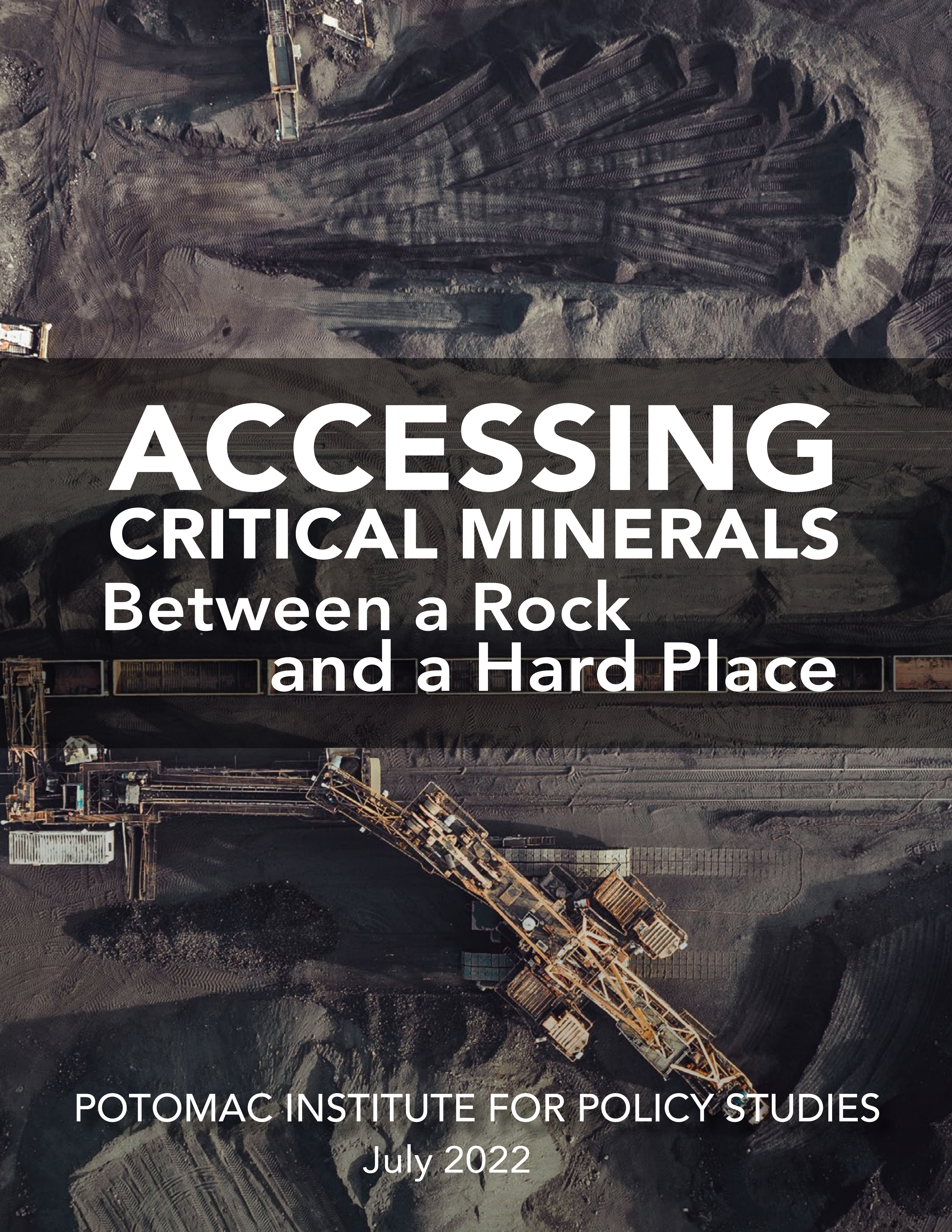

ACCESSING CRITICAL MINERALS

Between a Rock and a Hard Place

POTOMAC INSTITUTE FOR POLICY STUDIES

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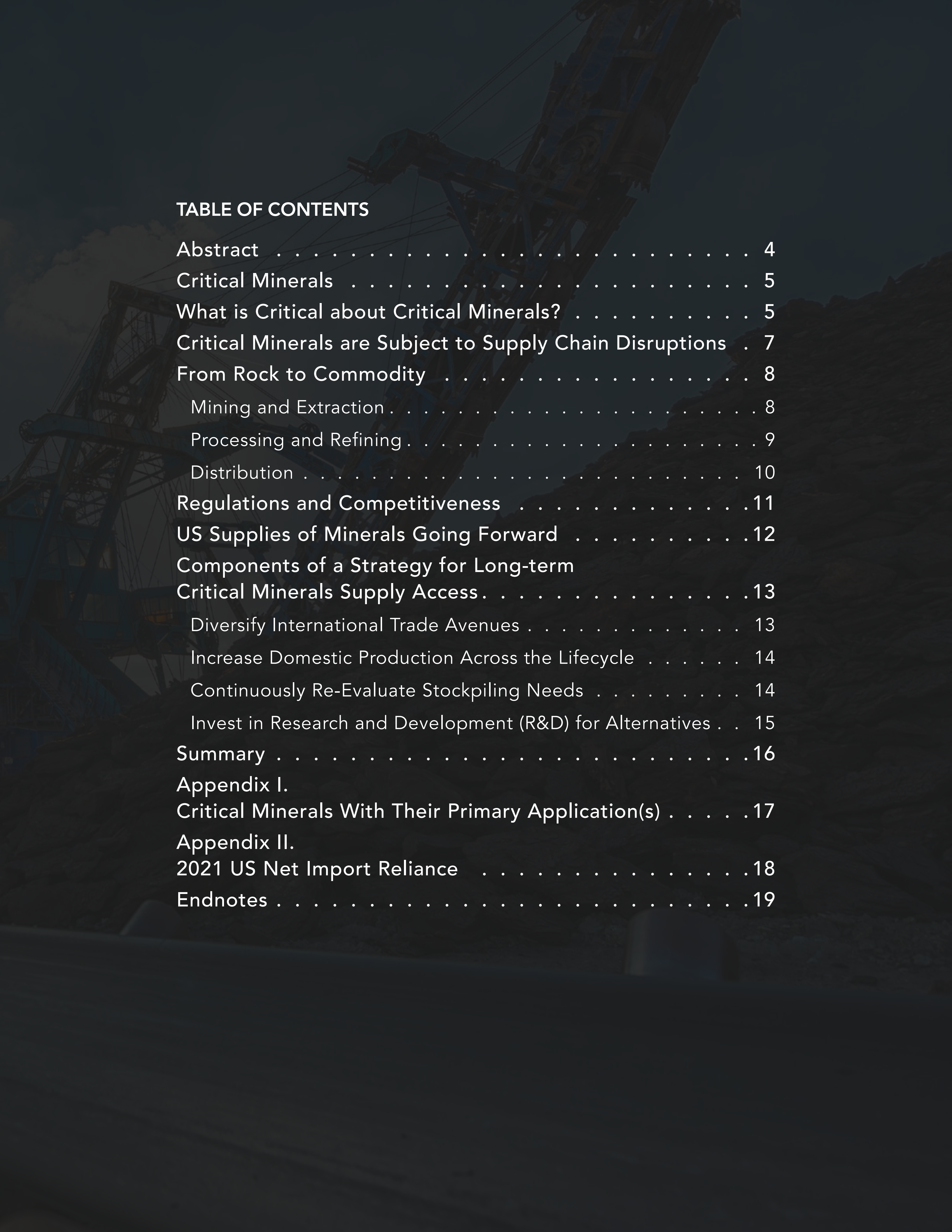
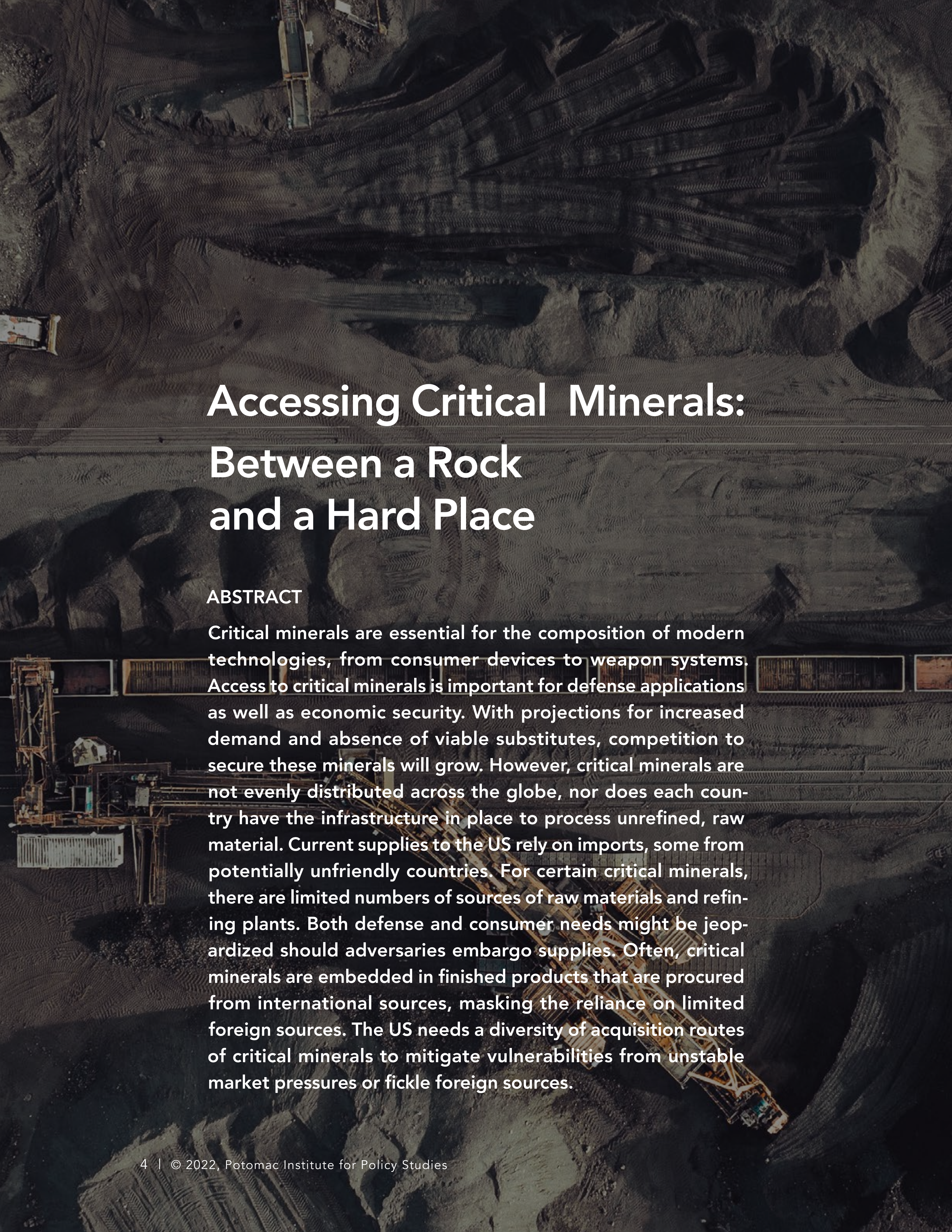


TABLE OF CONTENTS



Accessing Critical Minerals: Between a Rock and a Hard Place

ABSTRACT

Critical minerals are essential for the composition of modern technologies, from consumer devices to weapon systems. Access to critical minerals is important for defense applications as well as economic security. With projections for increased demand and absence of viable substitutes, competition to secure these minerals will grow. However, critical minerals are not evenly distributed across the globe, nor does each country have the infrastructure in place to process unrefined, raw material. Current supplies to the US rely on imports, some from potentially unfriendly countries. For certain critical minerals, there are limited numbers of sources of raw materials and refining plants. Both defense and consumer needs might be jeopardized should adversaries embargo supplies. Often, critical minerals are embedded in finished products that are procured from international sources, masking the reliance on limited foreign sources. The US needs a diversity of acquisition routes of critical minerals to mitigate vulnerabilities from unstable market pressures or fickle foreign sources.

