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Critical Minerals and Materials for Selected Energy Technologies

August 6, 2024

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Partly in response to rising global temperatures, domestic and international policymakers have pursued alternative energy sources as an energy transition from fossil fuels. Some countries have set climate goals, such as balancing the amount of greenhouse gases emitted into the atmosphere by human activity with the amount of carbon removed from it (*net-zero emissions*). While the desire to reduce carbon dioxide and other greenhouse gas emissions is one reason nations may look to transition energy technologies, resource instability and fluctuating fuel prices are among other factors generating interest and innovation in lower-carbon alternatives, including solar photovoltaic energy, wind energy, grid-scale storage batteries, and electric vehicles (EVs).

The increase in demand for new technologies corresponds with an increase in demand for the raw materials and resources required for their construction and maintenance. The growing demand for critical minerals and materials—especially in light of the possibility of adversarial countries being in the supply chain—has been of interest to policymakers. The infrastructure and technology advancements necessary to build and maintain extensive wind and solar developments, including the large-scale battery storage expected to accompany it, likely require greater use of critical minerals and materials. Wind and solar provisions have been included in major energy legislation enacted in recent years, including tax incentives and funding for infrastructure improvements and research and development. For EVs, increased consumer demand and recent legislation incentivizing EV adoption has increased the demand for the critical mineral and material components required for their construction, in particular the minerals required to formulate the large batteries that power them. The United States depends on imports for a wide array of these critical minerals and materials.

Congress has considered critical minerals in recent energy and infrastructure bills. Enacted legislation in the 116th and 117th Congresses—including the Energy Act of 2020 (P.L. 116-260, Division Z), the Infrastructure Investment and Jobs Act (IIJA; P.L. 117-58), P.L. 117-167 (known as the CHIPS and Science Act), and the law commonly referred to as the Inflation Reduction Act (IRA; P.L. 117-169)—has touched on addressing critical minerals supply security. Bills introduced in the 118th Congress consider topics such as promoting stable supply chains, onshoring domestic production, funding research and development, and creating new alternatives to rare or expensive materials.

Recent congressional interest in critical minerals and materials has focused on potential policy interventions across the supply chain. These include reforming domestic mining laws, incentivizing research and development of critical mineral recycling and alternatives, forming critical mineral task forces, and related strategies. Some hearings on this topic include, but are not limited to, discussing criteria for designating critical minerals, the role of federal research in mineral development, and the impact of the People's Republic of China on mineral supply chains.

SUMMARY

R48149

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Contents

Figures

Contacts

Introduction

Interest in critical minerals,[1] rare earth elements (REEs),[2] and critical materials has long been an area of concern to Congress. Domestic mining laws, such as the General Mining Act of 1872, have been in place for more than a century. In recent decades, much minerals and mining production has moved abroad due to many factors, including the higher costs of domestic production and environmental concerns. While demand for critical minerals crosses sectors of the U.S. economy, including health care, consumer electronics, and defense, particular interest in recent years has been paid to the critical minerals seen as necessary for a transition to lower-carbon energy sources, which is currently being pursued by certain policymakers in the United States and around the world.

Inputs for concrete and steel are the foundation of this country's physical infrastructure. Copper, steel, and aluminum are key components of the U.S. electrical grid. Should countries transition to new energy technologies such as solar photovoltaic (PV), wind turbines, and electric vehicles (EVs), other minerals such as lithium and cobalt may face heightened demand. These minerals face supply chain risks at many points, from original sourcing and extraction, through the processing and components stages, to end-use technology.[3] (See **Figure 1**.) Possible avenues for recycling exist along the supply chain.

Legislation such as the Energy Act of 2020 (P.L. 116-260, Division Z), the Infrastructure Investment and Jobs Act (P.L. 117-58), P.L. 117-167 (known as the CHIPS and Science Act), and the law commonly referred to as the Inflation Reduction Act of 2022 (IRA; P.L. 117-169) has provided support to develop the infrastructure and technology associated with development of additional energy sources and uses. Together, these acts address the supply chains of these minerals and the end-use demand technologies that use them. New infrastructure development likely relies on a consistent, secure, and stable supply chain of these minerals and material inputs. Manufacturing facilities, highway updates and electric vehicle charging stations, solar panel installation, and wind farms were either authorized or provided with appropriations in these acts. Both proposed and enacted legislation have also addressed aspects of critical minerals policy, such as increasing onshore production of minerals, reducing price volatility in the critical minerals market, and expanding opportunities for research and development (R&D) and new job creation.

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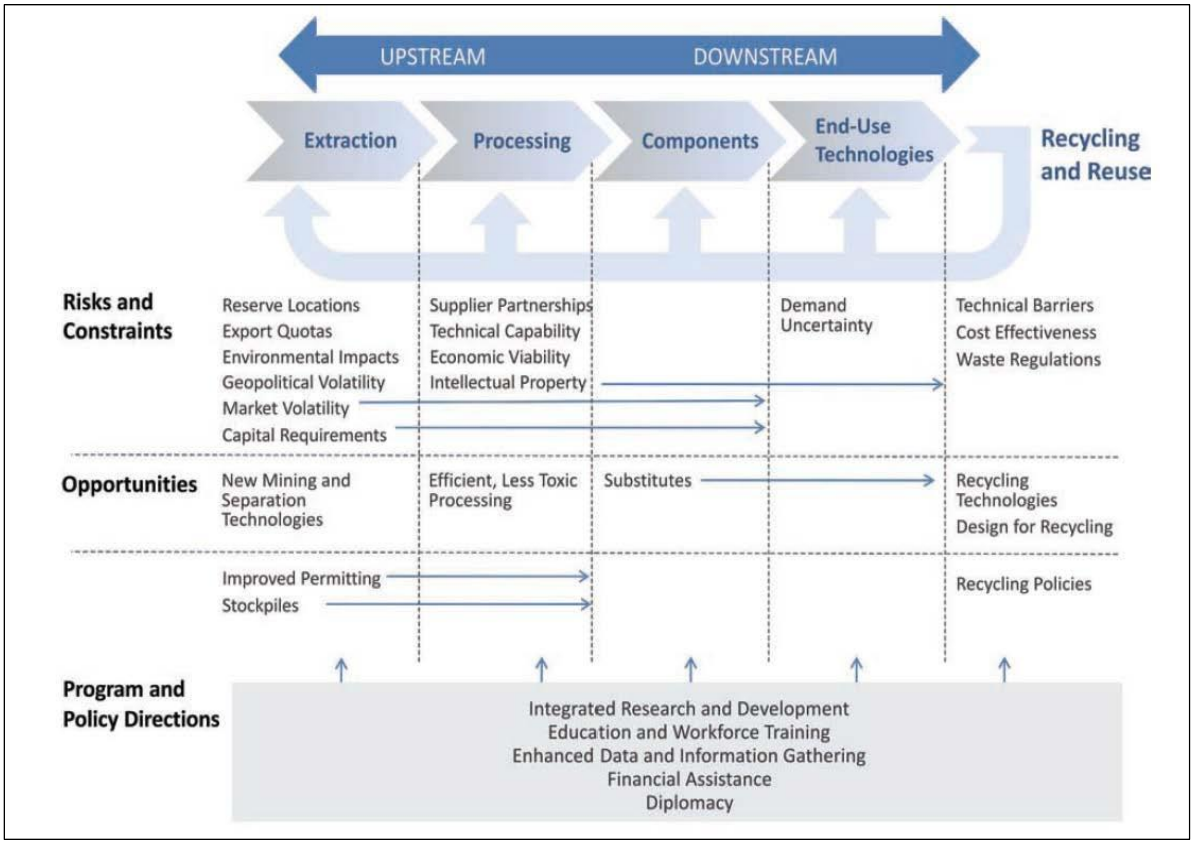
[1] *Minerals*, as defined in federal statute, refers to non-fuel minerals, mineral products and materials, and metals. Fuel minerals (or mineral fuels) include oil, gas, oil shale, coal, and uranium (Mining and Mineral Policy Act of 1970, 30 U.S.C. §21(a)).

[2] *Rare earth elements* include scandium, yttrium, and the 15 elements in the *lanthanide series*. The lanthanides range from atomic number 57 (lanthanum) to 71 (lutetium). U.S. Geological Survey, "Rare Earths Statistics and Information," https://www.usgs.gov/centers/national-minerals-information-center/rare-earths-statistics-and-information; Bradley S. Van Gosen et al., *Rare-Earth Elements*, U.S. Geological Survey, December 19, 2017, https://doi.org/10.3133/pp1802O; and Bradley S. Van Gosen, Philip L. Verplanck, and Poul Emsbo, *Rare Earth Element Mineral Deposits in the United States*, U.S. Geological Survey, Circular 1454, Version 1.1, April 2019, https://doi.org/10.3133/cir1454.

[3] Supply chain risks may include (1) geologic—whether the resource exists in nature, (2) technical—whether the resource can be extracted and processed, (3) environmental and social—whether the resource can be extracted and processed in an environmentally and socially acceptable way, (4) political—whether governments influence resource availability through policies and actions, and (5) economic—whether the resource can be extracted and processed at a cost that users are willing to pay. National Research Council, *Minerals, Critical Minerals, and the U.S. Economy* (Washington, DC: National Academies Press, 2008), pp. 6, 8, and 36, https://doi.org/10.17226/12034.

Figure 1. Critical Minerals Supply Chain and Considerations



Source: U.S. Department of Energy (DOE), *Critical Materials Strategy*, December 2010.

