and methodology was sufficient to address them. We also determined the group as a whole to be free of any inappropriate biases.

The comments of these experts generally represented their individual views and not those of the agencies, universities, companies, or nonprofits with which they were affiliated. The experts' comments also are not generalizable to the views of others in the field.

We transcribed the meeting to ensure that we accurately captured the experts' statements. After the meeting, we reviewed the transcripts to characterize the discussion and inform our understanding of all three researchable objectives. We provided the experts with a draft of our report and solicited their feedback, which we incorporated as appropriate, in accordance with our quality assurance framework.

Site visits

We conducted site visits to five critical mineral recovery facilities or firms to observe operations and interview subject matter experts. These site visits covered all three categories of nontraditional sources within our scope and took place in Pennsylvania, West Virginia, and California. The interviewees were industry and academic experts.

Patent analysis

We conducted a search and analysis of data from USPTO's PatentsView to identify trends in patent applications related to critical minerals recovery. These trends included the number of patents granted for each nontraditional source, by year and by the filer's country of origin.

We assessed the reliability of the patent data we used by reviewing USPTO documentation, interviewing knowledgeable officials, and reviewing data for potential errors, outliers, and omissions. We found the data to be sufficiently reliable for reporting on trends by year and country of origin.

Policy options

We proposed policy options to provide policymakers with a broader base of information for decision-making.[46] The options are neither recommendations to federal agencies nor matters for congressional consideration. They are also not listed in any specific rank or order. We are not suggesting that they be done individually or combined in any particular fashion. Additionally, we did not conduct work to assess how effective the options may be, and we express no view regarding the extent to which legal changes would be needed to implement them.

We identified three policy options to enhance the benefits of, or address the challenges associated with, domestic recovery of critical minerals from nontraditional sources. We identified these options on the basis of our literature review, expert meeting, interviews, and site visits. We also described maintaining the status quo as a policy option. We further analyzed each policy option by identifying the potential opportunities and considerations of implementing them.

We conducted our work from November 2022 to July 2024 in accordance with all sections of GAO's Quality Assurance Framework that are relevant to technology assessments. The framework requires that we plan and perform the engagement to obtain sufficient and appropriate evidence to meet our stated objectives and to discuss any limitations to our work. We believe that the information and data obtained, and the analysis conducted, provide a reasonable basis for any findings and conclusions in this product.

[46] *Policymakers* is a broad term including, for example, Congress, federal agencies, state and local governments, and industry.

Appendix II: Expert Participation

With the assistance of the National Academies of Sciences, Engineering, and Medicine, we convened a 3-day meeting of experts to inform our work on the recovery of critical minerals from nontraditional sources; the meeting was held virtually on July 24, 25, and 28, 2023. The experts who participated in this meeting are listed below. Many of these experts gave us additional assistance throughout our work, including 12 who agreed to review our draft report for accuracy, several of whom provided technical comments.

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Office of Fossil Energy and Carbon Management, Department of Energy

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Natural Resources Defense Council

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Appendix III: GAO Contact and Staff Acknowledgments

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In addition to the contact named above, the following staff made significant contributions to this report:

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