GAO

United States Government Accountability Office

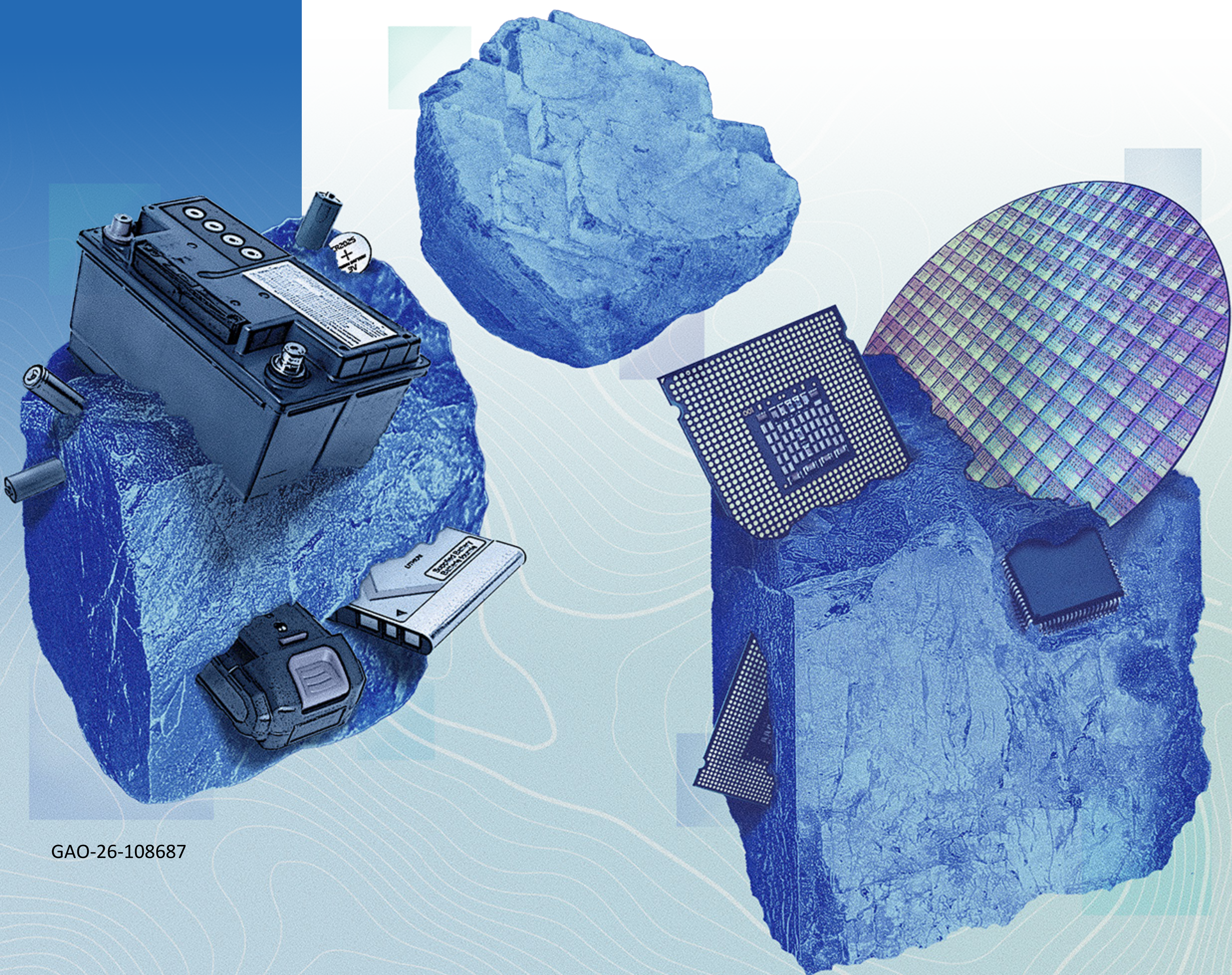
Report to Congressional Requesters

July 2026

TECHNOLOGY ASSESSMENT

Critical Minerals

Reducing U.S. Import Reliance with Substitution and Recycling Technologies



GAO-26-108687

The cover image depicts a variety of batteries and semiconductors embedded in rocks.

Cover source: Minakryn Ruslan (rocks)/ Hanna (car battery)/ Kuzmick (CR2025 battery)/ Andrii (rechargeable cordless drill battery)/ Ra (rechargeable slim camera battery)/ Kwangmoozaa (AA size battery)/ BTG (AA size battery)/ Roxana (AA size battery)/ Rachmattt (microprocessor)/ rvlsoft (microprocessor at angled view)/ Emilija (microchip)/ Scanrail (silicon wafer)/stock.adobe.com, GAO (composite). | GAO-26-108687

Highlights of GAO-26-108687, a report to congressional requesters

July 2026

Why GAO did this study

The U.S. considers 60 minerals as critical because they are essential to the nation's economy or security and have supply chains vulnerable to disruption.

Several critical minerals are key to the functioning of batteries and semiconductors, which have applications in electric vehicles, stationary grid energy storage, consumer electronics, and the defense industry. For example, lithium is a key component of modern batteries that are both lightweight and energy-dense. Semiconductors rely on the unique electrical properties of critical minerals such as gallium, germanium, arsenic, and indium.

U.S. executive and legislative branch policymakers have a long-standing goal to reduce critical mineral import reliance, through technological innovations and other approaches.

This report examines: (1) substitution and recycling technologies to reduce import reliance on critical minerals within the battery and semiconductor industries, (2) challenges to the development and adoption of these technologies, and (3) policy options to support reducing reliance.

To conduct this technology assessment, GAO interviewed federal officials and experts and reviewed academic papers, agency and expert documentation, and federal policy. GAO identified four policy options in this report (see next page).

View GAO-26-108687. For more information, contact Sarah Harvey at HarveyS@gao.gov.

TECHNOLOGY ASSESSMENT

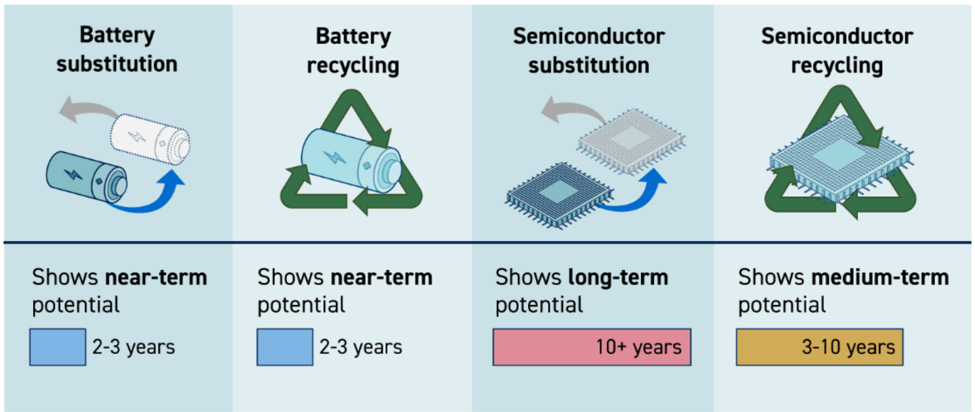
Critical Minerals

Reducing U.S. Import Reliance with Substitution and Recycling Technologies

What GAO found

Technologies like batteries and semiconductors are essential to the U.S. economy but rely on imports of lithium, gallium, and other critical minerals. GAO found that substitution and recycling technologies could help reduce U.S. reliance on these imports. But progress is likely to take many years in some cases.

Potential for technologies to reduce critical mineral import reliance



Source: GAO (analysis of agency and expert information and literature; illustrations). | GAO-26-108687

For batteries, substitution and recycling technologies offer near-term potential. For example, using lithium iron phosphate batteries for stationary grid energy storage might reduce imports of cobalt, manganese, and nickel in the next 2 to 3 years. But these batteries do not perform as well in other applications, like long-haul electric vehicles, due to their lower energy density. Lithium-free batteries are not yet commercially mature. Battery recycling technologies are mature and offer a pathway to reduce imports for copper, cobalt, lithium, and nickel in 2 to 3 years. These technologies aim to recover critical minerals at high rates through chemical leaching and smelting. Experts told GAO, however, that U.S. battery recyclers lack capacity. Additionally, available inputs for recycling (referred to as feedstock) are often landfilled or exported for processing.

For semiconductors, most substitution and recycling technologies are likely years away from maturity. Substitution is unlikely to have a near-term effect on import reliance of minerals, such as gallium and indium, because other materials do not perform as well as these critical minerals across the same conditions. Experts told GAO that industry will not adopt substitutes until they can perform at the same level as current semiconductor materials in the intended application. Technologies to recycle minerals from semiconductors also face challenges, such as an underdeveloped market. Semiconductor manufacturing scrap is a potential source of recycled minerals, though this is not yet standard practice in the U.S. Discarded electronics are another potentially large source, but their critical mineral content is low, and those minerals are generally mixed and bonded with other materials. Technologies to recycle this form of electronic waste are in pilot-stage development.

GAO identified four policy options that could support the goal of reducing critical mineral import reliance and help address challenges to recycling and substitution technologies. These options identify possible actions by policymakers, which include legislative bodies, government agencies (federal, state, and local), academia, standards-setting organizations, industry, and other groups. In general, these technologies have potential, with policy action, to reduce some of this reliance in the near, medium, or long term. See below for details on these options.

Policymakers could also choose to pursue non-technological policy approaches, such as increased domestic mining. Many non-technological approaches are the subject of current and proposed legislation and executive action (see report p. 6).