This report focuses on the key critical minerals and materials for four types of energy transition technologies: solar photovoltaics, wind turbines, electric vehicle batteries, and large-scale energy storage batteries. Some critical minerals and materials of interest for these technologies, according to the Department of Energy (DOE), are aluminum, cobalt, copper, electrical steel, fluorine, gallium, graphite (carbon), lithium, magnesium, nickel, platinum, silicon, silicon carbide, and certain rare earth elements.

Agency Roles in Critical Minerals and Materials

The Energy Act of 2020 codified updated definitions of "critical minerals" and "critical materials." The act delegated the U.S. Geological Survey (USGS) and DOE to determine what is included on the Critical Minerals List and the Critical Materials List.[4]

A "critical mineral" is 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.[5]

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[4] 30 U.S.C. §1606(a).

[5] U.S. Department of Energy, "What Are Critical Materials and Critical Minerals?," https://www.energy.gov/cmm/what-are-critical-materials-and-critical-minerals; 30 U.S.C. §1606(a).

A "critical material" is defined as

- any non-fuel mineral, element, substance, or material that the Secretary of Energy determines (i) has a high risk of supply chain disruption; and (ii) serves an essential function in one or more energy technologies, including technologies that produce, transmit, store, and conserve energy; or
- a critical mineral, as defined by the Secretary of the Interior.[6]

The Critical Minerals List and the Critical Materials List have many minerals in common, but also distinct differences. This, in part, arises from different agency focus in developing these lists. The USGS takes an economy-wide, industry-crossing, and historical look at critical mineral demand. DOE takes a more specific energy focus in its evaluation of current and projected demand for critical materials.

U.S. Geological Survey and Critical Minerals

The USGS conducts critical minerals resources analysis and research. The federal government, primarily under the USGS, has compiled international and domestic data on mineral resources and reserves for decades. Since 1900, the USGS has published the annual *Mineral Commodity Summaries* report, "the earliest Government publication to furnish estimates covering nonfuel mineral industry data."[7]

The Energy Act of 2020 charged the USGS with developing a list of "critical minerals" in coordination with the Departments of Defense, Commerce, Agriculture, and Energy and the Office of the United States Trade Representative.[8] The USGS is to update the list at least every three years in consultation with these agencies. The list is to include minerals that the USGS determines

> (i) are essential to the economic or national security of the United States;
>
> (ii) the supply chain of which is vulnerable to disruptions (including restrictions associated with foreign political risk, abrupt demand growth, military conflict, violent unrest, anti-competitive or protectionist behaviors, and other risks throughout the supply chain); and
>
> (iii) serve an essential function in the manufacturing of a product (including energy technology-, defense-, currency-, agriculture-, consumer electronics-, and healthcare-related applications), the absence of which would have significant consequences for the economic or national security of the United States.[9]

The minerals in the 2022 Critical Minerals List are

> aluminum, antimony, arsenic, barite, beryllium, bismuth, cerium, cesium, chromium, cobalt, dysprosium, erbium, europium, fluorspar, gadolinium, gallium, germanium, graphite, hafnium, holmium, indium, iridium, lanthanum, lithium, lutetium, magnesium, manganese, neodymium, nickel, niobium, palladium, platinum, praseodymium, rhodium, rubidium, ruthenium, samarium, scandium, tantalum, tellurium, terbium, thulium, tin, titanium, tungsten, vanadium, ytterbium, yttrium, zinc, and zirconium.[10]

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[6] 30 U.S.C. §1606(a).

[7] U.S. Geological Survey, "Mineral Commodity Summaries," https://www.usgs.gov/centers/national-minerals-information-center/mineral-commodity-summaries.

[8] 30 U.S.C. §1606(c).

[9] Ibid.

[10] U.S. Geological Survey, "2022 Final List of Critical Minerals," 87 *Federal Register* 10381-10382, February 24, 2022.

Department of Energy and Critical Materials

In the Energy Act of 2020, Congress directed DOE to compile a list of "critical materials" for energy technologies. These materials cover more than just minerals, including materials such as electrical steel that are crucial components of projected energy infrastructure and technology investments needs. The 2023 Critical Materials Assessment was released as required by the Energy Act of 2020 and took a global perspective and forward-looking approach to potential trajectories for material demand based on the market for new technologies. DOE's assessment includes analyzing advancements in key technologies, such as EVs and batteries, and outlines four possible trajectories for material demand based on high or low mineral intensities or deployment trajectories of energy technologies.

The materials on the 2023 Critical Materials List are

> aluminum, cobalt, copper, dysprosium, electrical steel, fluorine, gallium, iridium, lithium, magnesium, natural graphite, neodymium, nickel, platinum, praseodymium, silicon, silicon carbide and terbium.[11]

DOE's analysis is based on criticality in the short and medium term, with a five-pillared strategic framework:[12]

1. diversify and expand supply from primary sources;
2. develop alternative materials and systems;
3. enhance material and manufacturing efficiency;
4. promote a circular economy through recycling, reuse, and remanufacturing; and
5. use analyses to enable and speed up science discoveries.

DOE's Critical Materials Assessment ("DOE Assessment") is an extensive analysis of the materials necessary for energy technologies, with a focus on technologies they have evaluated based on their "criticality to global clean energy technology supply chains."[13] It assesses the supply chains of these materials, the various uses for these materials across the energy sector, and the market for these materials. According to the DOE Assessment, recent changes to the energy sector that may impact the market for minerals and materials include the following:[14]

- an increase in EV adoption, and a corresponding increase in the materials used in electric vehicles, including lithium-ion batteries, rare earth magnets, electrical steel, and power electronics;
- the global doubling of offshore wind capacity from 27 gigawatts (GW) in 2019 to 56 GW in 2021, also leading to higher demand for rare earth magnets;
- the expansion of stationary storage to meet the energy storage needs of large wind and solar development;
- a projected shift from silicon-based power electronics to silicon carbide and gallium nitride power electronics;

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[11] U.S. Department of Energy, "What Are Critical Materials and Critical Minerals?," https://www.energy.gov/cmm/what-are-critical-materials-and-critical-minerals.

[12] U.S. Department of Energy (DOE), *Critical Materials Assessment*, July 2023, p. i, https://www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf (hereinafter DOE Assessment).

[13] U.S. Department of Energy, "U.S. Department of Energy Releases 2023 Critical Materials Assessment to Evaluate Supply Chain Security for Clean Energy Technologies," press release, July 31, 2023, https://www.energy.gov/eere/articles/us-department-energy-releases-2023-critical-materials-assessment-evaluate-supply.

[14] DOE Assessment, pp. xi-xiii.

- an increase in grid expansion and modernization, EV infrastructure, and EV motors that may contribute to a higher demand for the electrical steel needed for grid construction; and
- the continued dominance of crystalline silicon in the solar photovoltaic market.

DOE conducted a "Criticality Assessment" using "updated analyses based on national and global priorities, technology advancement, and technology adoption trends."[15] This analysis in the DOE Assessment includes both short-term (2020-2025) and medium-term (2025-2035) projections of the expected demand for these critical materials (**Figure 2**). These assessments evaluate the importance of each material to the energy industry and the likelihood that these minerals will be subject to supply chain risks. These supply chain risks can come from a wide range of potential sources, from shifts in the market leading to the shuttering of mining operations, to domestic policy shifts refocusing on different industries, to tariff changes and geopolitical conflicts. Key minerals associated with energy transition—such as lithium, nickel, cobalt, graphite, and REEs—are all highly subject to supply chain risks in the medium term, according to DOE.

DOE works in collaboration with the private sector and research institutions to advance and fund research and development for critical materials. Programs across the agency provide funding to critical materials research, including through programs such as the Critical Materials Collaborative,[16] the Critical Materials Accelerator Program, and the Critical Materials Innovation Hub, and through funding opportunity announcements.[17] Much of the funding for these programs was appropriated in recent large energy and infrastructure legislation, primarily the IRA.[18]

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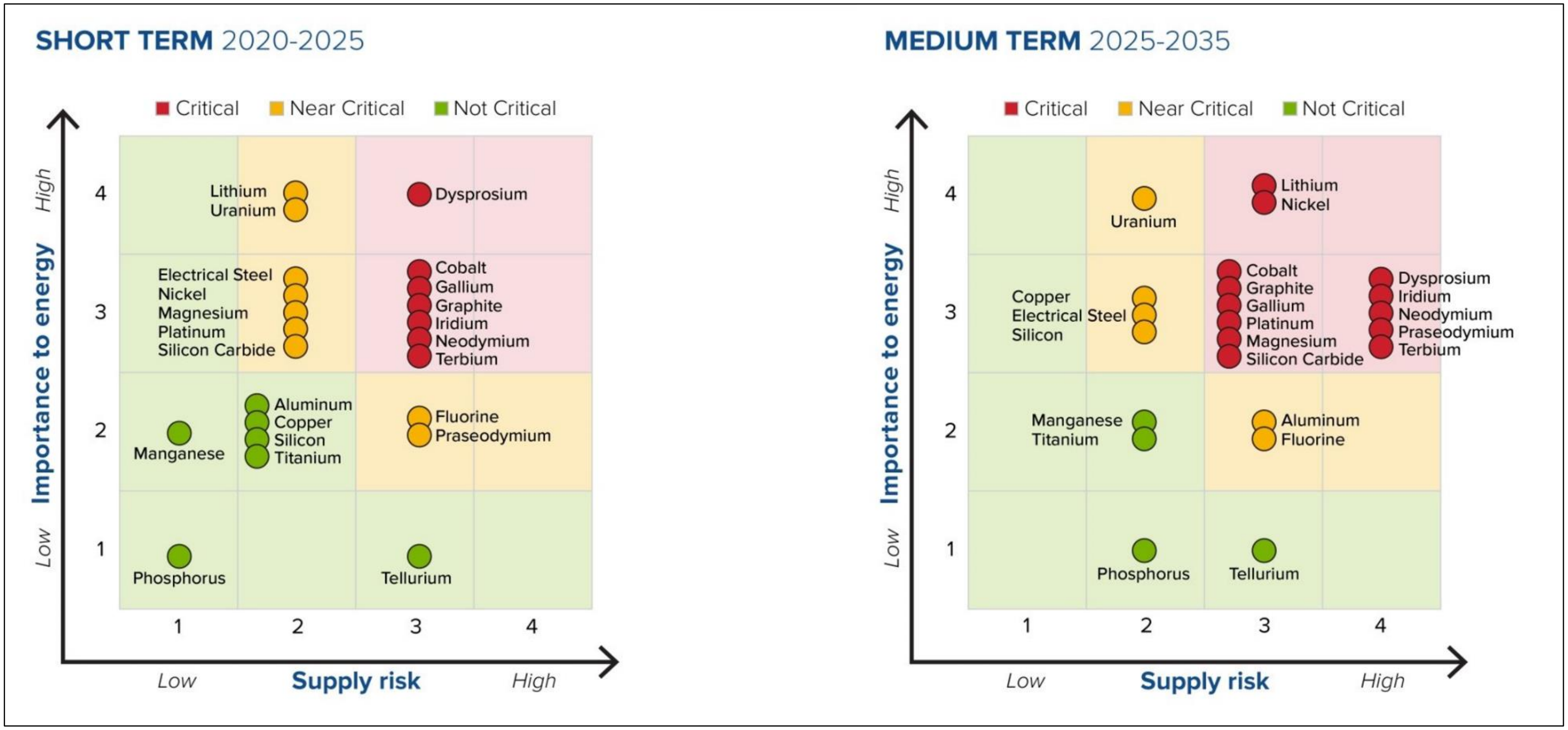
[15] Ibid., p. xiii.

