THE STATE OF CRITICAL MINERALS REPORT 2025

The Payne Institute *for* Public Policy
AT COLORADO SCHOOL OF MINES

FOREWORD

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BROADENING THE CRITICALITY LENS

Welcome to our third State of Critical Minerals report!

These reports, which accompany our annual symposium, seek to provide insights into the complex and deeply interconnected topics surrounding critical minerals. Our first report[1] provided a global overview highlighting China's domination of supply chains across the broad swath of critical minerals, creating strategic vulnerabilities.

Last year's report[2] focused on the U.S. response. We discussed the challenges involved with sourcing critical minerals and offered recommendations, noting that successful development will address community and tribal relations, simplify government approvals, alleviate workforce constraints, and offer incentives to spur an otherwise unsupportive investment landscape.

This year we seek to broaden the frame. First, we emphasize the entire value chain relative to what we believe is often an over-emphasis on mining, or the upstream. Indeed, Chinese dominance in refining/processing minerals is for many minerals a more significant risk than the mining of raw ore. Related, we consider the potential to extract byproducts from current mining operations.

Second, we broaden our attention on the number and uses of critical minerals. To date, the bulk of attention has focused on a handful of minerals most closely associated with clean energy. But the increased requirements for applications in defense and AI point to considerable growth in demand for a much broader range of materials and supply chains.

Another shift this year: when we address governmental response, we are more focused on markets and investment. The current administration is, of course, offering its own powerful examples. The Department of Defense’s blockbuster partnership with MP Materials brought a suite of unconventional tools to government financial support and its expressed interest in accessing resources, including outside the U.S., opens the door to other defense-related critical mineral resources “deals”. Yet it also appears smaller-scale investments can be powerful. Our work suggests, for example, that U.S. gallium needs could be funded for less than $15 million per year if there was adequate domestic processing capacity. We also observe that the U.S. could significantly lower copper imports if we recycled copper scrap ourselves vs. sending it overseas.

Finally, we continue to highlight some of the terrific work underway at Colorado School of Mines that will surely help the industry address and prioritize these challenges. From modelling of the impacts of minerals on power systems, to the enormous potential of waste-to-market, to tracking illicit supply chains, Mines remains at the forefront of these discussions.

On behalf of the Payne Institute, I hope you find this update, and our annual symposium for those attending, informative and thought-provoking. We thank you for your continued support and look forward to engaging with you further.

Morgan Bazilian

[1] The State of Critical Minerals Report 2023. The Payne Institute for Public Policy. https://payneinstitute.mines.edu/wp-content/uploads/sites/149/2023/09/Payne-Institute-The-State-of-Critical-Minerals-Report-2023.pdf

[2] The State of Critical Minerals Report 2024. The Payne Institute for Public Policy. https://payneinstitute.mines.edu/wp-content/uploads/sites/149/2024/09/Payne-Institute-The-State-of-Critical-Minerals-Report-2024.pdf

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THE STATE OF CRITICAL MINERALS REPORT 2025

EXECUTIVE SUMMARY

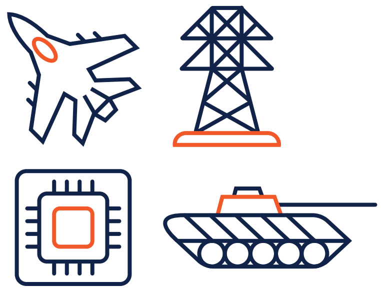
Defense and Technology Bolster Demand Growth Outlooks

The demand outlook for several smaller volume critical minerals has been bolstered by their use in defense systems. Prospective demand growth for copper and "battery minerals" remains strong, bolstered in part by AI.

- 80%-250%. The estimated demand growth for 10 key critical minerals for defense through 2035, bolstered by higher defense spending budgets across the OECD. Defense needs for one mineral, hafnium, might comprise nearly 30% of U.S. total demand.
- 400%+. The estimated demand growth by 2050 for 16 critical minerals for power generation and battery storage needs.
- Estimates based on updates to the Payne Institute Critical Minerals Intensity Tool.

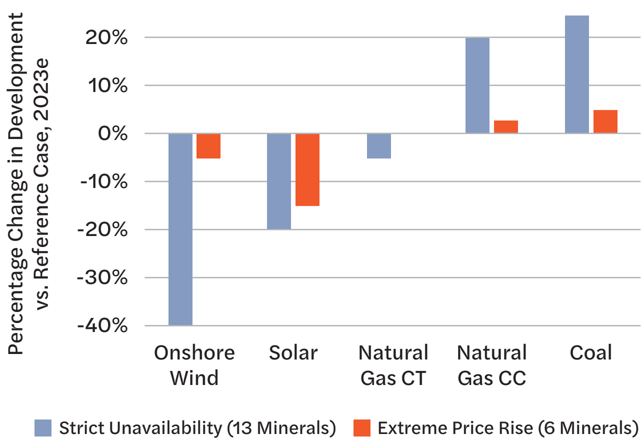
135%

The average growth in demand for 10 key critical minerals for defense needs in the next 10 years vs. the last 10



U.S. Power Generation Vulnerable to Availability of Certain Critical Minerals

No Minerals, No Megawatts. Securing a diverse supply of power is reliant on availability, and affordability, of over a dozen critical minerals.



13 **Minerals pivotal to which types of electricity generation are deployed in the U.S.**

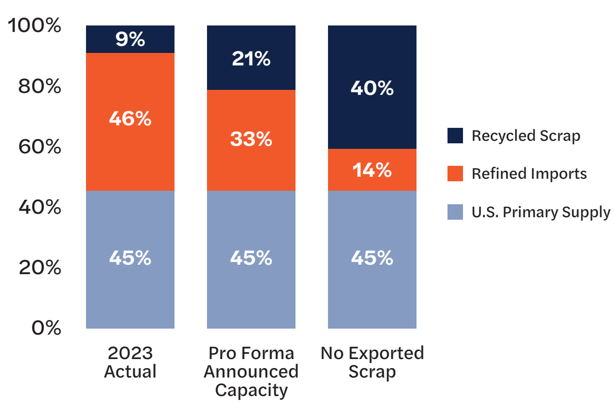
- Availability shocks in any one of 13 critical minerals could squeeze availability of wind and solar and swing deployment of power generation technologies by 25%+.
- Significantly higher prices of six of these minerals could result in a 10% or more reduction in deployment of solar generation.
- Analysis based on U.S. power system modeling from Mines Economics & Business professor Max Brown.

Processing More Scrap Could Cut U.S. Copper Imports

Recycled scrap could meet 40% of current U.S. copper demand.

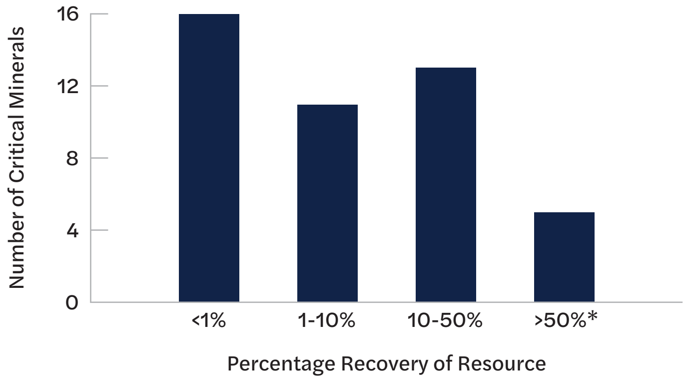
1/3 **Proportion of U.S. copper demand exported overseas in the form of scrap**

- Of the U.S. (apparent) demand for copper in 2023, 530 thousand tons, or 32%, was exported, in the form of scrap, to other countries. Of that exported amount, 40% was sent to China.
- U.S. scrap smelting expansion is underway; announced capacity will recycle ~20% of U.S. needs.
- Recycling all of U.S. scrap could have reduced import requirements to 14% of U.S. demand.



Recovering Byproducts for U.S. Self Sufficiency

Byproducts from active mines, if recovered, could form the basis for self-sufficiency across the USGS Critical Minerals list.



*Even 100% recovery only partially offsets imports.

27 **Critical minerals needs that can be met in the U.S. with 10% recovery of current byproducts**

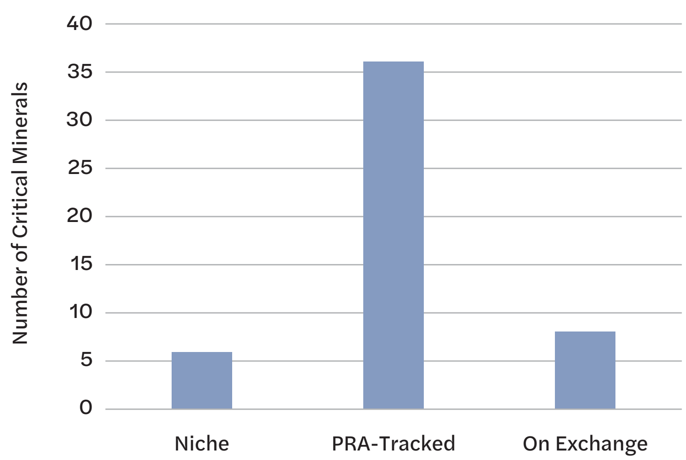
- The U.S. could cease importing 27 critical minerals altogether if 10% or less of the estimated available resources of those minerals could be recovered (and processed) from ongoing U.S. mining operations.
- The U.S. could become self-sufficient in another 13 critical minerals if up to 50% of these minerals could be recovered from mined resources.
- Estimates derived by Mines' Responsible Critical Minerals team.

Marketplaces Can Help Foster Capital Flows into Critical Minerals

Formal marketplaces can reduce opacity, reduce transaction costs, and mitigate risks in critical minerals trading.

42 **Of the 50 critical minerals on USGS list, the number traded bilaterally, not on exchange**

- Exchange-trading is sometimes seen as the goal for minerals markets, but is not suitable for all products. The vast majority of critical minerals products are traded via bilateral contracts.
- Formal marketplaces can reduce opacity, improve market efficiency, reduce transaction costs, and mitigate risks associated with bilateral trades.
- Government can support the establishment and growth of marketplaces, as well as complementary market infrastructure, such as storage and logistics. This could complement government measures including stockpiling and price floors.



PRA=Price Reporting Agency; provides benchmark pricing data. The mineral may or may not trade on a platform.

Government Support for Exploitation of Certain Critical Minerals can be Modest

For some crtitical minerals, U.S. consumption is as little as a few tens of tons per year. That suggests government support can cost only a few million dollars per year.

- Gallium is highly critical for defense and high tech manufacturing; substitutes to gallium arsenide (GaAs) and gallium nitride (GaN) semiconductors are thought to meaningfully compromise performance.
- One facility, owned by Nyrstar in Tennessee, could provide 40 tons per annum of gallium with an investment (estimated cost $150 Million) in processing capacity; this would reflect 6% of global production and 200% of USGS US consumption estimates.
- Purchasing all of Nyrstar's capacity would cost at most $15 Million per year (although there may be additional cost to produce high purity gallium).

$15 MILLION **What annual price support for gallium might cost the U.S.**

TABLE OF CONTENTS

INTRODUCTION

Critical minerals and associated supply chains have become a top-tier priority for governments globally. That awareness has spurred stakeholders from across government, industry, academia and advocacy to take action ranging from large-scale investments to reformulating permitting to improving market transparency and functioning.

Still, numerous hurdles exist. These challenges are largely hangovers from the troubled environmental and societal legacies of mining. The focus now is how to get mining and processing projects unstuck and ensure that they are undertaken in more economically and environmentally sustainable ways.

Arguably more important, and as the Payne Institute has pointed out for years, it is China's dominant market share downstream of mining, i.e. in refining/processing, that creates the most vulnerability. China's massive market share (either in country or controlled by Chinese entities) across dozens of processed critical minerals has been well established. And the real pain for countries, militaries, and governments is being felt across several sectors. China reduced rare earths quotas as early as 2009. It then imposed export restrictions in 2023 on gallium, germanium and rare earth processing equipment and this year on tungsten, tellurium, bismuth, indium, molybdenum and seven rare-earth elements and magnets.

It has taken time for understanding to emerge regarding how China has cornered the market in critical minerals. The depth of the "roots" of Chinese supply chains are arguably still not fully appreciated, both in terms of accessing raw minerals and the value of their vertical integration in terms of providing consistent demand for those minerals.