CRITICAL MINERALS

Earth's natural resources provide vital components used in technologies that have become fundamental to the US economy and US national security. Critical minerals are found in consumer electronics, green technologies, military hardware, medical tools and devices, automobiles, satellites, and many other modern technologies. Future developments in clean energy, smart cities, transportation, mobile communications, and other sectors will result in increasing demand for critical minerals.

US Executive Order 13817 released in December 2017 defines critical minerals as mineral resources—metals and non-metals—that are of vital overall importance to the US economy or national security:

> "(i) a non-fuel mineral or mineral material essential to the economic and national security of the United States,
>
> (ii) the supply chain of which is vulnerable to disruption, and
>
> (iii) that serves an essential function in the manufacturing of a product, the absence of which would have significant consequences for our economy or our national security."[1]

The government has a published list of minerals deemed critical to the United States and plans to update it every three years[2] (see Appendix I). In 2018, the Department of the Interior published a list of 35 critical materials for the US.[3] The US Geological Survey (USGS) recently released an amended list that includes 50 minerals.[4] The new list includes individual rare earth elements and individual platinum group elements rather than listing them grouped together. It includes nickel and zinc, but removes helium, potash, rhenium, and strontium. Most critical minerals are simply referred to by their principal metallic element, but some have been given common names referencing specific molecular pairing from which they are most frequently extracted, such as barite (barium sulfate), fluorspar (calcium fluoride), and graphite (a specific form of carbon).

Many of these minerals do not occur in terrestrial deposits as their free element, but rather, as components within rocks. They must undergo chemical separation from other elements in the rocks (i.e., refinement). For example, the element neodymium (Nd) is often found in the ore minerals monazite ($(Nd,La,Ce)PO_4$) and bastnäsite. The element cobalt (Co) is often found in cobaltite (CoAsS), erythrite ($Co_3(AsO_4)_2 \cdot 8H_2O$), glaucodot ((Co,Fe)AsS), and skutterudite ($CoAs_3$), or is obtained as a byproduct of nickel and copper smelting, which accounts for the majority of global cobalt output.[5]

WHAT IS CRITICAL ABOUT CRITICAL MINERALS?

Debate continues over which minerals should be included on the government's list, especially as supplies and suppliers change. Additions and removals of minerals already occurred in the update of the 2022 list. Criticality is a judgment call.

However, the US is increasingly dependent on critical minerals. For example, the average smartphone contains approximately 75 different mineral-sourced materials (see Figure 1),[6] including those deemed critical. Electric vehicles are estimated to use six times the amount of critical minerals relative to conventional cars.[7] Demand for critical minerals is increasing, with a predicted five-fold increase in use by 2050.[8]