[16] U.S. Department of Energy, "What Is the Critical Materials Collaborative?," https://www.energy.gov/cmm/critical-materials-collaborative.

[17] Office of Chief Financial Officer, *Department of Energy FY 2025 Congressional Justification*, vol. 2, U.S. Department of Energy, March 2024, https://www.energy.gov/sites/default/files/2024-03/doe-fy-2025-budget-vol-2-v4.pdf.

[18] Ibid.

Figure 2. U.S. Department of Energy Short- and Medium-Term Material Criticality Matrix



Source: U.S. Department of Energy, *Critical Materials Assessment*, July 2023 (DOE Assessment), p. xiv, https://www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf.

Notes: According to the DOE Assessment (p. 100), "'Importance to energy' and 'supply risk' are defined as weighted averages of several factors, each of which receives a score on a scale of 1 to 4. Short- and medium-term scores for importance to energy are based on a weighted average of two factors, while those for supply risk are based on a weighted average of five factors. For each factor, key materials are assigned qualitative scores of 1 (least critical) to 4 (most critical)." For more information, see DOE Assessment, pp. 100-105.

Critical Mineral and Material Supply

International Supply

When the earth's crust formed and shifted billions of years ago, critical minerals were dispersed across the planet in different concentrations and locations. Now this mineral distribution may impact modern-day foreign policy. Shifting technology demands for these minerals and materials can change the balance of power in a region. Some countries may have a monopoly on a critical mineral, potentially giving them a strategic advantage, drawing targeted investment, and posing governance challenges. Examples include the Democratic Republic of the Congo, which supplies 68% of the world's cobalt; South Africa, which supplies 74% of platinum globally; and Indonesia, which supplies 48% of nickel (**Figure 3**).[19]

The mining and processing of critical minerals for manufacturing is an energy-intensive and highly technical process. It requires space for the mining operation itself, as well as for separation and refining facilities.[20] Mining interests also emphasize that it takes significant time and financial investment to open and operate a mine and eventually make a profit.[21] The process of locating economically viable reserves of these minerals, obtaining approvals and permits, and breaking ground can take years. In countries with more stringent environmental protections, such as the United States, the process may take more time and resources, according to the mining industry.[22] In countries with less stringent mining and permitting regulations, it may take less time to open a mine, but those countries may face greater environmental consequences from the mining process.[23]

Figure 3 illustrates selected critical minerals and materials seen as needed for energy transition, identifying selected technologies that use them and where they are sourced. This report (and **Figure 3**) focuses on the use of these materials in four specific energy technologies: electric vehicle batteries, stationary storage batteries, solar photovoltaics, and wind turbines. As seen in the figure, some materials, such as gallium, are used in more than one of these technologies; others, such as silicon and silicon carbide, are used primarily in just one of these technologies. Thus, some energy technologies may compete for the same critical materials, while some may face competition from other industry sectors.

Figure 3 also illustrates where each material is sourced, noting the top five producers of each material, along with their global share. Some materials are dispersed across multiple countries; for example, lithium can be sourced in Chile, Argentina, Belize, Australia, and China. On the other hand, China controls large market shares of gallium (98%), magnesium (90%), and rare earth elements (70%). When sourcing of a critical material depends heavily on a single country,

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[19] U.S. Geological Survey, *Mineral Commodity Summaries 2024*, January 31, 2024, https://doi.org/10.3133/mcs2024.

[20] International Energy Forum, "How to Make Mining More Sustainable," January 8, 2024, https://www.ief.org/news/how-to-make-mining-more-sustainable; Adator Stephanie Worlanyo and Li Jiangfeng, "Evaluating the Environmental and Economic Impact of Mining for Post-mined Land Restoration and Land-Use: A Review," *Journal of Environmental Management*, vol. 279 (February 2021).

[21] National Mining Association, *Delays in the U.S. Mine Permitting Process Impair and Discourage Mining at Home*, May 2021, https://nma.org/wp-content/uploads/2021/05/Infographic_SNL_minerals_permitting_5.7_updated.pdf.

[22] Ibid.

[23] Charlotte Davey, "The Environmental Impacts of Cobalt Mining in Congo," Earth.org, March 28, 2023, https://earth.org/cobalt-mining-in-congo/.

particularly if the United States has a complicated relationship with that country, the supply chain for that material is more vulnerable than when multiple options for sourcing the material exist.

Note that other energy technologies, such as hydrogen and nuclear, may also compete for critical minerals and materials. These are not discussed in this report or illustrated in **Figure 3**. Further, some minerals and materials shown in the figure, such as copper and electrical steel, may be used in other industries beyond energy. Some may be critical to national security technologies. These competing interests—and any associated national security concerns—are outside the scope of this report.

China

China has prioritized its critical minerals and materials policy in recent decades. Some experts have concluded that China prioritized critical minerals and rare earth elements as early as 1992.[24] While China has significant reserves of some minerals and rare earth elements within its geographic borders, it has also strategically invested through its Belt and Road Initiative (BRI) in infrastructure and manufacturing capabilities in other nations.[25] Minerals mined in other nations may be imported to China for processing and refining.[26] China reportedly refines 68% of nickel, 40% of copper, 59% of lithium, and 73% of cobalt globally.[27]

Two examples of countries where China's BRI has invested in critical minerals are the Democratic Republic of the Congo (DRC) and Indonesia. Sixty-eight percent of global cobalt is sourced from the DRC, and Chinese companies own 80% of the DRC's cobalt production. These companies then send their cobalt to be processed and refined in China and then distributed across the globe.[28] China also funds mineral development in Indonesia.[29] As of 2024, Chinese-owned producers controlled 82% of Indonesia's battery nickel output. [30] Investments such as these have led China to control a substantive share of the global supply chains for these critical minerals.

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[24] Mark Burton, "Why the Fight for 'Critical Minerals' Is Heating Up," *Bloomberg*, November 20, 2023, https://www.bloomberg.com/news/articles/2023-11-20/critical-minerals-china-s-dominance-as-supplier-is-a-problem-for-the-west.

[25] CRS In Focus IF11735, *China's "One Belt, One Road" Initiative: Economic Issues*, by Karen M. Sutter, Andres B. Schwarzenberg, and Michael D. Sutherland.

[26] Rodrigo Castillo and Caitlin Purdy, *China's Role in Supplying Critical Minerals for the Global Energy Transition: What Could the Future Hold?*, Brookings Institution, Leveraging Transparency to Reduce Corruption project, July 2022, p. 6, https://www.brookings.edu/wp-content/uploads/2022/08/LTRC_ChinaSupplyChain.pdf.