It has also taken time for the various stakeholders to appreciate that critical minerals are not homogeneous but rather have myriad supply and demand conditions that point to very different ways that government or policy can (or should) engage in combatting China dominance.

It can be argued that much of the critical minerals focus of the early 2020s related to the idea of an energy transition. That narrowed attention, if not "officially" with respect to policy then effectively, to a handful of minerals that would likely be used in very large quantities in clean energy and battery storage such as lithium, nickel and cobalt.

Yet, although perception of the need for more energy has never been stronger given burgeoning Artificial Intelligence (AI) and the related demand for data centers, there is also focus on critical minerals used in the defense—especially in the USA—and electronics (again related to AI) industries. These point to demand for very different critical minerals, including rare earths, gallium, tantalum, tungsten and indium, to name just a few, that are inputs for all forms of weaponry, military vehicles, satellites, communications and high speed computer processing.

However, because they are required in much smaller volumes, there are more opportunities to raise supply and at a cost—to government, in terms of specific support—that can be considered quite small in the context of defense budgets or overall governmental outlays. We estimate, for example, that the cost to stockpile enough gallium to supply the military for the next ten years could be less than $15 Million per annum; stockpiling enough lithium to satisfy the needs of U.S. batteries over the same period could cost several orders of magnitude more.

These defense minerals are also very accessible; the U.S. is currently mining dozens in reasonable quantities. Separation and then refining capacity can be plausibly bolted on to existing mining and processing infrastructure. Research at Colorado School of Mines suggests that with modest

(<10%) recovery of domestic ore, the U.S. could be able to satisfy its needs (i.e. without imports) of 27 minerals. Government support appears necessary in part because of how China is exerting its influence across all critical minerals processing. Private mining and processing industries are facing meaningful challenges, with low prices squeezing profits and "squashing" economic return-based assessments for expansion, thereby squeezing out would-be competitors to Chinese entities. Examples abound, but include lithium, cobalt, and nickel, for which pricing has given up gains that were fueled by long term demand growth outlooks set in the "headier" days at the beginning of the decade, and are now below thresholds required to support new (Western) investment. And in rare earths, current pricing for NdPr Oxide, a non-substitutable component of batteries, is ~1/2 of what U.S. mining companies say they need to be profitable (even at scale).

Notably, the same can be said for copper, although only at an intermediate stage. Prices for semi-finished product (cathodes) set new highs in the U.S. in 2025. But refining margins are negative as a surge of Chinese-backed capacity has swamped the refining market.

Support also appears necessary because the lower volume requirement defense minerals—that are often byproducts that are left in mine tailings/wastes as noted above—are too small to be "worth it" for businesses to pursue. If these minerals are indeed deemed critical, it will fall on government to structure demand support (in what form and at what price) to supplement the market (price) to foster the necessary investment.

With respect to the nature of U.S. government support, there are clear signs of change. The Biden Administration embraced support for critical minerals development and processing domestically (as part of a broader industrial policy agenda) and, to a lesser extent, in friendly countries. Domestic critical minerals project support came from (1) the Department of Energy's Loan Program and Department of Defense, which issued $4 Billion in grants and loans (dominated by lithium and rare earths by virtue of large investments in Lithium Americas and Lynas, respectively), and (2) Inflation Reduction Act (IRA) tax credits including Advanced Manufacturing Production (45X) and the Qualifying Advanced Energy Project (48C).

The Trump Administration appears to be willing to expand the number of levers it might employ to support specific projects, including taking equity stakes and providing pricing guarantees. This was illustrated in dramatic fashion by the Department of Defense's recent significant investment in MP Materials (which had received loan support during the Biden Administration). Notably, the Administration's Executive Order 14201 in March 2025 appears to lay some groundwork to empower the Development Finance Corporation (DFC) to promote domestic mining and processing projects to supplement its (more narrow) international mandate. Meanwhile, the current administration has made access to critical minerals an integral part of diplomatic efforts in Ukraine, Democratic Republic of Congo and elsewhere.

At the same time, for both smaller and larger volume minerals, it is important for the US/OECD to develop more of its own separation/refining/processing capabilities (as has been recognized and encouraged in legislation including the IRA and the European Union's Critical Raw Materials Act). And investing to support recycling, or waste to value, capacity creates clear potential to make the most of existing finished product vs. exporting scrap to other countries.

Government support, and more specifically demand support, comes (or can come) with its own set of issues with respect to fairness (appropriate use of taxpayer dollars) as well as the risk of perverse impact on the broader market (i.e., market distortions) and non-supported competitors (i.e., picking winners and losers). Compounding these issues is that the market price for many minerals is not always clear, a function of often relatively small market size. These markets are not without mechanisms to support price discovery (most critical minerals rely on Price Reporting Agencies), but these thinner markets point to relative challenges in determining how much support is “enough”. In this 2025 State of Critical Minerals report we review some of these issues and the leading work being done at the Colorado School of Mines, including the Payne Institute, to address them. The sections that follow offer a look into specific aspects of addressing the challenge. These investigations include:

- **No Minerals, No Megawatts.** Work led by Mines Economics and Business Department professor Max Brown seeks to bring sophistication to the sensitivity to price and availability of various critical minerals to building various forms of power generation capacity. He finds that (un)availability of 13 minerals and extreme price spikes of six minerals can lead to reductions or increases of up to 40% vs. baseline expectations in building capacity in various power generation technologies.

- **Exploiting the Ore (The Illicit/Gray Market).** China appears to be leveraging its strengths in minerals refining/processing, creating a business model in which it takes raw ores, with low concentrations of any given mineral, and extracts a number of valuable minerals. This has to date been documented more in the gold market, including work led by Mines Mining Engineering professors Nicole Smith and Sebnem Duzgun. Trade data and anecdotal evidence that looks at low concentration of the primary mineral vs. industry shipping standards suggests it is applicable to critical minerals markets as well.

- **Exploiting the Byproducts.** Byproduct opportunity in the U.S. tailings/waste (from active and abandoned mines) can in several cases obviate the need for imports if it is extracted and processed. Work led by Mines’ Mining Engineering Department’s Elizabeth Holley and conducted by Mines’ Responsible Critical Minerals team has reviewed that potential and found that the needs for imports can be obviated for 27 critical minerals if <10% of what is currently being mined can be recovered.

- **Lowering Supply Risk.** In the same vein, research in Mines Department of Economics and Business under Ian Lange and Tom Brady quantitatively assessed the criticality impact of recovering six critical minerals from slag produced by primary smelters. They found that even with partial recovery from identified smelters, the U.S.’s supply risk as set by the Criticality Score falls 70% or more for gallium, germanium and lithium.

- **Leveraging the Toolkit for Government Support.** The Department of Defense’s investment in MP Materials and price support for its NdPr Oxide lays an aggressive marker for supporting the development of magnets in the U.S. Support, including stockpiling, for certain critical minerals such as gallium can be achieved for relatively little as volume requirements are low.

- **Copper Scrap as an Illustration of Recycling Potential.** The U.S. exported 1/3 of its copper requirements in the form of scrap in 2023 (of which 40% went to China). Raising scrap recycling capacity reflects an opportunity to gain more control over this valuable mineral.

DEEPER UNDERSTANDING OF DEMAND & THE SUPPLY CHAIN

NO MINERALS, NO MEGAWATTS

There is an increasing appreciation in the U.S. and elsewhere of the criticality of minerals to supporting economic growth and defense needs. As China has been increasingly assertive in exercising the leverage it has built, particularly in refined products, it has heightened the perception that the U.S. and other nations could simply (a) be left without needed minerals or (b) that meaningfully reduced supply could cost significantly more.

However, the complexity and interconnectedness of various systems make it challenging to assess the impact of such a loss of availability. In addition to some substitutes within specific products, systems might have various forms of supply, which would allow one form to compensate for shortfalls in another. The U.S. electricity generation system is one such, very complicated, system.

Mines' Economics and Business, with support from the Payne Institute, is engaging in this effort. Professor Max Brown has modeled U.S. Electricity generation through 2035. Building on a reference case that forecasts capacity in 10 power generation technologies[3], he models the impacts on the "system" given both price and availability "shocks" (i.e., price spikes and a lack of availability) in 33 minerals (or materials such as steel)[4].

Among the conclusions of Brown's work is that being unable to access sufficient quantities of any one of 13 different minerals (of the 33 minerals/materials studied) can cause significant disruption to planned/expected electricity generation going forward. The impact varies by mineral and generation technology, but broadly the model points to a reduction in renewable energy deployment (particularly batteries, onshore wind and solar) and for that "lost" generation to be made up for by natural gas (combined cycle plants) and coal. See Exhibit 1.

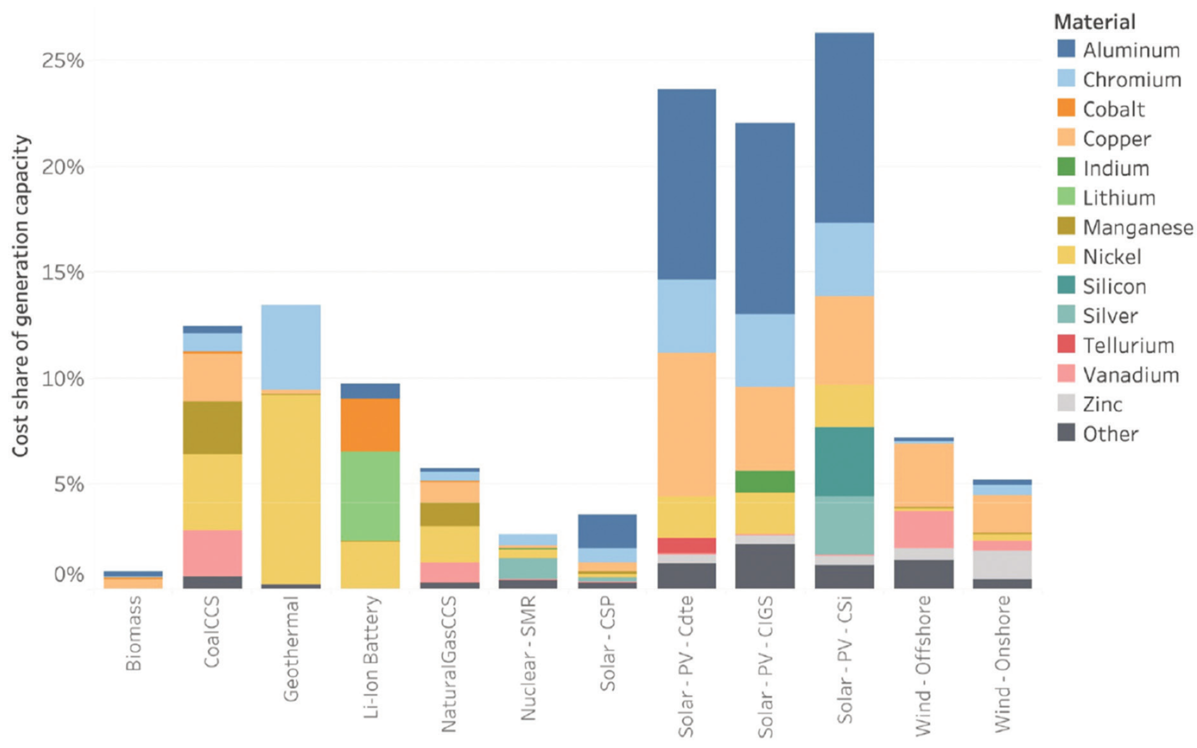
It is worth noting that there is assumed power generation growth of ~25% by 2035; that is not inconsistent with some forecasts and is informed by anticipated demand growth from data centers.

The modeling ties in research of mineral intensity (i.e., the amount of each material in a given power generation technology) and cost/availability curves performed by the Economic & Business department and Payne, respectively. See Exhibit 2 for the cost shares of materials for various power generation technologies and Exhibit 3 for an example of a cost curve.