Policy options to support reducing critical mineral import reliance and address challenges to substitution and recycling technologies

Policy options	Potential implementation approaches	Opportunities and considerations
Establish domestic manufacturing capacity for viable substitutes (report p. 23) Policymakers could consider building or repurposing existing manufacturing capacity to produce substitute technologies for batteries and semiconductors.	• Providing support for private capital investments in manufacturing plants for commercially available battery technologies. • Establishing facilities or partnerships to perform pilot-scale testing of semiconductor substitutes.	• Domestic manufacturing capacity could allow for near-term production of commercially available substitute technologies like lithium iron phosphate batteries, which could reduce import reliance on critical minerals like cobalt and nickel. • Battery and semiconductor production facilities are costly and tend to be specialized for the production of a particular technology.
Establish domestic recycling capacity (report p. 24) Policymakers could build domestic infrastructure to bolster the domestic capacity to recycle batteries and semiconductors.	• Providing support for private investment in factories for new battery recycling. • Collecting and sharing data on manufacturing scrap and end-of-life devices containing batteries and semiconductors. • Reviewing and streamlining permitting requirements and hazardous waste designations.	• Expanded domestic infrastructure could reduce or eliminate the need to ship partially processed batteries overseas for recycling. • Building domestic recycling infrastructure may not reduce import reliance for selected critical minerals in the near term, since building new or repurposing existing infrastructure can take a decade or more and require significant investment.
Secure inputs for recycling (report p. 25) Policymakers could support efforts to collect, sort, transport, and store manufacturing scrap and end-of-life devices for recycling and reuse.	• Establishing and overseeing national and local electronic waste collection programs that provide education and resources (e.g., drop-off locations) for consumers. • Providing financial incentives for industry to collect or retain manufacturing scrap and end-of-life devices for recycling.	• Securing a consistent supply of inputs for recycling and reuse could help reduce the need for critical mineral importation in the near term. • Although mature battery recycling technologies exist, securing additional inputs may exacerbate challenges related to the safety, transportation, and handling of hazardous materials. • Without demand and competitively priced recycled semiconductor materials, it may be difficult for recyclers to scale their operations and offset the amount of imported minerals required in the near term.
Support research, development, and testing (report p. 25) Policymakers could continue or grow support for research, development, and testing of substitution and recycling technologies.	• Supporting research to improve performance of lithium-free batteries. • Supporting research into battery recycling technologies that reduce or avoid the cost, waste issues, and environmental impact of current techniques. • Encouraging targeted materials research focused on semiconductor substitutes that maintain or enhance material performance and reduce the use of critical minerals when possible. • Supporting research on more efficient semiconductor recycling technologies that recover more critical minerals.	• Increased research could help overcome current limitations of existing technologies, resulting in better performance (e.g., higher energy density batteries, larger bandgap semiconductors) or higher commercialization potential (e.g., improved recovery of minerals from semiconductors). • Research, development, and testing efforts may not yield mature technologies in the near term.

Source: GAO. | GAO-26-108687

Table of Contents

Table

Figures

Abbreviations

AI	artificial intelligence
DOE	Department of Energy
EO	executive order
EOL	end-of-life
EV	electric vehicle
GaN	gallium nitride
LCO	lithium cobalt oxide
LFP	lithium iron phosphate
NCA	lithium nickel cobalt aluminum oxide
NMC	lithium nickel manganese cobalt oxide
NIST	National Institute of Standards and Technology
R&D	research and development
SiC	silicon carbide
USGS	U.S. Geological Survey
WBG	wide bandgap

U.S. GOVERNMENT ACCOUNTABILITY OFFICE
441 G St. N.W.
Washington, DC 20548

July 22, 2026

The Honorable Gary Palmer
Chairman
Subcommittee on Environment
Committee on Energy and Commerce
House of Representatives

The Honorable John Joyce, M.D.
Chairman
Subcommittee on Oversight and Investigations
Committee on Energy and Commerce
House of Representatives

Technologies essential to the U.S. economy and national security rely on minerals like lithium and gallium, which have been designated as critical by the Secretary of the Interior.[1] From 2018 to 2025, the list of critical minerals nearly doubled—from 35 to 60 minerals—when the U.S. Geological Survey (USGS) updated the list in November 2025. Furthermore, the supply for many critical minerals is fully or highly reliant on imports.[2] According to USGS, dependence on imports poses a risk of serious, sustained, and long-term supply chain disruptions that could impact the nation's security, defense readiness, and economy. China, in particular, controls much of the supply chain for a variety of critical minerals and has manipulated mineral prices and supply to restrict U.S. access or undercut competition. Import reliance can impact industries for which supplies of these minerals are necessary to meet increasing demand, such as the battery and semiconductor industries.

In July 2024, we reported on the status, challenges, and policy options for recovery of critical minerals from nontraditional sources.[3] For this technology assessment, you asked us to describe substitution and recycling technologies that are available for deployment in the near term (2 to 3 years) and that may reduce U.S. import reliance on critical minerals in the semiconductor and

[1]Critical minerals are defined as any mineral, element, substance, or material designated as critical by the Secretary of the Interior, acting through the Director of the U.S. Geological Survey. The Secretary determines that critical minerals (1) are essential to the nation's economy or security, (2) have supply chains vulnerable to disruption, and (3) serve an essential function in the manufacturing of a product, whose absence would have significant consequences for the nation's economy or security. Energy Act of 2020, Pub. L. No. 116-260, § 7002, 134 Stat. 2418, 2562-65 (codified, as amended, at 30 U.S.C. § 1606); Final 2025 List of Critical Minerals, 90 Fed. Reg. 50494 (Nov. 7, 2025).

[2]As of December 2025, USGS reported that 12 critical minerals had a net import reliance of 100 percent, and an additional 34 have a net import reliance of 50 percent or more. U.S. Geological Survey, *Mineral Commodity Summaries* 2026, (Reston, VA: Feb. 6, 2026).

[3]GAO, *Critical Minerals: Status, Challenges, and Policy Options for Recovery from Nontraditional Sources*, GAO-24-106395 (Washington, D.C.: July 31, 2024).

battery industries.[4] We examined (1) the state of and potential opportunities and impacts of these technologies to lessen import reliance on critical minerals within these industries, (2) challenges to the development and adoption of these technologies, and (3) policy options that could support the policy goal of reducing critical mineral import reliance. To address these objectives, we interviewed three federal agencies with relevant roles and responsibilities in managing and supporting critical mineral efforts in these industries. We selected 11 critical minerals for examination based on their import reliance and importance to the battery and semiconductor industries. We reviewed relevant literature, agency and expert documentation, and federal policy (both enacted and proposed), and interviewed experts on the development, use, and regulation of these technologies. See appendix I for a full discussion of our objectives, scope, and methodology.

We conducted our work from August 2025 to July 2026 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.

[4] In this report, we refer to near-term as 2 to 3 years, medium-term as 3 to 10 years, and long-term as more than 10 years.

1 Background

1.1 Critical mineral import reliance

The U.S. semiconductor and battery industries depend on sustained supply and stable prices of certain critical minerals. Figure 1 lists the 11 critical minerals that this report focuses on, along with details about their sources and uses.

Figure 1: Selected critical minerals import reliance, use, and primary import and production sources

Critical mineral[a]	Net import reliance as a percentage of apparent consumption in 2025	Semiconductor	Battery	Primary import sources (2021–2024)[b]	Primary production sources, 2025[c]
Arsenic	100%	●		China, 95%; Japan, 3% (metal)	Peru, 50%; China, 40%
Gallium	100%	●		Canada, 28%; Japan, 22% (metal)	China, 99%; Russia, 1% (primary)
Graphite	100%		●	China, 46%; Canada, 13% (natural)	China, 80%; Madagascar, 5% (mine)
Indium	100%	●		Republic of Korea, 25%; Japan, 22%	China, 70%; Republic of Korea, 16% (refinery)
Manganese	100%		●	Gabon, 64%; South Africa, 24% (ore)	South Africa, 38%; Gabon, 25% (mine)
Cobalt	79%		●	Norway, 26%; Finland, 16% (metal, oxide, and salts)	Congo, 73%; Indonesia, 14% (mine)
Aluminum	60%		●	Canada, 56%; United Arab Emirates, 8%	China, 61%; India, 6% (smelter)
Copper	57%		●	Chile, 68%; Canada, 16% (refined)	Chile, 23%; Congo, 14% (mine)
Germanium	>50%	●		China, 41%; Belgium, 27%; (metal)	*No reliable estimate found*
Lithium	>50%		●	Chile, 54%; Argentina, 43%	Australia, 32%; China, 21% (mine)
Nickel	41%		●	Canada, 44%; Norway, 11% (primary)	Indonesia, 67%; Philippines, 7% (mine)

Source: GAO analysis of expert and agency information and U.S. Geological Survey data. | GAO-26-108687

[a]Of the 60 critical minerals in the 2025 Final List of Critical Minerals, we deemed these as essential to the battery and semiconductor industries and selected applications. For more information on our methodology, see appendix I of this report.

[b]Top two import sources listed in descending order of import share.

[c]Top two production sources listed in descending order of production share.

Since at least 2021, the U.S. has relied on imports for 100 percent of five of the 11 selected critical minerals—arsenic, gallium, graphite, indium, and manganese. For another five—cobalt, copper, germanium, lithium, and nickel—the net import reliance remained the same, fluctuated year-to-year, or increased overall. Aluminum is the only critical mineral for which, over the same time period, the net import reliance decreased overall (61 to 60 percent).

1.2 Selected agency roles and responsibilities

The Department of Energy (DOE), USGS, and the National Institute of Standards and Technology (NIST) have significant roles and responsibilities in managing and supporting critical mineral technology research and development (R&D) efforts in the battery and semiconductor industries.