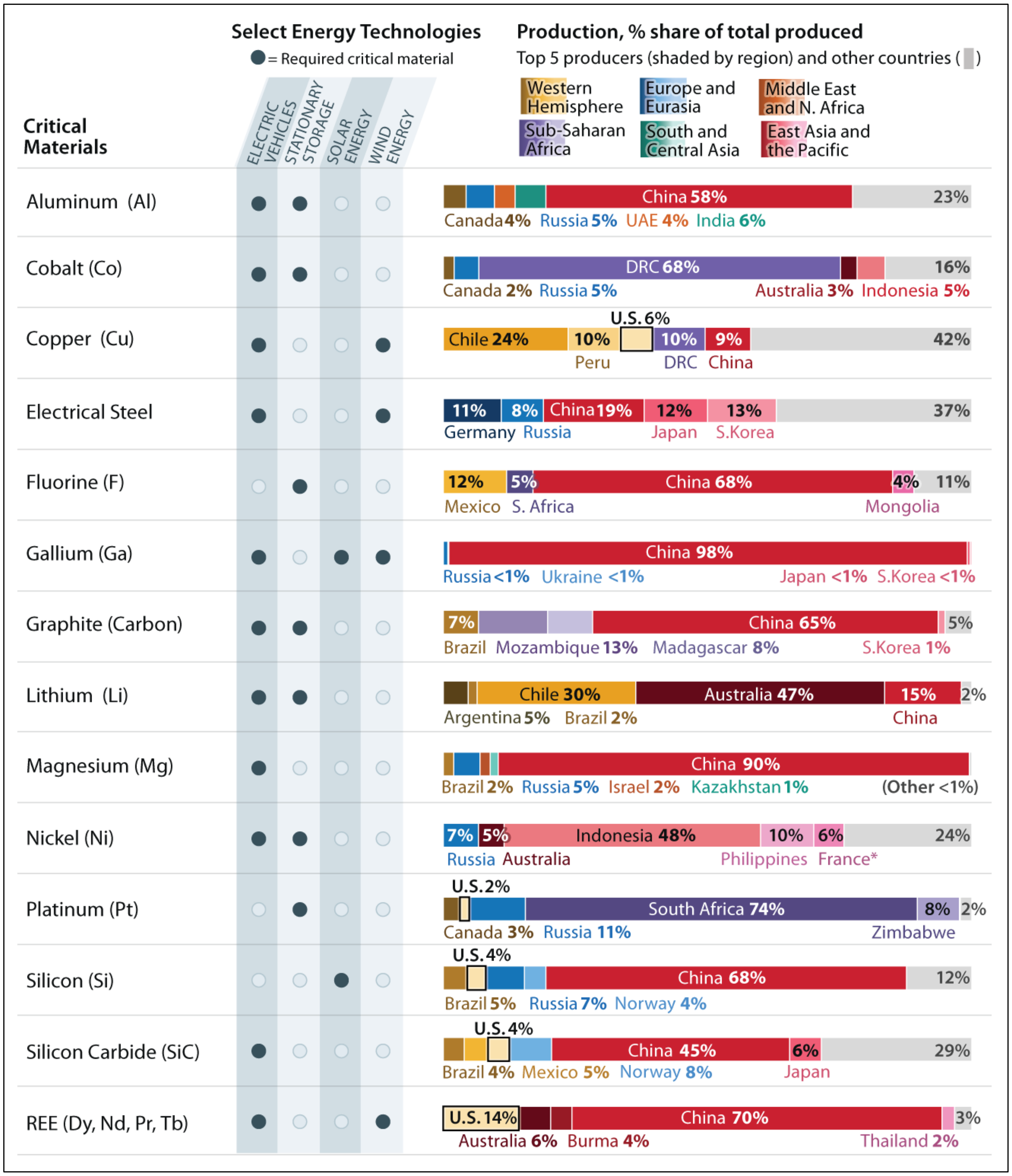
[27] J. Yeomans and F. Harter, "Who Owns the Earth? The Scramble for Minerals Turns Critical," *The Times*, May 1, 2022, https://www.thetimes.co.uk/article/who-ownsthe-earth-the-scramble-for-minerals-turnscritical-jbglsgm02. Copper shares correspond to estimates in International Energy Agency, *The Role of Critical Minerals in Clean Energy Transitions*, May 2021, https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions.

[28] U.S. Congress, Congressional-Executive Commission on China, *From Cobalt to Cars: How China Exploits Child and Forced Labor in the Congo*, hearing, 118th Cong., 1st sess., November 14, 2023, https://www.cecc.gov/events/hearings/from-cobalt-to-cars-how-china-exploits-child-and-forced-labor-in-the-congo#:~:text=80%25%20of%20the%20DRC's%20cobalt,battery%20makers%20around%20the%20world.

[29] Brian Harding and Kayly Ober, *Indonesia's Nickel Bounty Sows Discord, Enables Chinese Control*, U.S. Institute of Peace, Washington, DC, March 21, 2024, https://www.usip.org/publications/2024/03/indonesias-nickel-bounty-sows-discord-enables-chinese-control.

[30] Benchmark Minerals, *Infographic: China's Influence over Indonesian Nickel*, January 25, 2024, https://source.benchmarkminerals.com/article/infographic-chinas-influence-over-indonesian-nickel.

Figure 3. Critical Materials Production Across Selected Energy Technologies



Source: CRS using data from U.S. Geological Survey, *Mineral Commodity Summaries 2023*, January 31, 2023, https://doi.org/10.3133/mcs2023 and U.S. Department of Energy, *Critical Materials Assessment*, July 2023, https://www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf.

Notes: Production percentages are rounded and reflect 2022 production data. Production is in percent share of total produced for each material and is not an equivalent amount across materials. Graphite refers to natural graphite. REE = rare earth elements. The Department of Energy (DOE) has identified four REEs as critical materials: dysprosium (Dy), neodymium (Nd), praseodymium (Pr), and terbium (Tb). Nickel production attributed to France occurs in New Caledonia. UAE = United Arab Emirates. DRC = Democratic Republic of the Congo. For a comprehensive list of DOE's critical materials, see the section "Department of Energy and Critical Materials" above in this report.

Domestic Supply

The United States has minimal onshore critical mineral mining and manufacturing capability. The United States imports the vast majority of critical minerals used across sectors, including for energy technologies. The United States is reliant on imports for over 50% of consumption for 43 (of 50) critical minerals, and it has no domestic production for 14 of these.[31] Manufacturing and deployment of key energy technologies are susceptible to supply chain volatility from fluctuating prices, country export tariff policy changes, competing demand from other nations and industries, or other potential challenges.

The U.S. mining industry is governed by a series of three major mining laws: the General Mining Act of 1872, the Mineral Leasing Act of 1920, and the Materials Act of 1947.[32] Most of the critical minerals seen as necessary for energy transition fall under the jurisdiction of the General Mining Act of 1872.

The United States has some resources of key minerals (**Figure 4**); production of these minerals has not been widely developed for varied reasons. Mines such as the Jervois cobalt mine[33] in Idaho have broken ground and set up infrastructure, but have struggled to become commercially viable and maintain operations given market conditions.[34] Lithium resource development in Maine has reportedly faced opposition from local stakeholders.[35]

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[31] U.S. Department of Energy, "Developing a Domestic Supply of Critical Minerals and Materials," February 6, 2024, https://www.energy.gov/fecm/articles/developing-domestic-supply-critical-minerals-and-materials.

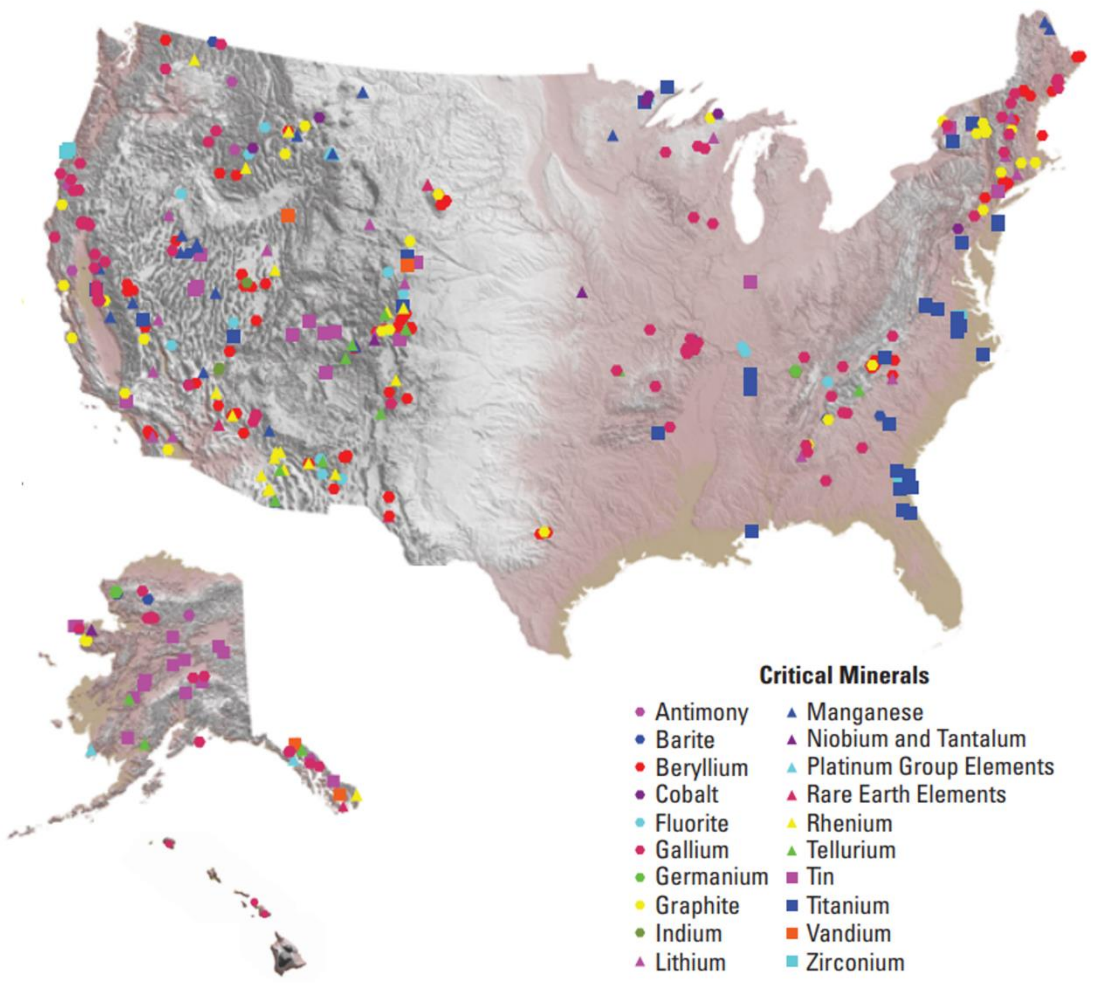
[32] The Mineral Leasing Act of 1920 separates "leasable minerals" such as natural gas, petroleum, and other hydrocarbons from the purview of the General Mining Act of 1872, while the Materials Act further specifies a set of separate regulations for materials such as sand and gravel. While some minerals may fall under the Mineral Leasing Act of 1920, the majority of critical minerals for the energy transition are regulated by the original General Mining Act of 1872.

