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Revitalizing America's Critical Mineral Industry: Fair Trade, Economic Security, and Community Resilience

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About the Roosevelt Project

The Roosevelt Project takes an interdisciplinary approach to understanding and managing the challenges of transitioning toward a deeply decarbonized U.S. economy, aiming to minimize worker and community dislocation while enabling at-risk regions to capture new opportunities for growth. Phase One developed the project's analytical foundation through cross-cutting studies on workforce transitions, community resilience, and policy design for a low-carbon economy. Phase Two applied this framework to four regional case studies—Southwest Pennsylvania, the Industrial Heartland, the Gulf Coast, and New Mexico—conducted with local partners to assess how industrial legacies, labor markets, and policy environments shape equitable decarbonization. Phase Three extends this work by examining U.S. industrial policy frameworks for the energy transition through three national case studies on the electric grid, decarbonized steel, and metals and mining, addressing how to expand transmission equitably, decarbonize heavy industry, and secure critical minerals supply chains. The project, initiated by former U.S. Energy Secretary Ernest J. Moniz, engages faculty and researchers across MIT and Harvard in economics, engineering, sociology, urban studies and planning, and political science.

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ROOSEVELT PROJECT REVITALIZING AMERICA'S CRITICAL MINERAL INDUSTRY: FAIR TRADE, ECONOMIC SECURITY, AND COMMUNITY RESILIENCE

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List of Abbreviations

AI	Artificial Intelligence
AMD	Acid Mine Drainage
APS	Announced Pledges Scenario
ARD	Acid Rock Drainage
ARECOMS	Authority for the Regulation and Control of Strategic Mineral Substances Markets
BEV(s)	Battery Electric Vehicle(s)
BHP	Broken Hill Proprietary Company Limited
BLM	Bureau of Land Management
CBAM	Carbon Border Adjustment Mechanism
CBA(s)	Community Benefits Agreement(s)
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
CMA	Critical Minerals Agreement
CMBAM	Critical Mineral Border Adjustment Mechanism
Co	Cobalt
CO2	Carbon Dioxide
CPR	Coarse Particle Recovery
CRC	Cottonwood Resource Council
Cu	Copper
CWA	Clean Water Act
DFC	The US International Development Finance Corporation
DfR	Design for Recycling
DRC	Democratic Republic of Congo
EGC	Entreprise Générale du Cobalt
EIS	Environmental Impact Statement
EMF	Escondida Mining Foundation
EPA	Environmental Protection Agency
ESG	Environmental, Social, and Governance (standards)
EU	European Union
EV(s)	Electric Vehicle(s)
FARN	Fundación Ambiente y Recursos Naturales
FAST-41	Fixing America's Surface Transportation Act, Title 41
FCEV(s)	Fuel Cell Electric Vehicle(s)
FPIC	Free, Prior, and Informed Consent
FPISC	Federal Permitting Improvement Steering Council
FTA	Free Trade Agreement
GHG(s)	Greenhouse Gas(es)
GNA	Good Neighbor Agreement
HPGR	High-Pressure Grinding Rolls
HVC	Highland Valley Copper
IEA	International Energy Agency
IMIP	Indonesia Morowali Industrial Park

IPCC	In-Pit Crushing and Conveying
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
ISL	In-Situ Leaching
ISR	In-Situ Recovery
LFP	Lithium Iron Phosphate (battery)
Li	Lithium
LNFP	Lithium Manganese Iron Phosphate (battery)
LMR-NMC	Lithium Manganese Rich NMC (battery)
LNMO	Lithium Nickel Manganese Oxide (battery)
LSPCM	Large-Scale Private Copper Mining
MAC	Mining Association of Canada
MINER	Mine Improvement and New Emergency Response act
MIW	Mining-Influenced Water
MSD	Musculoskeletal Disorders
MSP	Minerals Security Partnership
NAFTA	North American Free Trade Agreement
NCA	Nickel Cobalt Aluminum (battery)
NEPA	National Environmental Policy Act
Ni	Nickel
NMC	Nickel Manganese Cobalt (battery)
NPDES	National Pollutant Discharge Elimination System
NPRC	Northern Plains Resource Council
NZE	Net Zero Emissions
OECD	Organization for Economic Co-operation and Development
OMSHR	Office of Mine Safety and Health Research
PV	Solar Photovoltaic
REE(s)	Rare Earth Element(s)
RoD	Record of Decision
SMC	Stillwater Mining Company
SPA	Stillwater Protective Association
SQM	Sociedad Química y Minera
STEPS	Stated Policies Scenario
TSM	Towards Sustainable Mining
UNCTAD	United Nations Trade and Development
US	United States
USACOE	US Army Corps of Engineers
USD	US dollar
USFS	US Forest Service
USGS	US Geological Survey
USMCA	United States-Mexico-Canada Agreement
WTO	World Trade Organization
YLB	Yacimientos de Litio Boliviano
ZEA(s)	Zones d'Exploitation minière Artisanale

1. Executive Summary

The United States' economic strength, technological leadership, and national security all depend on a stable and reliable supply of critical minerals, such as cobalt, graphite, lithium, nickel, manganese, and rare earth elements (REEs). These materials are essential for advanced manufacturing, defense systems, energy infrastructure, and consumer technology. However, decades of underinvestment in domestic extraction and processing have left the United States highly import dependent, with vulnerable supply chains that are neither resilient nor secure. In this report, our focus is primarily on mineral extraction, but many of the issues discussed here apply equally—and in some cases even more acutely—to mineral processing. Indeed, processing is an essential and highly concentrated stage of the supply chain to which many of the same concerns we raise regarding security, sustainability, and equity pertain.

The lack of supply chain resilience is not a new problem. The consequences of import dependence have been felt before—most notably during the 1973 oil crisis, when geopolitical instability led to price shocks that rippled through the economy, driving inflation, unemployment, and strategic uncertainty. Today, when it comes to critical minerals, a similar dynamic exists: a handful of countries controls key stages of extraction and refining, leaving the United States exposed to supply disruptions, economic shocks, and geopolitical leverage from foreign suppliers. Mining of a given mineral may be geographically concentrated; however, mineral processing is even more so: China dominates this stage of the supply chain, refining the vast majority of the world's lithium, cobalt, and REEs.

China's domination of the processing phase is enabled by cost advantages, government subsidies, and China's long-term strategic investments in processing infrastructure. As a result, even when minerals originate from allied nations, the United States remains dependent on China for their final usable forms. This dependence is not just an economic concern; it is also a strategic vulnerability. Beijing has already demonstrated a willingness to weaponize its dominance, restricting exports of certain refined minerals in response to geopolitical tensions. China's ongoing grip on mineral processing is not inevitable, but without a shift in policy, the United States will remain at risk of supply disruptions that could cripple key industries.

At the same time, critical minerals play an important role in addressing another major challenge: climate change. As industries transition toward lower-emission technologies, demand for these minerals is projected to rise sharply, particularly in sectors such as battery storage, electric vehicles (EVs), and renewable energy infrastructure. The transition to cleaner energy must not come at the expense of sustainable resource management. Mining and processing must be developed in a way that minimizes environmental degradation and prioritizes long-term resource security.

Addressing the United States' vulnerabilities calls for a coordinated public policy effort. Strengthening domestic mining and processing capabilities as well as expanding US imports from key allies will not only reduce dependence on imports from China but also ensure long-term economic resilience. But as domestic production expands and imports from allies increase, past mistakes should not be repeated. Extractive industries have historically operated without sufficient oversight of environmental sustainability, worker safety, and engagement with affected communities. In the United States, this includes Native American tribes and other Indigenous communities, who have often borne disproportionate environmental and cultural costs from mining. Any expansion of critical minerals extraction must explicitly safeguard tribal sovereignty, treaty rights, and cultural heritage alongside environmental and economic concerns. If policy fails to address all these concerns up front, development will face costly delays, public opposition, and potential regulatory setbacks. US energy and national security and the climate imperative demand getting this right.

A better approach would be to establish a strategic framework that aligns industry, government, and local communities from the outset. Public investment, regulatory clarity, and incentives for innovation in extraction, refining, and recycling can accelerate responsible domestic production while ensuring that economic benefits are widely shared. At the same time, targeted policies to diversify imports and build alternative processing capacity outside of China can mitigate long-term supply chain risks.

This report outlines key policy recommendations to build a stronger, more resilient critical minerals industry in the United States—one that balances security, economic growth, and social responsibility. By addressing these issues in a timely manner, policymakers can save time, reduce costs, and build a more effective and equitable supply chain strategy. The recommendations in this report provide a starting point for ensuring sustainable energy technology transitions across two primary dimensions: securing sustainable supply and encouraging diversification of imports. Addressing the question of demand can also mitigate some of the aforementioned issues while furthering US competitiveness.

Recommendation I: Reform permitting to accelerate deployment of new projects

The US government should streamline the permitting process for critical mineral mines by holding reviewers accountable to deadlines, enforcing limits on permitting timelines, and implementing transparency and tracking measures. Enforcing review times should not preclude rigorous environmental review and sufficient public comment periods. A streamlined and incentivized permitting process that decreases lead times and inertia will encourage the development of domestic mining projects. At the same time, by setting high standards, such a process should ensure that the increase in mining activities does not come at the cost of environmental degradation or social unrest. Many of the permitting delays in the United States are due to unexpected factors that are difficult to predict at the beginning of a project, like local community reactions, legal challenges, or complications in obtaining environmental permits.[1]

Recommendation II: Create community benefits agreements (CBAs) for new projects

By initiating CBAs at the start of new projects, mining operators may take advantage of a multifaceted strategy that enhances community relations, mitigates operational risks, and stimulates local economic development, thereby securing them a social license to operate. CBAs should include the following goals: (a) minimize adverse impacts on local communities, economies, and the environment, (b) maintain open lines of communication between constituents, (c) provide member participation in mine decision-making, (d) bind members for the lifetime of the mine, and (e) establish processes to resolve disputes and avoid litigation.[2] This proactive approach can also offer a positive contrast to state regulation, where the state intervenes only once it has detected environmental harm. Furthermore, the federal government can incentivize the use of good neighbor agreements (GNAs), a type of CBA. Strong GNAs enable and support community groups to work alongside mining companies to build mines that can accommodate everyone's needs.

CBAs should be legally binding, attached to the mine site rather than a company, and supported by technical advisors to provide expertise. The mine permitting process in the United States is an iterative one: it is designed so that mines can change over time with very few binary permit-issuing decision points. The CBA framework allows for the involvement of community groups in that iterative process, helping shape mine operations at each decision point to better reflect environmental, social, and community priorities. Not only are CBAs a powerful tool for coalition-building in the mining industry, but their influence can also extend beyond it: the way mine operators interact with the local environment and community is the upstream foundation of multiple other industrial supply chains.

Recommendation III: Seek FAST-41 coverage
The mine permitting process can be streamlined by using existing policy infrastructure within the executive branch. The Federal Permitting Improvement Steering Council (FPISC) is currently considering a rule change to mining provisions in FAST-41 that would allow only critical mineral mines to be FAST-41 designated and would expand FAST-41 coverage to critical mineral supply chain activities. FPISC accepted comments on this proposed rule change in 2023. By taking action on this rule change, the federal government can provide greater certainty to mining companies, increase transparency in the mine permitting process, and integrate environmental review for critical mineral mining infrastructure.

Recommendation IV: Adopt best practices and advanced mining technology
The United States, Canada, and Australia could consider several policy options that are in their collective as well as self-interest to alleviate the challenges arising from the shift in mining employment from coal to critical materials:

- Workforce retraining and relocation programs: Develop and fund retraining and relocation programs specifically tailored to equip former coal workers with the skills needed in critical materials mining.
- Economic diversification initiatives: Support economic diversification in regions historically dependent on coal mining to reduce reliance on a single industry.
- Investment in education and research: Increase investment in research and education focused on critical materials mining, ensuring a steady pipeline of skilled workers.
- Community engagement and support: Implement policies that support communities impacted by the shift to critical materials mining, including job placement services and economic aid.
- Sustainable mining practices: Encourage and fund the development of sustainable mining technologies and practices to improve the industry's outlook and make it more environmentally responsible.
- Public-private partnerships: Foster collaborations between governments, educational institutions, and private companies to create training programs and expand job opportunities in critical materials mining.

Recommendation V: Adopt recent innovations in low-impact mining techniques
Traditional mining methods, such as open pit and underground mining, pose severe environmental risks. By adopting new low-impact techniques like electrification of operations, in-situ leaching, and precision mining, mining companies can reduce surface disturbance, soil erosion, and backfilling. This approach also facilitates quicker site revegetation and rehabilitation.

Important progress toward lowering mining emissions can be achieved either by increasing the operational efficiency or reducing the environmental impact of extraction activities (lowering emissions through an intensity reduction channel) or by switching from fossil fuel combustion and fossil fuel–based electricity to biofuels and renewable-generated electricity (lowering emissions through their direct reduction).

All these initiatives, technologies, and innovations can help achieve sustainability goals by reducing emissions, reducing energy consumption, improving efficiency, and reusing and recycling materials. While each of these approaches has its own challenges and limitations, used in combination, they can contribute significantly toward sustainable mining operations.

Recommendation VI: Establish additional bilateral agreements to secure critical supply

To reduce its overreliance on a limited number of mineral-processing countries, the United States should pursue additional bilateral and multilateral trade agreements that strengthen and diversify its sources of critical minerals. Strategic partnerships with mineral-rich and mineral-processing nations can ensure resilient and sustainable supply chains while reinforcing high labor and environmental standards. Agreements such as those with Canada and Japan already demonstrate how targeted bilateral arrangements can secure access to key materials like cobalt, graphite, and lithium while aligning with U.S. policies like the Inflation Reduction Act. Further integration through initiatives like the Minerals Security Partnership (MSP) can expand the pool of trusted suppliers and incentivize responsible resource governance globally.

In particular, expanding trade cooperation with countries like Australia and mineral-rich nations in Latin America will be essential to meeting the growing demand for mineral-intensive technologies. Many of these countries already hold free trade agreements with the United States or are members of the MSP, but deeper coordination—through task forces, tax treaties, and direct investment—will be needed to fully unlock their potential. Strengthening these bilateral ties will not only secure more stable and ethical supply chains but also support shared economic growth and reduce strategic vulnerabilities in the global minerals market.

Recommendation VII: Establish a border adjustment mechanism that accounts for labor, environmental, and processing practices in the critical minerals sector

Global competition in the critical minerals sector is distorted by wide disparities in labor protections, environmental standards, and processing practices. Countries with weak regulations often enjoy lower production costs, enabling them to outcompete U.S. and allied firms that adhere to higher standards. This cost advantage has fueled a concentration of refining capacity in countries like China, posing significant economic and strategic risks.

To address these imbalances, the United States should consider establishing a critical mineral border adjustment mechanism (CMBAM). Unlike traditional carbon border adjustments, the CMBAM would take a broader view of supply chain externalities. This mechanism would impose targeted tariffs on mineral imports from countries that fail to meet defined benchmarks for labor practices, local environmental impacts, and carbon emissions. This approach would discourage regulatory arbitrage, where companies relocate operations to low-standard jurisdictions, and instead incentivize sustainable practices across the global supply chain, helping to ensure that ethical and sustainable producers remain competitive.

Developing the CMBAM will require careful design and international coordination. Policymakers must define measurable benchmarks, establish transparent enforcement mechanisms, and navigate trade law constraints. Still, if implemented effectively, the CMBAM can become a cornerstone of responsible mineral supply chains—supporting domestic industry, advancing environmental and labor standards, and enhancing long-term economic and national security.

Recommendation VIII: Incentivize research for technological innovation
To drive technological progress in areas such as recycling, material efficiency, alternative battery chemistries, and sustainable solutions across the raw materials value chain, investments in and support for research, development, and innovation in critical raw materials (CRMs) should be actively encouraged and promoted in both the public and private sectors.

Technological innovation can be achieved through coordination and collaboration between institutions, banks, industries, and private sector stakeholders, creating synergies and maximizing the impact of existing funding programs. Furthermore, it is essential to prioritize access to financing for innovations related to CRMs. Given the challenges in securing funding for such projects, public institutions could play an important role in assisting research centers, universities, private entrepreneurs, and start-ups by improving access to financing and providing administrative support.

Recommendation IX: Incentivize research to address market uncertainties
To reduce the uncertainty that characterizes CRM markets, which hinders stakeholders' investment in the sector, research focused on the market dynamics and the supply chain of battery minerals should be promoted.

This effort should foster synergies between the research community and the private sector. Joint research projects could be established, where industry provides researchers with resources and expertise, and researchers contribute with cutting-edge studies. For example, such projects could explore how factors related to supply-chain risks evolve over time and propagate from raw materials to end products, or they could develop models to forecast mineral prices and quantities in ways that reflect the complexity of the sector.

A better understanding of potential supply and demand scenarios, price volatility, and supply chain bottlenecks would provide significant benefits for the industry as it attempts to develop new production capacity.

2. Setting the Stage

2.1. A Central Piece of the US Economy

Mining is fundamental to modern life. It supplies the raw materials essential for the construction, technology, defense, and energy sectors. Nearly every mineral and metal in use today—from the iron used in making steel for buildings to the copper found in electronics and the rare earth elements (REEs) used in advanced manufacturing—originates from mining operations. The demand for these resources is rapidly increasing, driven by industrial expansion, technological advancements, and global infrastructure growth. For example, it is estimated that around 700 million metric tons (Mt) of copper will be needed over the next 22 years, equivalent to the total copper mined in the past 5,000 years.[3] The World Bank projects a 500% increase in demand for minerals like graphite, cobalt, and lithium by 2050 as industries increasingly rely on these materials.[4]

The US economy depends heavily on imported minerals across nearly all industrial sectors. Advanced manufacturing, defense technologies, semiconductors, consumer electronics, and energy infrastructure all require a stable and reliable supply of materials like lithium, nickel, copper, and REEs. However, the United States lacks a diversified supply chain for these resources, making industry highly vulnerable to geopolitical risks and trade disruptions.

Today, China dominates global mineral processing and refining capacity, controlling 68% of nickel processing, 73% of cobalt processing, 78% of lithium processing, and more than 90% of REE refining. Many of these materials are not mined in China but are extracted elsewhere and then sent to China for processing. This is due to China's lower processing costs, weaker environmental regulations, and heavy government subsidies, all of which has helped the country consolidate its position in global supply chains. Relying on a single country for such a critical stage of mineral production presents clear economic and national security vulnerabilities.

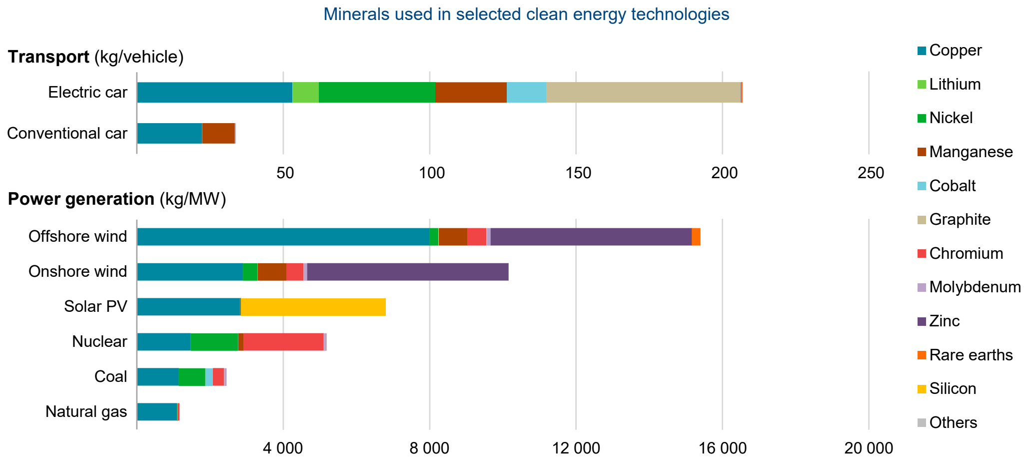
China has shown willingness to weaponize its dominance in mineral processing to gain geopolitical leverage. In 2023, it restricted its exports of gallium and germanium, both essential for semiconductors and military technologies, in direct response to US trade policies. This episode highlights how the current supply chain model leaves US industries vulnerable to disruptions beyond their control, which can affect everything from national security to domestic manufacturing and infrastructure development. Historically, to guard against the dangers of overreliance on foreign nations, the United States has prioritized energy independence; one can argue that the same principle now applies to critical minerals. Without proactive policy measures to diversify mineral supply chains, the United States risks long-term dependence on a small number of countries with concentrated control over mining and processing capacity.

Mineral supply chain vulnerabilities pose challenges for not only economic security but also industrial competitiveness. Companies that adhere to strict labor, environmental, and regulatory standards often struggle to compete against firms that cut corners. By ensuring that the price of minerals entering the US market reflects their true production costs, policymakers can level the playing field for domestic and allied producers that comply with responsible mining and processing standards.

An additional consideration is that while the industrial, defense, and technology sectors are the largest mineral consumers, the ongoing shift toward electrification and advanced energy systems is driving increased demand for select materials. Minerals such as copper, lithium, nickel, and graphite are critical for infrastructure modernization, transportation electrification, and power grid reliability. The United States' growing dependence on these minerals does not imply a replacement of existing industrial and technological needs but rather adds to them, further stressing existing supply chains. Therefore, ensuring that these materials remain available, affordable, and responsibly sourced is essential for the long-term stability of the US economy.

Several key minerals are essential for the development and deployment of clean energy technologies. Figure 1 illustrates the demand for minerals driven by the clean energy transition. According to the International Energy Agency (IEA), minerals play a pivotal role in various clean energy technologies, from power generation and electricity networks to electric vehicles (EVs) and battery storage systems. For example, although solar photovoltaic (PV) plants and wind farms do not rely on fuels for operation, they typically require more critical materials for their construction than fossil fuel–based systems.[5] Compared to conventional vehicle production, excluding aluminum and steel, EV production requires six times the amount of mineral resources. An onshore wind farm requires nine times more mineral input than a gas-fired plant of similar capacity (also excluding aluminum and steel).[6] According to the IEA, since 2010, "the average amount of minerals needed for a new unit of power generation capacity has increased by 50% as the share of renewables in new investment has risen."[7] This trend highlights the critical connection between minerals and clean energy technologies, signifying a shift from systems reliant on fuel to those dependent on minerals.

Figure 1: Mineral demand by clean energy technologies.



Source: IEA, 2022.[8]

Next, we elaborate on selected minerals that are critical due to the nature of their extraction, their high geographical concentration, or their associated geopolitical risks. Several government agencies—including the US Department of the Interior, through the US Geological Survey (USGS); the European Commission; and the governments of Canada and Australia—periodically publish lists of critical minerals.[9] Informed by the 2022 USGS list and the demand for minerals in the green energy transition as illustrated in figure 1, we provide an overview of cobalt, copper, graphite, lithium, manganese, nickel, and REEs in more detail. Note: These constituents are used not only in their elemental form but also as chemical compounds, including oxides and salts.