Department of Energy

The Energy Act of 2020 codified key roles and responsibilities for DOE to secure U.S. supply chains for critical materials and minerals.[5] The act generally requires DOE to carry out the following functions:

Designate a critical materials list. DOE designates a list of critical materials that have high risk of supply chain disruption and serve an essential function in one or more energy technologies. The latest was released in 2023.[6]

Conduct R&D. DOE conducts R&D to develop alternatives to critical materials, improve efficiency of critical material production and use, and advance recycling technologies. Since 2013, DOE's Ames National Laboratory led materials research and innovation within DOE's Critical Materials Innovation Hub (formerly known as the Critical Minerals Institute). This hub aims to enhance and diversify critical material supply, develop substitutes, unlock secondary sources, and perform crosscutting research.

Perform interagency and industry collaboration. DOE leads efforts to improve and increase communication on critical material efforts between federal agencies and with industry. In 2023, DOE established the Critical Materials Collaborative to operationalize these efforts.

Identify and develop technologies for recovery. DOE engages in efforts to identify nontraditional, domestic sources of critical minerals from mine waste and legacy mining sites. We previously reported on technologies that could operationalize these efforts.[7]

In November 2025, DOE reorganized various offices and functions, including the creation

[5]Energy Act of 2020, Pub. L. No. 116-260, § 7002, 134 Stat. 2418, 2562-77 (codified, as amended, at 30 U.S.C. § 1606).

[6]Notice of Final Determination on 2023 DOE Critical Materials List, 88 Fed. Reg. 51792 (Aug. 4, 2023); In May 2025, DOE issued a public notice which added metallurgical coal to DOE's critical material list. Critical Material List; Addition of Metallurgical Coal Used for Steelmaking, 90 Fed. Reg. 22711 (May 29, 2025).

[7]GAO-24-106395.

of DOE's Office of Critical Minerals and Energy Innovation. This office manages DOE's overall critical mineral strategy and leads investment in R&D, diversification of energy supply chains, and creation of manufacturing jobs.

U.S. Geological Survey

The Energy Act of 2020 also codified a variety of roles and responsibilities for the Department of Interior, primarily carried out by USGS, to identify and maintain a list of critical minerals and support the management of the nation's mineral resources. The act generally requires USGS to carry out the following functions:

Maintain a critical minerals list. As previously described, the act requires USGS to maintain, and review at least every 3 years, a critical minerals list. The agency carries out this task with input from the public and by publishing a final methodology to determine which mineral commodities qualify as critical.[8]

Conduct resource assessments. USGS collects and publishes a wide range of data to help users understand the nation's geology and support decision-making. For example, USGS conducts surface and subsurface mapping to identify potential domestic mineral deposits. In 2019, USGS launched the Earth Mapping Resources Initiative to modernize these efforts.

Develop and maintain analytical tools. USGS, in consultation with the Energy Information Administration, academic institutions, and others, develops and maintains computer models and similar analytical tools to evaluate critical mineral markets. These tools, among other things, provide insight and foresight into critical mineral production, consumption, and recycling patterns.

Lead competitive research program. USGS, jointly with the Department of Labor, is establishing a competitive grant program for higher education faculty and students to perform critical minerals research. Applicants may receive grants for up to 4 years to subsidize startup and equipment costs related to developing and training the future critical mineral workforce.

National Institute of Standards and Technology

NIST promotes U.S. innovation and industrial competitiveness by advancing measurement science, standards, and technology. NIST's efforts support advancements in a variety of industries and applications, including batteries and semiconductors. In addition, the CHIPS Act of 2022 requires the Department of Commerce, NIST's parent department, to manage a significant portion of the nation's semiconductor industry investments that support semiconductor R&D, standard-setting, and public-private collaboration.[9] A portion of this management is delegated to NIST. We previously reported on projects at

[8]U.S. Geological Survey, *Methodology and technical input for the 2025 U.S. List of Critical Minerals—Assessing the potential effects of mineral commodity supply chain disruptions on the U.S. economy*, 2025-1047 (Reston, VA: revised Apr. 15, 2026).

[9]CHIPS Act of 2022, division A of the law commonly known as the CHIPS and Science Act of 2022, Pub. L. No. 117-167, § 102(a), 136 Stat. 1366, 1372.

Commerce to strengthen the U.S. semiconductor supply chain.[10]

1.3 Critical mineral policy landscape

U.S. executive and legislative branch policymakers have a long-standing goal to reduce critical mineral import reliance. According to our review of current and proposed legislation, executive orders (EO), and other policies and guidance, policymakers have identified and continue to pursue several approaches to address this issue. This list is not exhaustive.

Strengthen public-private partnerships. In February 2026, the President announced Project Vault, which established the U.S. Strategic Critical Minerals Reserve. This $12 billion public-private initiative aims to protect the private sector from supply disruptions and price volatility.[11]

Establish trade alliances with international partners. In 2025, Congress proposed bipartisan legislative measures to facilitate trade arrangements with countries with whom the U.S. has friendly relations to reduce the risk of supply disruptions.[12] In addition, in January 2026 the President issued Proclamation 11001, which directed executive branch leaders to jointly continue or enter into new trade negotiations with critical mineral exporters.[13]

Establish long-term strategy. In February 2025, the President issued EO 14213, which established the National Energy Dominance Council, and directed the development of a long-term strategy to synergize existing cross-government efforts, reduce regulatory burdens at various levels, and enhance private sector investment.[14]

Promote technological innovation. Enacted in 2022, the CHIPS and Science Act appropriated more than $50 billion to incentivize semiconductor manufacturing, foster innovation through R&D, and develop skilled workforces.[15]

Increase domestic extraction, production, and processing capacity. In September 2020, the President issued EO 13953, which promoted research into extraction, processing, and recycling methods and acceleration of permitting processes for new domestic mining projects.[16]

[10]GAO, *Semiconductors: Information on Projects Funded to Strengthen U.S. Supply Chain*, GAO-26-107882 (Washington, D.C.: Dec. 11, 2025).

[11]"Introducing Project Vault, a critical mineral stockpile for American businesses," The White House, last modified February 2, 2026, https://www.whitehouse.gov/videos/introducing-project-vault-a-critical-mineral-stockpile-for-american-businesses.

[12]H.R. 6696, 119th Cong., *Restoring American Mineral Security Act of 2025* (introduced Dec. 12, 2025); H.R. 2444, 119th Cong., *Promoting Resilient Supply Chains Act of 2025* (introduced Mar. 27, 2025).

[13]Proclamation 11001, Adjusting Imports of Processed Critical Minerals and Their Derivative Products Into The United States, 91 Fed Reg. 2439 (Jan. 20, 2026).

[14]Exec. Order No. 14213, *Establishing the National Energy Dominance Council*, 90 Fed. Reg. 9945 (Feb. 20, 2025).

[15]CHIPS Act of 2022, Pub. L. No. 117-167, § 102(a), 136 Stat. 1372.

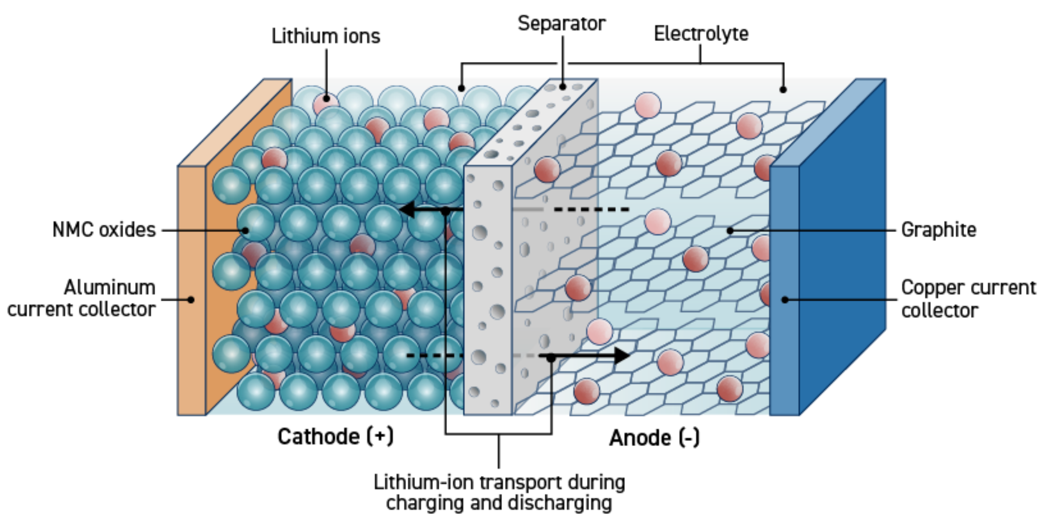
[16]Exec. Order No. 13953, *Addressing the Threat to the Domestic Supply Chain From Reliance on Critical Minerals From Foreign Adversaries and Supporting the Domestic Mining and Processing Industries*, 85 Fed. Reg. 62539 (Oct. 5, 2020).

1.4 Key definitions

Batteries

The term “battery” may refer to rechargeable or non-rechargeable devices that store chemical energy and convert it into electrical energy on demand. Batteries consist of two electrical terminals, a cathode (positive electrode) and an anode (negative electrode), separated by a chemical material, or “separator,” surrounded by a liquid, or “electrolyte” (see fig. 2). In lithium-ion batteries, the dominant rechargeable battery technology, the cathode is typically made of lithium-metal oxides, while the anode is typically made using graphite. In addition to lithium and graphite, five other critical minerals are essential to lithium-ion battery technology—aluminum, cobalt, copper, manganese, and nickel. Supplying these minerals is necessary to meet increasing demand for electric vehicles (EV), stationary grid energy storage, consumer electronics, and defense applications.