[33] Jervois Idaho Cobalt Operations, "Overview," https://jervoisidahocobalt.com/idaho-cobalt-operations/.

[34] Stacey Vanek Smith and Eric Whitney, "Cobalt Is in Demand, So Why Did America's Only Cobalt Mine Close?," *National Public Radio*, December 14, 2023.

[35] Alana Semuels and Kate Cough, "Gem Hunters Found the Lithium America Needs. Maine Won't Let Them Dig It Up," *Time*, July 17, 2023, https://time.com/6294818/lithium-mining-us-maine/.

Figure 4. United States Critical Minerals Locations



Source: U.S. Geological Survey (USGS), "United States Critical Minerals Locations," 2017, https://www.usgs.gov/media/images/united-states-critical-minerals-locations.

Notes: This graphic uses data from 2017, which predates the Energy Act of 2020 and the current U.S. Geological Survey's 2022 Critical Minerals List. Some of the minerals discussed in this report are represented in this graphic.

Some stakeholders view the domestic mining industry as a source of damage to the environment and to the communities these mines are located in; others see mining as a source of employment and economic opportunities. The 1872 Mining Act does not itself contain specific environmental protection provisions regarding the mining of hardrock minerals on federal lands. Mines on federal lands must comply with other relevant federal statutes such as the National Environmental Policy Act (NEPA), the Clean Air Act, the Clean Water Act, and the Endangered Species Act. New mining processes may have reduced environmental impact in comparison with historical technologies, while improvements in mitigation and recovery procedures may reduce the long-term impact of mining on the environment and communities.[36]

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[36] Tsisilile Igogo, *America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition*, U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains," February 24, 2022, p. ix, (continued...)

The General Mining Act of 1872 and the Modern Critical Minerals Industry

The General Mining Act of 1872 (Mining Act) formed the bedrock of U.S. mining policy during westward expansion in the 19th century, and the law remains in effect to this day. Among other provisions, it allows parties to explore for and mine hardrock minerals—such as gold, silver, copper, iron, and lead—on federal lands without specific authorization from the federal government. Upon discovery of a deposit of designated materials, parties may then file a claim with the government and begin the process for approval and permitting of production.

The mining industry in the United States has changed since its inception, with the scale of modern operations potentially much larger than those of the 1800s. With these changes, new laws have been enacted to address subsets of mining and extraction on federal lands, including coal, oil, and gas extraction; gravel and sand materials sales; and reclamation of lands used for energy extraction. The core provisions of the Mining Act—which have remained generally unchanged since its enactment more than 150 years ago—continue to guide hardrock mineral exploration and production on federal lands.

The Mining Act established the "claim and patent" system. Under this system, certain federal lands are opened to the public and eligible parties are permitted to stake a "claim" for tracts of land in areas owned and controlled by the federal government upon discovery of a deposit of designated minerals. This process is also called "location." The Bureau of Land Management recognizes a few different types of claims that can be located on land under its purview. These include lode claims (claims on mineral lodes or deposits with well-defined boundaries) and placer claims (claims on mineral deposits that do not qualify as lode claims).[37]

Changes in the market for critical minerals and materials have increased interest in domestic minerals and mining development. One reason for this increased interest is higher demand for materials that are used in lower-carbon energy sources and technologies.[38] Some but not all of the critical minerals and materials seen as needed for an energy transition have domestic deposits that reportedly can be produced economically. Congressional interest in developing domestic mineral mining and processing or sourcing from allied or friendly nations has grown in part in response to these technological applications. Hardrock minerals such as lithium, cobalt, graphite, nickel, and manganese are all mineral inputs deemed "critical" for energy technologies by the U.S. Geological Survey or the Department of Energy.

Critical Mineral and Material Demand

Critical minerals are in demand for use in energy technologies and in other industries across the economy. The increase in demand for new technologies corresponds with an increase in demand for the raw materials and resources required for their construction and maintenance. Estimates conducted by organizations such as the International Energy Agency (IEA) forecast an increase in all renewable electricity technologies, including solar photovoltaic and wind energy sources (**Figure 5**). The IEA projects that by 2028 solar photovoltaic will account for 12.6% of global

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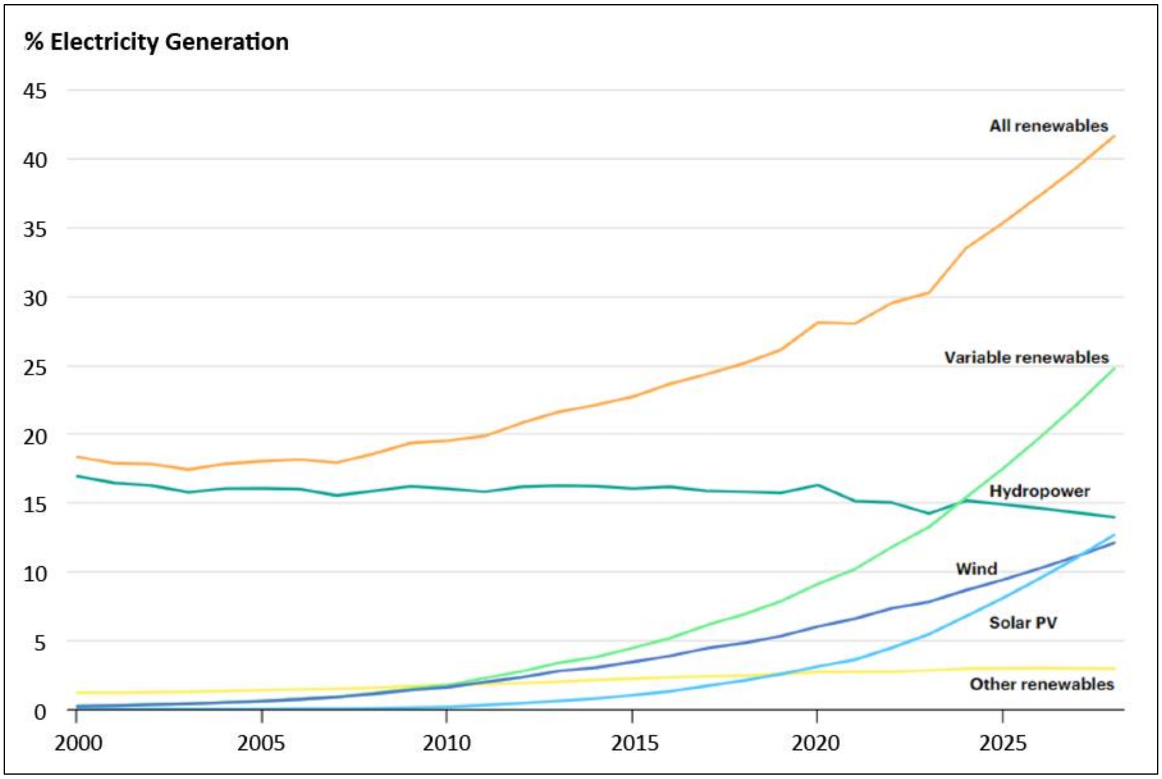
https://www.energy.gov/sites/default/files/2022-02/America%E2%80%99s%20Strategy%20to%20Secure%20the%20Supply%20Chain%20for%20a%20Robust%20Clean%20Energy%20Transition%20FINAL.docx_0.pdf.

[37] 43 C.F.R. §§3832.20–3832.22.

[38] DOE Assessment, p. 76.

electricity generation; wind will account for 12.1%;[39] and all renewable electricity sources combined will account for 41.6% of global electricity generation.[40]

Figure 5. Share of Renewable Electricity Generation by Technology, 2000-2028



Source: International Energy Agency (IEA), *Share of Renewable Electricity Generation by Technology, 2000-2028*, December 18, 2023, https://www.iea.org/data-and-statistics/charts/share-of-renewable-electricity-generation-by-technology-2000-2028, and IEA, Glossary, https://www.iea.org/glossary.

Note: All renewables = bioenergy, geothermal, hydropower, solar energy, wind energy, and ocean energy; Variable renewables = wind energy, solar energy, run-of-river hydropower, and ocean energy.

Solar Photovoltaic (PV) Energy

Solar photovoltaic (PV) electricity generation is one of the leading global renewable electricity generation technologies, and is expected to grow in the coming years (**Figure 5**).[41] In 2022, nearly 1,300 terawatt-hours (TWh) of global energy were generated by solar power,[42] and, according to the IEA, "Solar PV accounted for 4.5% of total global electricity generation, and it remains the third largest renewable electricity technology behind hydropower and wind."[43] Solar

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[39] International Energy Agency, "Share of Renewable Electricity Generation by Technology, 2000-2028," last updated December 18, 2023, https://www.iea.org/data-and-statistics/charts/share-of-renewable-electricity-generation-by-technology-2000-2028.

[40] International Energy Agency, *Renewables 2023*, January 2024, https://www.iea.org/reports/renewables-2023.

[41] Solar photovoltaics convert absorbed energy from sunlight into electricity. For more information on solar energy, see CRS Report R46196, *Solar Energy: Frequently Asked Questions*, coordinated by Ashley J. Lawson.