Exhibit 1: Change in 2035 Power Generation From the "No-Shock" Case by a Price Shock and Lack of Availability

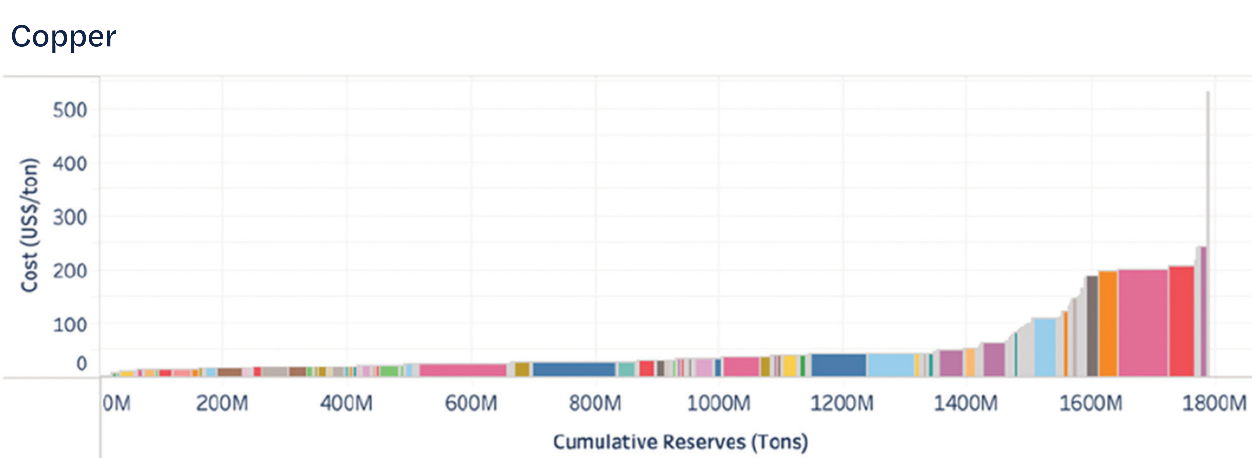
Source: Colorado School of Mines

Exhibit 2: Cost Share of Electricity Generation Capacity by Technology



Source: Colorado School of Mines

Exhibit 3: Cost Availability Curve for Copper



Source: Payne Institute from Company and Industry Reports

[3] Ho, J., et. al., 2021. Regional Energy Deployment System (ReEDS) Model Documentation: Version 2020. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy21osti/78195.pdf.

[4] Brown, M., Hotchkiss, E., Collins, G., Seyedrezaei, M., Bazilian, M., 2025. No Minerals, No Megawatts: How material costs and availability shape the future of the U.S. power sector. https://doi.org/10.1016/j.resourpol.2025.105607

DEFENSE CRITICAL MINERALS NEEDS RAMPING UP

In response to lingering conflicts in Eastern Europe and the Middle East, many nations have increased their defense spending. Between 2023 and 2024, global defense spending increased 9.4 percent, with Germany, Poland, and other NATO countries driving a significant portion of that increase[5]. Orders for military kit have also risen among NATO countries, pointing to an accelerated pace of building over the next decade vs. the previous one.

The basic tools of warcraft (fighter jets, tanks, submarines, and drones) are users of an array of critical minerals and as such the increased budgets point to rising demand for such minerals. A Payne-conducted study of such military equipment yields an expected demand increase of as much as 250% on an annualized basis for vanadium and manganese, ~200% for titanium and copper, and 80-100% for six other critical minerals (see Exhibit 4).

While this exercise does not come close to capturing all defense needs for minerals—examples abound in which defense needs mirror modern society's for so-called "dual use" technologies—it does show the impact of the accelerating build-out on mineral demand. Yet, it remains the case that the needs for critical minerals are generally not large in the context of current use in the broader economy (and perhaps offers insight why we have not seen prime contractors take focused steps to secure supply). The exception to the above point is hafnium, for which the expected deliveries might comprise nearly 30% of the U.S.'s current use (see Exhibit 4). (Hafnium is used in the turbine alloys in commercial and military jets. Pratt & Whitney builds the F-35's engine, and hafnium is used with tantalum and rhenium to make the crystalline metal heat-resistant.)

Exhibit 4: Annualized Demand for Military Equipment Buildout, 2025-2035 vs. Last 10 Years, by Mineral

(TONS/YEAR)	IMPLIED ANNUALIZED DEMAND OF EXISTING FLEET	ANNUALIZED MINERAL DEMAND FOR FLEET TO BE DELIVERED THROUGH 2035	PERCENT INCREASE	ANTICIPATED DEMAND AS % OF CURRENT U.S. ANNUAL CONSUMPTION
Rare Earths	45.6	90.4	98%	1%
Gallium	0.1	0.2	80%	1%
Tantalum	1.6	2.9	80%	0%
Rhenium	0.0	0.1	80%	0%
Hafnium	0.8	1.5	80%	28%
Vanadium	1.3	4.7	250%	0%
Chromium	144.5	290.4	101%	0%
Manganese	17.8	62.4	250%	0%
Titanium	1.2	3.5	203%	0%
Copper	178.7	532.8	198%	0%
Aluminum	448.7	758.5	69%	0%

Source: International Energy Agency, Bloomberg NEF, Payne Institute

[5] Stockholm International Peace Research Institute., April 28, 2025. Unprecedented rise in global military expenditure as European and Middle East Spending Surges. Available at: https://www.sipri.org/media/press-release/2025/unprecedented-rise-global-military-expenditure-european-and-middle-east-spending-surges (accessed August 17, 2025)

DEMAND RESPONSE TO CHANGING OUTLOOKS

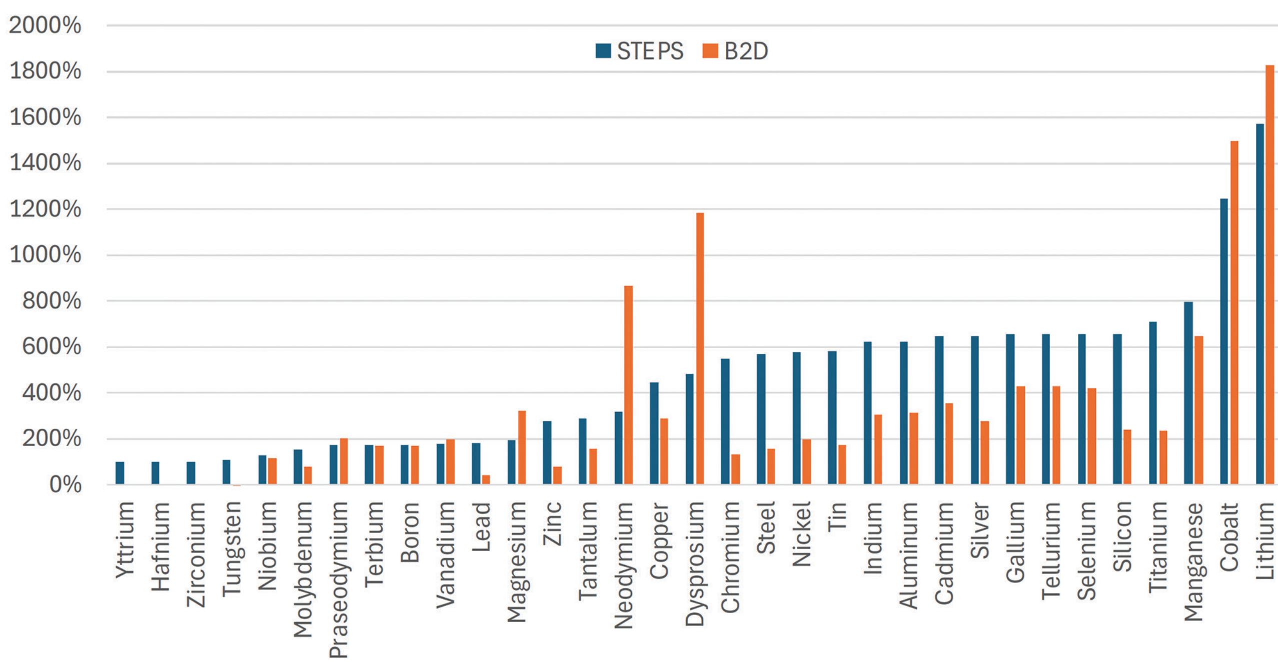
Awareness of the supply risk of critical minerals emerged (albeit with some lag) with the advent of scenario modeling related to the energy transition and the related electrification of the global economy. In other words as the International Energy Agency (IEA) and others began to publish scenarios/outlooks for the demand for solar and wind technologies and electric vehicles (EVs), it gradually became apparent that this portended a dramatic growth in demand for various critical minerals.

Approximately two years ago, Payne developed a "tool" to ascribe mineral intensity of the various power generation technologies (e.g., battery storage). This tool anchored its demand (by decade to 2050) for these demand drivers to the IEA's Below 2°C (B2D) scenario, first published in 2017, and Bloomberg New Energy Finance (NEF)'s EV and grid storage adoption outlooks. Payne's tool produced annual demand for over 30 minerals associated with those power generation and battery-associated technologies.

We have updated that work by applying the same mineral intensity assumptions to a new scenario: the IEA's Stated Policies Scenario (STEPS), published in 2021, along with the same Bloomberg NEF scenario. As the name suggests, STEPS based its outlook on policies that had been enacted or (firmly) announced, which although by no means guaranteed, reflected a greater likelihood of occurrence relative to other scenarios produced during that period, such as the IEA's Net Zero Emissions (NZE) scenario, that offered a view of "what it would take" for the planet to be at net zero CO_2-equivalent emissions by 2050.

The STEPS scenario resulted in substantive changes to the anticipated mineral demand growth relative to B2D. See Exhibit 5 for a summary of the results across the minerals studied. By and large, the expected demand over time for minerals rises in STEPS vs. B2D, although some notable exceptions include neodymium, dysprosium and, although they remain the modeled fastest growing minerals because of the continued expectation of EV and battery storage adoption, lithium and cobalt.

Exhibit 5: % Change in Annual Demand 2050 vs. 2020, by Mineral, by Scenario



Source: International Energy Agency, Bloomberg NEF, Payne Institute

THE GRAY MARKET IN CRITICAL MINERALS

Amid the ongoing debate over how to securely source critical minerals, not nearly enough attention has been paid to the threats posed by illicit flows, black markets, and covert supply chains. It is hard to assess their collective impact, but trade flow data suggest the value of these illicit supply chains reaches into the billions of dollars. In addition, illicit supply chains may cut off access to critical minerals from current mining operations and stable, politically aligned regions. The activity may often be led by unscrupulous actors, but even state actors can and will pursue illicit means to gain advantages; this includes not only leveraging organized criminal groups and other proxies but also directly exploiting regulatory, monitoring, and enforcement gaps that allow for unchecked flows of critical minerals.

One prominent example of criminality and geopolitical competition that illustrates such flows is the illicit exploitation of gold. Indeed, many of the same actors are already applying lessons learned from the illicit gold trade to create invisible supply chains of critical minerals, making gold a clear indicator of the methods and networks now emerging in other resource markets.

The record rise in gold prices is tied to a confluence of forces and events: economic and political uncertainty, conflict economies, the globalization of organized crime, the need to move illicit funds outside the regulatory and enforcement mechanisms of the global financial system, and a growing disenchantment with the U.S. dollar as the world's dominant currency. Illicit actors have capitalized on these conditions, embracing gold not only as a revenue stream but also a strategic asset and a vehicle for laundering and transferring illicit funds—an activity that shows no sign of abating.

While gold moves in a dozen or so forms through global supply chains, one form in particular is instructive here: gold ores and concentrates, which are classified under the same tariff code in international trade (Harmonized System Code 261690).

The trade in gold concentrate remains both highly opaque and poorly understood, a phenomenon highlighted in work led by Mines' mining engineering professor Nicole Smith[6]. In most jurisdictions, customs personnel are unfamiliar with the material and could rarely reliably identify it—an unsurprising limitation given that it often resembles nothing more than bags of dirty sand loaded into containers. Lacking standardized benchmarks, gold concentrate can be blended with other mineral concentrates or beneficiated at aggregation points, facilitating its movement in substantial volumes across international borders. These characteristics have created an enabling environment in which criminal networks in certain producing countries can transport illegally mined gold in concentrate form with minimal risk of detection, thereby laundering significant sums of illicit revenue through ostensibly legitimate trade flows.

The question of hidden value is magnified when cargoes not of concentrate but of raw ore are shipped vast distances to processing facilities. On the face of it, shipping raw gold ore is economically irrational: a typical grade of well under 10 g per Metric Tonne (MT) should not yield enough gold to even pay for a cargo's transit. Yet where things get more salient to critical minerals, and presumably begin to point to the economic rationale behind shipping so much tonnage, is that gold concentrate, and especially raw ore, never contains just gold. Even the highest-grade concentrate may have a tenor of 400 g per MT; the rest of the material will include a number of other minerals, including some with critical minerals designations. Refractory gold concentrate, for example—and a significant portion of the gold moving to China from the Andean region is pyrite gold—contains antimony, copper, silver, PGMs, lead, and other metals. Large quantities of gold ores and concentrates are going from South America to subsidiaries of a Chinese parent company that markets its ability to separate and process a wide array of critical minerals[7].