Figure 2: Rechargeable lithium nickel manganese cobalt oxide (NMC) battery



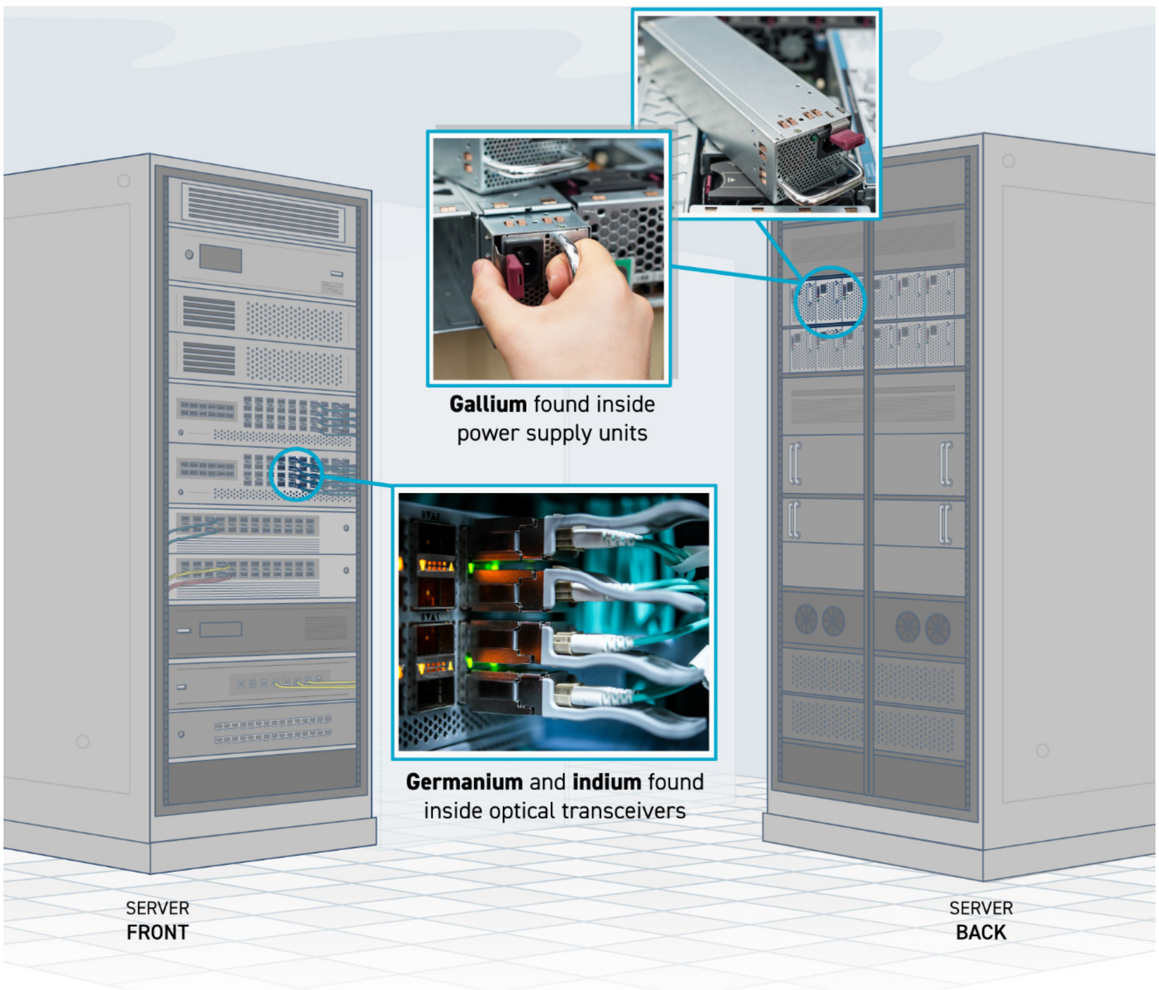
Source: GAO (analysis and illustration). | GAO-26-108687

Semiconductors

The term “semiconductor” can refer to the devices, commonly called chips, that are responsible for functions like computing, storing memory, and sensing in electronic devices. Chips are integral to nearly every modern electronic device. “Semiconductor” can also refer to a class of materials with properties that allow them to externally control the flow of electrons.

Advancements in semiconductor technologies have enhanced the capabilities of electronic devices and enabled a growing set of use cases. Traditional semiconductors commonly use one material, silicon or germanium, and enable smartphones, cars, medical devices, and a range of other devices. Compound semiconductors use two or more materials and offer superior performance in terms of speed, efficiency, and power handling for specific applications. For example, applications that use compound semiconductors include artificial intelligence (AI) data centers, which must efficiently manage large amounts of electrical power, and defense applications such as a missile that is exposed to extreme operating temperatures. Figure 3 shows how critical minerals are used in a server within an AI data center. Today's compound chips primarily use critical minerals such as gallium, germanium, arsenic, and indium, which have unique properties that lend themselves to the demands of certain applications.

Figure 3: Selected critical minerals in an artificial intelligence data center server



Source: GAO (illustration of servers); M-Production (power supply units)/Zoran Jesic (optical transceivers)/stock.adobe.com. | GAO-26-108687

2 Battery Substitution and Recycling Technologies

Substitution and recycling technologies for batteries could help the U.S. reduce reliance on foreign supplies of critical minerals such as lithium, cobalt, nickel, and copper. Switching to the production of batteries that do not use critical minerals could help reduce reliance on cobalt and nickel in the near term (2 to 3 years), but would likely not reduce reliance on lithium. Recycling, the most technologically mature pathway, could start to reduce demand for imported critical minerals—lithium, cobalt, nickel, and copper—within 2 to 3 years.

2.1 Battery substitution technologies

2.1.1 State of technologies

Lithium-ion batteries are the dominant rechargeable battery technology today. They most often use one of three combinations of elements (referred to as different chemistries) as the cathode material: lithium cobalt oxide (LCO), lithium nickel manganese cobalt oxide (NMC), and lithium nickel cobalt aluminum oxide (NCA).[17] Graphite is the dominant anode material in commercial lithium-ion batteries. These chemistries are all mature and have high energy density, meaning they store a large amount of energy relative to their weight.[18] High energy density is desirable for applications like cell phones, drones, and EVs. See text box for more information on the roles of critical minerals in commercial lithium-ion batteries.

Role of critical minerals in commercial lithium-ion batteries

13 Al Aluminum

Aluminum is used as the cathode current collector—conductive material that assists the transport of electrons. It is also used in some cathodes to improve the stability and usable lifetime of the battery.

27 Co Cobalt

Cobalt enables higher energy density in a battery by creating a stable, high-energy-density cathode that allows for long-lasting, fast-charging, safe performance. It also improves safety of the battery in high-temperature conditions.

29 Cu Copper

Copper is used as the anode current collector in lithium-ion batteries due to its high electrical conductivity.

6 C Carbon

Graphite—a naturally occurring, crystalline form of carbon—is used as the primary material for the anode where it acts as a stable "host" where lithium ions are stored during charging and released during discharge. It has high electrical conductivity, which is essential for fast charging.

3 Li Lithium

Lithium is used in batteries as the charge carrier that moves through an electrolyte between the anode and cathode to store and release energy. It is lightweight and has high energy density.

25 Mn Manganese

Manganese is a cost-effective additive in lithium-ion batteries and enhances structural integrity, safety, and energy density by reducing the amount of cobalt needed in a battery. It is also cheaper and more abundant than cobalt.

28 Ni Nickel

Nickel is used in some lithium-ion batteries for higher energy density, greater storage capacity, and longer EV driving ranges.

Source: GAO (analysis of literature; element boxes). | GAO-26-108687

[17]International Energy Agency. *Batteries and Secure Energy Transitions* (Paris, FR: Apr. 25, 2024). A fourth chemistry, lithium iron phosphate batteries, are not as prevalent in the U.S. and will be discussed in later sections.

[18]International Energy Agency. *Batteries and Secure Energy Transitions* (Paris, FR: Apr. 25, 2024).

2.1.2 Opportunities to reduce critical mineral import reliance

Substitution technologies could reduce import reliance for some critical minerals by using alternative battery chemistries. Lithium iron phosphate (LFP) batteries are a leading commercial battery option that may reduce critical mineral reliance in the near term (2 to 3 years). LFP batteries do not require cobalt, manganese, or nickel, but they still require lithium as well as phosphate, a critical mineral primarily used in agriculture. LFP batteries are a mature technology and are currently used in some EVs as an alternative to NMC and NCA batteries, as well as for energy storage.

Research is ongoing into new battery chemistries that would eliminate the need for some critical minerals commonly used in lithium-ion batteries. For example, sodium-ion batteries use sodium in place of lithium, with some variations potentially eliminating cobalt and nickel as well. In addition, vanadium flow batteries use an alternative chemistry that reduces the need for nickel, graphite, and cobalt but may increase the current import reliance of 41 percent for vanadium. These batteries are commercially available but not yet as widely adopted as lithium-ion batteries.

2.1.3 Challenges

Experts we spoke with said the market will rely on mature lithium-ion chemistries (LCO, NMC, and NCA) for the foreseeable future because of several challenges, including the following:

Known technical limitations. Mature lithium-ion chemistries (LCO, NMC, and NCA) have a high energy density that some current and near-term substitutes cannot match. As a result, EVs using LFP batteries currently have a shorter driving range than EVs using NMC or NCA. Current sodium-ion batteries have even lower energy density and could be limited to urban transportation, short-haul fleets, and energy storage. Table 1 details the performance characteristics of current lithium-ion batteries and potential substitutes.

