Securing Energy Abundance:

From Fuels to Critical Materials

Laboratory for Energy and Power Solutions (LEAPS) at Arizona State University

July 2026

LEAPS
The Laboratory for Energy And Power Solutions

ASU Arizona State University

The Laboratory for Energy And Power Solutions (LEAPS) at Arizona State University powers the world with scalable solutions that deliver clean, resilient, and equitable energy for all. LEAPS accelerates the deployment of energy innovations to implementation with a focus on microgrids, grid modernization, resilient infrastructure, energy access, energy security, and workforce development.

Laboratory for Energy And Power Solutions (LEAPS)
Arizona State University
7418 Innovation Way South
Mesa, AZ 85212

leaps.asu.edu

Correspondence can be addressed to asuleaps@asu.edu

Authors: Dylan J. Lanning, Nathan G. Johnson, Elena van Hove

Recommended Citation:

Lanning, D.J., Johnson, N.G., van Hove, E. (2026). Securing Energy Abundance: From Fuels to Critical Materials. Laboratory for Energy And Power Solutions, Arizona State University. https://leaps.asu.edu/

ChatGPT, Google Gemini, and Claude were used during this research to complement initial desk research and analysis. All AI references were verified for accuracy, and all language drafts were reviewed and further revised by the authors.

List of Acronyms and Abbreviations

BESS — Battery Energy Storage System
BGS — British Geological Survey
CIGS — Copper Indium Gallium Selenide
CMA — Critical Materials Assessment
CSIS — Center for Strategic and International Studies
DFC — U.S. International Development Finance Corporation
DOE — U.S. Department of Energy
DOS — U.S. Department of State
DRC — Democratic Republic of the Congo
EV — Electric Vehicle
EXIM — Export-Import Bank of the United States
FORGE — Forum on Resource Geostrategic Engagement
G7 — Group of Seven
GaAs — Gallium Arsenide
GaN — Gallium Nitride
GAO — Government Accountability Office
HF — Hydrogen Fluoride
IEA — International Energy Agency
ILO — International Labour Organization
LEAPS — Laboratory for Energy And Power Solutions
LFP — Lithium Iron Phosphate
MCC — Millennium Challenge Corporation
MSP — Minerals Security Partnership
NdFeB — Neodymium Iron Boron
NdPr — Neodymium-Praseodymium
Ni — Nickel
NRC — Natural Resources Canada
OHCHR — Office of the United Nations High Commissioner for Human Rights
PACT — Progressive African Communities and Territories
PEM — Proton Exchange Membrane
PGM — Platinum-Group Metal
Pt — Platinum
PV — Photovoltaic
R&D — Research and Development
REE — Rare Earth Element
SiC — Silicon Carbide
SmFeN — Samarium Iron Nitrogen
SOFC — Solid Oxide Fuel Cells
T&D — Transmission and Distribution
UN — United Nations
USGS — U.S. Geological Survey
USITC — U.S. International Trade Commission
USTDA — U.S. Trade and Development Agency

Executive Summary

For decades, U.S. energy security was defined by dependence on foreign petroleum; today, that same vulnerability is reemerging in the materials that build the electrical system itself. Sustaining the U.S. electrical system requires a reliable and abundant supply of cables, transformers, batteries, motors, turbines, solar panels, and power electronics. Those components increasingly require specialized minerals and engineered materials from supply chains that are concentrated, constrained, and in several cases are actively leveraged by strategic competitors.

The U.S. Department of Energy has identified eighteen materials, the "Electric Eighteen", as critical to energy technologies through 2035. The constraints on their supply are less geological than industrial, concentrated in the processing steps that convert raw ore into the battery-grade chemicals, magnet-grade rare earths, and semiconductor-grade materials that today's grid infrastructure requires.