Cobalt

Cobalt is one of several constituents of the active cathode materials in lithium-ion batteries, which are crucial for powering EVs and for various energy storage systems. Cobalt's role in these batteries is to enhance energy density, prolong battery life, and improve rechargeability. Beyond batteries, cobalt is also used in superalloys for aircraft engines and magnets and other high-strength alloys that require resistance to corrosion and high temperatures.[10]

In recent years, demand for cobalt has steadily increased, particularly in the battery sector, which now accounts for over 30% of total cobalt consumption.[11] The Democratic Republic of the Congo (DRC) dominates global cobalt production, contributing 74% in 2023—and this geopolitical concentration raises supply reliability concerns. These concerns are causing the battery industry to reduce its demand for cobalt as it shifts toward battery chemistry technologies that reduce or eliminate cobalt usage.[12] High-nickel chemistries and cobalt-free alternatives like lithium iron phosphate (LFP) batteries are gaining traction, reaching a 40% share in the EV industry in 2023.[13] Ongoing geopolitical risks, particularly related to the DRC, could further influence future supply stability and market dynamics.[14]

Copper

Copper is a uniquely important mineral for the energy transition, being integral to all major clean energy technologies, including EVs, solar photovoltaics (PV), wind turbines, and the electricity network, although it is not listed as critical by the USGS. Copper's exceptional properties—such as superior electrical and thermal conductivity, durability, ductility, and corrosion resistance—make it indispensable for the efficient functioning and longevity of these technologies.[15] EV batteries rely on copper anode current collectors; copper is also used in EV wiring and electric motors.[16] Solar and wind installations rely on copper for efficient power generation and transmission. Likewise, the expansion and modernization of electricity grids depends heavily on copper to ensure reliable and effective energy distribution.[17] Ensuring a secure and stable supply of copper is therefore paramount to successfully achieving global clean energy goals.

Demand for copper is projected to rise in the coming decades, driven by the rapid deployment of renewable energy systems and the adoption of EVs. While the construction sector remains the largest consumer of refined copper (30% in 2023), clean energy technologies are rapidly increasing their share, rising from 22% in 2015 to an expected 45% by 2030—under aggressive climate policies.[18] Specifically, global refined copper demand is expected to grow from 26 million Mt in 2023 to between 31 and 33 Mt by 2030, depending on the climate scenario, and could reach around 40 Mt by 2050 in the net zero emissions by 2050 scenario.[19] Copper demand for EVs alone is anticipated to grow more than twelvefold, accounting for up to 13% of total demand by 2050.[20] Post-2040, the pace of electricity network expansion may slow, slightly reducing copper demand growth.[21] However, overall demand is expected to remain robust due to sustained investments in clean energy infrastructure and technologies.

Graphite

Graphite, a crystalline form of carbon, has traditionally been used in applications like lubricants, electrical conductors, and metallurgy.[22] It is crucial in steelmaking and as electrodes in electric arc furnaces. Graphite's role is rapidly expanding in the battery industry, particularly in the production of anodes for EVs, where both natural and synthetic graphite are used. While natural graphite is primarily sourced from countries like China, Madagascar, and Mozambique, synthetic graphite is produced through energy-intensive processes, often concentrated in China and other industrialized nations.[23] This growing demand, combined with geographic concentration, raises questions about supply chain resilience associated with both natural and synthetic graphite.

The shift toward EVs and battery storage systems is set to more than double global graphite demand by 2030: it is projected to reach up to 18 Mt by 2050, a fourfold increase from 2023.[24] Although alternatives like silicon-doped anodes and other new chemistries may impact graphite use in the long term, graphite is expected to remain dominant in the near future. The adoption of these alternative chemistries faces significant technical and scaling challenges, such as achieving high cycle life and minimizing volume changes. Additionally, the move to electric arc furnaces for reducing emissions in steel production is likely to further boost demand for graphite electrodes.[25] By 2040, demand for graphite in metallurgical applications is projected to reach up to 3.8 Mt, up from 1.5 Mt in 2023.[26]

The United States imported 100% of all graphite consumed in 2023: from China (42%), Mexico (16%), and Canada (15%). There has been no domestic production of natural graphite in the United States since the 1950s.[27]

Lithium

Lithium has traditionally been used in applications such as ceramics, lubricants, and pharmaceuticals, but over the past decade, demand for it has significantly increased, particularly in battery production, a market segment that is now the dominant driver of global lithium demand. As one of the lightest elements in the periodic table, lithium is ideal for providing the high energy density that batteries require.[28]

Demand for lithium metal and lithium-containing chemicals is projected to rise sharply, outpacing the growth of all other critical minerals. By 2050, lithium demand is expected to reach between 1,200 and 1,700 kilotons (kt), depending on the climate scenario, representing a tenfold increase from current levels (165 kt in 2023).[29] This surge is primarily driven by clean energy technologies: the EV industry will account for approximately 90% of demand growth by 2050. Additionally, while battery storage currently accounts for a minor share of lithium consumption, it is expected to drive demand up to 130 kt by 2050—over ten times the current level.[30] Despite the emergence of alternative technologies such as sodium-ion and vanadium flow batteries, which may gain traction in certain markets, lithium-ion batteries are anticipated to remain dominant in the EV and storage sectors.[31] Furthermore, the potential development of solid-state batteries with lithium metal anodes could open new markets for lithium in its metallic form, further boosting demand in the coming decades.[32]

Manganese

Manganese is predominantly used in alloy steel, to enhance its strength and durability. Although the battery industry currently accounts for a small fraction of manganese demand, this is expected to change as the trend toward adoption of nickel manganese cobalt (NMC) batteries grows.[33] A shift toward increasing the proportion of manganese and nickel in relation to that of cobalt in these batteries is driving up the demand for high-purity manganese sulphates.

China is the major producer of these high-purity materials, supplying 97% of global battery-grade manganese sulphate.[34] Because the production process is complex and tailored to specific ore types and China has a significant advantage in expertise and infrastructure, it is difficult for the United States to diversify its supply chain. Despite there being refining projects underway in countries such as Australia, Canada, the Czech Republic, South Africa, and the United States, the current lack of diversified high-purity manganese production could become a bottleneck for the battery industry's expansion.[35] As demand for manganese-rich battery chemistries rises, ensuring a stable supply of high-purity manganese will be crucial for supporting the growth of EV and other clean energy technologies.

The United States has not produced a significant quantity of manganese ore with a content greater than 20% since 1973; in 2023, it imported 100% of its manganese consumed, from South Africa, Gabon, and Australia.[36] Although globally, land-based manganese resources are abundant, they are irregularly distributed. In the United States, these resources are of very low grade, exacerbating their extraction costs.

Nickel

Nickel plays a crucial role in the production of high-performance batteries, which are ideal for EVs. It is predominantly used in the cathodes of lithium-ion batteries, where it enhances energy density, resulting in greater battery efficiency, better overall performance, and extended driving ranges for EVs.[37] For these benefits, automakers increasingly favor high-nickel cathode chemistries, such as nickel cobalt aluminum (NCA) and nickel manganese cobalt (NMC). Beyond nickel's critical role in batteries, it is widely used in the production of stainless steel and other alloys essential in various industrial applications, ranging from construction to the manufacturing of consumer goods.[38]

The demand for nickel and nickel-based compounds is growing significantly, driven primarily by increasing use of high-nickel battery chemistries in the EV sector. Global nickel demand, which hovered around 2.4 Mt per year between 2018 and 2020, surged to approximately 3.1 Mt in 2023, and all energy transition scenarios project that it will to continue to rise.[39] Demand is expected to reach 4.5–5.6 Mt by 2030, depending on the projected climate scenario.[40] Whereas the clean energy sector will drive much of the demand growth, nickel will continue to play a significant role in the production of alloys, particularly stainless steel, a sector that will retain 35% to 50% of market share by 2050.[41] The concentration of nickel production in a few regions and the environmental challenges associated with its mining and processing pose potential risks to supply stability, especially as demand continues to rise.[42]

Rare Earth Elements (REEs)

REEs are a group of 17 metals that are chemically similar and often found together in various deposits.* Despite their relative abundance in the Earth's crust, they are

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* REEs: Scandium (Sc), yttrium (Y), and the lanthanides: lanthanum (La), cerium (Ce), praseodymium (Pr), neodymium (Nd), promethium (Pm), samarium (Sm), europium (Eu), gadolinium (Gd), terbium (Tb), dysprosium (Dy), holmium (Ho), erbium (Er), thulium (Tm), ytterbium (Yb), and lutetium (Lu).

termed "rare" because they are seldom found in sufficiently concentrated forms to make their extraction and refinement economically viable.[43] REEs are critical to the energy transition due to their indispensable role in numerous clean energy technologies, particularly wind turbines and EVs.

Elements like neodymium and dysprosium are used to manufacture powerful permanent magnets, which are essential in high-efficiency generators that convert wind energy into electricity.[44] Direct-drive wind turbines, favored over gear-driven turbines for their superior reliability, require these high-efficiency generators. REE magnets are also used in electric traction motors, which are among the most energy-efficient devices available, offering energy savings of 20–40% compared to conventional electric motors.[45] Furthermore, incorporating small quantities (1–2 kg) of magnet REEs in an EV's motor can significantly reduce the need for other critical minerals in the vehicle's battery—like lithium, nickel, and cobalt—by as much as 60–80 kg per vehicle.[46] This efficiency makes REEs crucial for not only improving EVs' performance but also reducing their overall material footprint.

As the clean energy transition accelerates, the demand for these critical elements is expected to continue to rapidly increase. Global demand for magnet REEs nearly doubled from 2015 to 2023, reaching 93 kt. Total magnet REE demand is projected to reach 131 kt by 2030 and further increase to 181 kt by 2050—twice the current level.[47]

Figure 2: Mineral demand for clean energy technologies doubles or nearly triples between today and 2030 under projected climate scenarios. Source: IEA, 2024.[48]

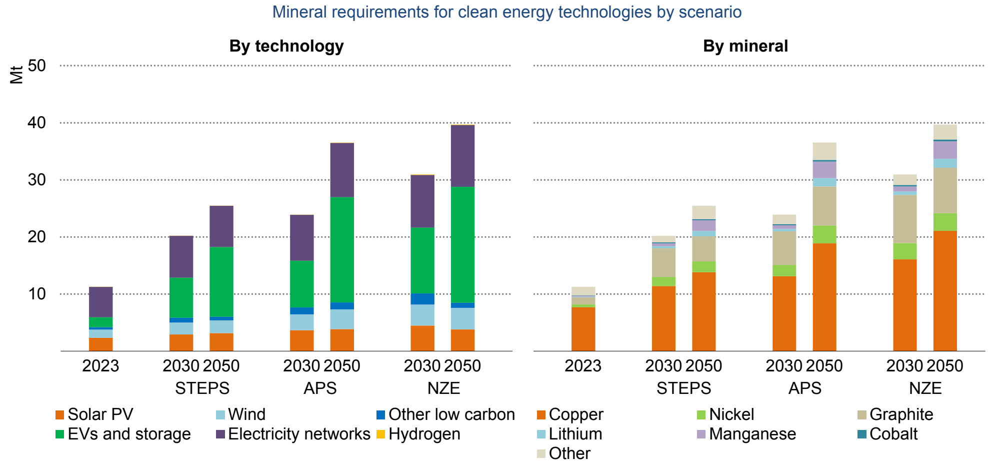


Figure 2 presents the projected demand for minerals used in green energy technologies under three distinct energy transition scenarios, according to IEA projections.[49]

- Stated Policies Scenario (STEPS): In this scenario, current policy measures provide a pathway for and shape the energy transition, including policies that are actually in place and under development, such as the US Inflation Reduction Act of 2022.
- Announced Pledges Scenario (APS): The APS assumes that all long-term emissions and energy access targets, including net zero commitments, will be met on time and in full, even in cases where specific policies are not yet in

place to achieve these goals. The APS aligns with the goals of the Paris Agreement, focusing on reducing greenhouse gas emissions and limiting global temperature rise to 1.7°C by 2100, with a 50% probability.

- Net Zero Emissions (NZE) by 2050 Scenario: In the NZE scenario, the most ambitious pathway, the global energy sector achieves net zero CO_2 emissions by 2050 and limits global warming to 1.5°C by 2100. This scenario requires an extraordinary acceleration in the deployment of clean energy technologies and implies significant market behavioral changes, such as reduced preference for larger vehicles (e.g., lower SUV market share). As a result, the average battery size is expected to peak in the 2020s and gradually decline, lowering mineral requirements compared to other scenarios.

The left-hand graph in figure 2 shows that, across all three climate scenarios, the accelerating pace of the energy transition will significantly boost mineral demand. In the STEPS, demand doubles by 2030 and continues to grow thereafter. In the APS, demand more than doubles by 2030 and triples by 2050. In the NZE scenario, which projects the most aggressive adoption of clean energy technologies, demand for critical minerals surges, nearly tripling by 2030 and growing to over 3.5 times current levels by 2050, reaching nearly 40 million Mt. This graph highlights the critical role minerals will play in the global transition to cleaner energy solutions.

The right-hand graph in figure 2 highlights the significant demand for copper, nickel, graphite, lithium, manganese, and cobalt for the clean energy transition. Among these, copper stands out as having the largest projected demand, reflecting its critical role in electrical infrastructure, including wiring, renewable energy systems, and EVs. Graphite, nickel, and manganese also show substantial demand, and nickel and lithium show the most significant growth due to their essential roles in the rapidly expanding battery storage market. The shift in battery technology is notable: for instance, high-cobalt, low-nickel chemistries like NMC 333 are expected to be phased out by 2030.[50] In contrast, there is a growing preference for high-nickel chemistries, such as 96% Ni NMC, and a rise in the market share of lithium chemistry variants such as LFP, lithium manganese iron phosphate (LMFP), lithium-manganese-rich NMC (LMR-NMC), and lithium nickel manganese oxide (LNMO). Despite these shifts, high-nickel chemistries remain crucial in the long run.[51]

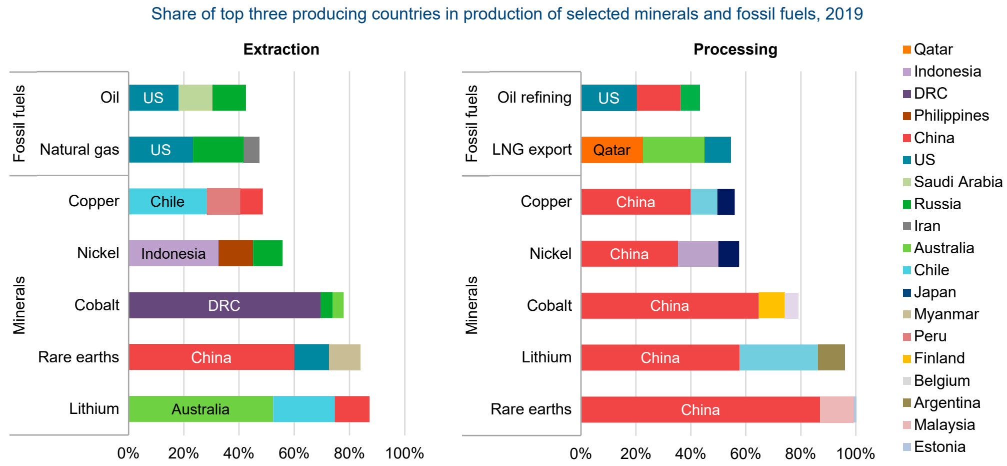
In summary, the central role critical minerals play in clean energy technologies is emphasized by the energy transition scenarios. As the adoption of clean energy technologies accelerates, the energy sector emerges as a key player in the minerals and metals industry. Furthermore, the relationship between minerals and energy is set to deepen, with varying types and volumes of mineral needs across different clean energy technologies and even within specific technologies. These minerals are essential not only for technological progress but also for achieving global climate objectives. For all these reasons, their secure and sustainable supply is a top priority for governments and industries worldwide.

2.2. Critical Minerals: More Geographically Concentrated Than Oil and Natural Gas

The geographic concentration of mineral resources is significantly more pronounced than that of oil and natural gas. Figure 3 shows the geographic concentration of both extraction and processing. Three examples stand out: the

DRC is responsible for 70% of the world's cobalt production, China controls 60% of the global production of REEs, and the top three producers of nickel and lithium account for more than 60% of the global supply. This geographic concentration is not limited to extraction alone. For instance, China also leads in mineral processing, holding a commanding position in the refining of several critical minerals. In contrast, the concentration of oil and natural gas is less severe: the top three producers account for approximately 42% and 50% of global production, respectively. This disparity highlights the unique challenges faced by the mineral sector, where supply chains are more vulnerable to disruptions due to their reliance on a limited number of key players.

Figure 3: Current production of numerous minerals critical for the energy transition is more geographically concentrated than that of oil or natural gas. Source: IEA, 2022.[52] Note: The figure shows the top three countries where extraction and processing are concentrated.



Ranked by market share, the geographic concentration is as follows: copper, nickel, cobalt, REEs, and lithium. However, lithium is less geographically concentrated than cobalt and REEs, as the leading producer splits the market with the other top three producers: 50% of lithium is extracted in Australia, 20% in Chile, and 13% in China. Lithium processing is likewise split: half occurs in China and the other half in Chile and Argentina.

Cobalt

Extraction:

The DRC is the world's leading producer of cobalt, responsible for 74% of global output as of 2023.[53] Cobalt is one of the DRC's main sources of revenue and is critical to the nation's economy. The country holds the world's largest cobalt reserves: an estimated 6 million Mt out of a global total of 11 million. Most of the DRC's cobalt production is concentrated in the southern provinces of Haut-Katanga and Lualaba, known collectively as the Copperbelt. Despite the country's significant production capacity, the DRC faces challenges that can impact cobalt supply, such as ethical concerns related to mining practices and political instability.[54]

Australia and Canada, while smaller players, also have substantial cobalt mining operations. Australia's Mount Isa region is known for its cobalt deposits, and

Canada's cobalt production is primarily concentrated in Ontario's Sudbury Basin. Both countries have been ramping up cobalt production to meet the growing global demand for battery metals, driven by the expansion of the EV market and other high-tech industries.

Processing:
China dominates the global cobalt processing industry, accounting for a staggering 77% of the market in 2022.[55] China's leading position is underpinned by the significant investments it has made in the cobalt value chain, having recognized the metal's importance in battery technology, particularly for EVs. China's dominance in processing gives it considerable control over the global cobalt supply chain.

Finland is the second-largest player in cobalt processing, with 8.6% of the global market share. Finland's advanced metal refining industry, which benefits from cutting-edge technology and strong environmental standards, supports its role in the global cobalt market.

Canada, with a 3.6% share, also plays a vital role in cobalt processing, leveraging its rich deposits and long history of cobalt production.

In 2023, the United States imported 67% of its cobalt consumed in the form of metal, oxide, and salts, predominantly from Norway (25%), Canada (15%), Finland (13%), and Japan (12%), all of them reliable partners. Despite Norway's reliability as a supplier, the DRC's political instability and challenges related to conflict minerals create potential vulnerabilities for the United States.

Copper
Extraction:
Copper production is concentrated in a few key countries: Chile, Peru, and China take the lead. Together, these three nations account for approximately 55% of the world's copper production.

Chile stands out as the world's largest producer, contributing 5.3 million Mt in 2023, approximately 27% of the global output. The country's copper mining operations are predominantly located in the Atacama Desert; the Escondida, Collahuasi, and Chuquicamata mines there are among the largest and most productive in the world.[56] Chile's production has remained relatively stable; recent growth has been driven by the expansion of existing mines and the development of new ones.

Peru follows as the second-largest copper producer, contributing 2.6 million Mt in 2023, approximately 10% of the global output. Major mining operations in Peru include the Antamina, Cerro Verde, and Las Bambas mines.[57] Peru's copper production has been trending upward, supported by increased investments in mining infrastructure.

China, while primarily known for its consumption of copper, is also a significant producer, ranking third globally. In 2023, China produced about 1.7 million Mt of copper, roughly one-third of Chile's production.[58] China's copper mining operations are spread across several provinces, including Jiangxi, Zhejiang, and Henan. In recent years, China has boosted its domestic mining activities to reduce its reliance on copper imports, demonstrating its strategic approach to securing essential resources.

The United States imported 46% of its refined copper in 2023, primarily from Chile and Peru. While neither Chile nor Peru is a NATO member, both maintain stable diplomatic and economic relations with the United States. Chile, as the world's leading copper producer, plays a crucial role in meeting US demand. Because of copper's prevalence in the global economy, it was imported in several forms, including:

- Copper content of blister and anodes:
  - Finland: 93%
  - Other countries: 7%
- Copper content of matte, ash, and precipitates:
  - Canada: 37%
  - Belgium: 21%
  - Japan: 16%
  - Spain: 11%
  - Other countries: 15%
- Copper content of ore and concentrates:
  - Mexico: 52%
  - Canada and other countries: 48%

Processing:
China is the dominant copper processing force, holding a substantial market share of 42.3% in 2022.[59] This dominance is driven by the massive demand for copper from China's electronics and construction industries. To meet its domestic needs and to maintain its leading position in the global copper market, China has made significant investments in its refining capacities.

Chile is not only the world's largest copper miner but also the second-largest processor, with an 8.1% market share.[60] Chile's processing capabilities are supported by its abundant local resources and well-established smelting and refining infrastructure.

Other notable contributors are Russia, Japan, the United States, and the DRC, which together account for approximately 20.7% of global copper processing. However, their combined output is dwarfed by that of China due to its immense processing capacity.

Lithium
Extraction:
Australia, Chile, and China are the top three lithium producers, and Australia leads the charge.

The Greenbushes mine in Western Australia is one of the world's largest lithium mining operations and significantly contributes to the country's lithium output. Over the past decade, Australia has experienced a lithium production boom, driven by the escalating demand for lithium-ion batteries used in EVs and energy storage systems.

Chile—home to the Salar de Atacama, one of the world's richest lithium brine deposits—is the second-largest lithium producer. Despite Chile's lithium mining challenges, such as water scarcity and environmental concerns, particularly in the arid regions where lithium brine extraction occurs, the country's production has steadily grown.[61]

China is a major consumer of lithium and also ranks as the third-largest producer. The country's lithium production is concentrated in mineral-rich provinces such as

Sichuan and Qinghai.[62] In recent years, China has ramped up its lithium production to support its burgeoning EV industry and reduce its dependence on lithium imports.

Processing:
Lithium processing is somewhat more geographically diversified than that of cobalt and REEs. However, China remains the global leader, holding a 58% share in 2019. China's dominance in this sector is a result of its strategic focus on securing resources for its rapidly growing EV battery industry. The country's processing capacity is critical to its broader strategy of controlling the global supply chain for key battery materials.

Chile and Argentina also play significant roles in lithium processing, with market shares of 29% and 10% in 2019, respectively. Their prominence is closely linked to their vast lithium brine resources and increasing investments in lithium extraction and processing infrastructure.

The United States imported 25% of its lithium consumed in 2023, primarily from Argentina (51%) and Chile (43%). Argentina is a significant trading partner of and maintains positive relations with the United States. While Argentina is not a NATO member, its role as a major lithium supplier makes it a critical strategic ally of the United States. Australia, a top global lithium producer and strong geopolitical ally of the United States, further bolsters the security of the lithium supply chain.