The largest actor securing gold ores and concentrates is China, which imported nearly 3 million MT in 2024, according to its self-reporting to UN Comtrade. The numbers in the Andean region alone are staggering: according to the Colombian trade analytics platform SICEX, over the past two years China has imported from Ecuador over 375,000 MT, at a declared value of over USD 1.7 billion, while Peru has shipped to China over 625,000 MT valued at USD 1.44 billion. A close look at the data reveals that many of those cargoes, as declared, are not concentrate, but rather are raw ore. But on bills of lading for such shipments, only the primary mineral is customarily declared, sometimes at well under industry standards of concentration. In other words, critical minerals can travel undeclared, hidden in plain sight, from countries of origin to global hubs of midstream processing. This is not a black-market flow of critical minerals, but it certainly qualifies as gray.

It is important to note that China is only one actor among many. Every mineral supply chain is complex, and with that complexity comes an array of vulnerabilities, links where product can be diverted, concealed, and sold on the black market or re-integrated into legitimate commerce for profit. Some of the gold concentrate departing from Colombia and Ecuador is the product of mines operated by criminal gangs and designated terrorist groups. Sometimes, as in Venezuela and Colombia now, critical minerals such as coltan transit clandestine supply chains from illegal mines to black market buyers. In Mexico, tons of mineral concentrates, primarily gold and silver, have been robbed from barges, trucks and storage facilities, inevitably going to buyers capable of laundering those products into midstream throughput.

The picture this presents is itself complex and refractory. On one side, while the world's attention is on conflict zones rich in critical minerals, comparatively stable regions are being quietly stripped of them. While making off with critical minerals in such a fashion may not be illegal under the relevant regulatory frameworks, it is clearly geostrategic (and it deprives exporting countries of royalties or other compensation for the value of their resources). On the criminal side, agile non-state actors, sometimes operating as state proxies, construct a shadow trade in illicit minerals that quietly generates enormous profits to nefarious ends.

Just as the rising demand for gold led to illicit flows that grew in value, sophistication, and variety of actors, the need for critical minerals has opened the door to shadow flows that are far too seldom included in the strategic picture. Gray markets are already booming. Black markets are expanding. Some of the players involved, both state and non-state, are dangerous adversaries. It is a matter of national security to identify those flows, understand their underlying dynamics, and disrupt them where appropriate. No sound and comprehensive critical minerals strategy will allow them to flourish unchecked.

QUANTIFYING THE (REDUCTION IN) CRITICALITY

As the U.S. pursues more diverse and resilient critical mineral supply chains, a key opportunity is presented by the recovery of such minerals from mining operations, both those that are active as well as legacy operations that have left behind waste piles across the country. Critical minerals are almost always byproducts of primary targets of mining, and therefore refining, operations. Their recovery offers clear benefits of expediency, minimizing the environmental impact or actively reducing environmental impact, and creation of income streams to fund such recovery—a concept captured in an overarching term Waste-to-Market (W2M)—relative to opening new mines. With a wide array of conditions and concentrations of byproducts in current and legacy mining operations, the technical readiness and economics of their recovery is site-specific.

The idea and potential of W2M is considered in detail in this report, in the section entitled Recovering Byproducts beginning on page 27. That section describes a comprehensive review by the multi-disciplinary Responsible Critical Minerals (RCM) team at Colorado School of Mines of the byproducts composition in active mines. That team's work suggests that recovering 10% or less of the available

[6] Smith, N.M., K. Seguin, U.M. Saka, S. Duzgun, A. Smith-Roberts, D. Soud, J. White. 2024. Gold supply chain opacity and illicit activities: Insights from Peru and Kenya. Journal of Illicit Economies and Development. 6(1): 42-59. https://par.nsf.gov/servlets/purl/10558660

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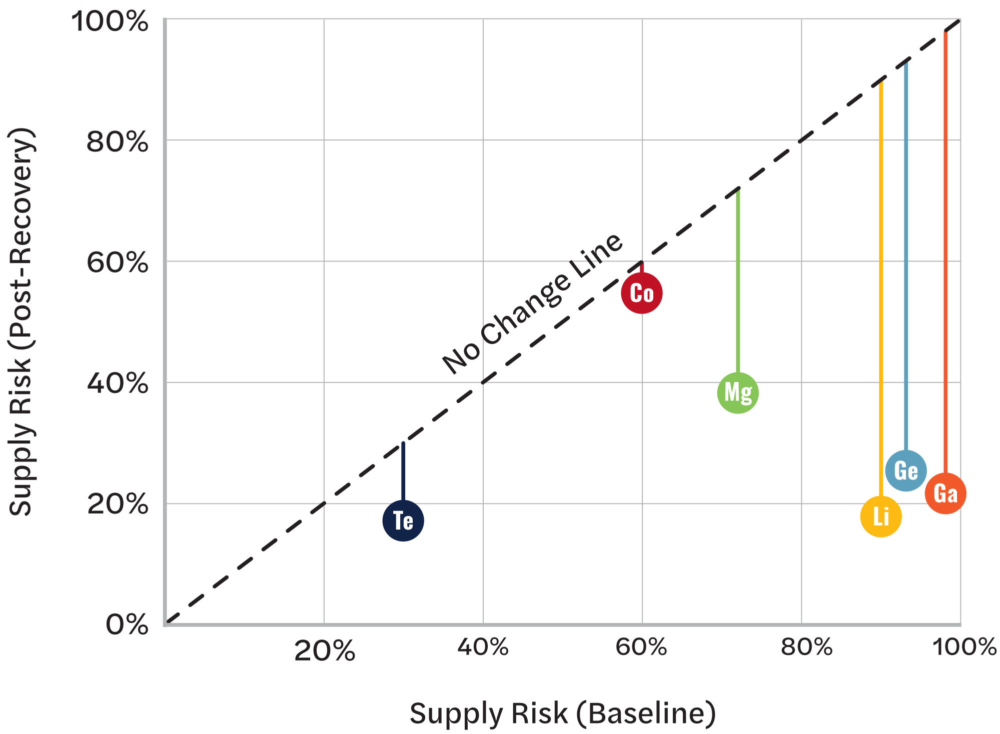
resources of current mine byproducts could obviate the need for the U.S. to import 27 critical minerals on the USGS list. The section also addresses targeted research being done related to more recovery potential from waste in specific abandoned mines.

To offer a different perspective on the same topic, a research effort within Mines Economics and Business department quantified the potential to reduce the supply risk of specific critical minerals by adding recovery capacity for those minerals to existing U.S. smelters. For example, the study evaluated the impact of adding germanium recovery to the Nyrstar zinc smelter in Tennessee. The study concluded that a few of these discrete steps could reduce the supply risk for the U.S. of obtaining gallium, germanium and lithium by over 70% (see Exhibit 6 and for reference, the specific minerals and projects are listed in Table 1).

The assessments calculate a "before and after" for supply risk based on three variables: (1) the dependence (in the U.S.) on net imports, (2) an adjusted Herfindahl-Hirschman Index for Global Production, which is a measure of production concentration, excluding the domestic share.; and (3) an adjusted Herfindahl-Hirschman Index for Import Trade, which is a measure of the diversity of import partners.

It is important to note that, as with the RCM analysis mentioned above, the technical viability or economics of implementing this additional recovery was not considered. Rather the research simply offers perspective that discrete actions could have a very significant impact on the U.S.'s import dependence.

Exhibit 6: The Reduction of Supply Risk (Relative to the Baseline) From Adding Discrete Refining/Separation Capacity to Existing Smelting Facilities



Source: Critical Minerals Innovation Hub, Colorado School of Mines

Table 1: Estimated Recovery Potential of Critical Materials from U.S. Primary Smelters (metric tons/year)

Smelter Type	Recoverable Critical Material	Theoretical Recovery (t/yr)	Practical Recovery (t/yr)	Facility/Location	Status
Zinc	Germanium	30	—	Nyrstar, Clarksville, TN	Co-located recovery facility announced (2023)
Copper	Tellurium	—	20	Kennecott, Utah (Rio Tinto)	Operational recovery circuit
Boron	Lithium	5000	10 (Pilot scale)	Boron, CA (Rio Tinto)	Pilot plant producing battery-grade lithium
Aluminum	Gallium	5	—	Alcoa/Century (Multiple States)	Based on lab-scale slag analysis
Aluminum	Magnesium	2.5	—	Alcoa/Century (Multiple States)	Recovery theoretically possible; no commercial practice
PGM	Cobalt	12	—	Columbus Complex, MT (Sibanye-Stillwater)	Co-produced with nickel; not economically recovered

Source: Critical Minerals Innovation Hub, Colorado School of Mines

Notes:
Theoretical Recovery: Estimated based on slag concentration and national waste output Practical Recovery: Indicates actual or pilot-scale recovery rates where available
"—" implies no confirmed commercial-scale recovery

This work was supported by the Critical Materials Innovation Hub, funded by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Materials and Manufacturing Technologies Office.

GOVERNMENT INTERVENTION, MARKETS, & PRICE DISCOVERY

As governments increasingly seek to secure critical minerals supply, numerous policy solutions are available. These include stockpiling, tax credits, guaranteeing minimum prices, and direct equity investments in mines. The dollar cost of a government commitment level will vary significantly depending on the mineral in question. For example, of the annual U.S. demand for the 50 minerals currently deemed critical by USGS, cesium is just a few thousand kilograms , whereas aluminum is millions of metric tons. While, in practice, governments are not the primary buyers of critical minerals, the difference in cost should the government purchase the entire U.S. annual requirement would range from a few million dollars to multiple billions of dollars per year.

In some value chains market forces are less effective in spurring more production and therefore targeted government input may be particularly meaningful for a comparatively low overall cost. For others, particularly larger volume markets that are very financialized, policy must be mindful of how markets will respond to new information and interventions.

In sum, what works for one mineral may not work for others and the market ripple effects of an intervention will differ based on the nature and depth of the markets themselves. These points are illustrated with a review of recent and potential government action related to copper, rare earths and gallium.

COPPER

U.S. Import Tariffs

Copper[9] is now subject to a Section 232 tariff, given, alongside industrial and commercial uses, it is "the second most widely used material by the Department of Defense and is a necessary input in a range of defense systems, including aircraft, ground vehicles, ships, submarines, missiles, and ammunition[10]."In a bid to reduce copper net import dependency and incentivize domestic production, tariffs were initiated in early 2025, starting with an investigative process. On July 8, 2025, the President set the expectation for a 50% tariff[11].

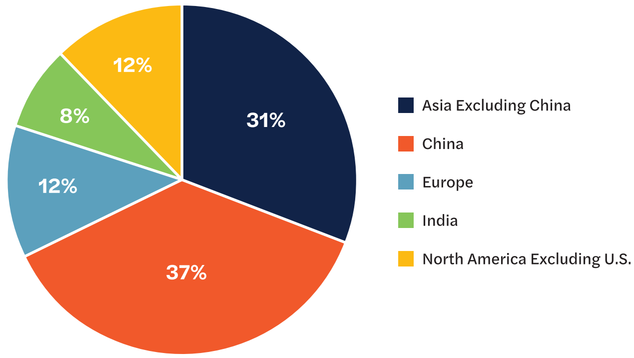
Relative to other minerals, the copper market is enormous and highly financialized given refined copper derivatives trade on commodity exchanges. As a result, market participants, assuming the tariff scope would cover imports of all copper products, were immediately able to express price expectations via futures contracts. The price of U.S. refined copper trading on the CME reached a premium of >30% above the London Metal Exchange (LME) prices[12]. U.S. imports of refined copper surged.

On July 30, the final tariff decision was announced[13]. Refined copper was excluded[14], albeit the door is left open to encompass it in future. The CME refined copper price premium therefore faded. U.S. inventories will now be drawn down and some product may even be sold overseas depending on how prices evolve. This situation illustrates how broad-reaching policy, or just the expectation thereof, can dramatically influence market behavior.

The Scrap Copper Opportunity

More niche markets, or specific products within a larger value chain (such as refined copper from scrap), may lend themselves to 'quicker fixes' than broad value chains within huge markets. Here, direct causal links between policy intentions and outcomes may be available. An interesting outcome from the tariff discussions was the attention placed on the large volume of copper scrap—~880,000 metric tons in 2023, with a refined copper equivalent of ~530,000 metric tons—that is exported out of the U.S., ~40% of which goes to China (see Exhibit 7)[15].