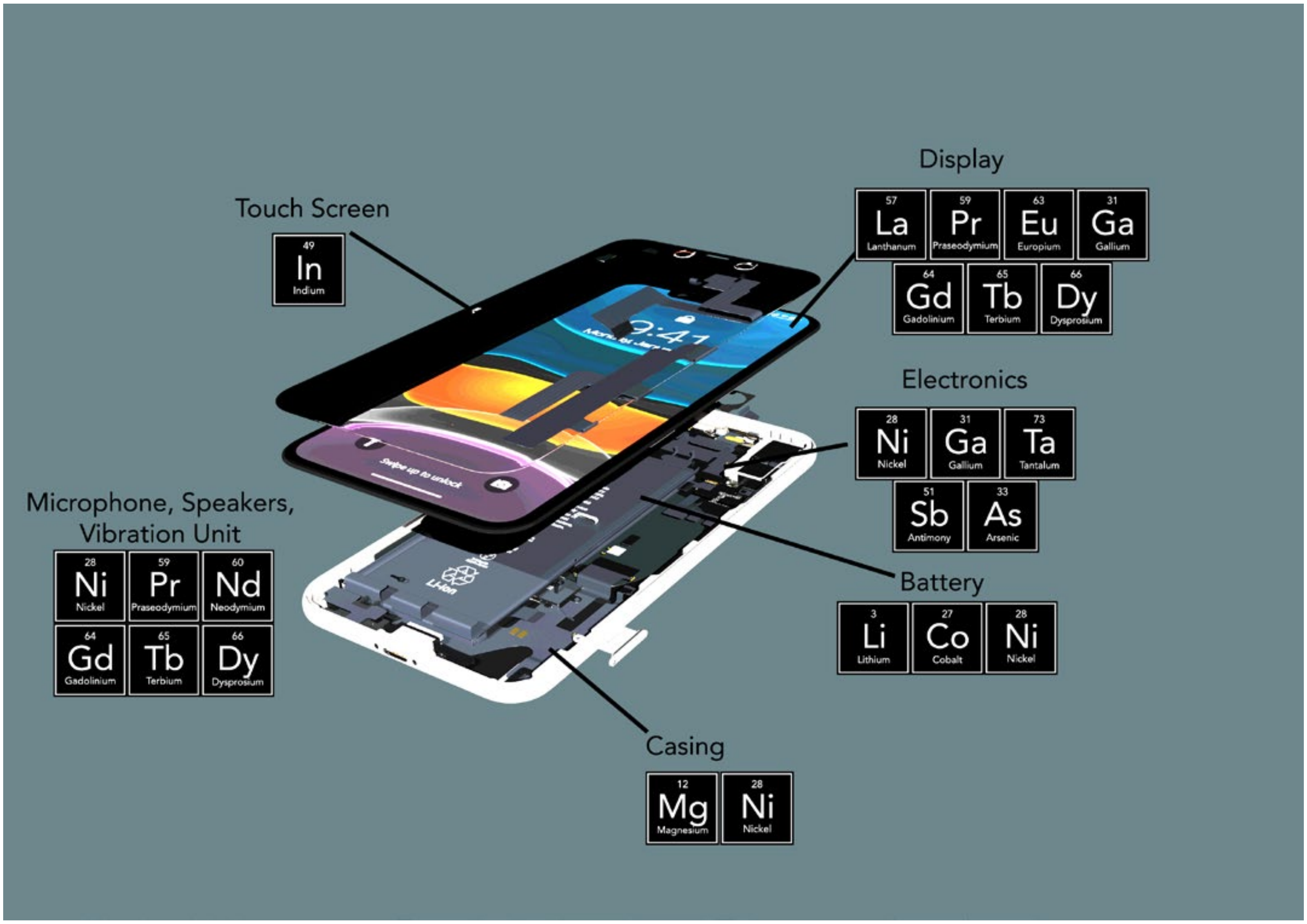


Figure 1. Critical Minerals within Various Smartphone Parts (Not all Inclusive) .[9]

Of the 50 designated critical minerals, the US is 100% reliant on imports for 14 minerals and more than 75% reliant on imports for an additional 10 (Appendix II details import reliance of critical minerals).

CRITICAL MINERALS ARE SUBJECT TO SUPPLY CHAIN DISRUPTIONS

Losing access to these critical minerals would expose the US to political, economic, and security risks.[10] Given the heavy US dependence on foreign sources and international supply chains for these minerals, the US is vulnerable to supply disruption.

Supply chains can be disrupted during periods of geopolitical turmoil, as in military or economic wars, trade embargoes, or nation-state punitive actions. During economic downturns, demand or supply may be impacted, causing imbalances that can have long-term aftereffects. Natural catastrophes, such as disease outbreaks or extreme weather events, can impact any point in the supply chain, perhaps causing reductions in available personnel or facilities. Competition for limited resources by industries that use critical minerals can result in distortions that are not based on pure economics, for example when industries owned by nation-states get preferential access to supplies. Finally, because the supply chains involve multiple geographical locations, shipping bottlenecks can also impact supplies.

Disruptions to trade can be used as a foreign policy tool. China has a stranglehold on many critical mineral supply lines. In 2010, China curtailed the shipment of rare earth elements (REEs) to Japan because of a maritime dispute.[11] In 2020, China similarly threatened to cut off REE supply to three US-based defense manufacturers,[12] endangering F-35 production, in response to a US defense deal with Taiwan. The Russian-Ukraine conflict in 2022 shined another spotlight on the ways that foreign policy decisions affect global supply chains. Russia accounts for about 40% of mined palladium production[13] and in the months following the initial conflict, the price of palladium increased by 80%.[14]

With growing demand and reliance on critical minerals,[15] not every user will be guaranteed access. The anticipated increase in market demand for certain materials, such as those used in lithium-ion batteries, and the uneven concentration of raw materials and processing capabilities across the globe could lead to competition among end-product manufacturers.[16]

Jessica K. Robertson / USGS

Peggy Greb, Agricultural Research Service, USDA

FROM ROCK TO COMMODITY

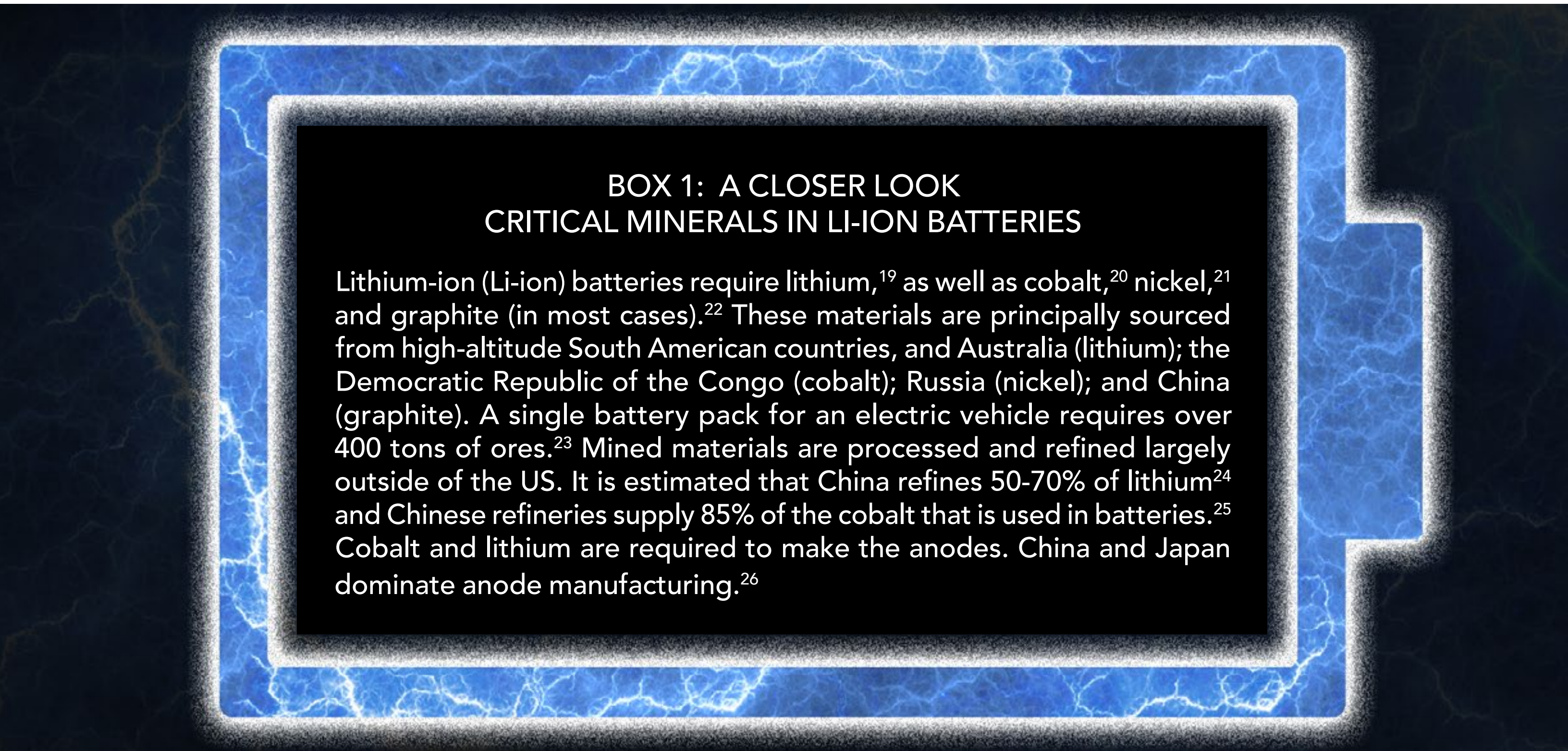
The source of minerals begins at a mine, or a collection of mines, located at points of geological concentration. After the rock, brine, or other material has been mined, the minerals must be extracted, separated, and processed. At various points, minerals are refined to increase purity, or to mix them in alloys or composites to achieve specific properties. Finally, they can be inserted into the myriad technologies they facilitate (see Figure 2).