Nickel
Extraction:
Nickel production is heavily concentrated in Indonesia and the Philippines, which together represent around 60% of global output.

Indonesia is the world's largest nickel producer and has significant mining operations in the Sulawesi and Moluccas regions, known for their rich laterite deposits. The country's nickel production has surged over the past decade, driven by the growing demand for nickel in EV batteries and other industrial applications.

The Philippines is the second-largest producer of nickel; its output primarily comes from the Caraga Region's laterite deposits. However, Philippine nickel production has fluctuated over the years due to changes in mining policy, environmental concerns, and weather conditions.

Russia is the third-largest producer of nickel, contributing nearly 7% of global output. Russia's production is mainly concentrated in the Norilsk-Talnakh region in Siberia. Production has declined slightly due to aging facilities and infrastructure.[63]

Processing:
Indonesia has emerged as the global leader in nickel processing, commanding a market share of 32.9% in 2022. This significant share is largely due to its abundant lateritic nickel ore reserves and its efforts to increase domestic processing capabilities, specifically to supply the growing EV battery market.

China follows closely with a 25.2% market share. Its strong nickel pig iron industry is vital for its vast stainless steel sector.

Other countries, including Australia, Canada, Finland, Japan, Norway, and Russia, maintain a moderate presence in nickel refining, with market shares ranging between 2.6% and 6.8%. However, these nations combined account for less than 25% of global nickel processing, highlighting the dominance of Indonesia and China in the global market.[64]

The United States imported 57% of its nickel consumed in 2023, primarily from Canada (46%)—a USMCA and NATO member and a secure and reliable source of US nickel imports. Additionally, although not a NATO member, Indonesia, a major global nickel producer, is strengthening its economic ties with the United States.

Rare Earth Elements (REEs)

Extraction:

REE production is overwhelmingly dominated by China, which accounted for nearly 70% of global output in 2023. China's share was even higher in 2016, reaching 83%. This dominance is due to China's vast reserves and its long-standing strategic focus on REEs.

Other significant producers include the United States, Myanmar, and Australia. The United States accounted for approximately 12.3% of global REE production in 2023. Much of its output comes from the Mountain Pass mine in California, which reopened mining operations in 2018 with additional environmental guardrails (work to reopen processing operations is ongoing).

Myanmar plays a notable role in the global REE market, contributing 38,000 Mt (10%) in 2023. Australia, which produced 18,000 Mt (5%) in 2023, has been increasing its production capacity to reduce reliance on Chinese imports.

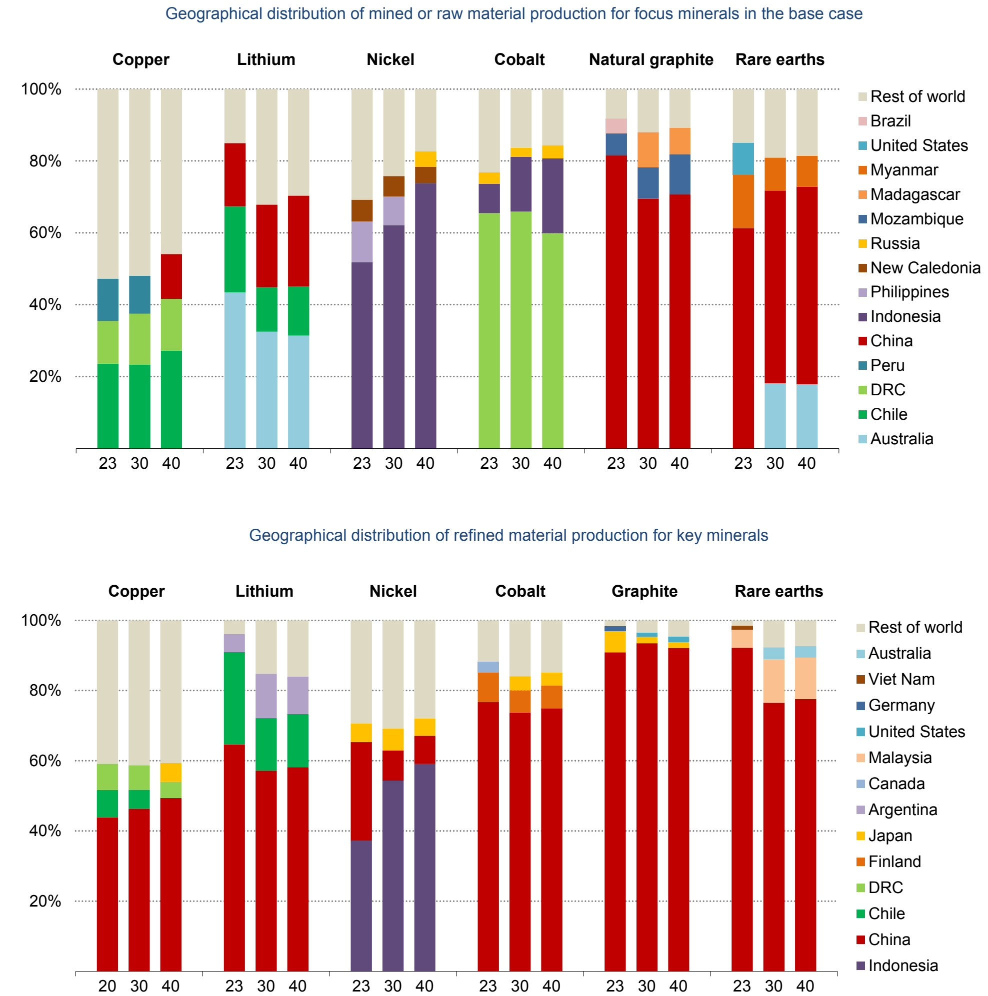
Processing:

China not only leads in REE production but also dominates the processing sector, handling nearly 90% of the world's REEs. China's processing capabilities are unparalleled, giving the country a near monopoly on the global rare earth supply chain. This dominance is reinforced by China's extensive investments in REE refining and separation technologies, which are critical for producing high-purity materials used in advanced applications.[65]

The United States and Australia, while significant REE producers, have limited processing capabilities, which forces them to rely on China for refining. This dependence on China raises concerns about supply chain stability.

The United States imports more than 95% of its REEs consumed, dominated by China (72%) and Malaysia (11%). The United States' dependence on China for REEs is a significant strategic vulnerability, given the crucial role these elements play in advanced technologies and defense applications. Secondary suppliers include Estonia, Japan, and Malaysia, though they, too, often source REEs from China and other countries.

Figure 4: IEA projections of the geographical distribution of extracting and processing key minerals for 2030 and 2040.



Source: IEA, 2024.[66]

Looking ahead, the geographical concentration of minerals in both extraction and processing is expected to remain high, and in some cases, it may even increase in 2030 and 2040 (see figure 4). According to estimates by the IEA, the majority of new mining projects are concentrated in the same regions that currently dominate production. This means that the concentration levels are unlikely to diversify significantly. In the refining sector, the situation is even worse. Between now and 2030, an estimated 70–75% of the projected supply growth for refined lithium, nickel, cobalt, and REEs—and nearly 95% for battery-grade spherical and synthetic graphite—will come from today's top three producers.[67] This high level of supply concentration underscores the risk of potential supply disruptions, whether due to physical accidents, geopolitical tensions, or other unforeseen events in key producing countries, potentially hindering the progress of the global energy transition.

2.3. The Net Import Reliance of the United States

Since 1990, the United States has become increasingly dependent on foreign sources to satisfy domestic demand for a wide array of mineral commodities. Despite the essential role critical minerals play in the green energy transition, US domestic mining output has declined in recent decades, placing the country's supply chain in a precarious position. The United States now imports more than half of its consumption of 43 out of 50 critical minerals and metals and does not produce at least 12 of them.[68] As noted earlier, the supply of these mineral commodities is becoming increasingly concentrated in a limited number of countries, when it comes to both extraction and processing. This growing reliance on imports from a few key players heightens the United States' vulnerability to the disruptive effects of geopolitical tensions and supply chain interruptions and poses significant national security and economic risks.[69]

Figure 5 illustrates the extent of US dependence on foreign sources for both raw and processed mineral materials. As of 2023, imports accounted for more than half of the apparent consumption of 49 nonfuel mineral commodities. Alarmingly, the United States was 100% net import reliant on 15 of them. Of the 50 mineral commodities identified in the USGS's "2022 Final List of Critical Minerals," the United States was entirely reliant on imports for 12 critical minerals; another 29, including 14 lanthanides (REEs), had a net import reliance greater than 50% of apparent consumption.[70]

How US Import Reliance Develops

The growing US reliance on foreign sources for mineral commodities stems from several key factors. First, the increasing demand for mineral commodities, both in quantity and diversity, plays a significant role. As technological advancements have accelerated, so too has the complexity of materials required. For example, several reports have highlighted that advanced electronics, which used only 12 elements in the 1980s, required as many as 56 by 2020.[71] The evolution in demand has outpaced domestic production capabilities, leading to greater dependence on imports.

Figure 5: US net import reliance as a percentage of apparent consumption in 2023 and the leading import sources for 2019–22. Note: Included are all minerals for which the US is 100% net import reliant and other selected minerals.

Data source: USGS, 2024.[72]

Moreover, the global distribution of mineral reserves is highly uneven. For instance, Chile holds more than twice the copper reserves of Australia (the country with the next-largest reserves) and supplied 64% of US refined copper imports in 2022.[73] The geographic distribution of resources compels the United States to look abroad to secure the minerals its industries require. It also means that the United States must diversify its import sources to ensure supply chain stability.

Another significant factor influencing the United States' import reliance is the relative cost of mineral production. Global variations in policy, labor costs, environmental regulations, and resource concentration affect the comparative cost of extracting and processing minerals, making it, in many cases, more economically viable to import minerals from countries with lower production costs than to develop and extract them domestically. For example, because US manganese resources are of much lower grade than those in South Africa and Gabon, the domestically refined mineral is more costly than the imported commodity; thus, the United States has opted to import 100% of its manganese consumed.[74]

Net Import Reliance Matters: Supply Chain Vulnerability

The United States' heavy reliance on imported minerals poses substantial risks, particularly when it comes to supply chain vulnerability. The road from mineral extraction to delivery has multiple stages, including mining, refining, and transportation. Disruptions at any point in this chain can lead to shortages, cost increases, and potential threats to economic stability and national security.

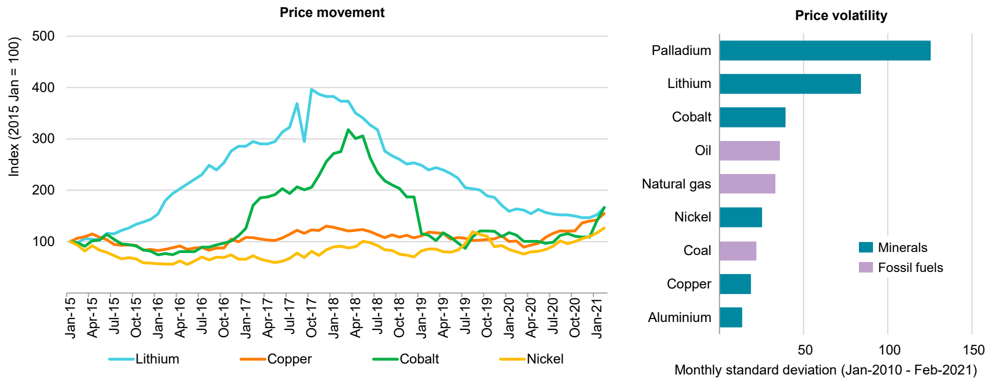
As discussed earlier, one of the most significant challenges associated with import reliance is the high concentration of critical minerals from a few key suppliers. This makes supply chains particularly susceptible to disruptions caused by trade disputes, extreme weather, or geopolitical tensions. For example, the DRC, which supplies over 60% of the world's cobalt, has a history of political instability and conflict, which have periodically affected its mining output.[75] Such disruptions can lead to significant shortages and price spikes, with wide-ranging impacts on industries dependent on these materials.

The concentration of mineral resources also increases risks associated with their suppliers' market power. For instance, in 1978, Gecamines in the DRC reduced cobalt production to artificially inflate prices, causing a sharp supply cutoff and a significant price spike.[76] The "cobalt crisis" highlighted concerns about the DRC's dominance in global cobalt production and influence on market stability.

Some minerals on which the United States depends are produced in regions with a history of political opposition to this country. For instance, in 2023, in response to escalating trade tensions with the United States and its allies, China imposed export restrictions on gallium and germanium, two minerals essential for semiconductors and military technologies. This move echoed its 2010 decision to cut REE exports to Japan amid a territorial dispute over the Senkaku Islands, demonstrating how geopolitical tensions can directly impact supply chains.[77] More recently, Chinese officials have signaled potential restrictions on REEs and other key minerals, warning that they may retaliate against US and EU policies that limit Chinese technology exports. These threats attest to the growing risk of supply chain disruptions as global competition for critical minerals intensifies.[78]

It's notable that because of the high concentration of mineral production, even minor disruptions can have outsized effects. For instance, labor strikes at major mines, such as Chile's Escondida (the world's largest copper mine), have historically led to substantial price increases and supply concerns.[79] Natural disasters, even in a single country, can also have significant impacts. The 2011 earthquake in Northern Honshu, Japan, temporarily disrupted one-quarter of the world's supply of iodine, which is critical for LCD screen production and other uses.[80]

Figure 6: The price volatility of critical minerals can be higher than that of oil and natural gas, due to supply chain vulnerabilities.



Source: IEA, 2022.[81]

Overall, these vulnerabilities contribute to the price volatility in the markets for critical minerals, which often surpasses that of more established commodities like oil and natural gas. As illustrated in figure 6, in 2010, the monthly standard deviation in prices for minerals such as palladium and lithium was more than double that of oil and natural gas. This volatility not only complicates planning and investment for industries reliant on these minerals but also has broader economic implications, especially as the global economy shifts toward greener energy solutions. In section 3.1, we explore the impact of mineral price shocks on the economy, particularly in comparison to oil price shocks.

2.4. The Impact of Critical Minerals on the Economy

Although the share of critical minerals in the overall economy is smaller than that of oil and fossil fuels, their strategic importance has grown significantly. As noted in section 2.1, the geographical and geological concentration of these minerals, coupled with increasing demand, makes their supply chains particularly vulnerable to disruptions. Any interruption, whether due to local labor market issues, geopolitical instability, extreme weather, or natural disasters, can cause substantial price volatility.[82] This volatility has the potential to ripple through the economy, affecting everything from manufacturing costs to consumer prices, similar to the oil crises of the past.

Historically, fluctuations in oil prices have had profound macroeconomic impacts, influencing inflation and unemployment and triggering shifts in energy policy and technology. Events like the 1973 oil crisis and the commodities boom of the 2000s demonstrated the immediate and widespread economic consequences of oil price shocks, which often lead to short-term demand destruction and GDP contraction, along with long-term gains in energy efficiency. In contrast, the economic effects of critical mineral price shocks, while significant, are less immediate. Such price shocks may lead to delays in capital investment and other challenges, particularly to long-term investment, technological advancement, and economic competitiveness.[83]

To study the differential impact between oil prices and critical mineral prices, the authors developed a comprehensive macroeconomic model.[84] Unlike oil, which primarily affects the cost of operating existing capital, minerals are integral to creating new capital, such as EVs and renewable energy infrastructure. The authors built on the framework established by Schubert and Turnovsky, which examines the effects of oil price shocks on the economy, and extended it to incorporate the distinctive role of minerals in the production of new capital that is crucial for green technologies.[85]

Specifically, a standard neoclassical growth model of an open economy that imports oil and minerals is examined. Output is produced with inputs of capital, labor, and oil, which is imported at an exogenous world price. New capital is built by investment in minerals, also at an exogenous world price, with associated adjustment costs. Unlike oil, which directly participates in the economy's production function, minerals influence future production through their role in capital formation, allowing for delayed effects due to investment cycles. Both investment costs for new capital and energy imports are paid for with exports of output, with trade balanced in every period. The economy is populated by agents that make decisions on consumption and labor supply. It also has access to the world capital market to borrow from international lenders. Borrowing is constrained by the lender's assessment of the economy's creditworthiness, and it is assumed the economy's borrowing premium increases with the country's debt-to-capital ratio.

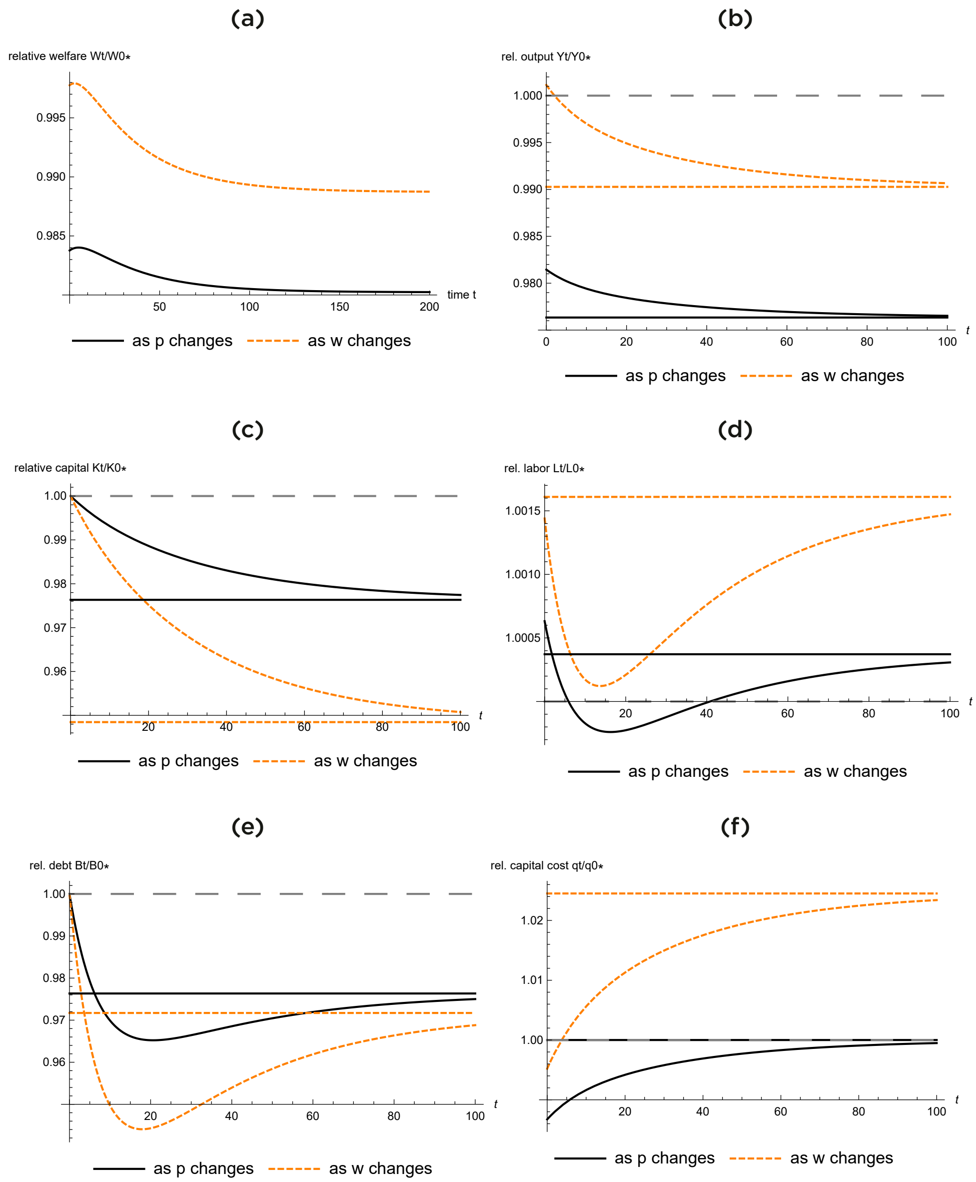
The authors investigated the impacts of oil price shocks and mineral price shocks under different scenarios of elasticity of substitution and the share of minerals and oil in GDP, representing economies of different OECD and developing countries. We also studied the impacts under two different schemes. Under the same-percent-shock scheme, we compared the transitional paths of the economy when mineral prices and oil prices, respectively, double. Under the same-budget scheme, we compared the transitional paths of the two price shocks, assuming in both cases that the economy's debt and deficit are fixed.

Key Findings

Figure 7 illustrates the impact of oil prices and mineral prices doubling, respectively. Our analysis reveals several key insights into the differential impacts of oil and mineral price shocks on the economy.

1. Long-term effects on output and welfare: Both oil and mineral price increases negatively affect economic output and welfare in the long run. However, the impact of mineral price shocks is less severe than that of oil price shocks. This difference is attributed to the distinct roles these resources play in the economy: while oil is a direct input into production, minerals are primarily involved in capital formation. This allows for a more gradual adjustment to price changes in minerals, mitigating the immediate impact on output.
2. Impact on labor usage: A notable finding is the contrasting effect on labor usage. In the short run, oil price shocks tend to reduce labor demand, as higher energy costs make production more expensive and reduce output. In contrast, increases in mineral prices lead to an increase in labor usage, as firms seek to offset the higher cost of capital by substituting labor, a more flexible input. In the long run, oil price shocks have little impact on labor, while the effect of mineral price shocks continues to promote labor usage, reflecting the ongoing need for labor in the production of new capital.

Figure 7: The impacts of oil price (p) versus mineral price (w) doubling on the economy. Note: The x-axis represents time (years), while the y-axis shows values relative to the pre-shock levels (the value prior to the price increase). Key findings indicate that both oil and mineral price shocks negatively affect long-term output and welfare, though the effects of mineral shocks are less severe due to minerals' indirect role in capital formation rather than as direct production inputs. Short-term labor impacts also differ: oil price increases reduce labor demand temporarily, while mineral price increases initially boost labor usage as firms substitute labor for costlier capital. Over the longer run, oil shocks have minimal effects on labor, whereas higher mineral prices persistently increase labor demand, driven by ongoing capital formation. In this figure, we assume the share of oil in GDP is 5%, the share of capital is 35%, and the share of labor is 60%. The share of minerals in capital is 14%, implying a 4.9% share of minerals in GDP. The detailed model and parameters can be found in Concordel, Ho, and Knittel (forthcoming).[86]



3. Role of financial markets: Our results demonstrate the important role financial market access plays in determining the long-term impact of price shocks. While the long-term effects of oil price shocks are primarily influenced by internal production conditions, the impact of critical mineral price shocks is governed by both the economy's production structure and its debt structure, which affects access to international finance. The relative rate of mineral prices to equity prices also plays a crucial role in determining the economy's ability to invest in new capital versus financing consumption through foreign debt.

Assumptions and Limitations

The authors note two important assumptions in our model, making our results an upper bound for the impact of mineral price shocks on the economy:

1. Uniform price increase across all minerals: The model assumes that the prices of all minerals increase simultaneously. In reality, this scenario is unlikely, as different minerals are concentrated in different regions and serve distinct roles in the supply chain. Consequently, their demand peaks at different times, leading to varying price dynamics.
2. No substitution with alternative materials: We assume that there are no viable substitutes for specific minerals in capital formation. However, in practice, as the price of a particular mineral rises, firms are likely to explore and adopt alternative materials or technologies. For instance, advancements in battery technology may lead to the use of different elements in place of traditional critical minerals, reducing dependence on any single resource (as has already been shown in the case of substituting cobalt with nickel).