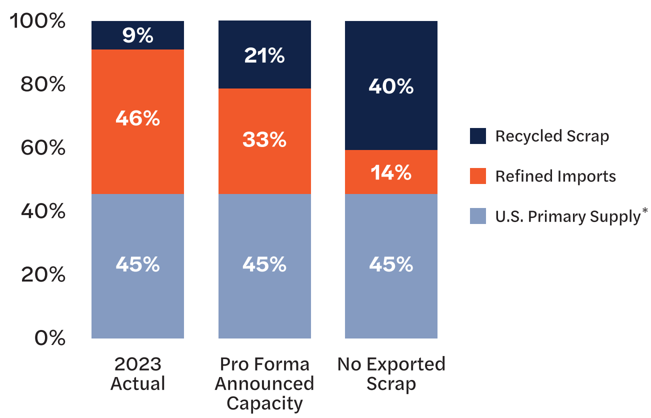
Exhibit 7: U.S. Copper Scrap Exports Distribution



Source: World Bank[16]

Expanding recycling capacity, already a significant contributor to annual U.S. consumption, could reduce import dependency from 45% down to less than 15%, assuming all exported material could be converted to refined copper onshore (see Exhibit 8).

Exhibit 8: U.S. Copper Sources, Including Scenarios for Scrap Recycling



Numbers may not sum to 100% due to rounding
Source: USGS[17], World Bank[18]

Assumptions:

- 61% conversion from exported scrap to refined copper output and a match between scrap supply and facility capabilities
- *U.S. primary supply includes stock changes and exports

New capacity is coming online—for example, the expansion of the Aurubis facility in Georgia—but not enough for full utilization of existing scrap[19]. So, is there an opportunity for more policy support targeted at this part of the value chain? The theoretical return on investment suggests so: it would be cheaper and faster—with a lower energy and carbon footprint—to expand scrap recycling capacity than to build new mines and primary smelting and refining, albeit supporting the overall value chain remains important. The government could accelerate this via a range of policy tools such as tax credits, loans, and other means to incentivize the build out of facilities and related infrastructure and logistics. Contracts for difference (CfDs) could support domestic scrap deals so that scrap suppliers are not penalized for selling material to U.S. recycling plants where overseas bids are higher.

RARE EARTHS

Government Investments and Price Support

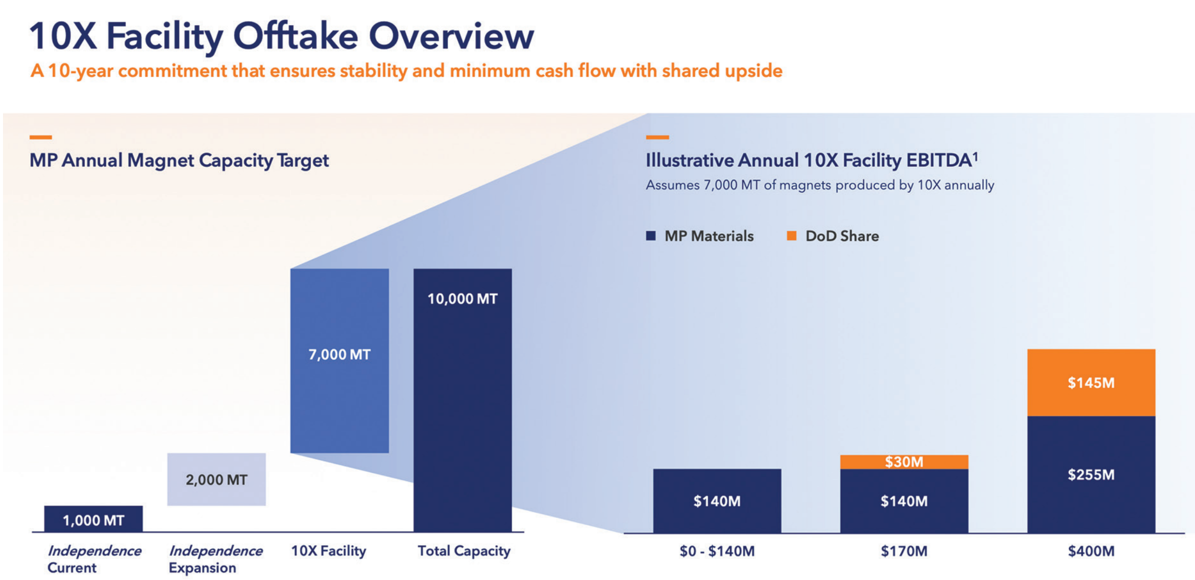
Government intervention, including at scale, has occurred for some time. In the U.S., the previous administration provided just under $5 Billion in support to mining and related projects (primarily loans). Internationally, various agencies have supported domestic and international mining operations as well and, most notably the Japan Organization for Metals and Energy Security (JOGMEC), have been authorized to employ more tools, including significant equity stakes.

The recent announcement of the Department of Defense's (DoD) investment in MP Materials marks a departure from U.S. policy both in scale and shape. First, to speak to scale, sponsoring MP's expansion is very significant relative to the current market. MP's targeted 10,000 metric tons per year (MTPY) of NdPr oxide (and magnet) capacity would fulfill over 60% of the U.S.'s recent demand.

And second, the partnership breaks new ground in equity investment by the U.S. government, which had been limited to smaller scale new technologies, and in profit sharing. And, by providing a price floor, the government is exposed up to a maximum of $1.1B per year (assuming the product cannot clear and earns $0, which is admittedly unlikely). The DoD's equity investment is worth over $700 Million more than it put in and it will participate in profit sharing over a $140 Million per year facility-level EBITDA threshold (see Exhibit 9).

Notably, the partnership appears to have had an intended effect of "crowding in" more private industry and investor participation. Coincident with the partnership announcement, MP announced that it had secured $1B in loans from Goldman Sachs and JP Morgan. Within a week, the company announced an off-take agreement with Apple for magnets, and its shares more than doubled. The company issued $650M in a secondary stock offering, exercising the "greenshoe" which allowed for upsizing the original offering.

Exhibit 9: MP Materials' Expansion Plans and Profit Sharing Agreement with the Department of Defense



Source: MP Materials

GALLIUM

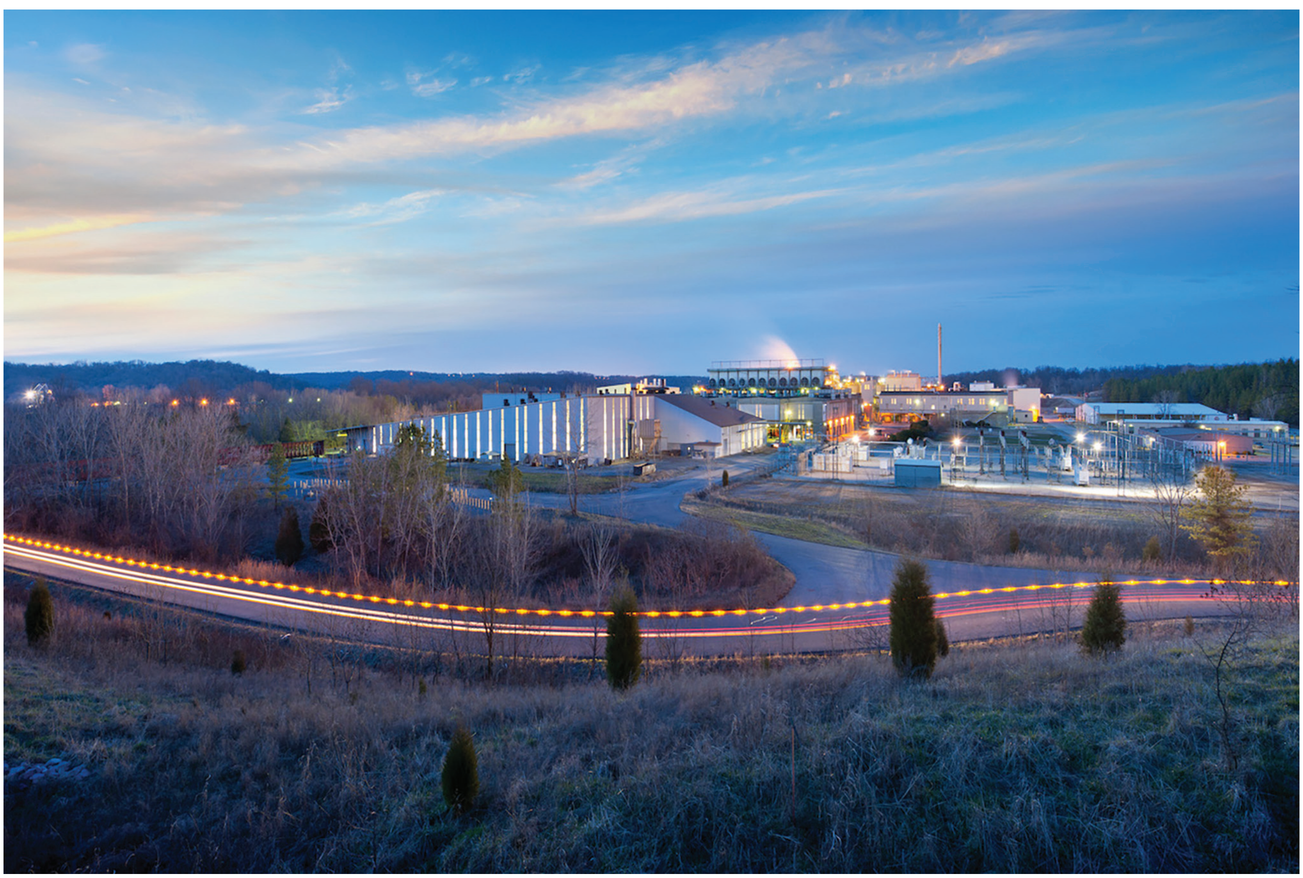
A Small Price For Security

The U.S. is presently net import reliant for gallium, which is used in semi-conductors and light-emitting diodes that are subsequently integrated into various telecommunications and defense-related applications[20]. The impact can be framed in different ways. On one hand, USGS recently estimated that a reduction in U.S. GDP of $3.1B could occur if China restricted net gallium and germanium exports for a full year[21], which equates to a small percentage of GDP given the small volumes involved. On the other hand, access to Gallium is indeed "critical" to fostering technologies that are expected to underpin long-term economic growth and which often overlap with modern military needs, pointing to far greater significance than an annual GDP measure suggests.

But, given the small amounts, the U.S. could attain self-sufficiency relatively easily. Gallium is a byproduct produced mostly from alumina production (from bauxite) and also from zinc-processing. Per USGS, domestic bauxite tends not to be suitable for alumina production given a high concentration of silica, however there are domestic zinc ores with a high gallium content[22]. With respect to current facilities, if Nyrstar's zinc smelter in Tennessee installs processing capacity it could provide ~40 metric tons of gallium per year[23].

USGS states current U.S. consumption of gallium is just 19 metric tons per annum (including the weight of the gallium content contained in gallium arsenide (GaAs) wafers)[24]. In 2024, the total value of imported gallium metal, most of which was high-purity, was approximately $4 million. For comparison, GaAs wafer imports totaled approximately $140 million[25]. Therefore, it seems plausible that the government could ensure gallium supply at what can be considered a very reasonable cost (even if the additional supply has a significant negative impact on market pricing as seems likely in this case.)

Exhibit 10: Nyrstar Zinc Smelting Operations, Clarksville, TN



Source: Nyrstar

So, why are facilities like Nyrstar not already co-producing gallium? Simply put, it's the economics. Gallium is a byproduct and overall demand pales into insignificance compared to that of the primary products (aluminum and zinc.) For many facilities it's just not material to the bottom line to co-produce it, regardless of its criticality designation.

However, in part because the volumes are small, price support to ensure its production would be relatively low cost. Nyrstar has estimated the capex required for processing capacity is $150 million[26]. And with an annual output of 40 metric tons of (lower purity) gallium[27], at a price of $375 per kg (based on an average of 2024 prices as reported by USGS[28]), the maximum cost of a CfD would be ~$15 million assuming no price cleared at all. It is worth noting that depending on the needs of U.S. buyers, additional refining capacity may be required to produce higher purity gallium metal (a 2024 USGS report based upon 2020 data states that high purity metal represented ~98% of U.S. imports[29]); however the overall cost of government support would still likely be fairly low given the amounts in question.