Global electricity demand is accelerating this urgency. The IEA projects global electricity demand growth of 3.6% annually through 2030, driven by electrification, industrial expansion, and data centers. The 2025–2026 period demonstrated the stakes concretely: China's export controls on rare earths saw neodymium praseodymium (NdPr) prices spike, and the ongoing conflict disrupting the Strait of Hormuz affected sulfur supply chains essential for battery material refining. These were not anomalies; they were previews of a structural vulnerability that will intensify as electricity demand grows and the grid expands to meet it.

STRUCTURAL VULNERABILITIES

1. Geographic concentration. Many minerals are primarily mined in one or two countries, creating single points of failure.

2. Midstream bottlenecks. Processing capacity is the binding constraint. Refineries and materials plants are technically complex, and capital-intensive.

3. Long lead times. New mines take 10–15 years to develop and produce. Market signals are more dynamic and cannot compress that cycle.

4. Co-product dependence. Some minerals are by-products of other metals and cannot be independently scaled.

5. Processing monopoly risk. China holds dominant or near-monopoly processing positions across nearly every critical material category. Export controls in 2025–26 demonstrated how that concentration can be used as political leverage.

STRATEGIC RECOMMENDATIONS

1. Finance allied refining. Deploy DFC, EXIM, and MCC financing, coordinated with FORGE partners, to build midstream processing capacity in resource-rich partner nations. The Lobito Corridor is one proof of concept.

2. Establish price floors. Government-backed minimum prices convert volatile commodity exposure into investable assets, unlocking institutional capital that spot markets currently deter. The Pentagon's NdPr floor is a model to extend.

3. Technical standards diplomacy. Embed industrial standards from allied nations into the design of first-generation allied-backed refineries. Standards set now will shape the supply chain architecture for decades.

4. Build in circularity. The energy assets being deployed today are future mineral stockpiles. Mandate design-for-recyclability and recovery, extend financing to mineral recovery infrastructure, and treat secondary supply as a quantifiable offset to primary demand.

5. Alternative technologies and materials. New technologies are emerging that can ease reliance on critical minerals. Innovations in battery chemistry and magnets can mitigate the risks associated with current supply chains.

These vulnerabilities are not confined to clean energy technologies; they span the entire electricity system, conventional and renewable alike. Copper illustrates the reach: a projected 30% supply deficit by 2035 will apply pressure across the energy sector, from transmission and transformers to nuclear plants and oil and gas operations. **The U.S. has the capital markets, the institutional architecture, and the allied relationships to lead the critical material resilience effort. The question is whether the policy response will match the strategic moment.**

I. Introduction: The Strategic Shift

For much of the twentieth century, energy security was defined by access to fuel. Oil fields, pipelines, and maritime chokepoints determined geopolitical leverage. Those threats could be immediately felt because fuel had to be extracted, transported, and burned every day, and disruptions translated quickly into price spikes and political pressure.

The strategic inputs of modern energy systems are changing, and the threat landscape is changing with it. The technologies that underpin contemporary power grids — such as batteries, generation assets, power electronics, and transmission infrastructure — are fundamentally materials-intensive. Energy security is therefore increasingly determined not only by fuel supply, but by the resilience of critical mineral supply chains. Control over mining, refining, and processing now shapes industrial competitiveness, geopolitical influence, and the pace of energy deployment across producing and consuming nations alike.

This shift does not render fossil fuel vulnerabilities obsolete, it compounds them. Price volatility, exposure to maritime chokepoints, and dependence on geopolitically unstable regions are active risks. **Diversifying electricity generation sources improves overall resilience, but only where the mineral supply chains underpinning each technology are themselves secure.**

Global electricity demand is accelerating this urgency. The IEA estimates global electricity demand grew 4.3% in 2024 and projects growth of 3.6% annually through 2030, driven by electrification, industrial expansion, cooling demand, and data centers (IEA, 2026a). Meeting that demand will require extracting and processing large quantities of specialized minerals for electrical infrastructure. This will change the risk profile both geographically and temporally as the global energy system shifts away from maintaining fuel flows and towards materials availability and processing capacity.