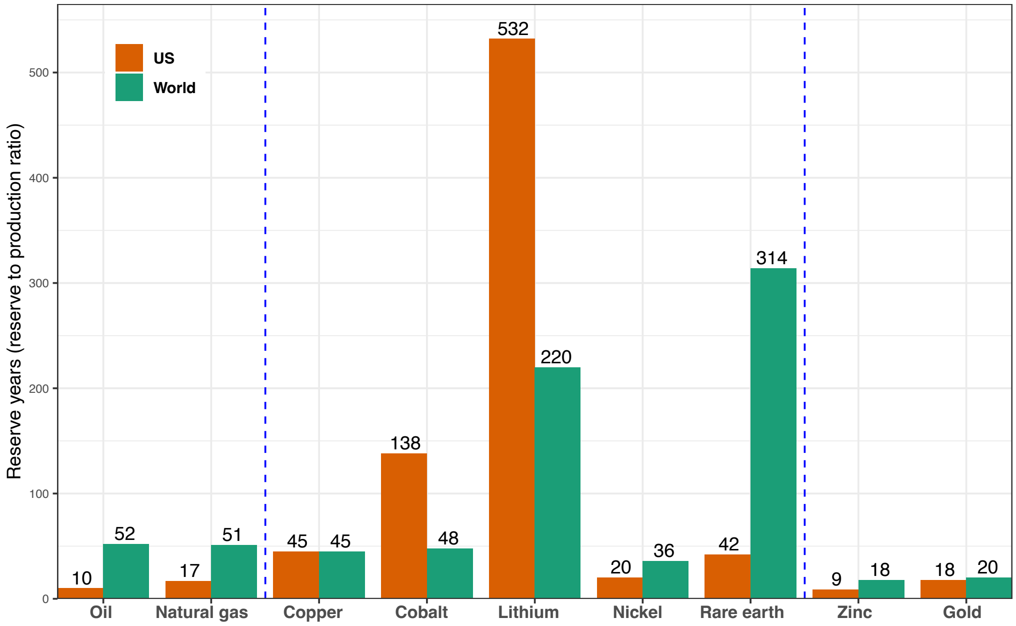
These assumptions suggest that the actual impact of mineral price shocks may be less severe than our model predicts, particularly as technological innovations and material substitutions continue to evolve.

Although the economic impacts of critical mineral price shocks may be less severe than those of oil price shocks, they still present significant challenges. These challenges could disrupt the economy, particularly as demand for these minerals continues to rise and their geographical concentration remains high. Our analysis emphasizes the need for a secure and stable supply; however, the reserves of critical minerals may not need to match the vast reserves traditionally held for oil. Understanding the current state of our reserves and resources is crucial for evaluating how best to meet future demand.

2.5. The United States' Current Mineral Reserves and Resources

The current status of mineral reserves and domestic production in the United States varies significantly by mineral, presenting a complex landscape of opportunities and challenges. While the United States possesses various mineral resources, the extent to which they are developed differs (see figure 8). For instance, the United States has substantial resources of certain minerals, like copper and cobalt, but because their domestic production often lags behind demand, the country must rely on imports. Conversely, the United States has limited domestic production capabilities of some minerals, such as graphite and manganese, which exacerbates its dependence on foreign sources.[87] An overview of the current state of reserves and production for selected critical minerals follows. Note: Reserves do not provide the full picture of US capabilities or lack thereof. Ideally, we would compare the costs associated with extracting the same amount of any given mineral.

Figure 8: Reserve years of selected critical minerals in the United States and globally in 2022–2023. Note: Data are collected from the IEA, EIA, and USGS Mineral Commodity Survey.[88]



Cobalt

Domestic production: In 2023, cobalt production in the United States was primarily derived from nickel-copper mining activities, with notable operations in Michigan and Missouri. The Eagle Mine in Michigan produced cobalt-bearing nickel concentrate, while in Missouri, efforts focused on processing historic mine tailings from nickel-copper-cobalt ore bodies.[89] Additionally, ore extraction commenced at a cobalt-copper-gold mine in Idaho, although operations were paused in March due to low cobalt prices.[90] Given these modest domestic mines, the United States remained heavily reliant on imports and recycled materials to meet domestic cobalt demand. The United States saw progress in cobalt processing and recycling projects, encouraged by government incentives like the Infrastructure Investment and Jobs Act of 2021 and the Inflation Reduction Act of 2022.

World resources: Although the United States has higher reserve years than the rest of the world (138 and 48 years of production, respectively), current cobalt extraction and processing in the United States is less economical than in the DRC and China. In fact, the gross total of identified resources of cobalt in the world is increasing, and it is greater than the identified cobalt resources in the United States. Domestically, the identified cobalt resources are approximately 1 million Mt, with significant deposits in Minnesota and occurrences in states like Alaska, Idaho, and Missouri.[91] Globally, identified cobalt resources total around 25 million Mt, predominantly located in sediment-hosted stratiform copper deposits in the DRC and Zambia, nickel-bearing laterite deposits in Australia and nearby island countries and Cuba, and magmatic nickel-copper sulfide deposits in countries such as Australia, Canada, and Russia.[92] Additionally, over 120 million Mt of cobalt resources are found in polymetallic nodules and crusts on the ocean floors.[93]

Copper

Domestic production: In 2023, the United States produced an estimated 1.1 million Mt of copper (valued at approximately $9.9 billion), an 11% decrease from the previous year. Arizona's production accounted for around 70% of the nation's output; additional mining took place in Michigan, Missouri, Montana, Nevada, New Mexico, and Utah.[94] Copper was processed at 25 mines, 2 primary smelters, 1 secondary smelter, 2 primary electrolytic refineries, 14 electrowon refineries, and 3 secondary fire refineries. Despite some delays and operational challenges, such as the snowfall and equipment failures that reduced capacity at the Bingham Canyon Mine, the United States continued to refine copper from both primary and secondary sources. The domestic market for copper was primarily driven by building construction (45%), followed by electrical and electronic products (22%), transportation equipment (16%), consumer and general products (10%), and industrial machinery and equipment (7%).

World resources: Global copper resources are extensive. The current global and domestic reserves of copper are 1 billion and 50 million Mt, respectively, each amounting to about 45 years of production. The USGS estimates identified global resources at 2.1 billion Mt as of 2015, alongside an additional 3.5 billion Mt in undiscovered resources. These resources are spread across various continents; significant deposits are found in South America, North America, and parts of Africa.

Graphite

Domestic production: The United States has not produced natural graphite since the 1950s and therefore fully relies on imports for its domestic consumption.[95] In 2023, around 95 companies, primarily in the Great Lakes and Northeast regions, consumed 76,000 Mt of imported graphite, valued at approximately $180 million. The main uses of natural graphite include batteries, brake linings, lubricants, powdered metals, and steelmaking. Demand for graphite, particularly in the lithium-ion battery sector, has been rapidly rising; in 2023, the number of US battery manufacturing facilities had grown from three (in 2019) to 10, and 28 more were under development.

In 2023, five companies were exploring or developing graphite mining projects in the United States: two in Alabama, one in Alaska, one in Montana, and one in New York. In July, the Graphite Creek Project in Alaska was awarded a $37.5 million grant through the Inflation Reduction Act of 2022. In November, a project in Alabama received a $3.2 million grant under the Defense Production Act. Two spherical graphite plants in Kellyton, Alabama, and Vidalia, Louisiana, were under construction in 2023; production was expected to begin in 2024. Additionally, five more plants in the United States were in early development.[96]

World resources: While domestic graphite resources are relatively small, global resources exceed 800 million Mt of recoverable graphite, representing 500 years of the current production rate. The world reserve of graphite is 175 years. China is the leading producer, responsible for 77% of the world's graphite production in 2023. China's export restrictions on certain graphite products in December 2023 heightened concerns about global supply security.

Lithium

Domestic production: In 2022, lithium was commercially produced in the United States from a continental brine operation in Nevada and from brine-sourced waste tailings at a magnesium producer in Utah. Additionally, in 2023, Exxon Mobil announced plans to open a lithium mine in Arkansas. Two companies processed lithium carbonate, chloride, and hydroxide into various downstream lithium compounds, withholding most production data to protect proprietary information.[97]

The majority of global lithium production came from seven mineral operations in Australia, one mineral tailings operation in Brazil, two brine operations each in Argentina and Chile, two mineral operations in Canada, five mineral and four brine operations in China, and one mineral operation in Zimbabwe.[98]

Globally, in 2022, batteries dominated lithium's end uses, accounting for 87% of demand, followed by ceramics and glass (4%), lubricating greases (2%), and other minor applications. The growing markets for EVs, portable electronics, and energy storage have significantly driven the uptick in lithium consumption in recent years. Due to the rapid increase in lithium demand for the green energy transition, established lithium operations worldwide expanded or were in the process of increasing production capacity. The US Department of Energy selected 12 lithium-based projects, funded with $1.6 billion from the 2022 Infrastructure Investment and Jobs Act, to support new commercial-scale domestic facilities for lithium extraction and processing, battery component manufacturing, recycling, and the development of new technologies to increase US lithium reserves.[99]

World resources: US and global lithium reserves are vast, equating to 156 years at the current production rate. Identified lithium resources worldwide have also expanded significantly due to ongoing exploration: they are now estimated at approximately 105 million Mt, equivalent to 583 years of current production. In the United States, measured and indicated lithium resources total about 14 million Mt, sourced from continental brines, claystone, geothermal brines, hectorite, oilfield brines, and pegmatites. Key global resources include those in Bolivia (23 million Mt), Argentina (22 million Mt), Chile (11 million Mt), and Australia (8.7 million Mt). There are other significant contributors (Canada, China, the DRC, Germany, Mexico, and several other countries), demonstrating the broad geographic distribution of lithium deposits.[100]

Manganese
Domestic production: The United States has not produced manganese ore containing 20% or more manganese since 1970.[101] Manganese ore is mainly consumed by six companies at seven facilities across the East and Midwest, primarily for steel production, either directly in pig iron manufacture or through upgrading the ore to ferroalloys. Manganese ferroalloys are domestically produced at two plants, and additional quantities of ore are used in non-metallurgical applications such as animal feed, batteries, and fertilizers.[102]

China dominates the production of high-purity manganese materials and supplies 97% of the global battery-grade manganese sulfate.[103] Utilizing highly specialized production processes, which depend on the type of ore, China has gained a significant advantage in expertise and infrastructure, posing a challenge for the diversification of the supply chain. Although refining projects are in development in countries like Australia, Canada, the Czech Republic, South Africa, and the United States, the current lack of diverse production sources for high-purity manganese creates a bottleneck for the growth of the battery industry.[104]

World resources: While global manganese resources are extensive, they are unevenly distributed. South Africa possesses about 70% of the global manganese resources, making it the dominant source.[105] In contrast, US resources are low-grade and costly to extract. As of 2023, the world's manganese reserves—of which South Africa and Australia together hold half, followed by China with 15%—are estimated to last 95 years at the current production rate.

Nickel

Domestic production: In 2023, the Eagle Mine in Michigan produced approximately 17,000 Mt of nickel concentrate, which was exported primarily to smelters in Canada and overseas. Additionally, nickel in crystalline sulfate was obtained as a byproduct of smelting and refining platinum-group-metal ores in Montana. Missouri also contributed with nickel-copper-cobalt concentrate from historic mine tailings. In September, the US Department of Defense granted $20.6 million to a nickel-copper-cobalt project in Minnesota, aiming to strengthen the domestic supply chain.[106] The current main uses of nickel in the United States are alloys, steels, electroplating, and other applications; stainless and alloy steel account for over 85% of domestic consumption.

World resources: US nickel reserves are expected to last 20 years at the current production rate, while global reserves are expected to last 36 years. Indonesia, Australia, and Brazil together account for 73% of the world's nickel reserves: 42%, 18%, and 12%, respectively. Global nickel resources are estimated at more than 350 million Mt, equivalent to 97 years at the current production rate. About 54% of these resources are found in laterites and 35% in magmatic sulfide deposits. The remaining 10% come from hydrothermal systems—including iron-nickel alloy, volcanogenic massive sulfide deposits, sedimentary-hosted polymetallic deposits, and seafloor manganese crusts and nodules—and 1% come from other sources, such as tailings.[107]

Rare Earth Elements (REEs)

Domestic production: In 2023, REEs were mined in the United States. Bastnaesite, a rare earth fluorocarbonate, was extracted as a primary product at a mine in Mountain Pass, California. Additionally, monazite, a phosphate, was stockpiled in the southeastern United States, and mixed rare earth compounds were produced in the western United States. The estimated value of rare earth compounds and metals imported by the United States in 2023 was $190 million, a 7% decrease from 2022. The leading domestic end use of REEs was in catalysts. Significant amounts of REEs are imported as permanent magnets within finished goods. Other uses include ceramics, glass, metallurgical applications, and polishing.

World resources: REEs are relatively abundant in the Earth's crust, but their concentration makes their extraction and processing less economically viable than those of many other minerals. The United States has a reserve of 42 years at the current domestic production rate. Globally, the reserve stands at 110 million Mt, equivalent to 314 years of current production. China holds 40% of the world's reserves, and Vietnam and Brazil each account for 20%. In North America, the United States has 3.6 million Mt of measured and indicated resources, while Canada has over 14 million Mt.[108]

Zinc

Domestic production: The estimated value of zinc mined in the United States in 2023 was $2.4 billion. Zinc was mined in five states at seven mining operations by five companies. Two smelters, one primary and one secondary, produced most of the country's commercial-grade zinc metal.[109] The majority of zinc consumed domestically was used in galvanized steel production, followed by brass, bronze, zinc-base alloys, and other applications.

World resources: The US and global reserves of zinc are 9 and 18 years, respectively, based on current production rates. Zinc production and reserves are much less concentrated compared to those of other critical minerals. As of 2023, the global reserve is 220 million Mt; Australia holds the largest share, 29%, and China the second largest, 20%. Zinc is the 23rd most abundant element in the Earth's crust. Global identified zinc resources are approximately 1.9 billion Mt, which equates to 158 years at the current production rate.[110]

Advancing US Mineral Supply

Considering the current state of mineral production and reserves in the United States, several key considerations must be addressed in order to increase domestic supply. As discussed in section 3, it is crucial to reform the permitting process so as to facilitate the development of new mining projects while also mitigating significant mining-related environmental and health impacts on communities and ecosystems.

3. Sustainable Supply

In the face of the energy transition, the United States could play a pivotal role in supplying critical minerals essential for technologies like EVs, renewable energy systems, and advanced electronics. However, realizing this potential requires overcoming significant impediments. Chief among these are (1) the negative externalities associated with mineral extraction and processing and (2) the need for reform in the permitting process to ensure a sustainable and responsible approach to resource development. Here we outline the background for these two dimensions.

3.1 The Negative Externalities of Mining and Minerals Extraction

Mining activities have impacts both locally (e.g., groundwater and soil pollution, plant growth inhibition) and regionally (e.g., habitat fragmentation, air pollution, acid mine drainage). The effects of mining and processing on human well-being include impacts both on miners and workers in the sector and on communities in intensive mining regions. The extent and breadth of environmental impacts underscore the need for pervasive sustainable mining practices to minimize damage.

The negative impacts of mining are inversely proportional to the level of mitigation in place. Mining and processing activities often reshape the host environment and can exacerbate preexisting vulnerabilities, particularly in regions where governments struggle or show reluctance to safeguard against severe social and environmental externalities. The practices of individual governments in managing and regulating their mining sectors vary by region, adding complexity to this issue. Indeed, the impacts of mining and processing operations differ significantly between regions like the United States and Canada—where stringent environmental regulations, labor standards, and community engagement requirements typically govern mining operations—and other parts of the world where regulatory frameworks may be less rigorous, allowing for greater environmental impacts and social challenges. In the appendix, we examine several case studies, contrasting mining practices in the United States and Canada with those of major producers in the rest of the world.

Environmental Externalities

The largest physical disturbances are located at the mine sites themselves, especially in the case of open pits (as opposed to underground mines) and the associated waste rock disposal areas, which range from hundreds to thousands of acres. Mineral processing also generates large amounts of waste, such as tailings (i.e., the waste stream resulting from ore processing) and slag (i.e., the waste resulting from metallic ore smelting). These waste deposits can pollute soils and water, as do mine tailings—most commonly through the oxidation of sulfide minerals, especially pyrite (strongly present in ores).[111] Once exposed to air and water, pyrite breaks down, producing sulfuric acid, which can inhibit plant growth at the surface of a waste pile. Bare, non-vegetated, orange-colored surface materials make some waste rock disposal areas highly visible, which is the most obvious result of these acidic conditions. The negative impact of mining on vegetation regrowth consequently undermines biodiversity, soil health, erosion control, water cycle regulation, and carbon sequestration, among other things.

During the extraction and processing phases, water can also be contaminated with toxic substances, such as acids, leaching agents, and heavy metals. The processing phase, particularly in certain regions, requires intensive use of water, which is also at risk of contamination. Sulfuric acid results in acid mine drainage (AMD), lowering the pH of water. AMD water also contains heavy metals, which generate a bioaccumulation effect for aquatic life in the environment.[112] If AMD is left uncontrolled, the resulting acidic and metal-bearing water may drain into and contaminate streams or migrate into the local groundwater, inhibiting its use for drinking water or irrigation.

At the regional level, the infrastructure that supports mining activities, including roads, ports, railway tracks, and power lines, can affect the migratory routes of animals and increase habitat fragmentation.[113] Some studies have explored specific examples: de Castro Pena et al. assessed the impacts of mining activities on the geographic distribution of eastern Brazil mountaintop endemic species, Zhuo et al. studied the effect of mining and road development on habitat fragmentation and connectivity of Chinese khulan, and Macura et al. highlighted the impacts of mining-related activities in the Boreal and Arctic regions' environmental systems.[114]

Pollutants associated with mining and processing can travel very long distances based on different transportation vectors. Air contamination has strong impacts on the environment: when sulfur dioxide, for example, reacts with atmospheric water vapor, it forms acid rain. The acidic conditions that develop in the soils where these emissions precipitate can harm existing vegetation and prevent new vegetation from growing. Similarly, waterways and atmospheric deposition have been found to pollute lakes by transporting the toxic metals released by mining and processing activities, with clear detrimental effects on the biota and on humans who consume aquatic organisms.[115]

Health Externalities

The health impacts of mining and processing, particularly of critical minerals, have been a subject of concern because of potential risks to both workers and surrounding communities. Mining operations are globally extensive and generate large quantities of particulates almost continuously, potentially yielding toxic contaminants.

Mining's impacts on health strongly depend on the resource as well as its production phase—i.e., exploration, mining, mineral processing, metallurgic processing, closure, and the related operations (excavating, crushing, grinding, separation, smelting, refining, and tailings management). The type, amount, and properties of mineral waste produced at different mines depend on the mineral, the process technologies used, and the geological context.

Mining environments emit dust and aerosol particles that can mobilize toxic elements, such as arsenic (naturally occurring on the earth), cadmium (in the earth's crust, associated with zinc, lead, and copper ores), cyanides (used in extraction processes), lead (resulting from mining activity), mercury (released from the breakdown of minerals in rocks), nickel (mined and also released by power plants and trash incinerators), and uranium (where mining and milling processes increase the amount of this radioactive element).

For example, polymetallic mines (where copper, gold, lead, silver, and zinc are extracted) as well as metal smelters produce pollutants, especially in the form of heavy metals (particularly lead); bulk metal mines produce primarily particulates. The type and magnitude of health impacts depend on the pollutants' type, size (i.e., ultrafine, accumulative, or coarse), concentration, and transportation pathways (i.e., air, water, soils, biota).

It is important to consider the population impacted by mining activities, whether they work in the mines or live in the surrounding area. Miners and workers in smelters can be affected by environmental exposure to dust, contaminated air, and noise pollution, as well as non-environmental hazards such as mining accidents. Environmental exposure to pollutants can result in a range of respiratory complications (e.g., pneumoconiosis, asbestosis, silicosis) and cancers caused by exposure to radioactive material (e.g., radon gas). Non-environmental hazards include injuries, fatalities, and stress from the working environment or managerial pressures. All these issues are exacerbated in the case of artisanal mining.[116]

Surrounding communities are also affected by contaminated air, water, soil, and plant and animal life. Communities are also at risk of social and emotional impacts—derived from, for example, the appropriation of land and alterations to social relationships.

Impact on Workers

One of the most hazardous occupations in the world, mining causes both short-term injuries and fatalities and long-term health impacts. Significant impacts on workers' health include cancer and respiratory diseases such as asbestosis (caused by the inhalation of asbestos fibers), silicosis (caused by exposure to respirable silica dust), and pneumoconiosis (particularly common in coal miners). Mining, by generating dust that may contain toxic elements, increases the risk of breathing impairments, tuberculosis, lung cancer (e.g., via air pollution, radon, or asbestos), and autoimmune diseases.[117] Other important physical effects not expanded on here include those of noise, heat, and humidity.[118]

Usually, miners are exposed to toxic elements through three routes: inhaling particles, swallowing particles that land on food or cigarettes, and direct contact with the skin or eyes. Due to the confined, poorly ventilated spaces where most miners work, inhaling toxic particles and pulverized airborne dust is the most common form of hazardous exposure.[119]

In the area of mental health, several studies have highlighted issues affecting miners (see Matamala Pizarro and Aguayo Fuenzalida for a literature review), such as "job strain, unsafety experiences, poor quality of sleep, non-subjective well-being, job unsatisfaction, social-relations conflict, risk of accidents and injuries, musculoskeletal disorders (MSDs), substance abuse, dangerous working conditions and demanding job organization."[120]

When discussing the health impacts of the mining sector, it's important to distinguish between the types of mining and minerals involved. For historical reasons, the literature has focused on coal mining. However, coal's relevance is expected to diminish over time due to the phase-out (or phase-down) policies necessary for the energy transition and, in the United States, cost competition with low-priced natural gas.

We have described the common factors that link the environmental and social impacts of mining across commodities; now, we briefly mention some examples of direct effects associated with exposure to specific metals.

Cobalt extraction is particularly harmful, as it can damage the eyes, skin, heart, and lungs and eventually cause cancer. These harms are magnified in artisanal, small-scale mining (a major issue in the DRC), while in areas where industrial, mechanized extraction is used (like the United States and Canada), we typically see fewer adverse health effects from contaminant exposure. Industrialized mining yields fewer social harms (e.g., child labor).

Lithium exposure can cause irritation and, at high levels, can provoke fluid buildup in the lungs, headaches, muscle weakness, and seizures. Lithium is highly reactive, corrosive, and flammable, especially in moist environments. Its production, which involves a leaching process, has some of the worst levels of ecotoxicity and generates the greatest health risks in the mining sector. Moreover, when lithium is extracted via brine, the evaporation ponds involved require substantial amounts of water, which is often sourced by diverting hydrological resources from nearby communities, affecting their livelihoods and the local environment. This is especially relevant in South America, a major producer of copper and lithium, where water scarcity is a significant problem.[121]

Prolonged contact with nickel can result in various adverse health outcomes, including allergies, cardiovascular and kidney diseases, lung fibrosis, and lung and nasal cancer. Since nickel has been used extensively for over a century, its health impacts are well documented and are being addressed through the ongoing efforts of organizations like the US Environmental Protection Agency. However, Indigenous rights remain a frequent source of controversy in the largest nickel-producing countries, such as Canada, according to the ISS.[122]

These acute examples demonstrate the need to analyze the social and environmental costs of each commodity on a project-by-project basis and along each supply chain, given the significant differences in minerals, mining techniques, and processing approaches.