Table 1: Battery types and key performance metrics

Battery	Energy density (watt-hours per kilogram)	Calendar life	Cost (dollars per kilowatt-hour)	Critical mineral content	Applications
Lithium cobalt oxide	150-200	3-5 years *(2-3 years in consumer electronics)*	*No reliable estimate found*	Lithium, cobalt, graphite	Consumer electronics (smartphones, laptops, cameras)
Lithium nickel cobalt aluminum oxide	240-260	5-8 years	$77	Lithium, nickel, cobalt, aluminum, graphite	Electric vehicles, energy storage, consumer electronics, civilian and military drones
Lithium nickel manganese cobalt oxide	250-280 (NMC811)	10+ years	$100	Lithium, nickel, manganese, cobalt, graphite	Electric vehicles, consumer electronics, civilian and military drones, energy storage
Lithium iron phosphate	120-260	10+ years	$100	Lithium, phosphate	Electric vehicles, energy storage
Sodium-ion	140-160	10+ years	$75-125	Manganese, phosphate	Electric vehicles, energy storage
Vanadium flow	30 watt-hours/liter	15-25 years	$0.0273	Vanadium	Energy storage

Source: GAO analysis of agency information and literature. | GAO-26-108687

Domestic manufacturing capacity and market uncertainty. Even when commercial substitutes exist, the U.S. has limited domestic manufacturing capacity to produce the batteries listed in table 1 above. For example, China produces over 98 percent of LFP batteries. Similarly, one Chinese company has announced plans to expand its commercial production of sodium-ion batteries to 149 gigawatt-hours, while one U.S. company, in April 2026, launched a 2 gigawatt-hour production facility for lithium and sodium batteries. Furthermore, long permitting processes exacerbate challenges to establishing domestic manufacturing capacity, according to experts.

In addition, market changes related to U.S. policy and mineral prices contribute to market uncertainty. For example, uncertainty in U.S. policy creates reluctance for manufacturers to make long-term commitments because they cannot predict future demand for their products. Experts we spoke with said unexpected cancellation of tax incentives decreased demand for EVs by consumers and prompted some manufacturers to abandon plans to produce

EV batteries.[19] At the same time, according to USGS, price decreases for lithium—from the 2022 high, lithium prices dropped about 86 percent by 2025—have undermined the case for investing in substitute technologies like sodium-ion batteries.[20]

2.2 Battery recycling technologies

2.2.1 State of technologies

Two mature processes exist for recycling batteries: pyrometallurgy and hydrometallurgy. In both of these processes, the battery is typically discharged, disassembled, and crushed into a black powdery substance called "black mass," which contains nickel, cobalt, and lithium. From here, different approaches may be used to refine black mass and extract the critical minerals. Pyrometallurgy exposes black mass to high temperatures up to 1500 degrees Celsius to create concentrated alloys of critical minerals and slag (a waste byproduct). Hydrometallurgy is the more common approach. This process dissolves the alloy, which can contain critical minerals such as cobalt, copper, and nickel, in acid and filters out high-purity cobalt and nickel. A further refinement step allows recovery of lithium. Hydrometallurgy can be used on its own or in combination with pyrometallurgy.[21]

U.S.-based commercial recyclers of lithium-ion batteries are using hydrometallurgy.[22] Total output, however, remains low because the U.S. does not have a robust source of inputs (referred to as feedstock) from manufacturing scrap, electronic waste, or other end-of-life (EOL) devices.[23] See figure 4 for an illustration of these processes.

[19]In at least one case, the company continued plans to produce batteries by pivoting to making batteries for energy storage rather than electric vehicles.

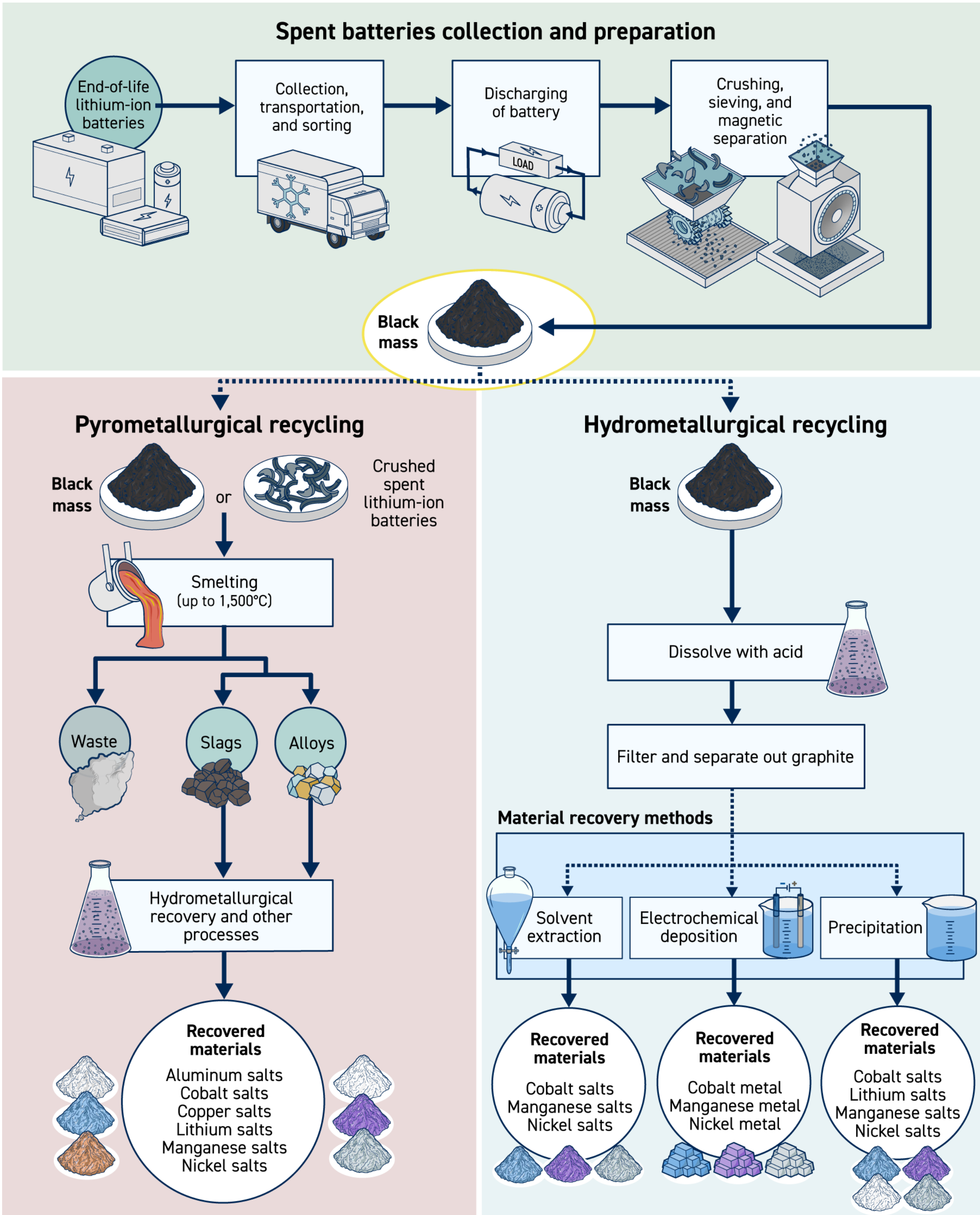
[20]U.S. Geological Survey. *Mineral Commodity Summaries 2026* (Reston, VA: 2026).

[21]In this case, pyrometallurgy would be performed first and the material would be further refined with hydrometallurgy to extract additional critical minerals.

[22]Commercial recyclers such as some in Belgium, Japan, and Canada are using pyrometallurgy.

[23]We define manufacturing scrap as discarded materials, byproducts, or defective products generated during the manufacturing of a product. This scrap can be collected, recycled, and reused.

Figure 4: Typical steps to pyrometallurgical and hydrometallurgical recycling of lithium-ion batteries



Source: GAO (analysis of literature; illustrations). | GAO-26-108687

A third technology, direct recycling, is the subject of ongoing research and development. Direct recycling processes vary, but one approach would reduce the processing steps removing the whole cathode and anode, repairing damage from use, and using them as parts for new batteries. Researchers at DOE's ReCell Center have collaborated with a manufacturer to develop a direct recycling process that could cost 40 percent less than pyro- or hydrometallurgical processes.[24] Experts estimated that if development projects are successful, use of direct recycling could grow.

2.2.2 Opportunities to reduce critical mineral import reliance

Recycling technologies could significantly reduce reliance on imported critical minerals—lithium, cobalt, nickel, and copper—within 2 to 3 years, according to experts. Experts told us that manufacturing scrap currently serves as the primary battery feedstock source. In addition, the recent growth in the battery market could create a growing source of material for recycling. According to one report, the supply of EV batteries for recycling was 250 kilotons in 2020 and is expected to reach more than 20,500 kilotons globally by 2040.[25]

Recycling domestically could eventually facilitate repeated reuse of minerals in what is known as a circular economy. The lead-acid battery recycling industry, according to one expert, currently provides more than 80 percent of raw materials for new batteries. That expert said that lithium-ion battery recycling could seek to replicate this level to reduce imports. For example, one study of the European Union market found that, with substantial investments in capacity, battery recycling could potentially provide up to 65 percent of Europe's total cobalt demand by 2050.

2.2.3 Challenges

The private sector faces several challenges before they can reduce reliance on imported critical minerals through domestic recycling or leveraging circular economy principles. These challenges include the following:

Known technical limitations. Hydrometallurgy's acid treatments generate toxic wastewater and have high operational costs. Pyrometallurgy requires extremely high temperatures that produce toxic gases and consume significant energy. Pyrometallurgy also does not typically recover lithium and graphite, two critical minerals that can be captured using hydrometallurgy alone. Direct recycling methods are typically tailored to specific battery types (e.g., lithium-ion) which could limit its effectiveness in handling all types of batteries, according to agency officials.

Recycling infrastructure capacity. Experts told us that recyclers have limited infrastructure at various points in the recycling process for a variety of reasons. Before recycling can occur, a primary challenge is securing a consistent supply of feedstock, since a large share of U.S. battery waste, including manufacturing scrap, whole

[24] The patent for this process is currently pending.