[42] International Energy Agency, "Solar PV Power Generation in the Net Zero Scenario, 2015-2030," last updated July 10, 2023, https://www.iea.org/data-and-statistics/charts/solar-pv-power-generation-in-the-net-zero-scenario-2015-2030.

[43] International Energy Agency, "Renewables: Solar PV," last updated July 11, 2023, https://www.iea.org/energy-

(continued...)

panels were first developed in the 19th century.[44] Further research and development, such as the innovation of semiconducting materials, has increased the efficiency of solar energy conversion.

Solar panels are increasingly used across the United States. In 2023, U.S. utility-scale solar electricity generation accounted for around 3.9% of total U.S. electricity generation.[45] The leading technology for current PV panels, crystalline silicon, provides lower production costs and easily available materials compared with alternative materials, making it the industry standard. As of 2021, 88% of the PV market was crystalline silicon, followed by thin-film PV at 9% and others at 3%. The minerals needed for solar panels, primarily crystalline silicon, are not scarce. According to the USGS, global reserves of silicon are ample relative to current demand.[46] According to the IEA, global demand for silicon for solar panels may grow to between 675,000 metric tons and 810,000 metric tons by 2040, based on different projection scenarios.[47]

China is the primary producer of silicon, and it produces silicon at a low cost. Although low-cost silicon has contributed to both the affordability and scalability of solar PV, it has also led to heightened competition for resources with countries of particular concern, such as China. This competition has affected domestic U.S.-based silicon solar cell manufacturers.[48] According to the USGS, the United States had an estimated 310,000 metric tons of silicon mine production in 2022.[49] By comparison, China had an estimated 6 million metric tons of annual silicon production in 2022.

Other technologies use resources such as copper, indium, gallium, and tellurium. These technologies make up a relatively small market share of the current solar PV industry, but changes to the market for solar PV may see decreased use of crystalline silicon and an increase of alternative thin-film PV compositions.

The critical minerals needed for solar panels include those involved in associated components. Inverters are power electronics components that convert the direct current (DC) generated by solar panels into alternating current (AC) needed for transmission and electric grid use.[50] Silicon-based inverters made up 76% of the inverters in 2022, followed by silicon carbide at 23.6% and gallium nitride at 0.4%.[51] Although these newer technologies may offer increased efficiency, the low cost, widespread infrastructure, and record of performance of crystalline silicon may indicate that silicon-based technologies will continue to lead the solar industry.

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system/renewables/solar-pv; International Energy Agency, *Renewables 2023*, January 2024, https://www.iea.org/reports/renewables-2023.

[44] Elizabeth Chu and D. Lawrence Tarazano, "A Brief History of Solar Panels," *Smithsonian Magazine*, https://www.smithsonianmag.com/sponsored/brief-history-solar-panels-180972006/.

[45] U.S. Energy Information Administration, "Frequently Asked Questions: What Is U.S. Electricity Generation by Energy Source?," last updated February 29, 2024, https://www.eia.gov/tools/faqs/faq.php?id=427&t=3.

[46] U.S. Geological Survey, *Mineral Commodity Summaries 2023*, January 31, 2023, https://doi.org/10.3133/mcs2023.

[47] International Energy Agency, "Demand for Silicon from Solar PV by Scenario, 2020-2040," last updated May 5, 2021, https://www.iea.org/data-and-statistics/charts/demand-for-silicon-from-solar-pv-by-scenario-2020-2040.

[48] U.S. Department of State, "Countries of Particular Concern, Special Watch List Countries, Entities of Particular Concern," last updated December 29, 2023, https://www.state.gov/countries-of-particular-concern-special-watch-list-countries-entities-of-particular-concern/#CountriesofParticularConcern.

[49] U.S. Geological Survey, *Mineral Commodity Summaries 2023*, January 31, 2023, https://doi.org/10.3133/mcs2023.

[50] *Direct current (DC) electricity* refers to the condition in which electric charge flows in one direction. *Alternating current (AC) electricity* refers to the condition in which the electric charge reverses direction periodically. Most electricity in the United States is generated and distributed in AC at a frequency of 60 Hertz (i.e., 60 cycles per second).

[51] DOE Assessment, pp. 34-35.

Wind Energy

Wind turbines generate a growing amount of electricity. In 2022, wind electricity generation reached more than 2,100 TWh globally, increasing by around 14% over the previous year, and accounted for 7.3% of global electricity generation.[52] Wind turbines require critical minerals and materials for their construction and maintenance. There are two main types of wind installations—onshore and offshore—and each has different costs and benefits. Onshore wind installations tend to require less infrastructure and have a more robust domestic supply chain than offshore wind installations; this can mean faster deployment, lower capital investment, and lower cost of maintenance, among other considerations. Offshore wind installations, which in 2022 represented 7% of the total global installed wind capacity, may benefit from faster and more consistent wind speeds and taller and larger installations, which result in more electricity generation than onshore wind systems on a per-turbine basis. Offshore wind installations have faced longer development timelines and more concerns over financing costs and supply chain constraints than onshore wind.[53] Domestically, the U.S. Energy Information Administration (EIA) projects that U.S. wind power electricity generation will grow from 430 TWh in 2023 to 476 TWh by 2025, an 11% increase.[54]

According to DOE, "average nameplate capacity per wind turbine reached 3 MW for newly installed turbines in the U.S. in 2021, and new 15-MW and 16-MW models of offshore wind turbines are nearing commercial availability."[55] The wiring for turbines uses large quantities of copper, requiring nearly 10 metric tons of copper per megawatt (MW) of capacity.[56] In addition, offshore turbines require copper for undersea cable wiring to deliver generated electricity onshore.[57]

Copper is a critical material as classified by DOE, but not a critical mineral as classified by the USGS. There has been bipartisan congressional support for adding copper to the critical minerals list, but USGS analysis determined that, although copper is an *essential* mineral, mitigating factors make copper accessible enough that it does not warrant *critical* mineral classification. In letters to Senator Kyrsten Sinema and Representative Bob Latta, USGS Director David Applegate wrote:

> While copper is clearly an essential mineral commodity, its supply chain vulnerabilities are mitigated by domestic capacity, trade with reliable partners, and significant secondary

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[52] International Energy Agency, "Renewables: Wind," last updated July 11, 2023, https://www.iea.org/energy-system/renewables/wind; International Energy Agency, "Share of Renewable Electricity Generation by Technology, 2000-2028," last updated December 18, 2023, https://www.iea.org/data-and-statistics/charts/share-of-renewable-electricity-generation-by-technology-2000-2028.

[53] For more information on offshore wind issues, see CRS Report R46970, *U.S. Offshore Wind Energy Development: Overview and Issues for the 118th Congress*, by Laura B. Comay and Corrie E. Clark.

[54] Energy Information Administration, "Solar and Wind to Lead Growth of U.S. Power Generation for the Next Two Years," *Today in Energy*, January 16, 2024, https://www.eia.gov/todayinenergy/detail.php?id=61242.

[55] DOE Assessment, p. 36.

[56] Ibid.

[57] U.S. Department of Energy, *Wind Energy: Supply Chain Deep Dive Assessment*, U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains," February 24, 2022, p. 18, https://www.energy.gov/sites/default/files/2022-02/Wind%20Supply%20Chain%20Report%20-%20Final%202.25.22.pdf. For more information on offshore wind energy, see CRS Report R46970, *U.S. Offshore Wind Energy Development: Overview and Issues for the 118th Congress*, by Laura B. Comay and Corrie E. Clark.

> capacity. As a result, the USGS does not believe that the available information on copper supply and demand justifies an out-of-cycle addition to the list at this time.[58]

Two key components of turbines, the generator and transformer, require large quantities and multiple grades of electrical steel.[59] Onshore wind turbines require 1.5 to 5.3 metric tons per MW capacity, while their offshore counterparts need 2.7 to 3.6 metric tons per MW. These figures account for all grades of electrical steel.[60] Materials such as electrical steel have established supply chains and manufacturing and recycling infrastructure due to their legacy uses across industries. However, electrical steel faces its own set of demand challenges.[61] Demand for electrical steel in the wind industry may face competition from other industries that require steel or specialty steel. Industry stakeholders have warned that demand for electrical steel outpaces supply and have asked the Biden Administration to "prioritize actions that will create a sustainable supply."[62] Currently, there is only one domestic producer of both grain- and non-grain-oriented electrical steels.[63]

Magnets in wind turbines also require critical minerals, primarily rare earth elements (REEs). Neodymium and praseodymium make up the main components of magnets used in wind turbines. Direct drive turbines require approximately 0.65 metric tons of permanent magnets per MW capacity, while hybrid drive turbines require approximately 0.2 metric tons of magnets per MW.[64] REEs have limited domestic supply and no large-scale domestic processing.[65]

Batteries

Batteries—such as those used in EVs and in stationary energy storage—are seen as a key component of increased wind and solar electricity generation. Although large amounts of electricity can be generated from wind and solar energy sources, the electricity must either be used immediately or stored for later use.[66] All forms of modern batteries use critical minerals for their energy storage; minerals used in batteries include lithium, cobalt, manganese, nickel, and

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[58] Letter from David Applegate, Dir., USGS, to Sen. Kyrsten Sinema, April 13, 2023, https://subscriber.politicopro.com/eenews/f/eenews/?id=00000188-4953-d998-ab8f-fb5f223b0000; Letter from David Applegate, Dir., USGS, to Rep. Bob Latta, May 1, 2023, https://subscriber.politicopro.com/eenews/f/eenews/?id=00000188-4952-d998-ab8f-fb5f8eb00000.

[59] Ibid.