Figure 2: Mineral Lifecycle

Mining and Extraction

Critical minerals are not uniformly dispersed geographically. There are but a few locations where each critical material is currently extracted. For example, South Africa and Zimbabwe produce 80% of the world's platinum, Australia and Chile produce 75% of the world's lithium, and the Democratic Republic of Congo (DRC) extracts 75% of the world's cobalt.[17]

Chinese companies have invested heavily in mines in many of these locations,[18] giving rise to concerns about lithium-ion battery supplies (see Box 1).



BOX 1: A CLOSER LOOK
CRITICAL MINERALS IN LI-ION BATTERIES

Lithium-ion (Li-ion) batteries require lithium,[19] as well as cobalt,[20] nickel,[21] and graphite (in most cases).[22] These materials are principally sourced from high-altitude South American countries, and Australia (lithium); the Democratic Republic of the Congo (cobalt); Russia (nickel); and China (graphite). A single battery pack for an electric vehicle requires over 400 tons of ores.[23] Mined materials are processed and refined largely outside of the US. It is estimated that China refines 50-70% of lithium[24] and Chinese refineries supply 85% of the cobalt that is used in batteries.[25] Cobalt and lithium are required to make the anodes. China and Japan dominate anode manufacturing.[26]

Critical minerals are often not easy to extract. Some are metals that are the main components in ore deposits, and others are minerals that are found in low concentrations and recovered as byproducts in the extraction of other metals. For instance, rare earth elements[27] tend to be found in low concentrations mixed in with other elements and minerals.[28] Separating elements often requires complex chemical processes, and results in waste materials that often contain toxic and/or radioactive byproducts.[29]

Processing and Refining

Extracted raw materials must be processed and refined to yield the usable form of critical minerals. Refining is not always done in locations near where the mining occurred. Countries' infrastructure to support both mining and refining may be different, whether for main-product minerals or byproducts. The US essentially does not have refining capacity for domestically mined nickel—and although copper is not currently on the critical minerals list, there are critical minerals that are byproducts of copper and often exported for processing.[30] While cobalt is a byproduct of operations at Lundin Mining's Eagle Mine in Michigan[31] (cobalt is mainly a byproduct of the processing of copper and nickel ores), it is not processed domestically.[32] China refines 87% of the cobalt is that is mined in the DRC,[33] a large source of cobalt worldwide. China also is the leader in tellurium production. Kennecott's Utah copper mine has recently started refining tellurium and will support U.S. manufacturing of photovoltaic solar panels.[34]

China's dominance in refining gives it large control over this step of the supply chain process, leaving many countries dependent on China. Minerals mined in the US have been exported to China for the processing and refining stages.[35] Similarly, 50-70% of all lithium extracted globally is refined in China.[36] Refined minerals are then purchased and used by manufacturing firms to make products.

Distribution

China's dominance in the downstream uses of distributed processed minerals has increased over the years. Before they are made into commodities that are distributed to end users, refined minerals are purchased by manufacturing firms so they can insert the minerals into the composition of products like permanent magnets, battery cells, printed circuit boards, microelectronics, and a host of other components. By 2014, China's downstream sectors accounted for about 70% of the demand of world's share of rare earth's—a rise from about 40% in 2004.[37] China led global REE production, with a domestic output of 168,000 metric tons (equivalent to about 60% of the global production) in 2021.[38] Along with building up several component manufacturers are located in China, domestically refined minerals, like REEs,[39] can offer the benefit of lower prices and fits with overall goals to expand the Chinese economy.

US critical mineral supply chain faces vulnerabilities in the limited domestic downstream activities. The US has limited domestic magnet manufacturing capability, especially for neodymium magnets, whereas China dominants this area with about a 92% share of the annual global magnet production.[40] To better ensure access for domestic civilian- and national security-related requirements, the US will need to build up domestic manufacturing industries for commodities that use these minerals.

How much we rely on minerals can be obscured when the focus shifts to tracking imports and exports of products like integrated circuits or cars. It can be challenging to track the imported or embedded reliance on critical minerals from other countries, especially within finished or semi-finished goods.[41]

Highsmith, Carol M., 1946

REGULATIONS AND COMPETITIVENESS

Could the US increase its mining and processing of minerals? Yes, but sound environmental concerns stand in the way.

Half of US critical mineral deposits are in cold-water trout and salmon habitats, and many are in protected public land areas.[42] Extraction of many critical minerals would impose large water requirements and risk groundwater contamination.[43] Improper mining could have dire consequences on wildlife preservations as well as water and air quality.