POLICY IMPLICATIONS

The rare earths/MP and gallium/Nyrstar examples raise important questions to consider in designing government support. These include:

- How much is needed to invest up front?
- How much is needed to support operations over time?
- How can the government encourage competitiveness?
- How willing should the government be to distort markets, which may create disincentives for other (non-supported) actors?

Second Order Effects

All policies will generate second order effects, requiring consideration of the wider system. Policy and financial assistance to encourage gallium production would significantly impact the global price given the current baseline volumes. Price collapses from a deluge of new supply are fairly predictable. However, equally important but harder to forecast is that more supply of gallium, or rare earths etc., may increase overall use from both existing and new demand sources. Technologies that could not previously scale owing to supply risks may become more viable. Therefore, an initial price crash (beyond prices supported by U.S. policy) may be followed by price recovery as the market adapts to more readily available supply.

Finally, policy targeting byproduct minerals may also need to address support for the primary product. If zinc facilities implement co-recovery, gallium production necessarily relies on continuing production of zinc. If, for some reason, the zinc market falls into trouble, output may be reduced or facilities closed down despite ongoing demand for gallium. This necessitates considering how much support should be given to a specific producer over any other, and how such support would impact the larger primary mineral market.

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FINDING A FAIR PRICE

Successful policy necessitates a comprehensive understanding of supply and demand conditions, and how chosen mechanisms will impact market pricing both domestically and globally. Such a foundation can help ensure that taxpayer funds are not overpaying when providing demand support. To put this differently, establishing a "fair" price is important. It is not, however, always that easy to establish fair pricing, particularly for smaller market minerals. Broader value chain and market reviews should also help mitigate against unnecessary adverse price impacts or other unintended consequences.

Minerals Markets Mechanics

In our recently published Critical Minerals Markets Primer[30], the Payne Institute explored how mineral markets vary in terms of size, participants, and other market influencing characteristics. Minerals are traded at several points along the value chain, for example as concentrates, intermediates, refined metals, and chemicals.

Exchanges, where minerals are traded as derivatives (primarily futures) are the most mature, most transparent markets. Such venues allow producers and consumers to hedge prices and provide visibility into future pricing. These functions can support business decisions and reduce some market risks. That said, not all risks can be fully mitigated, especially those that are harder to forecast and manage, for example geopolitical shocks. In addition, increasingly electronic and algorithmic trading can "increase the speed of reaction to information"[31] potentially exacerbating the impacts.

Exchange-trading is sometimes seen as the goal for minerals markets, but is not suitable for all products. It currently exists only for a small group of critical minerals—just eight of the 50 minerals designated critical by the USGS have one or more value chain product traded on an exchange. Only those minerals with sufficient demand where the product can be standardized are candidates and, even then, it doesn't mean a futures contract will succeed. Across the broader commodities complex, many contracts have been launched and subsequently discontinued over the years. Recently, several exchanges have established futures contracts for battery metals however, it's still too early to predict the trajectory for many of these.

The vast majority of critical minerals products are traded via bilateral contracts in the physical market, where price transparency and market risks vary depending on the specific mineral product. Some transactions are facilitated by intermediaries such as commodity trading houses, and many price negotiations may be supported by data compiled by major Price Reporting Agencies (PRAs)—Argus, Benchmark, Fastmarkets, and S&P Global Platts. PRAs have driven greater price transparency in off-exchange markets by capturing transaction and other market data, to publish reference prices, indexes, and benchmarks. Some PRA data is embedded within exchange trading where futures contracts are cash, rather than physically-settled.

Evolution in Minerals Markets

But, with growing demand for many minerals and an increasing focus on the security and efficiency of physical supply chains, there appears to be a significant opportunity for a bigger evolution in mineral market infrastructure. Formal marketplaces that operate outside of, and alongside, the exchange-traded world could further reduce opacity, improve market efficiency, reduce transaction costs, and mitigate some of the risks associated with bilateral trades. Moreover, governments, in tandem with policies to encourage more domestic supply, could support the establishment and growth of such platforms, as well as complementary market infrastructure, such as storage and logistics.

To offer an example, the EU is leading the development of a trading platform that would allow member countries and regional companies to aggregate mineral purchases in a bid to secure better pricing. Current feedback from minerals purchasers suggests that the appropriate focus would be in smaller markets as opposed to those with larger volumes, where supply chains are more mature[32]. A consortium led by PriceWaterhouseCoopers (PwC) and Sfera, a software company based in Slovakia, was selected by the EU to develop the platform[33].

In the private markets, Metalshub, launched in 2016, has partnered with the London Metals Exchange (LME) to track "green premiums", initially creating a low-carbon nickel briquette premium index[34]. The LME notes "tangible interest from corporates to use Metalshub as a platform for the discovery of low carbon price premiums" and is expanding the partnership to cover additional minerals products[35].

As governments ramp up their intervention in critical minerals, innovative market developments may enhance the multitude of policy tools that governments can employ to support mineral supply and market infrastructure.

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[35] London Metal Exchange (LME). n.d. Metalshub collaboration. Available at: https://www.lme.com/Trading/Initiatives/Metalshub-collaboration (accessed August 12, 2025)

RECOVERING BYPRODUCTS

Colorado School of Mines is the global leader in research on the science, engineering, and social science needed to unlock the critical mineral "byproduct" potential of U.S. mines. Recent research at Mines by the Responsible Critical Minerals (RCM) team revealed the U.S. could eliminate nearly all critical mineral imports by recovering more from the rock that is already mined[36]. In other words, federally permitted U.S. metal mines annually excavate and process enough critical minerals to nearly replace imports—if those critical minerals were recovered. This project has identified the "low hanging fruit": which critical minerals are most promising as byproducts at each U.S. mine, and sites where recovery of even a small percentage of a mineral could drastically reduce the need for imports of that mineral. The RCM team's powerful conclusion: the U.S. could be self-sufficient (i.e. not need to import) 27 of the 50 critical minerals on the recent USGS list if as little as 10% of what is believed to be available resources are recovered.

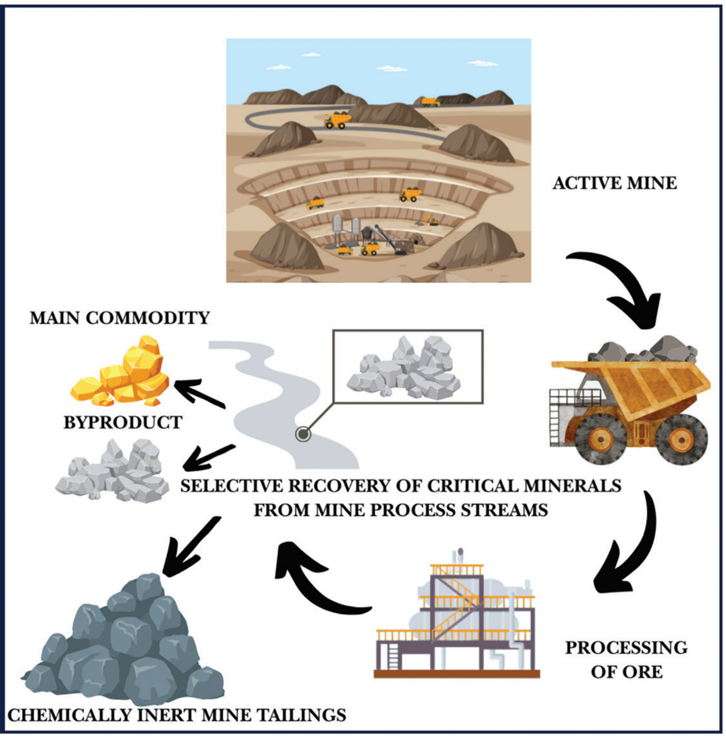
Byproduct Background

Byproduct recovery is defined as the production of a mineral alongside the "main product" that drives the economics of the mining operation. New research from the Responsible Critical Minerals team at Mines shows that the potential byproducts that can be recovered depend on the geology of the site, as well as the processing and extraction methods. Further, the RCM team's interdisciplinary research will enable this approach to critical mineral production (see Exhibit 11).

Exhibit 11: Schematic of Selective Recovery of Critical Minerals

RESPONSIBLE RECOVERY OF CRITICAL MINERALS AS A BYPRODUCT

Active research within the GCR group here on CSM's campus is currently addressing complex sociotechnical problems related to the energy transition, occurring at both global and national levels. Critical mineral recovery as a byproduct from the mine refining process is one of the many solutions that aid in responsible and sustainable mining practices. Recovering critical minerals upstream as a byproduct could significantly alter the mineral composition of tailings, making them more chemically inert.



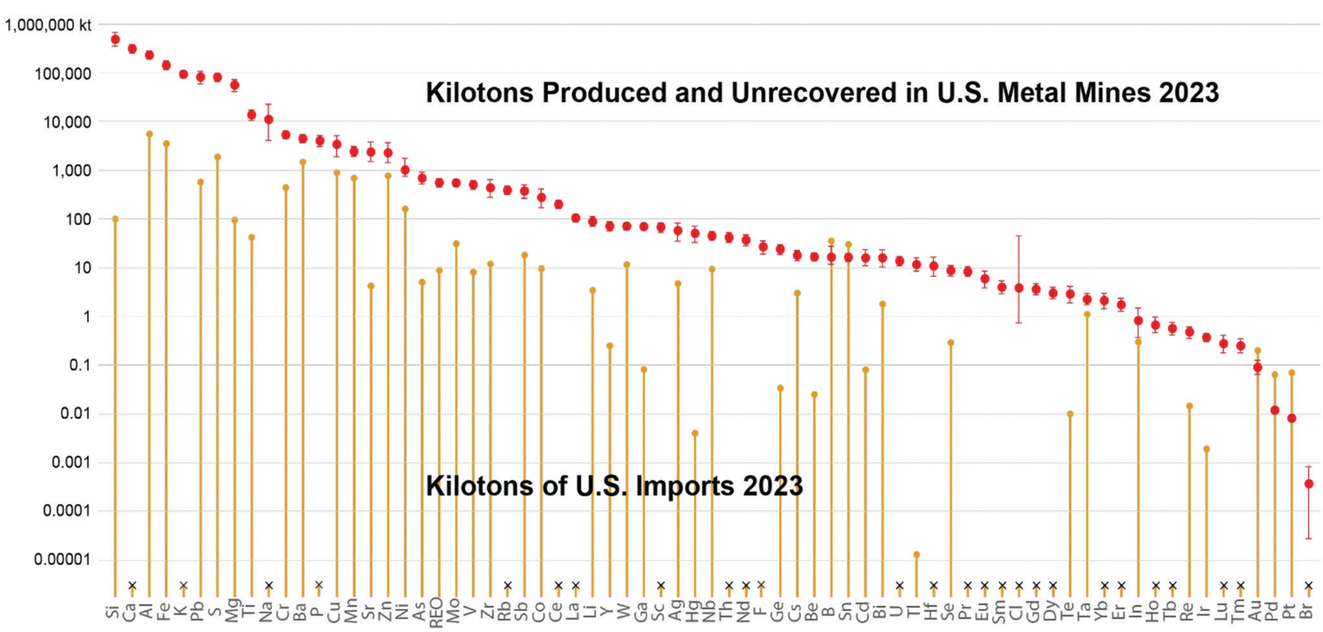
Source: Colorado School of Mines

Byproduct potential is site specific, and the examples are numerous. To offer just one, Rio Tinto mines the Bingham Canyon copper porphyry with skarn and epithermal overprints at the Kennecott Mine in Utah. The main products from this operation are copper, gold, and silver, but Rio Tinto also recovers tellurium as a byproduct within their processing circuit. Tellurium is an additive in metal alloys, aiding in machinability and adding strength and corrosion-resistance. Adding new processing circuits to the mine could enable byproduct recovery of other critical minerals. PhD student Karlie Hadden is working in collaboration with Rio Tinto's R&D team to characterize the operation's critical mineral endowment and identify strategic points along the processing circuit where recovery of these minerals is technically feasible.