[60] "Electrical steels are the most-often used materials among all soft magnetic materials. Electrical steel is classified into two types: non-oriented (NO) electrical steel and grain-oriented (GO) electrical steel. NO steel is widely used in motors and generators, in which the magnetization direction is rotated in the sheet plane. GO is mainly used as a core material of transformers, in which the magnetization is unidirectional." Yasuyuki Hayakawa, "Electrical Steels," *Encyclopedia of Materials: Metals and Alloys*, vol. 2 (Elsevier, 2022).

[61] DOE Assessment, pp. 78-79.

[62] Letter from Alliance for Automotive Innovation et al. to President Joseph R. Biden, Jr., May 22, 2023, https://www.electric.coop/wp-content/uploads/2023/05/5-22-23-Electrical-Steel-Summit-POTUS.pdf.

[63] Sonal Patel, "U.S. Power Sector Trade Groups Flag Critical Electrical Steel Crunch," *Power*, May 25, 2023, https://www.powermag.com/u-s-power-sector-trade-groups-flag-critical-electrical-steel-crunch/.

[64] Ibid., pp. 68-69.

[65] The United States has one REE mine, Mountain Pass Mine, which integrated processing of rare earth elements into its mining facility in 2023; see Mountain Pass Mine, "What Are Rare Earth Elements?," https://mpmaterials.com/what-we-do/.

[66] In the absence of sufficient energy storage, during times of low electricity demand wind and solar electricity production may be curtailed to protect the electrical grid. If electricity supply and demand differ by too much, electric power system components and customer equipment could be damaged, leading to system instability or potential failure. For more on variable renewable energy and electric reliability, see CRS Report R45764, *Maintaining Electric Reliability with Wind and Solar Sources: Background and Issues for Congress*, by Ashley J. Lawson.

graphite. New research developments have reduced the quantities of critical minerals required to construct a battery and diversified the types of minerals needed. Nevertheless, the demand for batteries likely will increase proportionally with demand for increased wind and solar generation, and the demand for critical minerals will increase with it (**Figure 3**). In addition, the rise of electric vehicles has led to increased demand for the critical mineral components that make up the smaller lithium-ion batteries that are currently the industry standard for EVs.

Electric Vehicle Batteries

Sales of electric vehicles have increased in recent years, both domestically and internationally. According to the IEA, EV's share of vehicle sales has more than tripled globally between 2020 and 2022. The share in 2022 was 14%, up from 9% in 2021 and less than 5% in 2020.[67] As the demand for EVs has grown, so has the demand for the mineral and material inputs for their construction. As of 2024, most EV manufacturing and sales occur outside of the United States, but domestic interest in EVs—from both consumers and manufacturers—has increased.[68]

For their construction, EVs require mineral and material components similar to those required for equivalent internal combustion engine vehicles; however, they diverge for key components.[69] Congressional interest has focused on access to or supply of critical minerals required for EV batteries. Less concern has been focused on EV motors, which generally require small quantities of rare earth elements.[70]

Lithium-ion batteries require lithium, cobalt, manganese, nickel, and graphite. Inside the battery, commonly called a *battery pack*, is an assembled component generally consisting of packaging and mounting structures, an electronic and electrical control system, and battery cells. Each cell contains two electrodes (a cathode and an anode), an electrolyte (a chemical solution that allows electricity to flow between the electrodes), and a separator (a physical barrier between the cathode and anode).[71] See **Figure 6**. The relatively high cost of electric vehicles is in part attributable to the batteries, and the cost of the batteries is closely tied to the price of the minerals and materials needed for their manufacture. In recent years, however, battery prices have declined

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[67] International Energy Agency, *Global EV Outlook 2023*, April 2023, https://www.iea.org/reports/global-ev-outlook-2023.

[68] For more on incentives for electric vehicles (EVs), see CRS Insight IN12003, *Inflation Reduction Act of 2022: Incentives for Clean Transportation*, by Melissa N. Diaz.

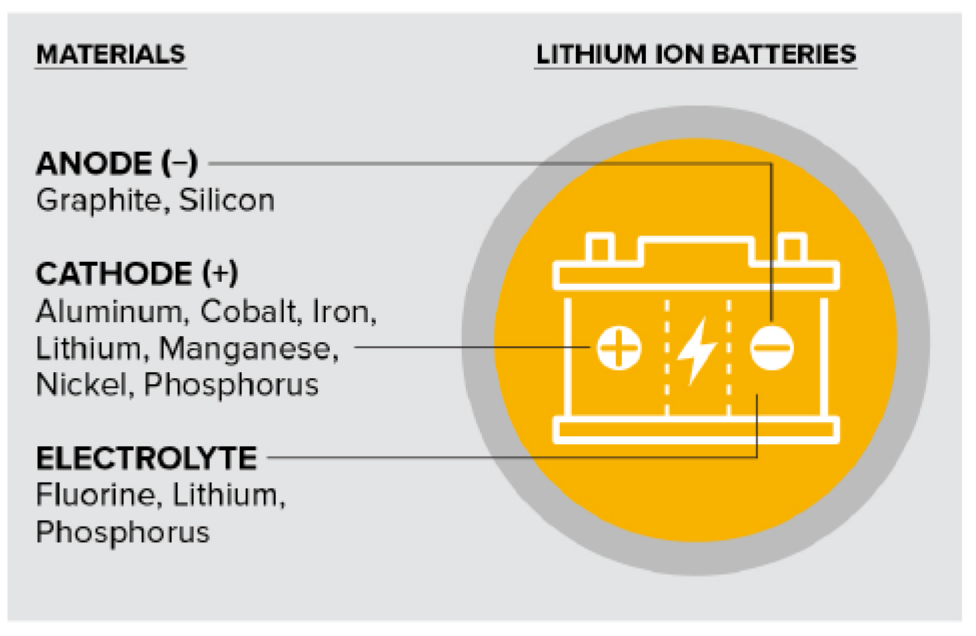
[69] The main physical differences between an EV and an internal combustion engine vehicle (ICEV) lie in the power train: the major components of an EV power train include a battery, a motor, and ancillary systems, while the major components of an ICEV power train include liquid fuel storage, combustion chambers (and cooling system), transmission, and an exhaust system (with emissions controls). For an overview of EVs and the differences between EVs and ICEVs, see CRS Report R46231, *Electric Vehicles: A Primer on Technology and Selected Policy Issues*, by Melissa N. Diaz. For an overview of potential environmental impacts of ICEVs and EVs, see CRS Report R46420, *Environmental Effects of Battery Electric and Internal Combustion Engine Vehicles*, by Richard K. Lattanzio and Corrie E. Clark.

[70] The average weight of a neodymium magnet in an EV is a little under three kilograms; neodymium is a rare earth element and a critical mineral (Eric Onstad, "China Frictions Steer Electric Automakers Away from Rare Earth Magnets," *Reuters*, July 19, 2021). Rare earth elements are a group of elements considered critical by the U.S. Geological Survey; for more information on rare earth elements, see CRS Report R46618, *An Overview of Rare Earth Elements and Related Issues for Congress*.

[71] The cathode is the positive battery terminal, and the anode is the negative battery terminal. During battery use, negatively charged electrons flow from the anode to the cathode; charging the battery reverses this flow and electrons flow from the cathode to the anode. For more information on lithium-ion batteries and their components, see Argonne National Laboratory (ANL), "Science 101: Batteries," https://www.anl.gov/science-101/batteries. For an earlier look at the domestic EV supply chain, see CRS Report R41709, *Battery Manufacturing for Hybrid and Electric Vehicles: Policy Issues*.

overall. DOE estimated in 2023 that the costs of battery packs had decreased by nearly 90% from 2008 to 2022,[72] while analysis by BloombergNEF showed that battery prices reached record lows at the end of 2023.[73]

Figure 6. Key Components of Lithium-Ion Batteries



Source: U.S. Department of Energy, *Critical Materials Assessment*, July 2023, p. 21, https://www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf.

Notes: Other battery components not shown.

The cathode side of the battery generally contains the more expensive minerals and chemical formulations. Different mineral formulations provide varying benefits, including longer lifespans, longer charge cycles, and decreased battery weights. Lithium is the predominant mineral in current EV batteries, with cobalt, manganese, and nickel making up different ratios of the cathode formula depending on the type of battery formulation. Each of these minerals is sourced from different regions and may be subject to varying refining processes. Lithium is found naturally in both hardrock and brine form, and it is currently produced in Australia (47%), Chile (30%), and China (15%), among others. Cobalt is primarily mined in the Democratic Republic of the Congo (68%), with Indonesia (5%) and Australia (3%) following. Indonesia holds 48% of global nickel production, followed by the Philippines (10%) and New Caledonia (6%). (See **Figure 3**.)[74] Battery electrolytes also require some critical minerals, including lithium salts, but this may vary across different battery formulations.

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[72] U.S. Department of Energy, Vehicle Technologies Office, "FOTW #1272: Electric Vehicle Battery Pack Costs in 2022 Are Nearly 90% Lower Than in 2008, According to DOE Estimates," *Transportation Fact of the Week* newsletter, January 9, 2023, https://www.energy.gov/eere/vehicles/articles/fotw-1272-january-9-2023-electric-vehicle-battery-pack-costs-2022-are-nearly.

[73] BloombergNEF, "Lithium-Ion Battery Pack Prices Hit Record Low of $139/kWh," November 26, 2023, https://about.bnef.com/blog/lithium-ion-battery-pack-prices-hit-record-low-of-139-kwh/.

[74] For more detailed analysis of specific battery minerals and chemistries, see CRS Report R47227, *Critical Minerals in Electric Vehicle Batteries*.