[25] Breiter, A., Schuldt, T., Linder, M., Siccardo, G., Vekić N., "Battery Recycling Takes the Driver's Seat," *McKinsey & Company Automotive and Assembly* (Mar. 13, 2023).

EOL batteries, and black mass, is exported to other countries for processing.

Recyclers use facilities to store, process, and transport EOL lithium-ion batteries, which can be considered hazardous waste by regulation.[26] These facilities must comply with permitting policies that protect the public from the potential hazards—such as fire—associated with improper disposal of lithium batteries. But meeting the requirements could delay new construction.[27]

Furthermore, transportation and handling of feedstock is a challenge due to how black mass is characterized and regulatory requirements for handling it. Regulations require that the generator of black mass (i.e., the recycler) determine whether it could be hazardous waste. According to a DOE report, however, since the hazardous waste characteristics of black mass can change over time while it is in storage, transporters often do not know the current characteristics of what they are handling and therefore assume it is hazardous. As a result, maintaining compliance can increase costs for recyclers.

[26]Most lithium-ion batteries on the market are likely to meet the definition of hazardous waste under the Resource Conservation and Recovery Act. Most lithium-ion batteries when discarded would likely be considered ignitable and reactive hazardous wastes (carrying the waste codes D001 and D003, respectively). Commercial waste generators are responsible for determining whether any waste they produce is hazardous waste, including lithium-ion batteries at their end of life. (40 C.F.R. § 273.2). Lithium-ion batteries are also regulated as a hazardous material under the Department of Transportation's Hazardous Materials Regulations (HMR; 49 C.F.R. § 173.185). The HMR applies to any material the department determines can pose an unreasonable risk to health, safety, and property when transported in commerce. Lithium-ion batteries must conform to all applicable HMR requirements when offered for transportation or transported by air, highway, rail, or water.

[27]For more information about the complexities of permitting, see Congressional Research Service, *Data Center Energy Infrastructure: Federal Permit Requirements* (Washington D.C.: Dec. 12, 2025); GAO, *Hazardous Waste: EPA Should Take Additional Actions to Encourage Treatment, Storage, and Disposal Facilities to Manage Climate Risks*, GAO-25-106253 (Washington D.C.: Nov. 14, 2024); and *Energy Infrastructure Permitting: Factors Affecting Timeliness and Efficiency*, GAO-18-693T (Washington D.C.: Sept. 6, 2018).

3 Semiconductor Substitution and Recycling Technologies

Most semiconductor substitution and recycling technologies are likely years from maturity and would only reduce critical mineral import reliance in the long and medium terms. Substitution technologies are emerging and may be used in future AI data center and defense applications (in 10+ years) given sufficient time and resources. These substitutes, however, may not completely replace the critical minerals the U.S. currently relies on. Emerging technologies have medium-term potential (in 3 to 10 years) to increase recycling efficiency, but challenges include the complexity of recovering critical minerals from EOL chips and an underdeveloped domestic recycling market.

3.1 Semiconductor substitution technologies

3.1.1 State of technologies

Semiconductors commonly used in defense and AI data center applications rely on the unique properties of minerals such as gallium, germanium, arsenic, and indium. One such property, called bandgap, is a physical feature that determines the extent to which a semiconductor conducts or blocks an electric current. The gallium-based compound semiconductor, gallium nitride (GaN), has a wide bandgap (WBG), making it especially good at managing large amounts of power and high voltages of electricity. As a result, GaN is a leading semiconductor for certain applications within defense systems and AI data centers because it can operate in challenging conditions, such as high temperatures, and manage electricity more efficiently than standard chips.[28]

Other semiconductors have a property known as high electron mobility, enabling them to rapidly process data. These semiconductors, which include the compounds silicon-germanium and indium-phosphide, might perform networking functions in an AI data center, where processing speed and data throughput are paramount. Furthermore, gallium-arsenide chips have high electron mobility and the ability to withstand high temperature environments and radiation, and thus may be used for communications in some defense systems.[29]

3.1.2 Opportunities to reduce critical mineral import reliance

Development of substitute technologies for compound semiconductors is emerging and may reduce reliance on imported critical minerals—gallium, germanium, arsenic, and indium—for certain applications in the long term (10+ years). The first step is to identify alternative materials that possess the properties described above. Some potential next-generation materials for WBG semiconductors include boron nitride,

[28]Semiconductors, under different conditions, can switch between being conductors of electricity and being insulators. The ability to switch between these states is the basic function of a semiconductor. WBG semiconductors, like GaN and SiC, can better resist unwanted current flows, which can improve the efficiency in power electronics by reducing power losses.

[29]Gallium-arsenide chips are made by combining high-purity arsenic metal with gallium.

aluminum nitride, and diamond.[30] Research on these substitutes is ongoing but still in the early phases. For example, one researcher we spoke with is exploring the physics properties of boron nitride and told us that it has WBG properties, but research is still ongoing to examine its electrical performance as a chip. Similarly, research is in the early stages on substitute materials for high electron mobility semiconductors. According to one expert, germanium has no known alternatives.

3.1.3 Challenges

The likelihood that substitute materials will have a near-term effect on critical mineral reliance is small. Substituting some or all of the critical minerals in semiconductors presents several challenges, including the following:

Limited applications for substitutes. A one-to-one substitution of semiconductor materials is not possible because different materials do not perform equally across the same range of conditions. For example, the semiconductor silicon carbide (SiC), is a mature, WBG material, like GaN.[31] But it is not suitable to replace GaN in certain scenarios. For example, SiC can handle higher voltages than GaN but GaN outperforms SiC in switching efficiency, making GaN a better choice for applications like radar. According to industry experts, substitute technologies would need to perform at the same level or higher than current materials in the intended application for companies to adopt them.

R&D is focused on performance, not substitution. Experts told us that industry-driven R&D focuses on enhancing material performance—making chips faster, smaller, and more powerful—instead of future supply chain concerns. Though companies are aware of the potential for supply chain disruption, such as China's gallium and germanium export controls starting in 2023, concerns around access to critical mineral supply chains have not changed industry R&D motivations. Materials R&D is costly and can take decades. Years of research are needed to understand the physical properties of a new material, identify the limitations it would face as an electrical device, and determine how to manufacture the chip to overcome those limitations. This process is not nimble enough to adapt to unpredictable changes in markets for critical minerals, though one industry group said that companies are beginning to encounter supply chain risks.

Manufacturing constraints deter commercialization of new materials. Substitute materials also face the challenge of transitioning from laboratory research to fabrication and, ultimately, commercialization. This is due in large part to the high costs associated with semiconductor manufacturing. For example, fabrication plants can cost upwards of $15 billion dollars to construct and equip with essential equipment like advanced photolithography

[30] These materials are known as ultrawide-bandgap semiconductors because they have bandgap energies much greater than the 3.4 electron volts of GaN or 3.2 electron volts of SiC. The Materials Research Society, *Ultrawide-bandgap semiconductors: An overview* (Dec. 28, 2021), https://doi.org/10.1557/s43578-021-00458-1; Aluminum and boron appear on the *Final 2025 List of Critical Minerals*.

[31] SiC is a chemical compound created by combining carbon and silicon.

machines, which currently cost up to $400 million.[32]

High fixed costs disincentivize companies from adopting new materials because their operations are optimized for particular materials. Companies define semiconductor materials, performance specifications, and purity levels required for their unique application. Once companies make these decisions, they make high capital investments to install unique equipment and develop processes to manufacture these chips.

As a result, academic researchers and small businesses working on material innovations often have difficulty accessing the necessary equipment to test whether the candidate materials they study could make effective chips. Universities that conduct semiconductor R&D often do not have the advanced equipment required to prototype new technologies, and the availability and usefulness of their facilities can be limited due to problems like lack of professional staff to operate and maintain the equipment. As of February 2025, there was one public research center with prototyping capacity in the U.S., and recent federal investment has emphasized strengthening semiconductor production capacity over materials innovation or testing.[33]

3.2 Semiconductor recycling technologies

3.2.1 State of technologies

Critical minerals like gallium, arsenic, germanium, and indium appear in manufacturing scrap and EOL devices. These two feedstock sources require different technologies to recover and recycle target materials.

Manufacturing scrap. Manufacturing scrap frequently consists of known, concentrated, high-purity materials generated during semiconductor production. Minerals from this source could be recovered using several techniques, including pyrometallurgy and hydrometallurgy (see section 2.2.1 above). As of 2026, just one U.S. company was recovering and refining gallium, in addition to germanium and indium, from manufacturing scrap for use in new semiconductors.