Impact on Communities

The risks of adverse health impacts extend far beyond a mine's perimeter. Beyond those employed in mining, the industry also affects the surrounding communities.

The high concentrations of potentially harmful contaminants and particulate emissions from mining result in severe contamination of soil, water (surface and aquifer), and air. Communities may be impacted via groundwater and surface water as contaminants make their way through the food chain, resulting in ingestion of contaminants from the soil.

As discussed, different contaminants are associated with different health effects. For instance, particulate matter, dispersed via atmospheric dust and aerosol, is linked to respiratory disease and gastrointestinal problems, while heavy metal exposure can cause organ damage and poisoning. The contamination risk is also group-specific: for instance, children are particularly vulnerable to contaminated soil because their frequent hand-to-mouth activity increases their risk of ingesting it, leading to gastrointestinal problems, developmental delays, and elevated levels of toxic metals in their blood.[123] Pregnant women living near mining areas may face additional health risks, such as reduced hemoglobin levels.[124]

The spatial extent of contamination—a significant parameter to measure—depends on the type of pollutant and, consequently, the transportation vector. For example, fine particles (PM10 or smaller), such as those resulting from surface mining, smelting operations, or road dust, disperse readily into the environment, often in association with aerosols, and may be disseminated through the air over large distances, creating a vast spectrum of contamination.

In the case of heavy metals, studies have shown that, based on measured blood lead levels in communities near smelters, the critical distance for contamination is

0.5 to 4 kilometers from the point source of emissions. One study looked at 800 mines and the communities living within 5 kilometers and found that hemoglobin levels in adult women were strongly depressed and that their ability to recover hemoglobin levels after blood loss during pregnancy and delivery was particularly impaired. The authors of the study, Von der Goltz and Barnwal, linked this and other health conditions to heavy metal toxicity.[125]

3.2 Permitting in the United States

Before a mine can operate, the mining company must first obtain the necessary permits. Permitting requirements ensure that mines meet rigorous environmental and safety standards intended to mitigate potential adverse impacts. The permitting process begins at the exploration phase, and permits must be in place before construction begins. The US permitting process extends across the federal, state, and local levels—each state having its own requirements and standards for water use, air quality control, and wildlife protection.[126] While the regulatory framework is essential for safeguarding environmental and community health, it can often extend the timeline for bringing a mine into operation. A single mining project may require obtaining as many as 30 different permits from various authorities, a process that can span several years—in many cases, 7 to 10 years or longer—from exploration to production.[127] Such lengthy timelines create a major bottleneck in the effort to increase domestic mineral output.

The United States faces a competitive disadvantage against countries like Australia, Canada, and Chile, where mine permitting processes have shorter timelines.[128] Furthermore, predictable permitting timelines in these countries encourage investment, potentially exacerbating US reliance on imports.

Each permitting process is unique: it depends on the size of the mine and the land where the mine is to operate. Typically, the permitting process begins at a state's department of natural resources or environmental quality. State and local permits typically pertain to hazardous materials and waste, mining operations, occupational safety, and environmental factors—that is, protecting attributes of the local and regional environment like air quality, water quality, and habitat preservation.[129] Some states allocate water use with a single permit, like Alaska, while others, like Arizona, allocate water use on a resource-specific basis and require separate permits to access surface, ground, or recycled water resources.[130] Depending on the unique attributes of the project, other state and federal agencies then get involved.

At the federal level, agencies like the Bureau of Land Management (BLM), Army Corps of Engineers (USACOE), Environmental Protection Agency (EPA), and Forest Service (USFS) can be involved in the permitting process, depending on the features of the mining project. Federal permits encompass all the same categories as state and local ones (hazardous materials and waste, mining operations, occupational safety, and environmental factors), but federal agencies also review and approve the mine plan.[131]

The following list shows categories of permits commonly encountered at the local, state, and federal levels.

Local Permits

- Large mine permit. Issued by the local or state government for the mine to operate within that jurisdiction. Small-scale mine permits are also issued depending on the size of the mine.

State Permits

- Water allocation, protection, and/or quality permits. Issued by the state equivalent of a department of natural resources or department of environmental quality. Water use may be streamlined into one permit or may require multiple permits, depending on the state. Water use permits depend on the water rights in the state. Water protection or quality permits may extend to the federal level and are based on standards set by the EPA.
- Air quality permits. Issued by the state equivalent of a department of natural resources or department of environmental quality. Air quality permits may extend to the federal level and are based on standards set by the EPA.

Federal Permits

- Environmental review. The Environmental Impact Statement (EIS), a study on environmental impacts that is open to public comment, informs the National Environmental Policy Act (NEPA) review, which integrates environmental factors across federal agencies. After the NEPA review, a Record of Decision (RoD) is often issued by USFS or BLM to permit or deny project continuation. The EIS, the NEPA review, and the RoD are not permits; rather, they are authorizations that provide review, analysis, and critical information that other agencies with permitting authority may use to make their decisions.
- Clean Water Act (CWA) permits. Common CWA permits include Section 404 Permits and National Pollutant Discharge Elimination System (NPDES) Permits. Section 404 regulates the discharge of dredged or fill materials to waters and wetlands; such permits are issued by USACOE. NPDES regulates pollution discharge to US waters; such permits are issued by the EPA.
- Clean Air Act Permits. Issued by the EPA to regulate sources of air pollution.
- Endangered Species Act Permits. Issued by the US Fish and Wildlife Service to regulate the incidental take of endangered or threatened species. These permits also include requirements to minimize disturbances to wildlife.
- National Historic Preservation Act Permits. Issued by the EPA to regulate mines sited on or near historical sites. This applies to sites that are categorized as historic properties on the National Register of Historic Places.
- Plan of Operations. Grants permission to mine on federal lands. Issued by BLM and USFS, in coordination with other relevant federal agencies.

Long permitting timelines present a challenge to onshoring mining activity and slow down the supply of critical minerals—many of which are necessary for accelerating the energy transition. US permitting timelines are much longer than those of other countries.[132] For example, the permitting process takes 7 to 10 years on average in the United States compared to 2 years on average in Canada and Australia.[133] In Australia, permitting timelines are relatively shorter because there are fewer agencies involved in issuing permits and timelines for permit review within agencies are shorter.[134] In Canada, permit requirements are established at the beginning of a project, so timelines are better defined and more predictable.[135] Oftentimes, permitting delays in the United States are due to unexpected factors that are difficult to predict, like local community reactions, legal challenges, or complications in obtaining environmental permits.[136] Many mines undergo NEPA review, which can be one of the lengthiest parts of the permitting process. Additionally, many states have adopted a state-level NEPA-equivalent review process.[137] These environmentally rigorous reviews could be streamlined with interagency coordination in permit review and approval.

There have been a number of legislative proposals in the US Congress intended to streamline the permitting process and prevent delays. These have received support from mining and EV companies and skepticism from environmental groups concerned about the detrimental effects of cutting corners in environmental reviews. Mining and EV companies are interested in the necessary supply coming online as soon as possible and see parts of the permitting process as a source of unnecessary delay. In contrast, environmental groups see the permitting process as an extensive review necessary for projects to meet rigorous environmental standards. While balancing these two views maybe challenging, there are likely to be ample opportunities for win-win arrangements.

When procuring local permits, mining companies may choose to make agreements with local communities to speed up the process. Community benefits agreements (CBAs), also known as good neighbor agreements, create long-standing relationships between the mining company and the community surrounding the mine site and ensure that the community receives certain benefits from the project. These can include provisions like a local hiring requirement, higher standards for water quality, collaboration on tailings facility design, and local traffic reduction.[138] Implementing CBAs takes time, not only during the phase of relationship building with the community before the project commences but also while maintaining the relationship over the course of the mine's lifetime. That said, taking time to work with the community to build a project can benefit all stakeholders, result in better social and environmental outcomes, and mitigate mine development delays during the permitting process.[139]

When developing mine sites, companies must account for the societal factors at play in the surrounding communities—particularly Indigenous and rural ones. More than half of the world's metals required for the energy transition are located on or near Indigenous lands.[140] Mining companies often face conflicts with these communities—in particular, disagreements on the socioeconomic value of the land. For example, mining can disrupt local traditions that rely on the natural environment, like hunting and fishing.[141] Though mining operations bring substantial economic activity, jobs, and infrastructure to more remote areas, they also bring demographic shifts that can increase inequities in already disadvantaged communities. For example, in South America, non-local workers have been known to migrate to mining communities in search of higher-paying mine jobs, driving up the prices of housing, education, and other goods and ultimately displacing the local population.[142] As more mines come online to meet the growing demand for metals required by the energy transition, these problems will continue to come to the forefront. Therefore, collaboration with the communities surrounding mine sites is a necessary step toward an equitable future for mining in the United States and abroad.

4. Recommendations to Increase Domestic Supply

4.1 The Roosevelt Perspective

The extraction and processing of critical minerals like cobalt, copper, lithium, nickel, and rare earth elements (REEs) pose significant environmental and societal challenges, especially for vulnerable communities. As the United States mobilizes to expand its supply of strategic metals and minerals—vital for the electrification of transportation, buildings, and other energy-intensive sectors and for national defense and security—it is essential that it does so in a manner that respects the principles of economy, environment, and equity.

It is crucial to ensure that vulnerable communities are not marginalized or harmed as we strive to meet the increasing demand for critical minerals. This section underscores the importance of sustainable practices that safeguard and enhance the health, livelihoods, and rights of affected populations. Mining operations should not disproportionately impact those living near extraction sites but rather contribute positively to the long-term sustainability of resource-rich areas. In this context, permitting, explored in section 3, plays a critical yet challenging role. For the United States, expanding the mineral supply is urgent, and permitting requirements can sometimes delay or even halt progress. However, it is necessary to ensure that mines adhere to strict environmental and safety standards and mitigate potential negative impacts. Striking a delicate balance between these competing priorities is key.

The growing expectation for the mining sector to contribute to sustainable development is driving progress in the industry. This is becoming particularly evident as the environmental, social, and health impacts of mining and processing activities are increasingly studied, monitored, and quantified. Section 3 explores these negative environmental and health externalities. Section 4 focuses on identifying a series of best practices. These include advanced land rehabilitation techniques, low-impact mining methods, waste reuse, eco-friendly equipment, and efforts to combat illegal mining, all of which are part of the industry's shift toward sustainability. Although some of these technologies are still in development and may not yet be economically feasible, the overall trend toward more environmentally friendly mining and processing practices is clear, especially given the increasing role of digitalization and technological advancements, which are explored further in section 4.

By emphasizing best practices, we uphold the Roosevelt Project's vision of balancing economic advancement with environmental stewardship and social equity. Our approach advocates for policies that support sustainable supply chains for critical minerals, ensuring that the energy transition is both swift and just.

4.2 Recommendations on Permitting

Crucially, to strengthen domestic supply and support the green energy transition, the United States must streamline its permitting process. Developments in countries like Australia, Canada, and Chile, which have reformed their systems to balance environmental protections with faster approvals, offer valuable lessons. Another important example comes from Germany, which, in response to geopolitical pressures, designated clean energy projects as critical to national security, reducing the number of required environmental assessments and streamlining bureaucratic procedures.[143] This allowed the country to rapidly expand its renewable energy capacity, offering a potential model for US reforms. As these examples show, a more efficient permitting process, with more predictable timelines and better coordination between regulatory agencies, could enable the United States to accelerate mineral production without compromising environmental protections.

Recommendation I: Reform permitting to accelerate deployment of new projects

The US government should streamline the permitting process for critical mineral mines by holding reviewers accountable to deadlines and implementing transparency and tracking measures. Future streamlining efforts can be built into existing measures, like FAST-41. Enforcing review timelines should not preclude rigorous environmental assessment and sufficient public comment periods. A streamlined and incentivized permitting process that decreases lead times and inertia will encourage the development of domestic mining projects. At the same time, by setting high standards, such a process should ensure that the increase in mining activities does not come at the cost of environmental degradation or social unrest.

As discussed in section 3, long permitting timelines present a challenge to onshoring mining activity and slow down the supply of critical minerals—many of which are necessary for accelerating the energy transition. US permitting timelines are much longer than those of other countries.[144] For example, the permitting process takes 7 to 10 years on average in the United States compared to 2 years on average in Canada and Australia.[145] In Australia, permitting timelines are relatively shorter because there are fewer agencies involved in issuing permits and timelines for permit review within agencies are shorter.[146] In Canada, permit requirements are established at the beginning of a project, so timelines are better defined and more predictable.[147] Many of the permitting delays in the United States are due to unexpected factors that are difficult to predict, like local community reactions, legal challenges, or complications in obtaining environmental permits.[148]

Twin Metals mine tells a story of risk and uncertainty in the mine permitting process. Currently, in the United States, a particular permitting dynamic is at play: so that mining companies can recover the costs of a 7- to 10-year permitting process, proposed mines tend to be particularly large.[149] While larger mines can generate greater economic growth for the surrounding area, they also tend to have greater environmental impacts. At the same time, many mineral deposits have already been found, and ore grades are declining.[150] Because of the interplay between these factors, mineral developments in the United States could take longer to permit today than they have in the past. The modernization of the permitting process should take this reality into account and provide avenues to address these challenges.

Though the current steps in the permitting process are necessary for rigorous review, some actions can be taken to speed up that process: for instance, holding reviewers accountable to limits on permit review times. Currently, in the United States, there are no maximum review times governing how long a permit can sit with any agency for review. Introducing maximum review times would incentivize agencies to familiarize themselves with projects in a timely manner and would also reduce the likelihood of politically induced delays. Canada's enforcement of maximum review times helps keep its mine permitting timelines much shorter than the United States' and can be looked to as an example.

Recommendation II: Create community benefits agreements (CBAs) for new projects

Mining operators should implement CBAs as a key tool to build trust, secure local support, and ensure that projects move forward efficiently. These agreements are not a regulatory hurdle; rather, they can serve as a critical enabler of timely project completion by proactively addressing matters such as community concerns, economic opportunities, and environmental safeguards. When CBAs are structured with clear, transparent commitments, they reduce opposition, mitigate operational risks, and foster long-term cooperation, helping avoid costly delays caused by public resistance or legal challenges.

By prioritizing local hiring, investment in local infrastructure, and environmental protections, CBAs ensure that mining projects deliver tangible benefits to the communities they impact. Reinforcing a partnership-based approach strengthens the industry's social license to operate and enhances regulatory compliance, investor confidence, and corporate reputation. Ultimately, responsible engagement with local stakeholders is not a barrier to project success—it is the foundation for long-term operational stability and accelerated project execution.

Evidence supporting this recommendation can be found in an example from East Boulder and Stillwater mines. A good neighbor agreement (GNA), one form of a CBA, was signed by community groups and the East Boulder and Stillwater Mines. The GNA was created with the goals of (1) minimizing adverse impacts on local communities, economies, and the environment, (2) maintaining open lines of communication between GNA members, (3) providing the opportunity for GNA members to participate in mine decision-making, (4) binding GNA members to the GNA for the lifetime of the mine, and (5) establishing processes to resolve disputes and avoid litigation.[151] The GNA takes a "precautionary and proactive" approach, particularly in its environmental provisions, empowering members as stewards of the local environment and promoting adaptability to any challenges that may arise. This proactive approach stands in contrast to state regulation, as the state intervenes only once it has detected environmental harm.

The GNA is a legally binding contract between the mine owner, Stillwater Mining Company (SMC); Northern Plains Resource Council (NPRC); Cottonwood Resource Council (CRC); and the Stillwater Protective Association (SPA).** NPRC, CRC, and SPA (the Councils) are all grassroots community organizations with voting members on the GNA's committees. The GNA is also supported by technical advisors, who provide expertise to SMC; two committees, which are the voting bodies on mine decision-making; and a GNA manager, who is employed to maintain the GNA full time. The GNA is attached to the mine property, a unique and critical feature of the agreement that requires it be upheld regardless of mine ownership.

The legally binding nature of this GNA, the on-demand technical expertise available, and the trust built among stakeholders are some of the critical successes that make the model worth replicating elsewhere. However, it has limitations. For instance, the volunteer nature of the GNA task force may make succession planning difficult. Furthermore, negotiating environmental standards depends on specific features of the ore body, a potential limitation to replicating this or any GNA. The mine permitting process in the United States is an iterative one: it is designed so that mines can change over time with very few binary

** SMC's ownership has changed over the years.

permit-issuing decision points. The GNA allows for the involvement of community groups in that iterative process, helping shape mine operations at each decision point to better reflect environmental, social, and community priorities.

Recommendation III: Seek FAST-41 coverage

The Fixing America's Surface Transportation (FAST) Act established the Federal Permitting Improvement Steering Council (FPISC) in 2015. Title 41 of the FAST Act creates a transparent permitting process for covered infrastructure. Mining projects became eligible for FAST-41 coverage in January 2021.[152] In 2023, the FPISC proposed revising the covered mining infrastructure such that only critical mineral mining, refining, and recycling projects are covered.[153] Interviews with mining companies indicated that these new rules will be beneficial for the mining industry. Projects can be covered under FAST-41 if they meet a set of objective criteria on environmental review and project size. Additionally, the Inflation Reduction Act (IRA) allocated $350 million to the FPISC to aid in eliminating roadblocks and enhancing environmental review.[154]

Mining operators should leverage FAST-41. By providing a more transparent, coordinated, and predictable federal environmental review and authorization process, FAST-41 can significantly reduce the time and uncertainty associated with obtaining necessary permits. This not only accelerates project timelines but also enhances predictability for project planning and investment decisions, potentially lowering costs and improving the viability of projects. Moreover, FAST-41's emphasis on interagency collaboration and stakeholder engagement can help address environmental and community concerns more effectively, thus contributing to the mining sector's social license to operate and fostering better relationships between mining operators and local communities and regulatory bodies.

Since mining is a newly covered project category and mines are not proposed in the United States very often, as of 2023, there was only one mining project in the United States that had been FAST-41 designated: a proposed zinc and manganese mine in southern Arizona. The list of covered projects has been expanded periodically and includes 10 projects as of 2025.[155] Once approved for FAST-41 coverage, mining developments are subject to a permitting process that integrates all federal environmental reviews and authorizations on a transparent and comprehensive timetable.[156] Additionally, federal legislation has been proposed to streamline permitting delays. In 2023, a bill was introduced in Congress that proposes permitting reforms on federal lands (H.R.209). The bill has received support from mining and EV companies and skepticism from environmental groups concerned about the detrimental effects of cutting corners in environmental reviews.

4.3 Recommendations on Best Practices

Recommendation IV: Adopt best practices and advanced mining technology

Communities and Health

It is essential for mining operators and regulatory bodies to implement comprehensive occupational health and safety measures that protect workers as well as effective environmental management strategies to minimize the health risks posed to nearby communities. Further research is needed to better understand and mitigate the adverse health impacts of mining and processing, especially in the context of critical minerals, to ensure the well-being of both workers and nonworkers alike.

The US government has already taken action to enhance safety in mines. The Mine Improvement and New Emergency Response (MINER) Act of 2006 permanently established the Office of Mine Safety and Health Research (OMSHR), under the direction of an associate director, within the National Institute for Occupational Safety and Health. The MINER Act grants OMSHR the authority to (1) award competitive contracts and grants to institutions and private entities to encourage the development and manufacturing of mine safety equipment and (2) award contracts to educational institutions or private laboratories for the performance of product testing or related work with respect to new mine technology or equipment.

Mining companies play a central role in minimizing the spread of diseases within their workforce by adhering to occupational health and safety standards, improving living conditions, providing adequate health services, and investing in preventative measures. For example, in the area of respiratory diseases, progress has been made toward achieving higher-quality mine ventilation that provides clean air flow to miners, as well as instituting regulations that prevent miners from working in higher-than-acceptable levels of dust (monitored by air sampling instruments). All this has been achieved through continuous innovation in equipment and software, which has led to increased mechanization and automation of the sector.

In the pursuit of environmental justice and community well-being, it is crucial to consider critical mining employment opportunities. Such opportunities can further equitable economic development, especially in communities affected by mining activities, which are often marginalized. By providing fair and meaningful employment, mining companies can contribute to local economies, enhance social inclusion, and help mitigate the adverse environmental and social impacts of mining. This approach is integral to fostering sustainable practices in the industry, ensuring that the benefits of resource extraction are shared equitably and that local communities are not disproportionately burdened by its impacts.

Firstly, the shift in mining employment from coal to critical materials marks a significant transformation in the industry, underlining changing economic and environmental priorities. This transition is reshaping the workforce landscape, as the skills required for mining critical materials like lithium, cobalt, and REEs differ from those needed in the coal industry. Workers previously employed in coal mining areas are now facing the need to adapt to new technologies and processes associated with critical materials mining. This shift also has geographical implications, as critical material deposits are often located in different regions than traditional coal reserves, leading to a shift in the geographic location of job opportunities. Consequently, regions historically reliant on coal mining are facing economic and social challenges, while new areas are emerging as centers for critical material extraction. This transition calls for targeted training programs and policies to facilitate workforce adaptation and mitigate the socioeconomic impacts on communities that previously depended on coal mining. The United States and Canada could consider several policy options to alleviate the challenges arising from the shift in mining employment from coal to critical materials:

- Workforce retraining and relocation programs: Develop and fund retraining and relocation programs specifically tailored to equip former coal workers with the skills needed in critical materials mining.
- Economic diversification initiatives: Support economic diversification in regions historically dependent on coal mining to reduce reliance on a single industry.

- Investment in education and research: Increase investment in research and education focused on critical materials mining, ensuring a steady pipeline of skilled workers.
- Community engagement and support: Implement policies that support communities impacted by the shift to critical materials mining, including job placement services and economic aid.
- Sustainable mining practices: Encourage and fund the development of sustainable mining technologies and practices to improve the industry's outlook and make it more environmentally responsible.
- Public-private partnerships: Foster collaborations between governments, educational institutions, and private companies to create training programs and expand job opportunities in critical materials mining.

Secondly, the interactions between Indigenous communities and critical mining developments in the United States and Canada are complex and often contentious, primarily due to the profound impacts of mining on Indigenous culture and the lands and environment they steward. For instance, the proposed Thacker Pass lithium mine in Nevada has been a focal point of conflict: the local Indigenous community has raised concerns about environmental damage and the desecration of their sacred sites. Similarly, in Canada, the development of the Voisey's Bay nickel mine in Labrador involved extensive negotiations with the Innu and Inuit communities, addressing concerns over land rights and environmental impacts. These examples underscore the broader issue of how mining projects can disrupt Indigenous ways of life and environments. Often, Indigenous communities are situated in regions rich in minerals, placing them at the forefront of disputes around potential mining developments. The challenge lies in balancing the economic benefits that mining may bring to Indigenous populations with their rights and well-being. In academic discourse, there's a growing emphasis on the need for genuine consultation with and consent from Indigenous communities, as outlined in the United Nations Declaration on the Rights of Indigenous Peoples.