Some ores for REEs (and other critical minerals) contain radioactive byproducts, such as thorium and uranium.[44] These, and other, toxic byproducts must be chemically separated and sequestered. Reportedly, the production of one ton of processed rare earth metal can generate up to 2,000 tons of toxic waste.[45]

The mining permit process in the US averages 7 to 10 years. In contrast, countries considered to have similar environmental guidelines, like Australia and Canada, have typical permitting processes of 2 years.[46] Mining and refining operations require a large, trained workforce, [47] but US labor protections make it difficult for American companies to compete globally (see Box 2 on the history of financial challenges confronting the Mountain Pass mine in California). Similarly, the Albemarle lithium mine in North Carolina[48] shut down in 2021 because the then-depressed global lithium prices could not balance the regulatory and operating costs.

BOX 2. MOUNTAIN PASS MINE

The history of the mining operation at Mountain Pass is illustrative of the problems facing the US mining industry. In the mid-1900s, the US dominated much of the global market for REEs and related materials. From the mid-’60s to the ’80s, Molycorp’s Mountain Pass (MP) mine in California was considered the world’s top source of rare earth oxides.[49] But environmental and financial challenges at Mountain Pass led the mine to close in 2002. Molycorp reopened MP in 2012, but China’s increased production greatly outpaced demand, driving down prices and forcing Molycorp into bankruptcy in 2015. In 2017, MP Materials Corp purchased the mine and by 2020, Mountain Pass supplied almost 16% of the world’s REE production. In October 2020, Shenghe (a Chinese company) was the sole buyer of the mine’s rare earth concentrates, which it sent on to China for processing.[50] The mine went public in 2021, and the Nuclear Regulatory Commission authorized the mining license to be transferred; Shenghe has about 8% ownership of MP Materials, now.[51] The mine continues to face hurdles and investing complexities.[52] In February 2022, the US Department of Defense (DoD) announced it would be investing just over $100 million to enhance America’s rare earth supply chain resiliency, including $35 million to MP Materials to separate and process heavy REEs at the Mountain Pass facility in California.

Bradley Van-Gosen/U.S. Geological Survey

US SUPPLIES OF MINERALS GOING FORWARD

In economic supply-and-demand, when supply is limited, we typically see prices rise. For critical minerals, sudden price increases can be excessively disruptive.

The world has long dealt with limited supplies of oil and gas and has contended with supply disruptions. Other supply chain issues, particularly access to semiconductor chips, have become prominent recently and highlight overlapping concerns with the supply of critical minerals. Supplies of critical minerals will likely not meet demand in the future. Each mineral is likely to necessitate a different strategy to ensure a stable and reliable supply.

Executive Order 14017 in February 2021 launched a 100-day review and strategy development process to address vulnerabilities in our supply chains of key products, including critical minerals and materials with the goal of securing the US's critical supply chains.[53] In April 2022, the Defense Production (DPA) was invoked to boost critical mineral production domestically. The National Strategic and Critical Minerals Production Act,[54] intended to change rules and regulations surrounding mining permitting in the US, has been introduced in various forms several times in Congress since 2012, but has yet to pass. Hearings regarding critical minerals continue on the Hill.

A strategy to stabilize long-term critical minerals supply is needed. Legislations, executive orders, and other literature such as reports by the Government Accountability Office[55] and the Wilson Center "mosaic" approach recommending 13 private sector, government, and international actions,[56] have stressed the significance of supply loss and needed action.

Here, we lay out four components of such a strategy for critical mineral access:

Diversify International Trade Avenues

Increase Domestic Production Across the Lifecycle

Continuously Re-Evaluate Domestic Needs

Invest in Research and Development (R&D) for Alternatives

Each is discussed briefly in the next section.

COMPONENTS OF A STRATEGY FOR LONG-TERM CRITICAL MINERALS SUPPLY ACCESS

Diversify International Trade Avenues

Reliance on a single supplier is unstable. Having multiple competing supply chains may decrease access risks, as is typical with other commodities. Strategic partnerships through prior agreements can help ensure reliability.

Japan's experience in 2010 offers partnership lessons. China had raised duties on certain critical minerals, including REEs, and was accused of effectively banning exports of REEs to Japan.[57] Japan then pursued alternatives to reduce its dependency on China (see Box 3 on some of the history and actions taken following the Japan case in 2010).

Proactively finding multiple supply pathways is often feasible. "Friendly-shoring" efforts would deepen ties with trusted foreign partners to address similar supply chain trade concerns.[58] For example, uranium is produced and exported from Canada[59] and lithium by Pilbara Minerals in Australia.[60] Japan has made headway in processing and refining REEs.[61] Arsenic is imported to the US from Morocco and Belgium (in addition to China). There are proposals to create a "Five Eyes for critical minerals,"[62] or to leverage the United States-Mexico-Canada Agreement (USMCA)[63] to establish a North American mining center based on mineral reserves.

Even with multiple supply channels, suppliers must contend with price differentials and potential dumping practices by competitors. Mountain Pass mine, discussed earlier, went bankrupt in part due to its inability to compete with lower prices from China.[64] For strategic materials, it may be necessary to pay a premium to ensure supply stability.

Box 3: Japan's Rare Earth Elements Lessons

Following a supply disruption of REEs from China, Japan started investing in Lynas, an Australian rare earths mining company and now the largest REE producer outside China. Japan extended loans, including a 10-year loan extension in 2019, for expansion plans and to move a processing plant in Malaysia to Western Australia.[65] Japan has thus decreased its import reliance on China for rare earths from 90% to 58% in less than 10 years.[66] The US currently imports 78% of its REE needs from China (and 6% from Estonia, 5% Malaysia, and 4% Japan).[67] The World Trade Organization has criticized China's export restrictions on rare earths.[68]

Peggy Greb, Agricultural Research Service, USDA

Increase Domestic Production Across the Lifecycle

Establishing US domestic vertical supply chains for certain critical minerals and their applications may be highly desirable, but will not always be feasible. Hurdles include scarce natural reserves, environmental factors, low availability of skilled labor, insufficient market demand, and other economic constraints. Industrial policies focused on specific strategic needs and subsidized domestic production can quickly become prohibitively expensive. Government initiatives, like utilization of DPA, reforming of permitting processes to be faster, and other incentives and grants, will be needed to expand all parts of the supply chain elements—not just mining.