EOL devices. EOL devices include discarded cell phones, computer monitors, and other electronics. It contains critical minerals, but in smaller quantities as compared to other sources of semiconductor recycling feedstock. Mineral recovery for EOL devices involves disassembling the products, sorting the subcomponents, and separating the desired minerals from other materials to which they are chemically or physically bonded. Technologies to perform this process efficiently for semiconductor materials do not currently exist on a commercial scale,

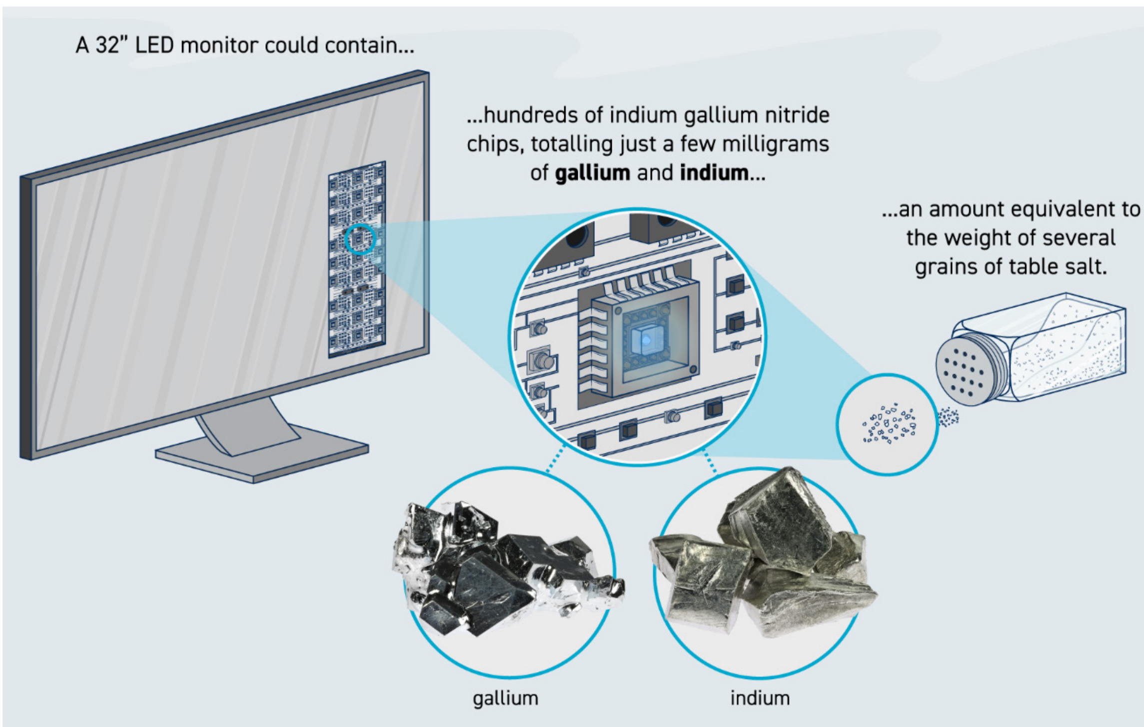
[32]"Photolithography" is the manufacturing process that patterns electronic features on a semiconductor material. It involves etching nanoscale level patterns with a laser using more precision than the naked eye can perceive.

[33]The Chips and Science Act of 2022 appropriated $11 billion for semiconductor R&D. This funding included support for the National Semiconductor Technology Center, which aimed to support prototyping. However, funding changes in August 2025 have stalled efforts to build this program.

although laboratory and pilot testing using improved pyrometallurgical, hydrometallurgical, and alternative techniques are underway. One company we spoke with is developing a new approach and is aiming for commercial deployment in the next 2 to 3 years. In addition, two academics we spoke with are developing technologies that are already or may be in pilot testing within that same timeframe, with a third in the process of moving from laboratory to pilot testing.

Figure 5 shows an example of the critical minerals that could be recovered from a computer monitor.

Figure 5: Critical minerals in a consumer device



Source: GAO (illustration); Björn Wylezich (gallium and indium)/stock.adobe.com. | GAO-26-108687

3.2.2 Opportunities to reduce critical mineral import reliance

While experts said the U.S. would not likely achieve critical mineral supply independence through recycling alone, recycling offers a path to bolster supply chain resilience for AI data center and defense applications. One expert said that even if recycling could only replace a marginal percentage of U.S. supply, any progress in this area would align with policymakers' goal to reduce critical mineral import reliance. Another expert, taking a long-term view (approximately 10 years), said that critical minerals from domestic recycling could one day become the primary source of supply with imported materials serving as a supplement.

According to one expert, manufacturing scrap could become a secondary supply for semiconductor materials like gallium, germanium, and indium in the medium to long term (3 to 10+ years). Recent funding announcements to increase recycling efforts may help the U.S. act on this opportunity. For example, in late 2025, the Department of Defense announced funds to support domestic gallium recovery from manufacturing scrap.[34] And in early 2026, DOE awarded funding to companies to recover gallium from various sources, including manufacturing scrap.[35] We did not find a reliable estimate of the potential reduction in import reliance, but it could be significant. DOE estimates that more than 50 percent of raw material can be lost during the manufacture of a semiconductor.[36]

Recycling from EOL devices could also supplement the U.S. supply of critical minerals with domestic materials.[37] According to the Global E-Waste Monitor, the U.S. is the second largest source of electronic waste worldwide. It is estimated that the majority of U.S. EOL devices are not recycled, meaning it goes to the landfill, is exported, or is otherwise unaccounted for. As such, the U.S. has a potentially large secondary supply of critical minerals in this feedstock source.

3.2.3 Challenges

While efforts to recycle semiconductor materials show some promise, several challenges remain that impede larger scale recycling in the near term:

EOL device recycling efficiency. Achieving efficient EOL device recycling is difficult because the critical minerals exist in small quantities, compared with the overall quantity of waste. In addition, electronics companies have unique consumer electronic designs, meaning efficient EOL recycling must be able to separate target materials across diverse products and material compositions. Furthermore, some critical minerals are particularly challenging to separate. For example, certain thermal separation approaches do not recover gallium. Gallium also easily combines with and damages aluminum, making recovery more difficult for products containing both. According to experts, it may not be possible for a single recycling technology or method to separate all desired target minerals, and each approach must be economically viable.

Underdeveloped recycling market. The domestic market for the recycling of both manufacturing scrap and EOL devices is limited, owing to the interrelated problems of low capacity, low availability of recycling feedstock (e.g., industrial scrap or recycled consumer electronics), and high cost of

[34]See the Department of Defense funding announcement https://www.war.gov/News/Releases/Release/Article/4338685/department-of-war-awards-299-million-to-create-a-us-domestic-supply-of-gallium/.

[35]See the DOE funding award announcement https://www.energy.gov/cmei/articles/does-office-critical-minerals-and-energy-innovation-selects-five-organizations.

[36]U.S. Department of Energy, *2023 Critical Materials Assessment* (Washington, D.C.: July 2023), 229.

[37]EOL waste recycling is not tracked at the federal level. As such, we did not estimate the quantity of critical minerals that would be generated from recycling EOL waste.

recycling. Recycling semiconductor manufacturing scrap is not yet standard practice in part because of the cost of recycling. Recyclers, therefore, do not currently have the steady stream of feedstock they would need to scale the process and bring down its cost.

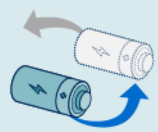
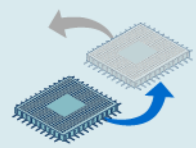
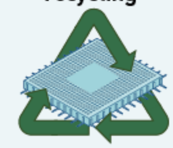
The low rate of EOL device collection in the U.S. also limits recycling capacity. It is challenging to collect EOL devices from a dispersed set of actors, such as individual consumers and businesses. The U.S. does not have a national EOL device collection program.

4 Policy Options

We identified four options policymakers could consider that may reduce reliance on imported critical minerals by advancing substitution and recycling technologies (see fig. 6).[38] In some cases, these options may provide some near-term reduction in import reliance. For example, one option is for policymakers to establish domestic recycling capacity. Current technologies for battery recycling are mature enough that this option could offset a large share of critical mineral imports, such as lithium, if capacity to recycle batteries were increased. In other cases, near-term reduction of import reliance is unlikely, and long-term effects are difficult to predict. For example, policy intervention to advance semiconductor substitution technologies may not make measurable impacts in the near term because these technologies face long development timelines and technical challenges.

[38]Potential policymakers include legislative bodies, government agencies (federal, state, and local), academia, standards-setting organizations, industry, and other groups.

Figure 6: Substitution and recycling technologies crosswalk

Technology approach	Battery substitution 	Battery recycling 	Semiconductor substitution 	Semiconductor recycling 
Potential	Near-term 2-3 years	Near-term 2-3 years	Long-term 10+ years	Medium-term 3-10 years
Challenges	Domestic manufacturing capacity and market uncertainty Known technical limitations	Recycling infrastructure capacity Known technical limitations	Limited applications for substitutes Research and development focused on performance Manufacturing constraints	End-of-life waste recycling efficiency Underdeveloped recycling market
Relevant policy options				
Establish domestic manufacturing capacity for viable substitutes (4.1)	●		●	
Establish domestic recycling capacity (4.2)		●		●
Secure inputs for recycling (4.3)		●		●
Support research development and testing (4.4)	●	●	●	●

Source: GAO (analysis of agency and expert information and literature; illustrations). | GAO-26-108687

In general, substitution and recycling technologies have potential to reduce some critical mineral import reliance in the near, medium, or long term. To bridge the gap, policymakers could choose to pursue non-technological policy approaches, many of which are the subject of current and proposed legislation and executive action (see section 1.3). For example, establishing new trade partnerships may diversify U.S. critical mineral supply chains and reduce the risk of supply disruptions. Similarly, continuing efforts to increase domestic extraction, production, and processing capacity may help establish a supply of critical minerals that reduces the need for imports. The policy options presented below can complement such approaches.

For each policy option, we provide one or more potential implementation approaches, opportunities the option may present, and some factors to consider. This list is not exhaustive.

4.1 Establish domestic manufacturing capacity for viable substitutes

Policymakers could consider building or repurposing existing manufacturing capacity to produce substitute technologies for batteries and semiconductors. Such work could help develop a manufacturing process for substitutes and eventually transition fully commercialized technologies into full production.

Implementation approaches. Policymakers could choose to implement this policy option in a number of ways, including, but not limited to:

- Providing support for private capital investments in manufacturing plants for commercially available battery technologies. This support could include tax incentives; public buyback guarantees, where the government commits to buy a minimum supply; or direct public investment.

- Establishing facilities or partnerships to perform pilot-scale testing of semiconductor substitutes.

Opportunities. Domestic manufacturing capacity could allow for near-term production of commercially available substitute technologies like LFP batteries, which could reduce import reliance on critical minerals like cobalt and nickel. In addition, pilot scale facilities could help accelerate the commercialization of new semiconductor substitutes—currently a lengthy and costly process.