What follows are examples of policies that can help foster a just and considerate mining development process by ensuring that Indigenous communities have a significant say in whether and how mining projects proceed.

- Enhanced consultation processes: Establish mandatory, thorough consultation processes with Indigenous communities for any proposed mining projects on or near their lands.
- Legally binding consent: Implement frameworks requiring free, prior, and informed consent from Indigenous communities before mining activities commence.
- Environmental impact assessments: Require comprehensive environmental impact assessments by neutral, expert third parties that incorporate traditional Indigenous knowledge and perspectives.
- Equitable benefit sharing: Develop agreements for the fair distribution of mining benefits—including job opportunities, community development projects, and financial compensation—prior to exploitation.
- Cultural heritage protection: Enforce strict regulations to protect culturally and spiritually significant sites from the impacts of mining activities.
- Capacity building and education: Support education and training programs for Indigenous communities to participate meaningfully in mining-related decisions and operations—in conjunction with the workforce programs mentioned previously.

- Environmental awareness: Implement programs in Indigenous communities that enhance their awareness of broader environmental issues and weigh the necessity and benefits of mining developments, creating engagement around a common objective (net zero, for instance).

Environment
The US mining sector has made considerable progress in adopting best environmental practices to minimize its ecological footprint. According to the Environmental Protection Agency (EPA), the assessment of an ecological footprint should consider five core elements, which then translate to best management practices:

1. Total energy use and renewable energy use (e.g., installing onsite renewable energy systems to meet all or a portion of the project's electricity demand).
2. Air and atmospheric pollutants and greenhouse gas emissions (e.g., equipping field machinery with clean-emission technology for exhaust systems).
3. Water use and impacts to water resources (e.g., using a closed-loop, or recirculating, system to treat groundwater).
4. Materials management and waste reduction (e.g., choosing materials with recycled content).
5. Land management and ecosystem services (e.g., installing soil berms around low-lying work areas to prevent soil erosion caused by stormwater runoff).

Best practices can be divided into two categories: those undertaken to mitigate the impact of mining while activities are still happening and to counteract it after mining activities have ceased (i.e., cleanup). Geographical disturbances and environmental effects endure after mining has ceased—until the disturbed areas are stabilized and reclaimed for other uses, such as wildlife habitat or recreation.

Within the second category, a subdivision can be made: between those activities aimed at returning landscapes and ecosystems to their original shape and composition (i.e., restoration and reconstruction) and those directed toward alleviating the problems caused, not restoring the land to its original condition (i.e., remediation, reclamation, rehabilitation).

Historically, the majority of mines were not subject to stringent environmental regulations. The one requirement may have been that they restrict further pollution after closure—but in most cases, there would have been no requirements at all. Nowadays, regulations are much stricter: new mine developments are required to have not only operation and closure plans that define how a specific site will be reclaimed on cessation of mining but also comprehensive environmental impact assessments before commencing mining operations.

After decommissioning, modern active mines may be required to return the land to its original state so that it can potentially support all its previous ecological functions once again. Those sites should not be viewed merely as disused or abandoned mines, and the land should no longer be "closed"; rather, the goal is to bring the site back to its pristine state as much as possible. But land cannot always be returned to its exact original state; hence a "recovery gap" lies between the pre-mining native ecosystem and the post-mining ecosystem. When mitigation plus restoration cannot close the recovery gap, offsets may be used to try to address the residual impacts of mining. However, the current application of offsets rarely, if at all, can achieve like-for-like or net gain outcomes for impacted ecosystems.[157]

During mining, operators should:

- Implement low-impact mining techniques. Traditional mining methods, such as open pit and underground mining, pose severe environmental risks. By adopting new low-impact techniques like in-situ leaching, mining companies can reduce surface disturbance, soil erosion, and backfilling. This approach facilitates quicker site revegetation or rehabilitation.
- Reuse mining waste. Mining generates significant amounts of waste, including tailings, waste rock, and wastewater. This waste can be reused on- and off-site. Waste rock can be used for backfilling and reconstructing mined terrain to prevent soil erosion; treated mine water can be reused for various purposes; and toxic tailings can be utilized in the production of bricks and paint extenders and in agroforestry. Economically valuable metals can also be extracted from waste piles. Further research and development are necessary to make these methods economically viable on a large scale.
- Utilize eco-friendly equipment. Mining companies can switch to more environmentally friendly equipment. Battery-driven and electric-powered machinery reduces carbon dioxide emissions; more durable equipment reduces resource consumption and environmental harms associated with equipment breakdown. Cleanup operations themselves could be powered by on-site renewable energy sources.
- Strengthen enforcement mechanisms against illegal mining. Illegal mining bypasses environmental regulations, thus contributing to environmental degradation. Adherence to environmental standards, as well as accountability, can only be enforced through legal mining.
- Enforce responsible water management practices. It is critical to implement water recycling and treatment systems to reduce freshwater consumption, prevent contamination of nearby bodies of water, and adhere to stringent regulations for wastewater discharge. For example, by characterizing mining-influenced water (MIW), we can better understand the nature and extent of contamination and determine an adequate treatment method (e.g., using a neutralizing material, such as limestone, to balance the water's pH). Additionally, innovative techniques such as dry-stack tailings management may be employed to minimize the use of water in waste disposal.
- Implement soil management techniques. One such technique is soil capping, which involves installing covers (caps) to stabilize soil and waste piles and reduce exposure to contaminated areas. Alternatively, soil treatment addresses soil disturbances imposed by mining operations in order to restore soil quality: e.g., through soil washing, soil vapor extraction, and bioremediation.

Two further best practices worth mentioning are the prevention of acid rock drainage (ARD) and the control of smelter emissions.

ARD is a significant environmental concern associated with mining activities. When sulfide minerals present in rocks and ores are exposed to air and water, they can oxidize, resulting in the generation of acidic and metal-rich drainage. Preventive measures to minimize the occurrence of ARD include implementing appropriate waste management practices, such as proper containment and isolation of sulfide-bearing materials, as well as utilizing geochemical and hydrological controls to limit the exposure of sulfide minerals to air and water.

Smelters, which are integral to the processing of certain minerals, can release various pollutants into the atmosphere. To address this issue, mining companies invest in advanced emission control technologies, such as scrubbers, filters, and electrostatic precipitators, to remove or reduce harmful substances, including particulate matter, sulfur dioxide, and heavy metals, from the smelter emissions. Stringent regulations and monitoring programs are in place to ensure compliance and minimize the impact of smelter operations on air quality and human health.

Post-mining, mine operators should:

- Employ rehabilitation, reclamation, and remediation techniques at mining sites. Modern mining techniques often cause significant environmental disruption, stripping topsoil and raising acidity levels in the environment. This can render the area inhospitable to new vegetation and lead to prolonged soil erosion. Companies can employ land rehabilitation techniques for soil treatment, including using biosolids to replenish depleted topsoil and waste rock to fill excavated areas; reclamation techniques to reconvert disturbed land to its former soil and vegetation state; and remediation techniques, such as removing, reducing, or neutralizing substances, waste, or hazardous material from a site.
- Manage tailings responsibly. Tailings impoundments are permanent fixtures in the landscape. Management of mine tailings implies storing them in a specially designed impoundment called a tailings facility, which requires significant lifelong maintenance efforts to adequately protect communities and ecosystems. Progress is being made: for instance, associations such as Earth Works are publishing extensive guidelines for responsible mine tailings management.[158]

The mining industry is undergoing a period of rapid change, driven by technological advancements and a broader shift toward more sustainable practices. This transformation is disrupting traditional operations and bringing about new efficiencies that help address environmental challenges. Beyond operations scaling and developments, there are some technologies that could potentially transform operations and contribute to the increase of supply. They can be categorized as technologies that (a) optimize mining operations, (b) increase the efficiency of processing, and (c) advance decarbonization.

Optimization of Mining Operations
Mining outputs can be increased through a combination of digital and non-digital solutions; examples follow.

Digital Solutions
Several applications are based on automated and autonomous systems (e.g., those capable of 24/7 operations, unconstrained by human operators' schedules), Internet of Things devices (e.g., those that monitor equipment performance and status), and AI and machine learning (e.g., systems capable of using advanced data and analytics to improve decision-making based on patterns, trends, and predictions).

- The use of automation for precision mining is rapidly gaining traction as companies seek to enhance productivity and reduce operational costs. Harnessing the power of data and automation has the potential to drastically reduce emissions and contribute to sustainability in the sector by increasing efficiency and reducing waste. Caterpillar's MineStar Command, for example, uses advanced technologies for machine control, monitoring, automation, and health reporting, reducing the environmental footprint of the mining operation.
- The use of automated systems to predict and schedule maintenance can lead to improved efficiency and extend equipment life. Sensors and AI systems can

predict when a machine is likely to fail, allowing for preventive maintenance prior to failure, which minimizes both downtime and inefficient operations that induce overconsumption of resources (i.e., material and energy waste).
- Through automated data analysis and AI, mining companies can analyze large amounts of data to identify inefficiencies and implement improvements. AI applications can predict market demand, enabling mine operators to adjust production accordingly, reducing overproduction and waste. AI can also optimize transport, hauling, and conveying operations, thus reducing energy costs—from diesel to electricity—and cutting emissions.

Non-Digital Solutions

It is worth highlighting non-digital solutions such as advanced drilling techniques, improved fragmentation techniques, in-situ leaching, and efficient haulage systems.

- Innovations in drilling technologies, such as directional drilling and automated drilling systems, can improve the accuracy and efficiency of drilling operations. This enables more precise targeting of mineral deposits, reduces wastage, and increases overall productivity of the upstream operations.
- Optimal rock fragmentation is crucial for efficient mining operations. Techniques such as controlled blasting, precision drilling, and use of automated rock breakers can help achieve the desired fragmentation, facilitating easier extraction and reducing downtime for clearing blockages.
- In-situ leaching (ISL), also known as in-situ recovery (ISR), is a mining method that involves pumping a leaching solution—often a weakly acidic but nontoxic chemical, like oxygen, carbonate, or bicarbonate ions—into the ground to dissolve the target mineral, which is then pumped back to the surface for recovery. Compared to traditional mining methods, ISL significantly reduces both waste and surface disturbance. Cameco, a Canadian company, for example, uses CO_2-O_2 ISL for uranium mining.
- Implementing advanced haulage systems, such as conveyor belts, in-pit crushing and conveying (IPCC), and automated trucking systems, can streamline material transportation within the mining site. These systems minimize the need for manual handling, reduce truck wait times, and improve overall efficiency, leading to increased mining outputs.

Optimization of Processing

Several technologies could help increase both the output and the recovery rate of mined ore.

- Coarse particle recovery (CPR): The CPR process is an emerging innovation that allows for more efficient recovery of coarse particles that are generally lost in traditional processing methods. By capturing these particles, CPR can increase overall recovery rates and reduce waste. Two promising developments in this area are grind-circuit roughing and coarse particle scavenging.[159] Grind-circuit roughing recovers particles directly from the grind circuit using a novel material acting as a "copper sponge." It attracts mineralized particles and has the potential to boost ball mill throughput by up to 20% without changing grind size (for copper).[160] On the other hand, coarse particle scavenging extends the range of particle sizes recoverable during flotation. It combines the principles of density separation and flotation to prevent coarser particles from sinking, thus increasing the chances of recovery.

  These technologies could not only optimize concentrators' operation, improving recoveries and throughput, but also reduce water and energy consumption when reprocessing old tailings, making brownfield expansions more economical. Moreover, they offer opportunities to redesign greenfield mines, saving on capital requirements and water and energy usage.

- Flash flotation: Flash flotation is a process used in mining to recover minerals from ore deposits. It's designed to remove coarse, high-grade particles from the recirculating load in the grinding circuit, hence improving overall plant performance and reducing the loss of valuable minerals.
- High-pressure grinding rolls (HPGR): This energy-efficient grinding technology can significantly improve the mineral recovery process by applying high pressure to crush ores, increasing the surface area of the particles and enhancing the leaching process.
- Advanced gravity separation: Centrifugal gravity concentrators are being refined to improve the recovery of fine particles. These systems use the principles of centrifugal force to separate particles based on density, allowing for the efficient recovery of valuable minerals.
- Microwave pretreatment: This innovative technique uses microwave radiation to weaken the structure of ore before the grinding stage, making the subsequent extraction process more efficient.
- Froth flotation improvements: Developments in froth flotation, such as novel reagents and more efficient aeration methods, continue to enhance this essential mineral separation process. Better understanding of the surface chemistry of minerals and the use of advanced frothers and collectors can improve recovery rates.
- Artificial intelligence: Trained AI algorithms can optimize the process of sorting valuable minerals from waste rocks, improving mineral recovery rates. AI technologies can also predict equipment failures, enabling preemptive maintenance and reducing downtime.

Decarbonization Innovations

Technological progress is key to decreasing mining emissions, and several companies are already taking advantage of it, either by switching from fossil fuels to green energy sources or by directly reducing their CO2 emissions through less carbon-intensive technologies. Examples of actions that the mining industry is taking follow.

- Switching from fossil fuels to green fuels such as biofuels and synthetic fuels. Biofuels are considered carbon neutral because the CO_2 released when they are burned is offset by the CO_2 absorbed by the crops used to make biofuels as they grow. Synthetic fuels, if produced through a renewable source of energy, can also emit fewer pollutants and greenhouse gases (GHGs). A 2021 McKinsey report, "Creating the Zero Carbon Mine," concluded that sustainable fuels could reduce mining emissions by 40% to 70%.
- Switching from traditional vehicles and drivetrains to electric- or hydrogen-powered ones. Mining companies are already testing hybrid and fully electric vehicles for their operations. For instance, Boliden has a pantograph-charged hybrid at Aitik, Anglo American is developing a 300-metric-ton fuel cell electric vehicle (FCEV) haulage truck, and Newmont Goldcorp has the world's first fully electric mine at Borden. Companies like Sandvik and Epiroc, with their electric-powered drilling rigs and loaders, are leading in this area. Finally, the biggest lever of decarbonization is transitioning to green haulage, as haulage is a significant source of mining emissions. Switching from diesel-powered trucks to battery electric vehicles (BEVs) or hydrogen fuel cell trucks can significantly reduce not only carbon emissions

but also costs, as maintenance and fuel costs for BEVs and FCEVs are lower than for diesel trucks.

- Switching from fossil fuel–based electricity to renewable-generated electricity. Mining operations are increasingly powered by renewable energy sources, such as solar farms and wind turbines. Implementing green energy solutions can be more cost-effective, help operators meet sustainability goals—and address the challenge of supply when a mine is located in a remote area, far from the grid. A virtuous example is Rio Tinto's Gudai-Darri mine in Western Australia, where half of the electricity consumption is met with renewable energy, thanks to a 34 MW solar farm. The farm generates enough clean energy to power 6,000 households, offsetting 90,000 Mt of CO_2 emissions per year.

Recommendation V: Adopt recent innovations in low-impact mining techniques

Traditional mining methods, such as open pit and underground mining, pose severe environmental risks. By adopting new low-impact techniques like electrification of operations, in-situ leaching, and precision mining, mining companies can reduce surface disturbance, soil erosion, and backfilling. This approach also facilitates quicker site revegetation and rehabilitation.

Important progress toward lowering mining emissions can be achieved either by increasing the operational efficiency or reducing the environmental impact of extraction activities (lowering emissions through an intensity-reduction channel) or by switching from fossil fuel combustion and fossil fuel–based electricity to biofuels and renewable-generated electricity (lowering emissions through their direct reduction).

All the initiatives, technologies, and innovations discussed in this section can help achieve sustainability goals by reducing emissions, reducing energy consumption, improving efficiency, and reusing and recycling materials. While each of these approaches has its own challenges and limitations, used in combination, they can contribute significantly toward sustainable mining operations.

5. Recommendations to Diversify Import Sources

In order to diversify the sources of critical mineral imports, it is fundamental to differentiate the origins of critical minerals. For this purpose, the United States can establish bilateral agreements that stipulate lower tariffs between the US and each critical mineral–exporting nation as well as establish a general framework that differentiates critical minerals based on how they were mined and apply that framework uniformly to all exporting countries.

Recommendation VI: Establish additional bilateral agreements to secure critical supply

Trade agreements are increasingly being used to diversify and strengthen critical mineral supply chains. Bilateral partnerships, in particular, have emerged as a key policy tool to create more resilient supply chains, allowing countries to collaborate on various levels, from coordinating policies to ensuring adherence to environmental and labor standards. Specifically, beyond investment cooperation, certain trade agreements also emphasize commitments to refrain from imposing import or export restrictions.[161] Additionally, these agreements often include provisions for market access and trade measures, aiming to foster sustainable supply chains for critical minerals through agreed-on environmental standards.[162] This approach achieves the dual goal of securing supplies of minerals while promoting sustainability and fairness in their extraction and processing.

While existing trade agreements can help achieve this dual goal to some extent, an approach involving more coordination with other countries is needed to ensure that US supply chains for processed and refined minerals are not overly dependent on a small set of countries—particularly China. Some policymakers have proposed forming a dedicated bloc focused on free trade in critical minerals, consisting of key mining and processing nations such as Australia, Canada, and Chile. Such a framework would allow participating countries to:

1. Align regulatory and environmental standards to ensure responsible mining and processing practices,
2. Facilitate trade with reduced tariffs and restrictions, improving supply chain efficiency,
3. Reduce reliance on China for processing and refining, ensuring more diversified supply sources, and
4. Integrate with existing US policies, including the Inflation Reduction Act (IRA), which prioritizes minerals sourced from free trade partners.

The IRA's domestic content requirements already mandate sourcing minerals from free trade agreement (FTA) partners, reinforcing the need to strengthen existing trade relationships and create new ones. However, not all major mining nations have FTAs with the United States, limiting the number of them that qualify for IRA incentives. Expanding the United States' critical mineral trade partnerships would ensure that key allies can participate in the growing demand for mineral-intensive industrial capacity while further reducing supply risks.

The United States has established several key bilateral partnerships to secure critical minerals. Canada has been a cornerstone of US supply chain security: Canadian companies are the only foreign entities recognized as a "domestic source" under Title III of the Defense Production Act of 1950.[163] This designation reflects the deep economic and security ties between the two nations.

The US-Canada trade relationship evolved from the 1994 North American Free Trade Agreement (NAFTA) to the 2020 United States-Mexico-Canada Agreement (USMCA), reinforcing cross-border supply chain integration. The IRA of 2022 further strengthens this partnership, as Canadian companies meet domestic sourcing requirements for minerals used in EV production. Canada remains a top source for US imports of cobalt, graphite, lithium, and nickel, thus playing a crucial role in supplying raw materials for advanced industries.[164]

Additionally, in March 2023, the two countries launched the Canada-US Energy Transformation Task Force and the Canada-US Joint Action Plan on Critical Minerals Collaboration, deepening cross-border cooperation on EVs, batteries, and critical mineral supply chains.[165]

Another example is Japan, the sixth-largest trading partner of the United States and a critical player in mineral processing and EV battery production. While Japan is not a major producer of raw minerals, it ranks among the top global refiners of key materials (e.g., cobalt) and is a significant exporter of processed minerals to the United States.

In March 2023, the United States and Japan signed a critical minerals agreement (CMA) to strengthen mineral supply chains, reduce dependence on China, and align labor and environmental standards. The agreement focuses on cobalt, graphite, lithium, manganese, and nickel and includes provisions such as:

- Not imposing export duties on critical minerals between the two nations,
- Collaborating on addressing nonmarket policies that distort global supply chains,
- Exchanging best practices for foreign investment review in mineral sectors, and
- Ensuring labor protections and employer neutrality in union-related matters.

Although Japan does not have a formal FTA with the United States, the Treasury Department designated the CMA as an FTA for IRA compliance purposes, highlighting the growing role of targeted mineral agreements outside of traditional trade structures.

The United States has also led multilateral efforts with mineral-producing and mineral-processing countries. In 2022, the US spearheaded the creation of the Minerals Security Partnership (MSP) to accelerate the development of diverse and sustainable supply chains for critical minerals. The initiative aims to:

- Promote responsible mining investments with strict environmental, social, and governance (ESG) standards,
- Reduce dependence on China for mineral processing and refining,
- Ensure fair market access for mineral-producing countries, and
- Encourage domestic value addition in mineral-rich countries.

MSP members include Australia, Canada, Estonia, the EU, Finland, France, Germany, India, Italy, Japan, Norway, South Korea, Sweden, the UK, and the US.[166] While this initiative is a significant step forward, it remains driven largely by policy rather than trade forces. To fully realize its potential and ensure supply chain diversification at scale, the MSP must integrate more formalized trade agreements and investment mechanisms.

Building on both existing FTAs and the MSP, the United States can benefit from establishing additional agreements with countries like Australia and those in Latin America.

Australia, which shares political values with the United States, holds vast reserves of critical minerals essential for the US economy. In 2022, Australia generated over AUD 20 billion (USD 14 billion) from the export of key minerals like aluminum, lithium, nickel, and zinc.[167] In May 2023, the two nations launched the Australia-United States Climate, Critical Minerals, and Clean Energy Transformation Compact, creating the Australia-United States Critical Minerals Taskforce.[168] The stated goal of this task force is to strengthen supply chains to meet US manufacturers' needs; both countries committed to identifying concrete actions to take and developing an action plan by the end of 2023. Further coordination is needed to deepen integration and investment in critical mineral projects.

Latin America plays a critical role in the global mineral market, yet the United States' engagement with the region remains underdeveloped—in contrast to China's greater capacity and increasing influence.

- Chile, Colombia, and Peru all have FTAs with the United States, but only a small portion of the minerals they mine are exported directly to the United States. Strengthening regulatory and trade collaboration could enhance their economic competitiveness, helping the United States reduce its reliance on mineral-dominant China.
- Encouraging Latin American countries to join the MSP would further integrate them into Western supply chains and ensure higher ESG standards in their mining sectors.
- While the 2023 US-Chile tax treaty was a positive step toward lowering investment barriers in the region, it is only the second tax treaty between the United States and a South American country. Similar agreements with Argentina, Brazil, and Peru would further support mineral trade and investment.

The US International Development Finance Corporation (DFC) opened its first Latin American regional office in São Paulo, Brazil, in 2024. Through this initiative, the United States has already invested USD 30 million in TechMet Limited to develop a major critical mineral mine in Brazil, signaling a growing commitment to the region's resource sector.[169] To secure long-term access to critical minerals, the United States must continue expanding its trade partnerships, investment agreements, and policy coordination with mineral-rich nations. Bilateral agreements, coordination through the MSP, and the establishment of a formal bloc focused on free trade in critical minerals will be essential to:

- Reduce reliance on China, which dominates in mineral processing,
- Ensure that mineral supply chains adhere to high labor, environmental, and ESG standards,
- Strengthen economic ties with key allies and emerging producers, and
- Align with IRA domestic content requirements while broadening US supply options.