This report examines that question across three dimensions: the nature of critical mineral dependencies in modern energy systems, the structural vulnerabilities that concentrate risk along the supply chain, and the interventions best positioned to address them.

II. Critical Materials and the Energy Sector

2.1 Defining Criticality

Critical minerals are defined not by geology alone, but by strategic function and supply risk. A mineral or material becomes critical when it is difficult to obtain at scale, challenging to substitute, essential to major energy infrastructure, and vulnerable to disruption due to concentrated production, constrained processing capacity, geopolitical friction, or long project lead times. **Criticality is therefore dynamic and shaped by technology choices, trade relationships, and national priorities as much as by the physical distribution of ores.**

This is why critical mineral lists vary by institution and evolve over time. As of 2025, the U.S. Geological Survey (USGS) maintains a list of sixty critical minerals assessed primarily from a supply-side perspective, focusing on importance to the broader U.S. economy. The U.S. Department of Energy (DOE) takes a narrower and more forward-looking approach when identifying materials, including minerals, alloys, and gasses which are critical specifically to energy technologies through 2035. Where the USGS methodology is retrospective and economy-wide, the DOE assessment is prospective and energy-specific.

The DOE defines a critical material as one that has a high risk of supply chain disruption and serves an essential function in one or more energy technologies, including those that produce, transmit, store, or conserve energy. Fuel materials are explicitly excluded from the DOE list, although fuels have their own criticality in the supply chain. From a field of thirty-eight candidate materials, the DOE identified the Electric Eighteen in the 2023 Critical Materials Assessment as critical or near-critical through 2035 (U.S. DOE, 2023).

2.2 The Electric Eighteen

The Electric Eighteen span five energy-sector application areas: materials for batteries and electrochemical storage; rare earth elements used in permanent magnets; platinum-group metals used in hydrogen technologies, fuel cells, and catalysts; semiconductor materials used in power electronics and solar technologies; and conductive and structural materials that form the physical and electrical backbone of energy infrastructure.

Table 1 — *The Electric Eighteen materials organized by illustrative application areas.* *Source: U.S. DOE (2023).*

Battery & Energy Storage	Permanent Magnets	Hydrogen & Fuel Cells	Power Electronics & Semi-conductors	Conductors, Structures, & Equipment
1. Cobalt 2. Fluorine 3. Lithium 4. Natural Graphite 5. Nickel	6. Dysprosium 7. Neodymium 8. Praseodymium 9. Terbium	10. Iridium 11. Platinum	12. Gallium 13. Silicon 14. Silicon Carbide	15. Aluminum 16. Copper 17. Electrical Steel 18. Magnesium

Not all eighteen carry equal urgency. DOE identified seven materials as critical in the short term in their 2023 study: dysprosium, neodymium, gallium, natural graphite, cobalt, terbium, and iridium. These face the most acute combination of supply concentration and energy importance today. A further group of eight materials — including lithium, nickel, magnesium, platinum, praseodymium, silicon carbide, fluorine, and electrical steel — were near-critical in the short term and projected to become critical in the medium term (2025–2035) as electricity demand accelerates. Three materials are classified as low-risk: copper, silicon, and aluminum. These are among the highest-volume inputs to the electricity system and are projected to reach near-critical status in the medium term as demand from grid expansion, solar deployment, and vehicle electrification outpaces supply growth.

DOE's 2023 assessment maps this risk landscape by scoring each of the Electric Eighteen and other candidate materials on two dimensions: importance to energy and supply risk. Figure 1 plots the final Electric Eighteen scores for both the short term (2020–2025) and medium term (2025–2035), showing both current criticality and trajectory. All twenty-three materials that passed DOE's initial screening from a candidate field of thirty-eight are plotted. Of the five materials shown that did not make the Electric Eighteen, uranium was excluded by definition since DOE categorizes it as a fuel, while titanium, manganese, phosphorus, and tellurium were assessed but scored below the criticality threshold on importance to energy or supply risk. **The movement of materials toward higher risk and importance over the medium term, particularly copper, lithium, nickel, and silicon, reflects the compounding pressure of rising demands on supply chains that cannot respond at the same pace**.