For certain specific minerals, it may be advantageous to invest in domestic refining capacity. Currently, many of the REEs that the US extracts from mines are shipped overseas for processing.[69] By processing locally sourced minerals domestically, international shipping can be eliminated, and domestic manufacturers can source refined minerals locally. Environmental and workforce concerns remain, but domestic solutions are available.

Furthermore, focus on midstream and downstream production, including expanding domestic manufacturing capabilities, can support supply chain robustness. Currently, China manufactures over 80% of lithium-ion battery cells.[70] China, Japan, and Germany dominate the production of high-performance neodymium-iron-boron (NdFeB) magnets.[71] Increasing US domestic manufacturing capacity could shift part of the supply chain concentration to us which would offer a more reliable access route and could complement foreign supplies.

Another approach to increasing US domestic supplies is to increase recapture by recycling. Currently, only 1-5% of REEs are recycled from end-products. Similarly, less than 5% of lithium-ion batteries are recycled in the US and EU.[72] For years, the US would ship large portions of waste material to Asia. The US Department of Energy has launched the "ReCell Center" to perform R&D to discover efficient methods for Li-ion battery recycling, with the goal of reducing the cost of batteries for electric vehicles. The commercial sector has also begun developing recycling capabilities to recover neodymium and dysprosium from electronics waste.[73]

Continuously Re-Evaluate Domestic Needs

The designation of what constitutes a critical mineral depends on current technology, supply, and demand. The list has been updated once and will need continual updating if it is to remain relevant and useful. The import dependency provided in the critical minerals list needs to better account for direct demand caused by imports of minerals embedded in finished or semi-finished products. This is especially noticeable between defense versus civilian needs, as exemplified with NdFeB magnets. It is reported that two-thirds of DoD's use of NdFeB magnets are direct imports, while 60% of civilian use of these magnets is embedded in the orders of other finished goods.[74] Foreign dependency and its impact on the US civilian economy is not captured as easily as the direct demands.

For minerals deemed critical, stockpiling is another approach to provide access contingency for select short-term needs. The DoD stockpiles critical minerals for national security purposes under the National Defense Stockpile as well as some minerals for clean energy technologies per a memorandum of agreement (MOA) with DoE.[75] Stockpiling has a long history in the US, from the Strategic and Critical Materials Stock Piling Act of 1939, to others in subsequent years such as the Strategic National Stockpile (mostly medical equipment), the Strategic Petroleum Reserve, and the National Defense Stockpile.[76] The latter, maintained by the Defense Logistics Agency,[77] contains about a billion dollars' worth of commodities.[78]

Legislation introduced in 2022 would create a strategic reserve of REEs and restrict defense industry purchases of REEs from China to end US reliance on Chinese supplies of REEs by 2026.[79] A recent interagency agreement formalized a partnership between US agencies to increase stockpiling of minerals and other materials for clean energy and national security needs.[80] The agreement includes considerations for REEs, cobalt, and lithium.[81] Reserve material plans should consider supply amounts, duration, and also, in some cases, the domestic options for manufacturing and integration into end-products.

Of course, stockpiling is useful in acute emergencies, but does not solve a continuing, long-term supply restriction. Current stockpiling lists focus more on defense needs rather than the civilian economy needs. Invocation of the DPA in peacetime, another way to address short-term needs, may inadvertently divert civilian supplies to other uses, causing market distortions. Stockpiles are thus of limited value except in dire circumstances.

Invest in Research and Development (R&D) for Alternatives

Research and development activities may uncover comparable or improved capabilities separate from today's processes or materials. Research might lead to better and more efficient end-products that make use of components with more accessible supplies. Alternative materials and advances in mining, processing, and recycling can relieve pressure on the current critical minerals supply chains.

Research in the field of materials science has explored substitute materials for neodymium[82] in wind turbines and magnets.[83] Advanced Research Projects Agency–Energy (ARPA-E) sponsored a "Rare Earth Alternatives in Critical Materials" (REACT) project to study replacements for REEs.[84] Other research efforts are exploring practical superconducting materials.[85] Research involves risk, but payoffs can be large.

Research might lead to improved extraction and refinement methods to obtain minerals. The development of new extractive techniques could shift the economic balance of mineral deposits previously deemed incapable of delivering a positive return. Offshore deep-sea mining might deliver new supplies of minerals, if additional policy issues can be overcome such as debates over UN treaty ratification and mining regulations.[86] Some believe asteroid mining may also provide accessible reserves of critical minerals if costs can be reduced enough. The Marshallton Research Laboratories is continuing a research project on new methods for chemical separation of REEs.[87]

SUMMARY

Critical minerals are essential for the composition of many consumer devices and defense applications. Demand is expected to rapidly increase in the upcoming years, but it is unclear if supplies will be available to all. US defense and commercial sectors will be negatively impacted if access to needed material becomes limited. The "critical mineral" designation already signals that there may be a supply chain vulnerability of these materials due to reliance on imports.

To mitigate risk, we need to address the stability of supplies. Supply chains encompass mining, processing, refining, and manufacturing. We have discussed approaches to increasing access, namely:

- Diverse International Trade Avenues
- Increase Domestic Production Across the Lifecycle
- Continuously Re-Evaluate Domestic Needs
- Invest in Research and Development (R&D) for Alternatives

Ultimately, a diverse range of policies, both for supplies and alternatives, leads to the most robust secure access to critical minerals.