By reinforcing existing agreements, securing new partnerships in Latin America, and deepening investment ties with MSP nations, the United States can build a resilient and diversified supply chain of ethically sourced critical minerals, ensuring both economic and national security stability in the decades ahead.

Recommendation VII: Establish a border adjustment mechanism that accounts for labor, environmental, and processing practices in the critical minerals sector

Ensuring a stable and resilient supply of critical minerals is essential for the US economy, national security, and industrial competitiveness. The global minerals market, however, is far from a level playing field. Many of the world's critical minerals are mined in one country and then sent to another—most often China—for processing. This extreme concentration of refining capacity allows companies that underpay workers, degrade local environments, and ignore best practices to enjoy a significant cost advantage over those that adhere to higher standards.

Recent geopolitical events underscore the strategic risks associated with this imbalance. For example, China has demonstrated willingness to weaponize its control over critical mineral processing by restricting exports of gallium and germanium in response to US trade policies—materials that are essential for semiconductors and military applications. These restrictions highlight the vulnerability of a supply chain that is overwhelmingly dependent on a single nation for refining capacity.

Not all mineral producers and processors play by the same set of rules. While many US and allied companies follow strict labor, environmental, and safety standards, others—particularly in jurisdictions with weaker regulatory frameworks—enjoy a cost advantage by sidestepping similar obligations. This has led to a global race to the bottom, where cost-cutting measures in one country incentivize similar practices elsewhere—leading to one player dominating the playing field.

To correct this imbalance, the authors propose establishing a critical mineral border adjustment mechanism (CMBAM): a trade policy tool designed to align mineral pricing with responsible production standards. Unlike traditional border adjustments focused solely on carbon emissions, the CMBAM would broaden the scope of import regulations to include:

- Labor standards. Companies that do not pay a defined living wage in the country of operation would face an import tariff proportional to the shortfall.
- Environmental standards. When mining or processing operations fail to utilize environmental best practices and generate excess local pollution, an import tariff would be applied based on the estimated damage per unit of mineral produced.
- Carbon emissions. While emissions would not be its sole focus, the CMBAM would still account for them as one factor in assessing responsible production.

To exemplify how the CMBAM would operate, let's imagine the United States is importing one ton of nickel from Country A at a price of $16,000. Had Country A paid a CMBAM-defined living wage, the wage cost of that ton would have been $1,000, but at Country A's actual wages, it was only $400. The CMBAM places a labor tariff on the imported ton equivalent to the difference: $600. Furthermore, suppose mining practices in Country A generated an additional $300 worth of impact on the local environment, relative to CMBAM-defined best practices. Therefore, the CMBAM levies an environmental tariff of $300. Finally, suppose the carbon emissions of Country A led to $500 worth of additional greenhouse gas emissions social costs, relative to the emission rate of US companies. The carbon adjustment thus adds $500. Combined, the CMBAM adjustments add $1,400 to the cost of the ton of imported nickel, bringing it to $17,400. Overall, implementation of the CMBAM would ensure that companies cutting corners—whether on wages, environmental protections, or responsible processing—do not unfairly undercut firms adhering to best practices.

Although the CMBAM would account for the carbon intensity of imported minerals, it's important to note that the United States does not currently impose a domestic price on carbon. Therefore, strictly speaking, applying a carbon tariff on imports is not a way to level the playing field between domestic and foreign producers. Absent adopting a price on carbon, one way to address this discrepancy is to benchmark imports against the average carbon intensity of minerals mined and processed in the United States. Under this approach, imports with higher carbon intensity than the US average would be taxed based on the difference, using the current social cost of carbon as the valuation metric. This would avoid penalizing low-emissions producers abroad while still promoting carbon-efficient production practices globally.

Caveats and Considerations

While the proposed CMBAM offers a comprehensive approach to aligning trade policy with responsible production practices, several key considerations must be addressed:

- Economic rationale: It could be argued that poor labor conditions and local environmental damage abroad do not represent externalities imposed on US consumers. From a strictly economic efficiency standpoint, these are not costs directly affecting US citizens—and thus imports should not be subject to border adjustments because of them.
- Moral and normative argument (stewardship): One response to the above objection is that the United States, as a major player in global trade, has a responsibility to use its leverage to promote higher labor and environmental standards worldwide. Implementing border adjustments could help raise the global baseline and reduce exploitation.
- Strategic industrial policy justification: Even from a US-centric perspective, the CMBAM can be defended as industrial policy. By penalizing imports that benefit from weak labor and environmental regulations, the US government can support domestic firms that operate under higher-cost but more ethical and sustainable standards—thus preserving competitiveness and fostering a robust domestic critical minerals sector.
- Measurement and implementation challenges: Defining what constitutes a "living wage" and "best environmental practices" across diverse jurisdictions and verifying their implementation is a complex and potentially contentious undertaking. Transparency in methodology as well as enforcement mechanisms would be critical to ensuring credibility and effectiveness.
- International trade relations: Such a mechanism could be challenged under WTO rules or spark retaliatory measures. Careful design and diplomatic engagement would be required to avoid undermining broader trade relationships while pursuing the intended policy goals.

Key 1: Correcting Market Distortions to Strengthen Supply Chain Security

The current imbalance in the critical minerals supply chain is a direct consequence of cost advantages gained through low labor standards, weak environmental protections, and regulatory loopholes. The CMBAM is not intended to punish any one country but rather to ensure that all mining and processing operations compete under fair and transparent conditions.

- Market distortions are driven not just by mining but also by Processing: While mining is geographically concentrated, processing is even more so. China controls most global refining capacity for key minerals like lithium and REEs. While many raw materials are mined in Africa, Australia, and Latin America, most of them are sent to China for processing, mainly because China's lower environmental and labor standards significantly reduce the cost of refining.

- Cost advantages matter: Companies operating in regions with weak labor laws and lax environmental regulations can produce and refine minerals at artificially low prices. This undercuts responsible firms, whether in the United States, Canada, Europe, or other mineral-producing nations, that follow best practices.
- Market distortions are a global issue: While China dominates mineral processing, it is not the only jurisdiction where low-cost production is achieved at the expense of workers and the environment. Some companies operating in parts of Africa, Latin America, and Southeast Asia also engage in practices such as high-pollution refining, suppressing wages, and maintaining below-standard working conditions. The CMBAM, by design, would address these market distortions wherever they occur.

By applying a transparent and rules-based tariff structure, the CMBAM would ensure that companies playing by the rules are not priced out of the market but remain competitive. This would level the playing field without resorting to protectionism, fostering responsible mining and processing operations both in the United States and abroad.

Key 2: Moving Beyond Carbon to Address Multiple Externalities
A carbon-only focus is inadequate for tackling the unique challenges of the mining sector as the supply chain presents a broader range of externalities, from ecosystem destruction to poor labor conditions. These harms often occur far from the end consumer and are not reflected in market prices.

- Environmental damage beyond carbon: Mining operations pollute air, soil, and water; generate toxic waste; and can lead to irreversible ecological destruction.
- Labor exploitation in the mining sector: The industry remains plagued by unsafe working conditions, child labor, and low wages, especially in countries with weak labor protections.
- Regulatory arbitrage: Current market conditions incentivize companies to shift their mining and refining operations to jurisdictions with the weakest environmental and labor laws, resulting in what is effectively a global race to the bottom. The CMBAM would generate an incentive against companies that are evading social, environmental, and labor responsibilities by moving their operations to regions with the lowest regulatory standards.

Key 3: Augmenting Deterrents with Incentives
The CMBAM would serve as a necessary "stick" to complement the "carrots" already used to incentivize domestic mineral production. Legislation such as the IRA has provided substantial subsidies to encourage investment in US-based mining and processing. However, relying solely on subsidies to promote the domestic mining industry is not sustainable in the long term.

- Addressing budgetary constraints: Continued large-scale public subsidies for critical minerals will become increasingly difficult to sustain.
- Preventing market distortions: While subsidies encourage investment, they also may induce market inefficiencies and overreliance on government intervention.
- Ensuring long-term viability: Unlike direct subsidies, border adjustment mechanisms generate government revenue rather than requiring spending.

Challenges of Implementation
While the CMBAM model offers certain advantages, it comes with key implementation challenges:

- Measuring a living wage: The CMBAM model requires defining and quantifying a fair wage standard for each country. While there are initiatives that can help define standard living wages, such as the Global Living Wage Coalition, verifying and enforcing living wage standards in producing and processing countries poses difficulties.
- Assessing local environmental damage: Unlike carbon emissions, which have standardized global reporting frameworks, site-specific pollution and ecological harm are far more complex to quantify. Previous attempts to do this, such as environmental damage assessments under extractive industry regulations, provide a foundation but remain inconsistent across jurisdictions.
- Focusing on three factors at the expense of others: While the CMBAM framework targets labor, pollution, and carbon emissions, other ethical concerns in mineral production exceed its scope, such as community displacement, water use, and broader human rights violations. Policymakers must consider whether the framework should expand over time.

Summary

This report presents a critical mineral border adjustment mechanism as an essential tool for promoting economic fairness in the global mineral production and processing market, securing the United States' supply chain, and incentivizing sustainable global practices.

This policy would ensure that the price of minerals entering the US market reflects their true cost of production, preventing a race to the bottom while strengthening the resilience of domestic and allied supply chains. By implementing incentives and market corrections, the United States can better sustain a more competitive and ethical critical minerals industry.

Developing the CMBAM will require careful design to balance trade fairness and enforceability while addressing diplomatic concerns. Implemented effectively, the CMBAM can ensure that companies engaged in responsible mining and processing are not undercut by those that ignore environmental, labor, and economic obligations—making the supply chain stronger, more transparent, and more resilient.

6. Reducing Pressures on Demand

US demand for critical materials is projected to outpace the growth trends observed in recent years. For instance, by 2040, the annual average demand for nickel and cobalt is expected to be two and five times higher, respectively, than in the 2010s. Copper demand is also anticipated to continue the strong growth seen in the 2010s into the coming decades. This trend underlines, on the one hand, the need for substantial additional investment to meet the growing demand and, on the other, the opportunity to slow down the rate of growth. The authors note that, in this discussion, we are focused not on reducing overall demand but rather on slowing demand growth, by promoting recycling of materials and batteries, improving material efficiency, developing battery technologies that require smaller quantities of critical minerals, and optimizing the battery size of electric vehicles—measures that strongly depend on technological innovation.

The Role of Private Technological Innovation in Mineral Supply Chains

Innovations in technology have the potential to slow down the rate of growth in demand for critical raw materials in the coming decades. However, the interplay between the demand for critical materials and technology choices is complex. On the one hand, decisions by firms about the implementation of new technologies strongly influence the market for critical materials—for instance, affecting market prices by shifting the demand for certain minerals. On the other hand, firms must respond strategically to critical materials' price fluctuations and associated risks. This interplay generates significant uncertainty, particularly for industries like EV manufacturing, where investments are both high value and long term. For instance, the EV industry's preference for lithium-ion batteries increased demand for lithium, raising its market price; in turn, high demand and rising prices for lithium spurred innovations in extraction processes (e.g., brine extraction) and led to the development of alternative materials and battery chemistries, further altering market dynamics.

Private-sector companies adjust their strategies in response to evolving market conditions. In particular, fluctuating prices and supply risks encourage firms to diversify their sourcing and secure multiple suppliers or enter into long-term contracts to mitigate the effects of market volatility. They may also adapt their strategies, shifting to alternative technologies that use more readily available materials. Such adaptation is especially challenging in the face of high market uncertainty caused by unpredictable technological advancements, regulatory changes, and geopolitical factors.

Firms in industries that are highly dependent on critical minerals, therefore, must develop robust risk mitigation strategies to help navigate this complex landscape. These strategies might include investing in research and development of new technologies, creating more flexible supply chains, and exploring real options in manufacturing and technology development. The private sector must navigate the complex interplay between technology decisions and the critical materials market.

Industries Influence the Market Through Technological Innovation

Technological advancements have always shaped industries and thus markets. Renewable energy technologies, consumer electronics, and electric mobility represent three recent technological shifts that, through the usage of batteries, are impacting the critical raw materials market. The increase in battery demand has already started—and growth in the coming years is projected to be unprecedented. For example, McKinsey estimates that the entire lithium-ion battery chain is expected grow by over 30% annually from 2022 to 2030.[170]

Solar and wind energy are the top two renewable energy technologies linked to critical minerals. In the solar energy sector, the shift to thin-film solar cells made from cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) has led to notable advancements. These materials enable the production of lighter, more flexible, and potentially less expensive solar panels compared to traditional silicon-based cells. The 2021 edition of the International Technology Roadmap for Photovoltaics highlighted how these advancements have improved the applicability and efficiency of solar panels, allowing their integration into a wider range of surfaces and structures. In the wind energy sector, REEs in permanent magnets have made a significant impact by reducing the weight and size of generators, making it feasible to construct larger and more powerful turbines. As noted by the Global Wind Energy Council, this development is crucial for offshore wind farms, where larger turbine sizes directly translate to higher energy output and efficiency, significantly boosting the viability and capacity of wind energy projects.[171]

The use of REEs has allowed for significant advancements in consumer electronics, too—specifically in high-tech devices. For instance, neodymium is used in miniaturized yet powerful speakers and headphones, enhancing their portability and performance. The Consumer Technology Association notes that such advancements have led to more compact and efficient multifunctional electronic devices.[172] Moreover, the use of indium in touchscreens has enabled the development of responsive, high-definition displays for smartphones and tablets, improving user interaction and the overall functionality of touch-sensitive devices.

Battery Technology Innovation

The primary driver of the surge in mineral demand is batteries, due in part to growing demand in the energy sector for storage solutions and in part to the electric mobility revolution. In 2022, about 60% of lithium, 30% of cobalt, and 10% of nickel demand was for EV batteries—compared to around 15%, 10%, and 2% respectively just five years earlier.[173] Consequently, the choices made by car manufacturers in particular affect the entire supply chain, from sourcing raw materials to manufacturing and recycling.

The main shift in battery technology has been the transition to nickel-rich cathodes in lithium-ion batteries, such as nickel manganese cobalt (NMC) and nickel cobalt aluminum oxide (NCA). These materials have increased the energy density of batteries, allowing for reduced battery sizes and longer driving ranges for EVs. This transition is critical in addressing range anxiety among EV users, thus accelerating the adoption of EVs.[174] In addition to this, the exploration of solid-state batteries represents another major technological leap. These batteries, still in the developmental stage, promise higher energy density, faster charging times, and enhanced safety, potentially revolutionizing the EV industry. The implementation of this technology could significantly reduce dependence on traditional critical materials, opening up new avenues for battery composition and design.

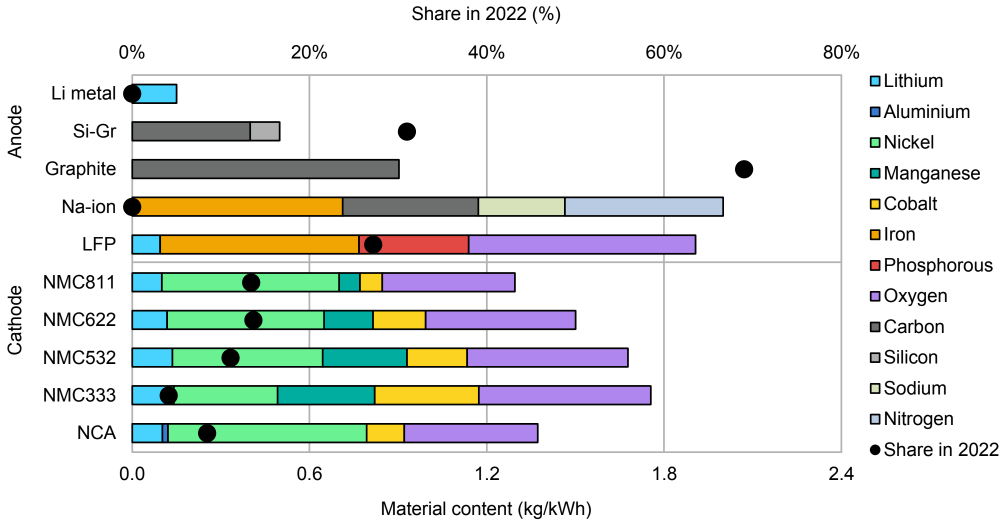
The most recent trends in battery technology are particularly evident in the choices of cathode and anode chemistries.

In terms of cathodes, two main chemistries exist: high-nickel (NMC and NCA) and lithium iron phosphate (LFP). High-nickel cathodes are favored for their higher energy density, which is particularly beneficial in extending the range of EVs.

However, their high nickel and cobalt content raises concerns about cost and supply chain risks, given the limited availability and geopolitical concentration of these minerals. On the other hand, LFP cathodes are gaining popularity as a more cost-effective and stable alternative. Although LFP offers lower energy density than high-nickel and cobalt chemistries, it has safety, cost, and longer cycle life advantages. This makes LFP batteries particularly suitable for applications with less critical weight and space, such as stationary storage and some EV segments.

When it comes to anode technologies, adoption of silicon-doped graphite is growing. Silicon anodes can, theoretically, hold more lithium than graphite anodes, lending batteries higher capacity and energy density. However, silicon expands and contracts significantly during charging and discharging, which can lead to battery degradation. To mitigate this, manufacturers are exploring silicon-doped graphite anodes, which combine silicon's high capacity with graphite's stability. This technology offers a promising pathway to enhance battery performance.

Figure 9: Material content in different anodes and cathodes.



Source: Adapted from IEA, 2023.[175]

Minerals Markets Influence Industry Choices Through Prices and Supply Chain Risks

Making long-term and high-value investment decisions and technological choices in a market characterized by uncertainty poses challenges—such as securing financing, given the impossibility of accurately estimating the risk-reward profile of such investments.[176] As a consequence, understanding the drivers of supply uncertainty and its complex interconnections with market prices is a crucial challenge in the mining industry, one that calls for strong collaboration between the research and industry sectors.[177]

Key factors include relative commodity prices; forecasts of supply and demand imbalances; and supply chain risks affecting the cost, availability, and sustainability of different battery chemistries.

Firstly, price trends for critical materials can directly impact the profitability and competitiveness of battery technologies. This is particularly true given that the prices of various minerals are strongly interconnected.[178] For instance, while LFP batteries are typically less expensive than NMC batteries, in 2022, the increasing price of lithium caused a relatively larger jump in the price of LFP batteries. While the market has been shifting toward LFP due to its lower costs and safety advantages, recent price trends like this one highlight the importance of the cost competitiveness of the underlying materials.

Secondly, forecasting of future supply and demand imbalances for critical materials can affect strategic decision-making by EV manufacturers. For instance, the trend toward larger electric vehicles and the requisite larger batteries could significantly increase demand for critical minerals, intensifying strain on supply chains. This could motivate manufacturers to invest in new alternative battery technologies. For example, production of sodium-ion batteries, which largely avoid using critical minerals, surged in 2023, suggesting that manufacturers are exploring alternatives to lithium-ion batteries due to concerns over lithium supply risks and price volatility. However, the pace and extent of this shift remain uncertain given the current advantages of lithium-ion batteries—namely their energy density and their lower cost per unit due to the scale of production. Another important recent technological development is the emergence of solid-state batteries, which offer improved energy density and thermal safety. Additionally, other innovative technologies like lithium-sulfur batteries could potentially surpass current energy densities, though they have yet to overcome significant technological hurdles.

Finally, geographic concentration of critical minerals and potential disruptions in their supply chains can pose significant risks for EV manufacturers. For instance, cobalt, nickel, and manganese, which are used in NMC and NCA batteries, are more geographically concentrated—and their supply chains thus more vulnerable to disruptions—than the materials used in LFP batteries. However, LFP battery manufacturers have their own supply chain concerns, such as the potential for conflicting demands for phosphorus from the battery and agriculture sectors as well as the geographic concentration of phosphate rock resources. Fear of potential supply disruptions has led manufacturers to consider battery chemistries that use less critical minerals or have less geographically concentrated supply chains. For instance, to reduce costs and mitigate the social risks associated with cobalt mining, high-cobalt-content NMC chemistries are being phased out in favor of high-nickel/low-cobalt chemistries like NMC 721 and NMC 811. Conversely, LFP chemistry, which is more affordable and safe—although less energy-dense—is gaining market share. The increased demand for LFP batteries is driven by their use of only lithium as the key critical battery mineral, allaying manufacturers' concerns about supplies of other critical minerals.

To mitigate risks and ensure supply chain sustainability, EV manufacturers are innovating and diversifying their battery technologies. As discussed, examples of this include reducing the use of cobalt in NMC batteries (moving toward NMC 811, 721, and, in the future, 955), the resurgence of LFP batteries, and the potential emergence of sodium-ion and solid-state batteries. Moreover, technological progress will likely lead to higher-energy-density batteries, meaning that, over time, batteries will require less material per kWh—from slightly more than 200 Wh/kg in 2020 to around 350 Wh/kg in 2030. For example, in 2020, the average battery (NMC, NCA, LFP) required, per 100 kWh, 10 kg of lithium, 13 kg of cobalt, and 48 kg of nickel. In 2030, requirements per 100 kWh are projected to be 5 kg of lithium, 3 kg of cobalt, and 39 kg of nickel.[179]

The ongoing evolution of battery chemistries could also introduce challenges for the recycling industry, which will need to constantly adapt to process different types of batteries. Moreover, if the use of lower-value materials in LFP and sodium-ion batteries reduces the monetary incentive to recycle these batteries, strong policy support will be needed to ensure the sustainability of battery life cycle management.

Technological Innovation for a Circular Economy: The Role of Recycling

Recycling is an important channel through which the growth in demand for minerals can be slowed down. Recycling minerals from potential waste can reduce the demand for mined materials. Moreover, recycling can also help address the increasing generation of electronic waste (e-waste). Technological innovation plays a pivotal role in improving recycling systems and technologies, which must address various technical challenges, such as deterioration in the quality of raw materials during the recycling process. Innovative solutions like e-waste recycling, battery recycling, design for recycling (DfR), and "urban mining" are currently being developed.

The term urban mining refers to the extraction of valuable metals from e-waste. Because the electronics and electric vehicles boom entails large amounts of metals ending up in discarded products, many companies are pioneering technologies to recover those valuable resources, investing in hydrometallurgical and biotechnological methods. For instance, bioleaching uses bacteria to extract metals from electronic waste, offering a more environmentally friendly alternative to traditional methods.

Like urban mining, battery recycling will only continue to gain relevance as EV numbers rise. To recover valuable metals from lithium-ion batteries, companies are developing advanced techniques, such as wet chemistry processes, with significantly higher recovery rates than traditional methods like pyrometallurgy, which is also more energy-intensive.

As recycling gains importance, there is also a growing trend toward designing products for easier recycling at the end of their life. This can involve using less diverse materials, making devices easier to dismantle, and using materials that are easier to separate during recycling.

Recommendation VIII: Incentivize research for technological innovation
To drive technological progress in areas such as recycling, material efficiency, alternative battery chemistries, and sustainable solutions across the raw materials value chain, investments in and support for research, development, and innovation in critical raw materials (CRMs) should be actively encouraged and promoted in both the public and private sectors.