Considerations. Battery and semiconductor production facilities tend to be specialized for the production of a particular technology. Thus, significant investments in production of current technologies may not optimize critical mineral reduction in the long-term if the market shifts to other substitutes (e.g., if sodium-ion batteries replace LFP batteries).

4.2 Establish domestic recycling capacity

Policymakers could build domestic infrastructure to bolster the domestic capacity to recycle batteries and semiconductors.

Implementation approaches. Policymakers could choose to implement this policy option in a number of ways, including, but not limited to:

- Providing assurances to support private investment in factories for battery recycling. These assurances could include guaranteed prices from the government or direct public investment.

- Collecting and sharing data on the available amount of manufacturing scrap and EOL devices containing batteries and semiconductors to inform capacity planning by recycling businesses.

- Reviewing and streamlining permitting requirements and hazardous waste designations that create logistical barriers for recycling.

Opportunities. Agency officials and experts we spoke with agreed that the U.S. currently lacks the infrastructure needed to reduce import reliance through recycling. A more robust recycling infrastructure for semiconductors or batteries could make recycling more economical and expand the supply of minerals. In particular, expanded domestic infrastructure could reduce or eliminate the need to ship intermediate recycled products (e.g., black mass) overseas.

Considerations. Building domestic recycling infrastructure may not reduce import reliance for selected critical minerals in the near term, since building new or repurposing existing infrastructure can take a decade and require significant investment. In addition, infrastructure, especially facilities that handle and process hazardous waste, face regulatory burdens that may dissuade private investment. Thus, experts expect the U.S. to continue importing critical minerals over the near term.

4.3 Secure inputs for recycling

Policymakers could support efforts to collect, sort, transport, and store manufacturing scrap and EOL devices for recycling and reuse.

Implementation approaches. Policymakers could choose to implement this policy option in a number of ways, including, but not limited to:

- Establishing and overseeing national and local electronic waste collection programs that provide education and resources (e.g., drop-off locations) for consumers.
- Providing financial incentives for industry to collect or retain inputs for recycling.

Opportunities. Securing a consistent supply of inputs for recycling and reuse could help reduce the need for critical mineral importation in the near term. As more EOL batteries become available, particularly from EVs, a market for battery recycling and reuse could grow. A similar market may emerge in the medium term for semiconductor recycling as technologies advance for manufacturing scrap and EOL devices.

Considerations. Although mature battery recycling technologies exist, securing additional inputs may exacerbate challenges related to the safety, transportation, and handling of hazardous materials. In addition, without domestic recycling infrastructure to process increased inputs, the need to ship EOL batteries and black mass overseas for processing will remain in the near term. Without demand and competitively-priced recycled materials, it may be difficult for semiconductor recyclers to scale their operations and offset the amount of imported minerals required in the near term.

4.4 Support research, development, and testing

Policymakers could continue or grow support for research, development, and testing of substitution and recycling technologies.

Implementation approaches. Policymakers could choose to implement this policy option in a number of ways, including, but not limited to:

- Supporting research to improve performance of lithium-free batteries.
- Supporting research into battery recycling technologies that reduce or avoid the cost, waste issues, and environmental impact of current techniques.

- Encouraging targeted materials research focused on semiconductor substitutes that maintain or enhance material performance and reduce the use of critical minerals when possible.

- Supporting research on more efficient semiconductor recycling technologies that recover more critical minerals.

- Increasing adoption of or creating new knowledge sharing mechanisms to share industry best practices and, if necessary, establish standards.

Opportunities. Increased research could help overcome current limitations of existing technologies, resulting in better performance (e.g., higher energy density batteries, larger bandgap semiconductors) or higher commercialization potential (e.g., improved recovery of minerals from semiconductors).

Considerations. Research, development, and testing efforts may not yield mature technologies in the near term. For example, while past research efforts have produced gradual improvements in semiconductor substitution technologies, research and development to reach commercialization can take decades. Thus, experts expect U.S. manufacturers to continue to need minerals like gallium and germanium in the long term.

5 Agency and Expert Comments

We provided a draft of this report to the Department of Energy, U.S. Geological Survey, and the National Institute of Standards and Technology with a request for technical comments. The Department of Energy and U.S. Geological Survey provided technical comments, which we incorporated as appropriate. The National Institute of Standards and Technology reviewed the report and had no technical comments.

We also offered our selected experts the opportunity to review and comment on the draft of this report, consistent with previous technology assessment methodologies. Thirteen of those experts reviewed our draft report; we incorporated their comments as appropriate.

We are sending copies of this report to the appropriate congressional committee, the Secretary of Energy, the Directors of the U.S. Geological Survey and the National Institute of Standards and Technology, and other interested parties. In addition, the report is available at no charge on the GAO website at https://www.gao.gov/.

If you or your staff have any questions about this report, please contact me at HarveyS@gao.gov. Contact points for our Offices of Congressional Relations and Media Relations may be found on the last page of this report. GAO staff who made key contributions to this report are listed in appendix II.

//SIGNED//

Sarah Harvey
Director, Science, Technology Assessment, and Analytics

Appendix I: Objectives, Scope, and Methodology

For this technology assessment, you asked us to describe substitution and recycling technologies that are available for deployment in the near term (2 to 3 years) and that may reduce U.S. import reliance on critical minerals in the semiconductor and battery industries.[39] We examined (1) the state of and potential opportunities of these technologies to lessen import reliance on critical minerals within these industries, (2) challenges to the development and adoption of these technologies, and (3) policy options that could support the policy goal of reducing critical mineral import reliance.

To conduct our work for all three objectives, we did the following:

- We interviewed three federal agencies with relevant roles and responsibilities in managing critical mineral efforts in these industries. We interviewed officials from the Department of Energy (DOE), U.S. Geological Survey, and the National Institute of Standards and Technology. We also reviewed written responses from each agency to our questions and documentation provided by DOE officials.

- We selected 11 of 60 critical minerals for examination based on their import reliance and importance to these industries. We reviewed U.S. Geological Survey data on critical minerals to determine import reliance for each mineral from 2021 to 2025. We determined relevant importance by establishing which critical minerals are used in current or emerging battery types and semiconductors within selected applications. Specifically, batteries used in consumer electronics, defense, electric vehicles, and stationary grid energy storage applications, and semiconductors used in AI data centers and defense applications.

- We identified and selected experts for interviews and written responses to our questions from industry, advocacy and nonprofit organizations, and academia that conduct or fund research on critical mineral recycling or substitution technologies; that help develop or commercialize these technologies; or that regulate, oversee, or propose policies on the deployment of these technologies. To ensure we obtained a variety of perspectives, we also identified and selected experts based on our topical research and suggestions from other experts.

- We reviewed relevant literature identified by DOE officials, experts, and our literature search.

[39]In this report, we refer to near-term as 2 to 3 years, medium-term as 3 to 10 years, and long-term as more than 10 years.

- We reviewed current and proposed legislation, executive orders, and other policies and guidance issued by policymakers to identify the policy goal of reducing import reliance. In addition, we identified several approaches policymakers have and continue to pursue to address this issue. We developed challenges to the development and adoption of substitution and recycling technologies and four policy options that could help address them from the methodological steps listed above.

We conducted our work from August 2025 to July 2026 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.

Appendix II: GAO Contact and Staff Acknowledgments

GAO contact

Sarah Harvey, Director, Science, Technology Assessment, and Analytics (STAA),
harveys@gao.gov.

Staff acknowledgments

In addition to the GAO contact named above, the following STAA staff made key contributions to this report:

Will Bauder, Assistant Director and Senior Physicist

Wes Wilhelm, Analyst-in-Charge and Senior Systems Engineer

Tim Kinoshita, Senior Analyst

Georgeann Higgins, Analyst

Paulina Rowe, Analyst

Ben Shouse, Communications Analyst

Ryan Han, Visual Communications Analyst

These staff also contributed to this work:

Patrick Harner, Senior Attorney

Andrew Stavisky, Assistant Director and Senior Methodologist

Michael Smith, Senior Economist

GAO's Mission

The Government Accountability Office, the audit, evaluation, and investigative arm of Congress, exists to support Congress in meeting its constitutional responsibilities and to help improve the performance and accountability of the federal government for the American people. GAO examines the use of public funds; evaluates federal programs and policies; and provides analyses, recommendations, and other assistance to help Congress make informed oversight, policy, and funding decisions. GAO's commitment to good government is reflected in its core values of accountability, integrity, and reliability.

Obtaining Copies of GAO Reports and Testimony

The fastest and easiest way to obtain copies of GAO documents at no cost is through GAO's website (https://www.gao.gov). Each weekday afternoon, GAO posts on its website newly released reports, testimony, and correspondence. To have GAO e-mail you a list of newly posted products, go to https://www.gao.gov and select "E-mail Updates."

Order by Phone

The price of each GAO publication reflects GAO's actual cost of production and distribution and depends on the number of pages in the publication and whether the publication is printed in color or black and white. Pricing and ordering information is posted on GAO's website, https://www.gao.gov/ordering.htm.

Place orders by calling (202) 512-6000, toll free (866) 801-7077, or
TDD (202) 512-2537.

Orders may be paid for using American Express, Discover Card, MasterCard, Visa, check, or money order. Call for additional information.

Connect with GAO

Connect with GAO on Facebook, Flickr, Twitter, and YouTube.
Subscribe to our RSS Feeds or E-mail Updates.
Listen to our Podcasts and read The Watchblog.
Visit GAO on the web at https://www.gao.gov.
General inquiries https://www.gao.gov/about/contact-us

To Report Fraud, Waste, and Abuse in Federal Programs

Contact: Website: https://www.gao.gov/about/what-gao-does/fraudnet
Automated answering system: (800) 424-5454

Congressional Relations

David A. Powner, Acting Managing Director, CongRel@gao.gov

Media Relations

Sarah Kaczmarek, Managing Director, Media@gao.gov