APPENDIX I.
CRITICAL MINERALS WITH THEIR PRIMARY APPLICATION(S)

MINERAL	PRIMARY APPLICATIONS
Aluminum (Al)	Almost every sector
Antimony (Sb)	Lead-acid batteries and flame retardants
Arsenic (As)	Semi-conductors
Barite (Barium sulfite)	Hydrocarbon production
Beryllium (Be)	Alloying agent in aerospace and defense industries
Bismuth (Bi)	Medical and atomic research
Cerium (Ce)	Catalytic converters, ceramics, glass, metallurgy, and polishing agents
Cesium (Cs)	R&D
Chromium (Cr)	Stainless steels and other alloys
Cobalt (Co)	Rechargeable batteries and superalloys
Dysprosium (Dy)	Permanent magnets, data storage devices, and lasers
Erbium (Er)	Fiber optics, optical amplifiers, lasers, and glass colorants
Europium (Eu)	Lighting phosphors and nuclear control rods
Fluorspar (Calcium fluoride)	Manufacturing of aluminum, cement, steel, gasoline, and fluorine chemicals
Gadolinium (Gd)	Medical imaging, permanent magnets, and steelmaking
Gallium (Ga)	Integrated circuits and optical devices (e.g., LEDs)
Germanium (Ge)	Fiber optics and night vision technologies
Graphite (Mineral form of carbon)	Lubricants, batteries, and fuel cells
Hafnium (Hf)	Nuclear control rods, alloys, and high-temperature ceramics
Holmium (Ho)	Permanent magnets, nuclear control rods, and lasers
Indium (In)	Liquid crystal display technologies
Iridium (Ir)	Coating for anodes in electrochemical processes and chemical catalyst
Lanthanum (La)	Helps produces catalysts, ceramics glass, polishing compounds, metallurgy, and batteries
Lithium (Li)	Rechargeable batteries
Lutetium (Lu)	Scintillators for medical imaging, electronics, and cancer therapies
Magnesium (Mg)	Alloys and for reducing metals
Magnesium (Mg)	Alloys and for reducing metals
Manganese (Mn)	Steelmaking and batteries
Neodymium (Nd)	Permanent magnets, rubber catalysts, medical and industrial lasers
Nickel (Ni)	Helps produce stainless steel, superalloys, and rechargeable batteries
Niobium (Nb)	Steel and superalloys
Palladium (Pd)	Catalytic converters and as a catalyst agent
Platinum (Pt)	Catalytic converters
Praseodymium (Pr)	Permanent magnets, batteries, aerospace alloys, ceramics, and colorants
Rhodium (Rh)	Catalytic converters, electronic components, and as catalysts
Rubidium (Rb)	R&D in electronics
Ruthenium (Ru)	Catalysts, as well as electrical contacts and chip resistors in computers
Samarium (Sm)	Permanent magnets, absorber in nuclear reactors, and in cancer treatments
Scandium (Sc)	Alloys, ceramics, and fuel cells
Tantalum (Ta)	Electronic components (mostly capacitors and in superalloys)
Tellurium (Te)	Solar cells, thermoelectric devices, and alloying additive
Terbium (Tb)	Permanent magnets, fiber optics, lasers, and solid-states devices
Thulium (Tm)	Various metal alloys and lasers
Tin (Sn)	Protective coatings and alloys for steel
Titanium (Ti)	White pigment and metal alloys
Tungsten (W)	Wear-resistant metals
Vanadium (V)	Alloying agent for iron and steel
Ytterbium (Yb)	Catalysts, scintillometers, lasers, and metallurgy
Yttrium (Y)	Ceramic, catalysts, lasers, metallurgy, and phosphors
Zinc (Zn)	Metallurgy to produce galvanized steel
Zirconium (Zr)	High-temperature ceramics and corrosion-resistant alloys

(Adapted from the US Geological Survey 2022 List of Critical Minerals)[88]

APPENDIX II.
2021 US NET IMPORT RELIANCE*

COMMODITY	NET IMPORT RELIANCE (%)**	MAJOR IMPORT SOURCES (2017-20)
Arsenic	100	China, Morocco, Belgium
Cesium	100	Germany, China
Fluorspar	100	Mexico, Vietnam, South Africa, Canada
Gallium	100	China, UK, Germany, Ukraine
Graphite	100	China, Mexico, Canada, India
Indium	100	China, Canada, Republic of Korea, France
Manganese	100	Gabon, South Africa Australia, Georgia
Niobium	100	Brazil, Canada
Rubidium	100	Germany
Scandium	100	Europe, China, Japan, Russia
Strontium	100	Mexico, Germany, China
Tantalum	100	China, Germany, Australia, Indonesia
Vanadium	100	Canada, China, Brazil, South Africa
Tellurium	>95	Canada, Germany, China, Philippines
Potash	93	Canada, Russia, Belarus
REEs	>90	China, Estonia, Malaysia, Japan
Titanium	>90	Japan, Kazakhstan, Ukraine
Bismuth	90	China, Republic of Korea, Mexico, Belgium
Antimony	84	China, Belgium, India
Chromium	80	South Africa, Kazakhstan, Russia, Mexico
Tin	78	Indonesia, Peru, Malaysia, Bolivia
Cobalt	76	Norway, Canada, Japan, Finland
Zinc	76	Canada, Mexico, Peru, Spain
Barite	>75	China, India, Morocco, Mexico
Rhenium	72	Chile, Canada, Kazakhstan, Japan
Platinum	70	South Africa, Germany, Switzerland, Italy
Magnesium Compounds	55	China, Brazil, Israel, Canada
Germanium	>50	China, Belgium, Germany, Russia
Tungsten	>50	China, Bolivia, Germany, Canada
Nickel	48	Canada, Norway, Finland, Australia
Aluminum	44	Canada, UAE, Russia, China
Lithium	>25	Argentina, Chile, China, Russia
Zirconium	<25	South Africa, Senegal, Australia, Russia

*For some mineral commodities (hafnium), not enough data is available to determine the exact percentage of import reliance. For others (beryllium) the US is a net exporter of less than 20% net import reliant.[89]

** Net import reliance as percentage of apparent consumption.

ENDNOTES

1 "A Federal Strategy To Ensure Secure and Reliable Supplies of Critical Minerals." Executive Order 13817, 20 December 2017. https://www.federalregister.gov/documents/2017/12/26/2017-27899/a-federal-strategy-to-ensure-secure-and-reliable-supplies-of-critical-minerals.

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