Technological innovation can be achieved through coordination and collaboration between institutions, banks, industries, and private sector stakeholders, creating synergies and maximizing the impact of existing funding programs. Furthermore, it is essential to prioritize access to financing for innovations related to critical minerals. Given the challenges in securing funding for such projects, public institutions could play an important role in assisting research centers, universities, private entrepreneurs, and start-ups by improving access to financing and providing administrative support.

Recommendation IX: Incentivize research to address market uncertainties
To reduce the uncertainty that characterizes critical raw materials markets, which hinders stakeholders' investment in the sector, research focused on the market dynamics and the supply chain of battery minerals should be promoted.

This effort should foster synergies between the research community and the private sector. Joint research projects could be established, where industry provides researchers with resources and expertise and researchers contribute with cutting-edge studies. For example, such projects could explore how factors related to supply chain risks evolve over time and propagate from raw materials to end products, or they could develop models to forecast mineral prices and quantities in ways that reflect the complexity of the sector.

A better understanding of potential supply and demand scenarios, price volatility, and supply chain bottlenecks would provide significant benefits for the industry as it attempts to develop new production capacity.

7. Conclusion

It is critical for the United States to secure a stable and sustainable supply of critical minerals, which are indispensable to national security, economic growth, and the transition to a clean energy future. The nation's current overreliance on foreign sources, particularly China, for mineral extraction and processing presents significant vulnerabilities that threaten economic resilience and geopolitical stability. Addressing these vulnerabilities will require a multifaceted approach that balances domestic production expansion, import diversification, demand reduction strategies, and sustainability considerations.

A primary recommendation of this report is to streamline the permitting process for domestic mining projects through regulatory reform, while maintaining rigorous environmental and social safeguards. Because permitting delays (often caused by bureaucratic inefficiencies and unpredictable community opposition) hinder the development of new mining operations, reforming the permitting process would allow the United States to accelerate project timelines, mitigate supply chain risks, and ensure that mineral extraction aligns with best practices in environmental stewardship and community engagement—and, more importantly, ensure that local communities benefit from mining operations.

Furthermore, fostering new partnerships with allied nations to develop alternative mineral processing capacities would reduce dependence on China, which dominates critical minerals refining. Countries such as Canada, Australia, and several European nations possess the resources and technological expertise to serve as alternative processing hubs. Strengthening trade agreements and investing in shared infrastructure can enhance supply chain resilience and create mutually beneficial economic opportunities.

Just as critical as increasing supply is reducing demand pressures through innovation and recycling initiatives. Investment in alternative battery chemistries, material substitution, and efficient recycling processes can extend the life cycle of critical minerals and decrease overall consumption. These strategies align with broader sustainability goals and position the United States as a leader in responsible resource management. Further government incentives to promote circular economy models will drive innovation in recycling technologies and sustainable mining practices.

The transition toward a more sustainable mineral supply chain also requires proactive engagement with local communities. Establishing legally binding community benefits agreements (CBAs) ensures that the economic benefits of mining developments are equitably distributed, social license to operate is maintained, and community concerns are addressed early in project development. This approach reduces opposition and fosters collaboration between mining companies, policymakers, and affected communities.

An important policy tool discussed in this report is the critical mineral border adjustment mechanism (CMBAM), which aims to ensure that the price of imported critical minerals reflects standardized environmental damage mitigation and labor costs. This mechanism would impose tariffs or fees on minerals imported from countries with lower environmental and labor standards, discouraging reliance on unsustainable supply chains while incentivizing more responsible production methods globally. By aligning the cost structure of imported minerals with US regulatory standards, the CMBAM would help protect domestic industries from unfair competition, encourage responsible mining practices worldwide, and reduce the incentive to offshore critical mineral processing. Implementing this mechanism would reinforce the broader strategy of securing a resilient and ethical supply chain while advancing US leadership in sustainable resource management.

Finally, continuous investment in research and development is essential to maintain US competitiveness in mineral extraction and processing. Advanced mining techniques, such as low-impact mining and precision extraction, can minimize environmental degradation while improving operational efficiency. Public-private partnerships should be leveraged to accelerate innovation and workforce development in the critical minerals sector.

By executing these strategic actions, the United States can build a robust, secure, and sustainable critical minerals industry. The path forward requires coordinated policy efforts, investment in technological advancements, and a commitment to environmental and social responsibility. If executed effectively, these initiatives will not only safeguard national security and economic interests but also facilitate the country's leadership in the global clean energy transition.

Appendix

Cobalt

While the global reserves of cobalt—estimated at 7.6 million metric tons (Mt), according to the United States Geological Survey—are distributed across various countries, the Democratic Republic of the Congo (DRC) stands out as the primary producer, accounting for over 70% of the world's cobalt. However, due to growing demand, mining activities in other nations, such as Australia, Canada, and the United States, are increasing.

Democratic Republic of the Congo

In the DRC, a country grappling with long-standing challenges such as ethnic conflicts, violence, corruption, and health crises like Ebola, the abundance of valuable minerals, including cobalt, has not translated into significant benefits for the population. Instead, multinational corporations have seized a considerable share of cobalt production, which yields substantial profits. Furthermore, recent reports highlight the less-than-ideal conditions surrounding much of the cobalt production in the DRC, where artisanal miners play a predominant role.

Artisanal miners, essentially freelance workers, toil in perilous and exploitative conditions, earning meager wages for their efforts. Armed with rudimentary tools like picks, shovels, and makeshift instruments, artisanal miners—including child laborers recruited by militia groups—operate in dangerous environments, where frequent collapses lead to fatalities. This harsh reality is widespread and often embedded within the formal cobalt supply chain.

Industrial mines often coexist with and incorporate the activities of artisanal miners, blurring the distinction between cobalt extracted through high-tech industrial means and cobalt mined using artisanal labor. The coexistence of formal and artisanal mining in the DRC serves as a means of boosting cobalt production.

Increasing attention from the international community has put pressure on the Congolese government, which has promised to address governance issues in the cobalt sector. In 2019, as part of reform efforts, it established two state-owned entities: the General Cobalt Company (EGC) and the Authority for the Regulation and Control of Strategic Mineral Substances Markets (ARECOMS).

EGC holds a monopoly on purchasing, processing, and marketing artisanal cobalt in the DRC. It is charged with ensuring high social and environmental responsibility standards in cobalt production and establishing traceability from mine to consumer. However, since 2019, ECG has been largely inactive. It was established to ensure the viability of special artisanal mining zones or ZEAs (zones d'exploitation minière artisanale), but so far, political and bureaucratic problems have prevented it from achieving this goal.

ARECOMS functions as an industry watchdog, overseeing the production and export of strategic minerals crucial to the country's economic and national security. This entity aims to maintain an attractive and stable market for strategic minerals while preventing money laundering and terrorism financing among the companies it regulates.

North America

The landscape of cobalt mining in Canada and the United States presents very different characteristics. In 2022, Canada produced more than 3,000 Mt of cobalt, all of which was a secondary product of nickel mining—hence it is discussed in the section on nickel. The US position is marked by less abundant cobalt resources: it is in the process of establishing its first and, to date, only cobalt mine in decades, located in Idaho, near a decommissioned open pit cobalt mine.

The commencement of domestic cobalt production was met with enthusiasm from US officials, who anticipated that it could expedite the development of minerals crucial for domestic and national security. While the operation was not considered large on the global scale, it was projected to meet approximately 10% of the current US cobalt demand.

The Idaho Cobalt Project was initially intended to be overseen by the Australian company Jervois Global; cobalt would subsequently be shipped to a refinery in São Paulo, Brazil, as the United States lacked suitable refining facilities. However, in April 2023, due to declining cobalt prices and the impact of inflation on construction costs, the mining project was halted just as it approached the production phase—after more than two decades of intermittent starts and stops.

The first proposal for the Idaho Cobalt Project was submitted by Formation Capital Corporation US in the early 2000s, after which there were several exchanges between the company and the US Environmental Protection Agency, the US Forest Service's Salmon-Challis National Forest, and others. Notably, the area has a history of grappling with mining activities' adverse social and environmental impacts. The previous cobalt mine in the region, the Blackbird Mine, operational in the 20th century, caused ecological devastation, such as the contamination of nearby creeks in the Salmon-Challis National Forest, poisoning the local flora and aquatic life. As Jervois prepared for production, concerns were raised about whether the government had imposed adequate financial obligations on the company to address potential ecological damage.

It is noteworthy that Jervois employs a tunnel system rather than an open pit mine, and on project completion, the tunnels are expected to be filled to facilitate revegetation of the area. The company has also constructed a wastewater treatment plant and ponds to contain and treat water from the mine, preventing it from mixing with surrounding streams.

Lithium

While global lithium production is dominated by Australia, Chile, China, and Argentina, which collectively contribute over 95% of the world's lithium, the United States holds what are believed to be the world's second-largest lithium deposits. The states of California, Nevada, and North Carolina account for an estimated 4% of the world's lithium reserves. Despite this, the United States has only one active lithium mine, in Clayton Valley, near Silver Peak, Nevada. The site is operated by the American company Albemarle Corporation, which also runs a mine in Chile's Salar de Atacama and is a large stakeholder in the world's largest hard-rock lithium mine, in Australia.

The majority of the world's lithium reserves are concentrated in the Lithium Triangle, a high-altitude region in the Andes mountains shared by Argentina, Chile, and Bolivia. This area is optimal for lithium production from brine thanks to its dry and sunny weather, which facilitates the natural evaporation process. Brine lithium production involves extracting underground brine from salt plains, evaporating the water through direct sun exposure, and adding chemicals to produce lithium carbonate.

However, lithium extraction presents socio-environmental challenges, particularly concerning water consumption, biodiversity impact, and disruptions to traditional economic activities near the salt flats, as emphasized by a 2023 report by the Economic Commission for Latin America and the Caribbean.[180] The report advocates for stricter regulations and standards to ensure the sustainability of lithium extraction.

Argentina

Argentina welcomes foreign investment in the extraction of mineral resources, including lithium (e.g., by Chinese enterprises). However, mining is a decentralized sector, essentially regulated by the country's provinces as per the constitutional reform adopted in 1994, which granted provinces the original domain over the natural resources within their territory. But provincial management does not always support environmental and social regulation, and it has reportedly hindered communication between corporations and local communities. A 2023 study by Díaz Paz et al. shows how lithium mining in Argentina is often associated with social injustice, unequal access to information, and conflicts around issues such as water consumption.[181] However, from a purely economic point of view, Argentina's strategy seems to be bearing fruit, as it now has more than 40 lithium mining projects in development.

Lithium extraction is booming in Argentina's arid Puna Plateau, despite local communities expressing their concerns and advocating for their rights. While they do not oppose mining per se, they have collaborated on a document asserting their rights to consultation and free, prior, and informed consent (FPIC). They seek an official guarantee from the state that mining will not harm their ecosystem and that their cultural perspectives on the environment will be respected. A 2019 report by the Fundación Ambiente y Recursos Naturales (FARN) provides interesting insights from local perspectives on the social and environmental impacts of lithium mining.

Chile

In Chile, due to outdated regulations, the lithium industry is also facing challenges. Companies must first secure a mining concession to explore and exploit mineral deposits and then fulfill certain obligations, such as paying fees and royalties, in order to maintain the validity of the concession. For example, SQM and Albemarle hold major leasing agreements signed in the 1980s, which are due to expire in 2030 and 2043 respectively, raising concerns about the continuity of their mining operations. On the one hand, the Chilean government has made several calls for a national lithium company, but the constitutional requirement for public companies to be legislatively approved makes immediate nationalization unlikely. On the other hand, the government acknowledges its reliance on successful companies due to its limited capacity and expertise in the industry and recognizes the important role of SQM, as well as Albemarle and other overseas companies, in maintaining Chile's so-called lithium boom. In the meantime, there are continuous clashes between mining companies and local communities; the latter have reported deterioration of the Atacama salt flat ecosystem, impacting the landscape and groundwater levels and contaminating the water deposited in irrigation canals.

Some environmental regulations govern mining companies' operations in Chile: for example, the Resolutions of Environmental Qualification. In 2016, the government initiated sanctions proceedings against SQM because it extracted more brine than the legally established quota and damaged ecosystems. As a consequence, SQM presented a plan that included USD 25 million to improve its monitoring system and carry out further environmental studies. The company also offered USD 15 million in annual contributions to "sustainable development" efforts, but Indigenous communities resisted the proposal as, in their view, it would not repair the damage caused. However, some progress has been made. For example, the Council of Atacameño Peoples has set up monitoring stations in a lagoon on the salt flat to track changing water levels independently.

Bolivia

Bolivia's perspective is quite different from those of Argentina and Chile. Despite holding one of the world's largest lithium reserves, its production is stagnating. Bolivia nationalized the lithium industry in 2008, giving the state control of access, extraction, and production. However, because the country lacks infrastructure development and technical capacities, nationalization has not facilitated increased production. Bolivia is now exploring partnerships with foreign companies that can provide the necessary technology. As the government evaluates six companies for mandatory partnership with the state-owned Yacimientos de Litio Boliviano (YLB), local representatives, well aware of the environmental and social impacts that lithium mining has had on neighboring Argentinian and Chilean communities, are working to draft local regulations, demanding water treatment plants and waste removal plans as well as royalties for the infrastructural development of the local communities.

North America

North America also has a developing lithium industry. Although the United States possesses over 3% of the world's reserves, it has only one moderately producing lithium mine (Silver Peak in Nevada) and several new and potential lithium mines. There are lithium deposits in several US states—notably Maine, which has one of the richest-grade ores globally—and Quebec, in Canada. However, many of these projects are years away from production, mainly due to delays caused by environmental lawsuits. The multiple entry points for litigation in US regulatory law contribute to these delays.

For instance, Maine maintains some of the country's strictest mining and water quality standards, prohibiting the excavation of metals in open pits larger than three acres. There have been no active metal mines in the state for decades and no permit applications since the passage of a particularly stringent law in 2017. Maine's Department of Environmental Protection requires a deposit's owners to apply for permits under the 2017 Metallic Mineral Mining Act—a costly and time-consuming process with a USD 500,000 application processing fee.

Another case is the Thacker Pass lithium mine in Nevada. Although exploration began in 2007, construction was delayed until March 2023 due to numerous legal challenges from local communities and Indigenous tribes, which are ongoing. While the owning company, Lithium Americas, has engaged in consultations on community involvement, the tribes continue to oppose the mining project since they consider the site to be sacred. They object to what they view as a rushed environmental review, threats to critical wildlife habitat, and disruption of cultural sites. Lithium Americas has made some efforts to mitigate the environmental impacts of its lithium mining project: the company has committed to making the project carbon neutral by recycling sulfuric acid on-site and using the generated heat for power, as well as relying on geothermal sources. Additionally, the project is designed to minimize light pollution and traffic impacts. The company has purchased water rights from local ranches, ensuring it will draw the same amount of water over a full year as is currently used during the growing season alone.

Nickel

Indonesia contributes 39% of global nickel production; the other major producers are the Philippines, New Caledonia, Russia, Australia, and Canada (listed in order of output).

Indonesia

Indonesia holds the dual distinction of both being the largest nickel producer and having the largest nickel reserves. The Indonesian government is actively focusing on the mining sector, recognizing the economic opportunities arising therein. For instance, the 2020 Mining Law Amendment transferred the authority over mining business licensing to the central government alone. Additionally, the so-called Omnibus Law on Job Creation featured regulations that were notably oriented toward the private sector.

Indonesia's largest nickel reserves are located in Sulawesi. In this region, the Chinese company Tsingshan operates the Indonesia Morowali Industrial Park (IMIP), a hub for nickel processing dedicated to the stainless steel industry. Although prominent Chinese companies dominate the processing sector, they source inexpensive ore from numerous smaller, predominantly Indonesian-owned mines scattered throughout the rainforest. In 2023, the Indonesian government was planning to open at least eighteen new nickel mines in the Tompotika peninsula.

Nickel mining in Indonesia has various adverse effects on the country's rainforests (such as the 83,000-hectare Tompotika rainforest), including soil erosion, which leads to flooding and soil contamination. In some instances, this contamination has turned the coastal waters of the Pacific Ocean a deep red color, as reported by local communities. Furthermore, nickel processing demands significant amounts of energy, which is mainly supplied by coal-fired power plants. Consequently, nickel production in Indonesia is notably carbon-intensive, emitting an average of 58.6 Mt of carbon dioxide equivalent per Mt of metal equivalent produced, compared to the global average of 48 Mt, as indicated by data from Skarn Associates. In response, members of local communities have initiated demonstrations, riots, and, in some cases, armed confrontations with miners, resulting in the detention of several protesters.

Due to these environmental, social, and governance (ESG) risks, nickel mine operators in Indonesia have encountered challenges convincing environmentally conscious car buyers, socially responsible investors, and the public that they can uphold labor standards, manage waste responsibly, reduce their carbon footprint, and minimize biodiversity impacts.

North America

The Eagle Mine in Michigan stands as the sole primary nickel mine in the United States, while Canada boasts over 100 operational mines, making it the world's sixth-largest producer. Notably, the nickel extracted in Michigan is sent to the nearest smelters in Canada, and a portion of the final product eventually returns to the United States, primarily in the form of stainless steel products.

In an effort to reduce US import dependency and considering the expected closure of the Eagle Mine in 2029, several new nickel mining projects are currently navigating the road map of the United States' permitting procedures. Two such projects, Twin Metals and PolyMet, have been proposed in Minnesota, but neither has successfully completed the full permitting process despite nearly a decade of attempts. Another project, the Tamarack Nickel Project in Minnesota, developed by Talon Metals, involves an agreement with Tesla for the supply of nickel. Local groups have expressed particular concern about the Tamarack project's potential impact on the region's abundant water resources.

Among the world's leading producers, Canada (along with Australia) has garnered recognition for its strong ESG ratings in nickel production, demonstrating a commitment to responsible mining practices and mitigating environmental and social risks. This is attributable primarily to Canada's stringent regulations on the mining industry and the country's climate commitments. For instance, in 2004, the Mining Association of Canada (MAC) launched the Towards Sustainable Mining (TSM) initiative, outlining standards for environmental stewardship, mandatory reporting, and regular independent assessments. Both major nickel producers in Canada, Vale and Glencore, actively participate in this initiative. However, these efforts do not shield the companies from controversy. For instance, Glencore, which has been operating the Raglan Mine in Quebec since 1997, faces challenges due to the adverse effects of nickel transportation on residents' health in the port neighborhood of Limoilou in Quebec City.

Copper

Copper has long maintained a strong presence in the global market and is now gaining increased prominence in sectors related to the energy transition, such as superconductivity applications, EVs, earth-coupled heat pumps, solar energy, and nuclear waste disposal canisters.

Copper production is more geographically diverse than that of other critical metals. Latin America, including Chile, Mexico, and Peru, is the main producing area, accounting for 40% of global production. In contrast, according to USGS data, the United States contributes 6%, and Canada contributes 3%. The availability of major domestic deposits makes the United States self-sufficient in copper, as is not the case with the other minerals previously examined.

Chile

Chile is the largest copper-producing country, and its industry has experienced strong development in the last three decades, driven by Codelco, the state-owned copper mining company, and the rise of large-scale private copper mining (LSPCM). There is evidence of mining activity's impact on the surrounding communities, both in health and environmental terms. For instance, Zanetta-Colombo et al. (2022) have shown that Indigenous communities in northern Chile are exposed to toxic metals from mining activities.[182] The environmental impacts are significant, even of mining sites located in remote areas, such as the Escondida copper-gold-silver mine—the world's largest copper mine, contributing 5% to the world's copper production and 20% to Chile's total output. This mine is situated in the Atacama Desert—a vast and sparsely populated region where, nevertheless, arid conditions pose an environmental challenge. Despite efforts to mitigate this issue, including the use of desalinated seawater, freshwater extraction from aquifers affects local biodiversity.

Moreover, copper mining generates substantial waste, including waste rock, spent ore, and tailings. Fortunately, the arid conditions at the Escondida site limit the potential for acid mine drainage (AMD). In an attempt to compensate for the mine's adverse impacts, various initiatives have been implemented in the area. In 1997, the Escondida Mining Foundation (EMF) was established as an autonomous nonprofit organization. EMF offers diverse educational programs, including teacher training, school management enhancement, scholarship programs, and English classes. Additionally, it provides training and technical assistance to small businesses. For instance, it has supported the establishment of a manufacturing business that produces textiles using traditional techniques and materials employed by Indigenous peoples from the region.

Furthermore, Codelco initiated the Buen Vecino (Good Neighbor) development program in 2003, aiming to enhance environmental and social conditions in nearby communities. Private companies in Chile are also taking proactive measures. For instance, Teck Resources has invested CAD 2 million in northern Chile to establish a learning center, which offers classes on entrepreneurship, business skills, and economic advancement for Indigenous women. Moreover, Teck Resources entered into agreements with local organizations representing 16 communities near its Highland Valley Copper site, introducing joint decision-making on regulatory matters through consensus. This collaborative effort resulted in developing communications protocols and a community working group to guide consultations regarding land use and mining operations. Another example is Anglo American, which has committed to water conservation in its mining operations and collaborates with local communities to develop efficient water management methods in Chile. Recognizing the challenges rural communities face due to severe droughts, Anglo American established the Rural Water Programme (Agua Potable Rural), applying its water management research and technology to find solutions for over 100,000 people in affected communities.

North America

In the United States and Canada, the environmental impacts of copper mining have long been documented. An Earthworks inquiry reported results from reviews of state and federal documents for 14 copper sulfide mines, representing 89% of US copper production in 2010.[183] All the mines experienced pipeline spills or other accidental releases. At 13 of the 14 mines, water collection and treatment systems failed to control contaminated mine seepage, resulting in significant water quality impacts in the area. A particularly dramatic example is the collapse of a dam at the Mount Polley copper-gold mine—the largest environmental mining disaster in Canadian history. In all, 24 million cubic meters of mine waste went into a nearby lake that served as a food source for surrounding Indigenous communities.

Many proposed projects face public opposition. This includes major projects such as Resolution Copper in Arizona and Pebble in Alaska, both condemned by local communities due to their potential impacts on water resources. The Resolution Copper project is currently entangled in a lawsuit with local communities and the Apache tribes of Oak Flat. Interestingly, the land was already protected from mining for religious preservation in 1955, but the National Defense Authorization Act for 2014 included language allowing a land transfer to Rio Tinto and BHP Billiton, two parent companies of Resolution Copper. As for the Pebble site, in January 2023, the US Environmental Protection Agency (EPA) effectively vetoed the project, citing a provision of the Clean Water Act.

Another important case is that of Twin Metals' proposed copper-nickel mine in Minnesota (mentioned in the nickel section). The leases were first granted in 1966 and have been passed along to successor companies over the years, though no mining has yet taken place on the site. Twin Metals acquired the leases in 2011 and thereafter spent more than ten years preparing for the site's development. The company sought to renew the leases in 2012, but the Obama administration denied the request in 2016, after determining it had discretion to do so since mining had not started. The Trump administration reversed course and renewed the leases in 2019, but in 2021, under the Biden administration, the US Forest Service proposed a 20-year ban on mining in Minnesota's Boundary Waters region, which was confirmed in 2023 by the US Department of the Interior. The rationale behind the ban was that mining could pollute the wilderness's streams and lakes with potentially toxic waste.

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