Detailing the Opportunity

The RCM team detailed the U.S. byproduct potential for 70 elements through a review of active U.S. mining locations. The team calculated the amount of critical minerals that are mined (but unrecovered) at each U.S. federally permitted metal mine. They compared this potential resource with recent annual U.S. imports of those minerals to determine what proportion of the available resources would need to be recovered in order to replace imports. Of 45 minerals with U.S. import data, 16 could replace imports if less than 1% of the available resource were recovered, 11 required at most 10% recovery and 13 required between 10 and 50% recovery to replace imports (see Exhibits 12 and 13). It is important to bear in mind that the geological endowment does not in and of itself speak to the practical or economic constraints related to recovery of these minerals. Their presence represents a significant opportunity to raise domestic self-sufficiency. However, if they remain unrecovered, these critical minerals become waste, contributing to the environmental and social impact of mining.

Exhibit 12: Kilotons Produced and Not Recovered in U.S. Metals Mines, 2023

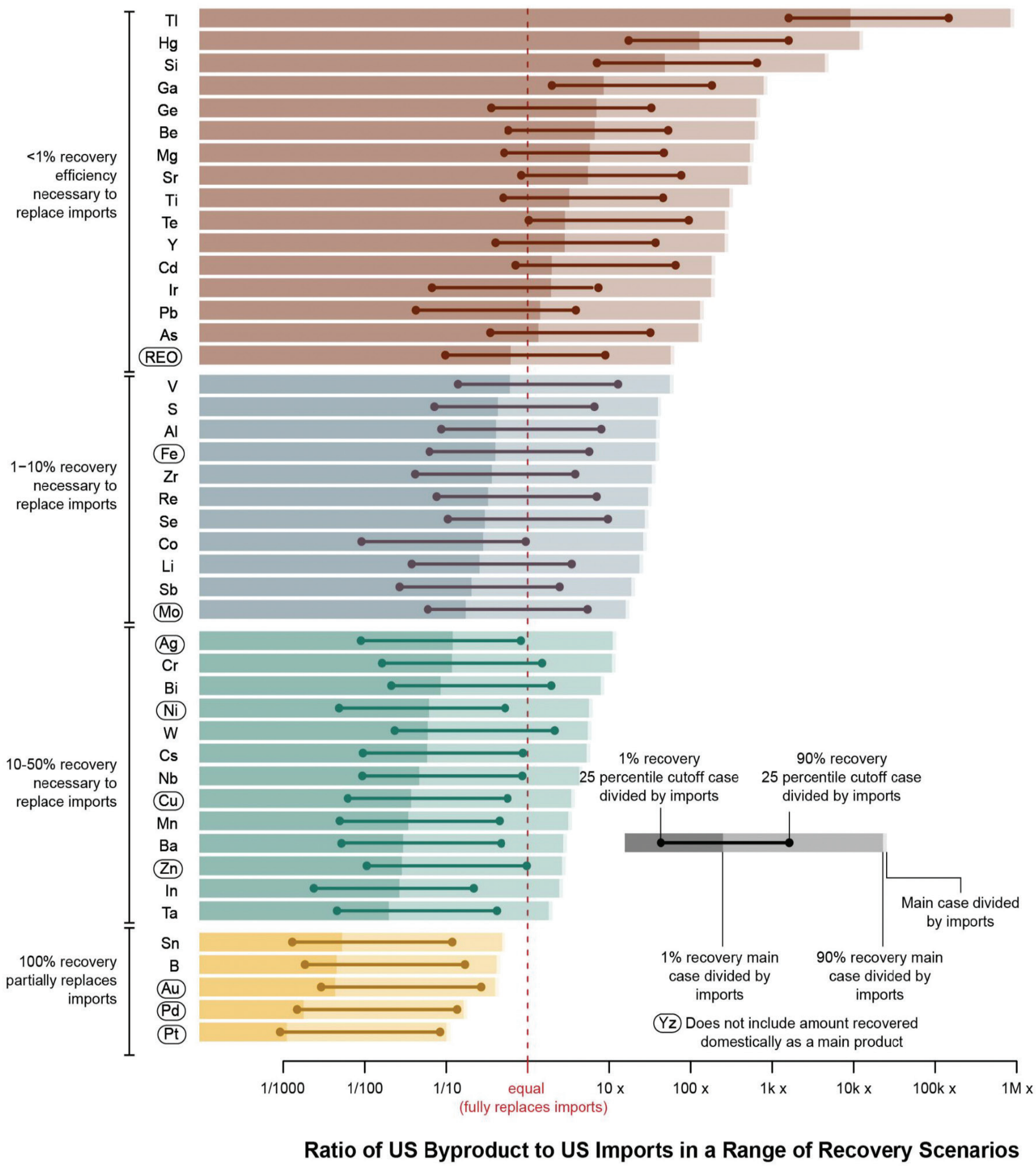


x = No import data

Source: Colorado School of Mines

[36] Holley, E.A., Hadden, K.M., Hammerling, D., Eggert, R., Spiller, D.E., Nelson, P.P., 2025. Byproduct recovery from active domestic metal mines could dramatically reduce U.S. import reliance for critical minerals. Science.

Exhibit 13: % Recovery of U.S. Byproducts Required to Replace Imports



Source: Colorado School of Mines

RECOVERING MINERALS FROM MINE WASTE

Critical Minerals from Mine Wastes

In addition to recovery of critical minerals during ore processing at active mines, the accumulated wastes at these sites can serve as a resource for critical minerals for the U.S., as can the legacy mine wastes and mine waters at abandoned sites. Colorado School of Mines leads the way on this work, while also developing new uses for the waste once metals have been removed.

The state of practice is still early-stage. With that said, Mines' RCM team has identified barriers and opportunities for mine waste reprocessing[37]. Unlocking this potential will require interdisciplinary workflows for sampling, characterization, resource estimation, and new methods of mineral processing and extractive metallurgy.

Ongoing work at Mines is, however, already bearing fruit. To offer just one example, PhD candidate Fan Yang evaluates the concentration of zinc (Zn), a critical mineral, which is hosted in the tailings produced by zinc mines. By using leaching in conjunction with traditional flotation techniques, tailings rich in zinc can be further concentrated to improve zinc recovery. This method allows for 60-70% of Zn to be recovered from material that would have been previously discarded and stored as waste. The study illustrates how modern metallurgical circuits can unlock value from seemingly low-grade tailings and reduce the long-term footprint of active mines.

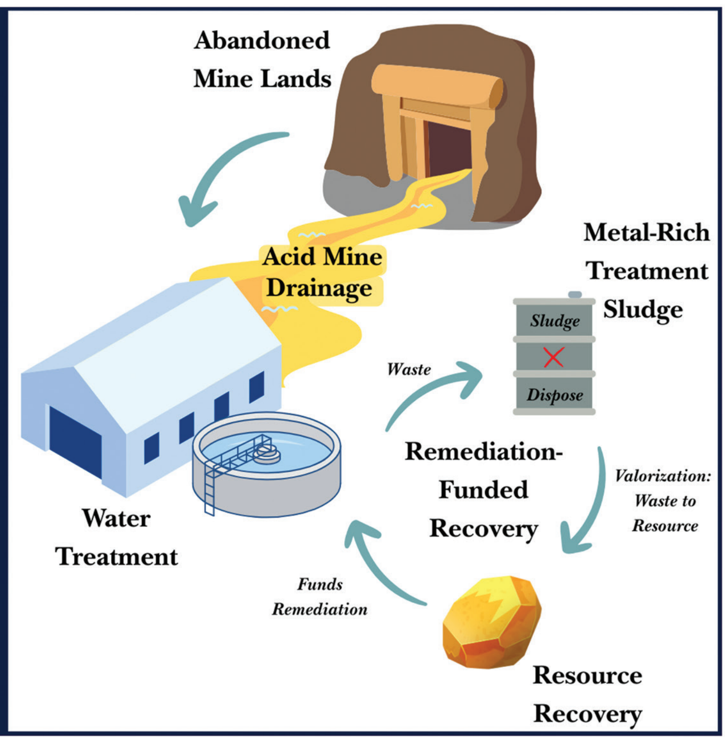
Accessing Critical Minerals from Abandoned Mines

Related to the above, although arguably more urgent from an environmental protection perspective, is the challenge of how to recover critical minerals from the toxic legacy of abandoned hardrock mines. PhD candidate Molly Morgan is working to tackle this national challenge. Focusing on acid mine drainage (AMD) from historic mining in Idaho Springs, Colorado, she explores how valuable elements like copper can be traced, recovered, and returned to the supply chain (see Exhibit 14). Her findings support a new view of this historic environmental hazard as a potential domestic resource.

Exhibit 14: Schematic of Critical Mineral Recovery from Acid Mine Drainage

RESPONSIBLE RECOVERY OF CRITICAL MINERALS FROM AMD

Research in Idaho Springs, CO demonstrates how metals like copper, concentrated in acid mine drainage (AMD) sludge, can be traced, recovered, and repurposed. These findings support pilot projects under the 2024 Good Samaritan Remediation of Abandoned Hardrock Mines Act, which may aim to align mine cleanup efforts with critical mineral recovery in select cases.



Source: Colorado School of Mines

Morgan's work also relates to the implementation of the 2024 *Good Samaritan Remediation of Abandoned Hardrock Mines Act.* The Act allows qualified third parties—such as NGOs, local governments, and non-liable companies—to undertake cleanups of abandoned mine lands without assuming full legal liability for pre-existing pollution. Specifically, it establishes a pilot program of 15 sites to test how these voluntary cleanups can improve environmental outcomes while enabling the responsible recovery of critical minerals from waste. As a co-organizer of the Good Samaritan Implementation Kickoff Summit hosted by the Mines Responsible Critical Minerals Team and Trout Unlimited, Morgan and PhD candidate Jordan Calderon helped convene national stakeholders—including federal and state regulators, tribal nations, industry leaders, and environmental groups—to shape early pilot efforts. Her research helps define what successful, science-based, and sustainable remediation looks like under this new legal framework.

Other work at Mines is complementing this effort. PhD student Caroline Ruppert builds on this work by mapping and geochemically characterizing abandoned mine waste across the Rocky Mountains to clarify how solid waste and drainage chemistry co-evolve. Caroline's regional datasets will identify which waste piles contain economically relevant metal inventories and which pose the greatest hazard, providing a decision framework that could guide targeted remediation efforts.

And in Flat, Alaska, PhD candidate Isabelle Harris evaluates century-old gold-placer tailings that now host elevated concentrations of high-field-strength elements such as chromium, gold, hafnium, tungsten, and zirconium. Bench-scale gravity-concentration tests achieve near-total recovery of these metals into high-grade heavy-mineral concentrates, showing that legacy placer sites worldwide may be able to diversify critical mineral supply and contribute to a circular economy by returning valuable metals to active use.

[37] Holley, E.A., Fahle, L., Zaronikola, N., Malone, A., Nelson, P., Spiller, E., Bullock, R., 2025. U.S. industry practices and attitudes towards reprocessing mine tailings for metal recovery. Resources Policy, 105643. https://doi.org/10.1016/j.resourpol.2025.105643