Graphite (carbon), a material with a wide range of applications across sectors, is typically used in the anode side of the battery and comes in two forms: natural and synthetic graphite.[75] Natural graphite is commonly grouped into three commercial commodities or categories: amorphous, crystalline (flake), and crystalline (lump or chip). Synthetic graphite can be manufactured for use in any of these commodity groups. Different battery formulations may use different forms or grades of graphite.[76] According to the USGS, no domestic mine production of graphite occurs in the United States, but five companies are exploring or developing mining projects for graphite.[77] In addition, two more spherical graphite plants are under construction, one in Kellyton, Alabama, and one in Vidalia, Louisiana, with expected production beginning in 2024.[78] Alternatives to graphite may also change the market for battery anode materials. Silicon anode batteries may be a viable alternative to traditional graphite, but they are susceptible to deforming due to the large volume change in silicon after repeated charge cycles.[79] Research into alternative battery chemistries and minerals is underway. Funding for research that focuses on alternatives for scarcer or more expensive minerals and materials has increased in recent years.

The tax credits for EVs enacted in the IRA may make EVs more affordable to consumers, but the tax credits require that eligible vehicles use critical minerals and materials sourced either domestically or from trade-partner nations.[80] In response to these sourcing requirements, the Biden Administration has pursued critical minerals agreements with trade partners. An example is the Critical Minerals Agreement signed by the United States and Japan.[81] That agreement

> memorializes the shared commitment of the United States and Japan with respect to the critical minerals sector to facilitate trade, promote fair competition and market-oriented conditions for trade in critical minerals, advance robust labor and environmental standards, and cooperate in efforts to ensure secure, transparent, sustainable, and equitable critical minerals supply chains.[82]

The Biden Administration is considering critical minerals agreements with other trade partners to ensure that minerals sourced from trade partners qualify for the IRA tax credit.[83]

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[75] Jinrui Zhang, Chao Liang, and Jennifer B. Dunn, "Graphite Flows in the U.S.: Insights into a Key Ingredient of Energy Transition," *Environmental Science and Technology*, vol. 57, no. 8 (February 15, 2023).

[76] Spherical graphite is made by processing flake graphite into round "potato-shaped" orbs and then coating them in conducive carbon. This process allows for increased rate capability and long-term stability. Laura Gottschalk et al., "Spherical Graphite Anodes: Influence of Particle Size Distribution and Multilayer Structuring in Lithium-Ion Battery Cells," *Batteries*, vol. 10, no. 40 (January 23, 2024).

[77] U.S. Geological Survey, *Mineral Commodity Summaries 2024*, January 31, 2024, https://doi.org/10.3133/mcs2024.

[78] Ibid.; Sally Helm, "A Graphite Processing Plant in Alabama Could Help the U.S. Rely Less on China," *All Things Considered*, National Public Radio, June 28, 2024, https://www.npr.org/2024/06/28/nx-s1-5018657/a-graphite-processing-plant-in-alabama-could-help-the-u-s-rely-less-on-china.

[79] Jun Lee et al., "Silicon Anode: A Perspective on Fast Charging Lithium-Ion Battery," *Inorganics*, April 24, 2023, https://doi.org/10.3390/inorganics11050182.

[80] For more information on these tax credits, see CRS In Focus IF12600, *Clean Vehicle Tax Credits*, by Donald J. Marples and Nicholas E. Buffie.

[81] For more information on the U.S.-Japan Critical Minerals Agreement, see CRS In Focus IF12517, *U.S.-Japan Critical Minerals Agreement*, by Kyla H. Kitamura.

[82] Office of the United States Trade Representative, "United States and Japan Sign Critical Minerals Agreement," press release, March 28, 2023, https://ustr.gov/about-us/policy-offices/press-office/press-releases/2023/march/united-states-and-japan-sign-critical-minerals-agreement.

[83] CRS Insight IN12145, *Proposed U.S.-EU Critical Minerals Agreement*, by Shayerah I. Akhtar and Andres B. Schwarzenberg; CRS In Focus IF11123, *U.S.-UK Trade Relations*, by Shayerah I. Akhtar.

Grid-Scale Energy Storage

As variable renewable energy sources such as wind and solar expand, so too will the need to store the generated energy. These energy sources generate electricity only while the wind is blowing or the sun is shining, and the electricity that is generated must be either transmitted for immediate use or stored. Grid-scale energy storage is one option to balance variable renewable energy sources, and deployment of grid-scale energy storage—especially batteries—is increasing.[84]

Grid-scale battery storage installations require both large quantities of minerals and a substantial geographic footprint. In particular, grid-scale storage's large size gives it an advantage over EV battery packs—the weight and size are not as significant a consideration when evaluating different chemical formulations. With grid-scale storage, because space is of less concern, battery chemistries other than lithium-ion—which is preferred in EVs due to the technology's high energy density—may be considered. While some of the minerals—such as lithium—were discussed above, other chemistries—such as vanadium redox flow,[85] zinc-bromine flow, and sodium-sulfur batteries—are unique to the stationary storage market.[86]

Redox flow batteries (RFBs) are seen as suited to stationary storage, as the critical minerals for energy storage are diluted in a liquid solution.[87] RFBs, if developed at scale, could decrease the amounts of critical minerals needed for energy storage.[88] The anolyte and catholyte, which take the place of typical anodes and cathodes, would use current battery mineral inputs such as lithium and cobalt, as well as additional inputs such as vanadium (diluted in water) as a mineral resource. The necessary amounts of expensive minerals such as lithium and cobalt would be reduced relative to conventional battery technology.[89] Projections from DOE indicate that flow battery market share may grow to 10%–15% if costs fall and the technology matures by 2040.[90] There are other methods of storing energy, including resources such as pumped hydropower, which has the largest energy storage capacity in the United States but requires specific topography.[91]

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[84] For background on balancing variable renewable energy sources, see CRS In Focus IF11257, *Variable Renewable Energy: An Introduction*, by Ashley J. Lawson.

[85] Zebo Huang et al., "Comprehensive Analysis of Critical Issues in All-Vanadium Redox Flow Battery," *ACS Sustainable Chemical Engineering*, vol. 10, no. 24 (June 3, 2022).

[86] For more information on this topic, see CRS Report R45980, *Electricity Storage: Applications, Issues, and Technologies*.

[87] Christian Doetsch and Jens Burfiend, "Vanadium Redox Flow Batteries," in *Storing Energy*, 2nd ed., ed. Trevor M. Letcher (Elsevier, 2022).

[88] American Chemical Society, "Are Vanadium Flow Batteries Worth the Hype?," *Reactions* science videos, November 15, 2023, https://www.acs.org/pressroom/reactions/library/are-vanadium-flow-batteries-worth-the-hype.html.

[89] Ibid.

[90] DOE Assessment, p. 64.

[91] U.S. Energy Information Administration, "Electricity Explained: Energy Storage for Electricity Generation," last updated August 28, 2023, https://www.eia.gov/energyexplained/electricity/energy-storage-for-electricity-generation.php.

Issues for Congress

Critical minerals and materials continue to be an important part of U.S. manufacturing and infrastructure and are of interest to Congress. Transitioning the energy sector toward low-carbon energy sources such as wind and solar energy likely requires large quantities of critical minerals and materials. Minerals and materials may face increased demand from lithium-ion batteries, solar panels, wind turbines, and other applications. Mineral and material resources are finite, distributed unevenly across borders, and may require several steps to mine, refine, and convert into a final product form. Critical minerals and materials policy for the energy transition is complex and could require a range of potential strategies to increase domestic production or recycling, build resilient supply chains, develop and produce new technologies, and strengthen national security.

Congress has held hearings on a wide variety of topics related to critical minerals and materials production, manufacture, R&D, and more. Some examples from the 118th Congress include, but are not limited to, the following hearings:

- *Hearing to Examine Opportunities to Counter the People's Republic of China's Control of Critical Mineral Supply Chains*,[92]
- *The Role of Federal Research in Establishing a Robust U.S. Supply Chain of Critical Minerals and Materials*,[93]
- *Examining the Methodology and Structure of the U.S. Geological Survey's Critical Minerals List*,[94] and
- *Securing America's Critical Materials Supply Chains and Economic Leadership*.[95]

A wide variety of bills have been introduced in the 118th Congress on multiple issues related to critical minerals and mining. Some examples include, but are not limited to, updating the General Mining Act of 1872 to reflect current mining demands on federal lands (H.R. 2925; S. 1742), creating consistency between the DOE Critical Materials and USGS Critical Minerals lists to include minerals such as copper that are necessary for energy transition technologies (H.R. 8446), and creating an intergovernmental critical minerals task force to coordinate between agencies to better facilitate critical mineral policies (S. 1871).

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[92] U.S. Congress, Senate Energy and Natural Resources Committee, *Full Committee Hearing to Examine Opportunities to Counter the People's Republic of China's Control of Critical Mineral Supply Chains*, hearings, 118th Cong., 2nd sess., September 28, 2023. According to the description, "The purpose of this hearing [was] to examine opportunities to counter the People's Republic of China's control of critical mineral supply chains through increased mining and processing in the United States as well as international engagement and trade."

[93] U.S. Congress, House Science, Space, and Technology Committee, *The Role of Federal Research in Establishing a Robust U.S. Supply Chain of Critical Minerals and Materials*, hearings, 118th Cong., 2nd sess., November 30, 2023.

[94] U.S. Congress, House Natural Resources Committee, *Examining the Methodology and Structure of the U.S. Geological Survey's Critical Minerals List*, hearings, 118th Cong., 2nd sess., September 13, 2023.

[95] U.S. Congress, House Energy and Commerce Committee, Environment, Manufacturing, and Critical Minerals, *Securing America's Critical Materials Supply Chains and Economic Leadership*, hearings, 118th Cong., 2nd sess., June 13, 2024.

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