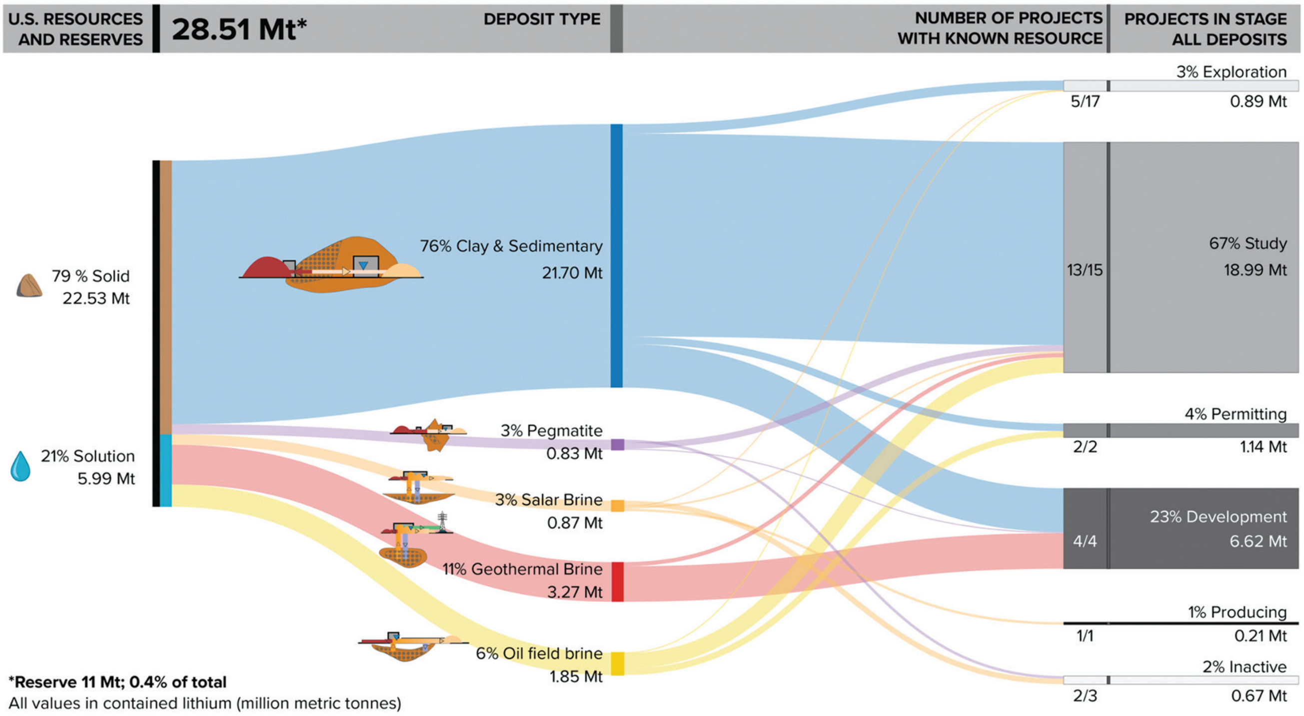
NEW MINES

OPPORTUNITIES FOR DOMESTIC PRODUCTION

Three new studies by the Responsible Critical Minerals team at Mines show that the geological endowment of mineral and ore deposits in the U.S. includes enough cobalt, nickel, manganese, graphite, and lithium to meet domestic demand for a long time[38,39,40]. These three papers inventory the known U.S. resources and project status for each of the five battery minerals, identifying where policies and investments are needed to prevent supply bottlenecks. In the case of lithium, most of the known resources are in clays, oilfield brines, and geothermal brines (see Exhibit 15)—none of which have yet demonstrated recovery at commercial scale. R&D funding will be needed to unlock this potential.

The relatively smaller endowment of cobalt, for example, in comparison to the Democratic Republic of Congo, also raises questions about how best to balance domestic production against the need to also cultivate responsible and reliable global supply chains. The team's recent review of graphite and manganese highlights the potential for domestic production, although neither have been mined in the U.S. in decades. Developing the known deposits in a market dominated by China will require incentives or differentiated markets.

Exhibit 15: Distribution of Lithium Resources



Source: *Brett et al. (2025)*[41]

In related work, PhD candidate Jordan Calderon is investigating the U.S. mine-permitting process and how its various components influence the development of new mineral projects. Drawing on case files and public records from federal, state, and local agencies, he is analyzing mining timelines to better understand where and why delays occur. The findings aim to inform policy debates with statistical evidence and support responsible mineral development without compromising environmental or community safeguards.

[38] Brett, A., Holley, E.A., Deberdt, R., Fahle, L., Smith, N.M., 2025. Lithium production in the United States: Sociotechnical review of sites, environmental impacts, social acceptance. Resources Policy, 105599. https://doi.org/10.1016/j.resourpol.2025.105599

[39] Holley, E.A., Smith, N., Malone, A., Fahle, L., Eggert, R., Lee, J., Bazilian, M., 2025. Nickel and cobalt availability from U.S. mines and refineries: Assessment of five dimensions of mineral availability. Resources Policy, 105687. https://doi.org/10.1016/j.resourpol.2025.105687

[40] Holley, E.A., Fahle, L., Smith, N.M., Deberdt, R., Calderon, J., Gibbs, G., Bazilian, M., 2025. Graphite and manganese mining in the US: proposed projects and federal battery mineral policies. Resources Policy 108: 105689. https://doi.org/10.1016/j.resourpol.2025.105689

[41] Brett, A., Holley, E.A., Deberdt, R., Fahle, L., Smith, N.M., 2025. Lithium production in the United States: Sociotechnical review of sites, environmental impacts, social acceptance. Resources Policy, 105599. https://doi.org/10.1016/j.resourpol.2025.105599

UNDERSTANDING COMMUNITY RESPONSES

For all of the emphasis on byproduct, waste recovery, and recycling opportunities, it remains very likely that diversifying critical minerals value chains and bolstering self-sufficiency in mineral access will still require the development of new mines. As has been well documented, the process of getting approvals —and thus of developing new mines—has become more complicated and slower over time. This is due, above all, to the growth in concern and/or opposition from the public and local communities and their increased demands to participate in and influence permitting decisions.

As with technical fields, Colorado School of Mines is providing instrumental insights into the complex dynamics of support and opposition that surround new mining proposals. One example relates to the aforementioned work on battery minerals, and specifically cobalt and nickel. Proposals to develop the largest U.S. deposits, in Minnesota, have garnered polarized reception and been the subject of numerous protests and lawsuits. Examples like this underscore that responsible critical mineral development requires new approaches that address community priorities and engage a broader set of perspectives. Across three interrelated social science projects, the Responsible Critical Minerals team at Mines is examining the social perceptions of critical minerals project development in the U.S. Meanwhile other team members are specifically looking at mine permitting challenges, while additional interdisciplinary efforts analyze trends toward vertically integrated mine-to-refinery projects.

The team uncovered significant differences in community acceptance and rejection depending on the specificities of each region. Debates in Idaho and Minnesota center on environment, identity, politics, and economy but reveal opposing perspectives. In the former, minimal controversy has surrounded the development of the cobalt belt, while in the latter, nickel projects face resistance[42]. Addressing the same question, research on the only primary nickel mine in the U.S., the Eagle Mine in Michigan, also uncovered differences, across time (instead of geographies). Our findings show that unequivocal acceptance of the mine, which was highly contentious from the onset of the project, has not been achieved, despite the mining company's gradual and sustained engagement with the broader community. This engagement has led to improved acceptance of the mining, trucking, and milling operations, but acceptance remains conditional on the continuous performance of the company, in particular in environmental terms. Finally, addressing the specific case of remining and reprocessing in Southeast Missouri, a region marked by an environmental legacy from mining, researchers at Colorado School of Mines find that long-term socio-economic and environmental dynamics define a "cautious optimism" that clashes with a traditionally contentious industry[43].Although the cobalt project appears to be relatively well-received in the region, limited corporate engagement risks jeopardizing this acceptance and prevents the community from being able to plan long-term to accommodate the coming mine. This stands in contrast to the Michigan case, where community engagement has been a hallmark of Eagle Mine's development, thus underlining even more that social perceptions are highly bound by factors such as geographies, time, and community composition.

An examination is also underway of the role of non-regulatory agreements in shaping community-company relations and advancing broader environmental governance in the mining sector. Led by PhD candidate Tinzar Htun, the research focuses on the Good Neighbor Agreement (GNA) at Sibanye-Stillwater's operations in Montana, a legally binding contract between the company and three local environmental organizations. During the 25 years of GNA implementation, the company has not experienced any litigation or major environmental disputes, an exceptional achievement in the mining sector. The study highlights key factors behind its success and longevity: bottom-up organizations with support from a larger NGO, an implementation model that ensures a shared decision-making process, third-party technical advisors who act as a bridge between the mining company and community groups, and commitment from all individuals who are involved in the GNA process[44].

[42] Malone, A., Smith, N.M., Holey, E.A., Htun, T., 2023. "Prospects for American cobalt: Reactions to mine proposals in Minnesota and Idaho" *Energy Research and Social Science* 105: 103284. https://doi.org/10.1016/j.erss.2023.103284

[43] Deberdt, R., Malone, A., Smith, N.M., 2025. Reprocessing and remining as grey extractivism: the example of cobalt from the Southeast Missouri Lead Belt. *Globalizations.* Latest Articles. https://doi.org/10.1080/14747731.2024.2441632

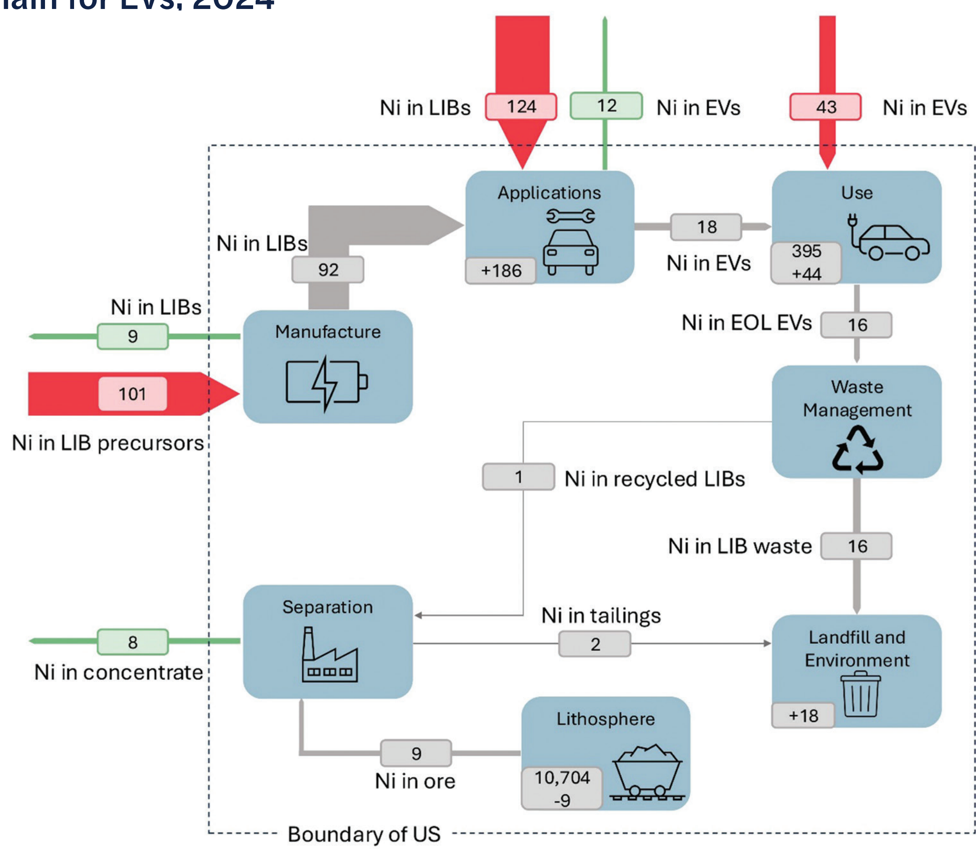
[44] Hutn, T., 2025, June. Non-regulatory agreements in the Mining Sector: Insights from the Good Neighbor Agreement in Montana [Conference presentation]. Critical Minerals Research Lab Conference, Resources for the Future. https://www.youtube.com/watch?v=3MUqLICr9w0

DOMESTIC MINE-TO-REFINERY PROJECTS

PhD candidate Tinzar Htun and MS student Grayce Gibbs are evaluating the social and technical development trajectories of vertically integrated mining-refining proposals, focused specifically on nickel and cobalt. The team is developing a socio-technical dataset of nickel-cobalt mining and refining projects proposed or currently under development in the U.S.. Htun is conducting research on discourses used by mining companies and project proponents to promote these vertically integrated cobalt and nickel mining and refining projects in the U.S..

Gibbs is evaluating the technical feasibility of the emerging projects, reviewing the geometallurgy and mapping material flows associated with the proposed domestic production chains. The mapping considers the various steps along the value chain beginning with total resources, initial extraction, separation, manufacture, use, and waste management to estimate the flow of nickel (see Exhibit 16) and cobalt into in-use stocks and waste streams in a year. Based on demand requirements and sales and trade data, the volume of the metals imported and exported is estimated. The material flow mapping shows an imbalance of flows with high import reliance for battery precursors and completed batteries. Limited recycling capacity and no domestic refining furthers this import reliance. A refining project is modeled to estimate the efficiency of a singular refinery by assessing the mass and energy balance, waste production, and carbon emissions. This work will enable an understanding of whether planned facilities are sufficient for supply and demand, and if they introduce competition or synergy.

Exhibit 16: Annual Nickel Flows and Stock Changes for the U.S. Lithium-Ion Battery Value Chain for EVs, 2024



Source: Colorado School of Mines

Notes: The dashed outline marks the national system boundary; arrows crossing it represent trade. Arrow labels give mass flows in kiloton Ni yr^{-1}. Numbers inside blue process boxes denote the net yearly change in the corresponding stock (+ accumulation, - drawdown). Red arrows indicate imports, green arrows exports, and grey arrows domestic transfers. Abbreviations: EOL = end-of-life.

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