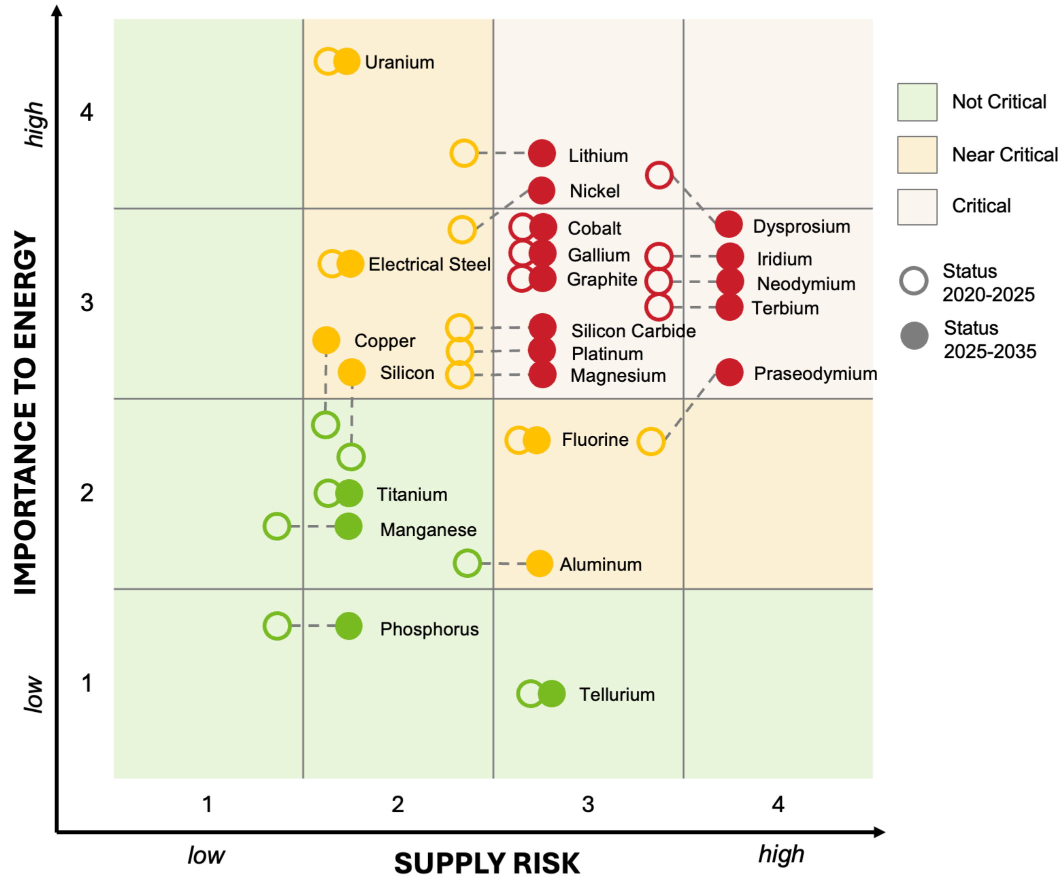

FIGURE 1 — *Critical materials for the U.S. energy sector.* *Data source: U.S. DOE (2023). Positions are approximate based on DOE 2023 CMA scoring categories. Figure source: ASU Laboratory for Energy And Power Solutions.*

2.3 Mineral Intensity Across the Electricity System

The growth in electricity demand and electrification will fundamentally shift the global energy system from being fuel-intensive to being materials-intensive. A solar PV plant requires no ongoing fuel input once built but requires roughly six times the mineral content of a comparably sized natural gas plant during construction (IEA, 2021). Wind generation requires nine times more mineral resources than a gas-fired plant of equivalent capacity. **This front-loading of materials is a structural feature of clean energy generation, such as solar, wind, nuclear, geothermal, and hydro, which benefit from long-term resilience to fuel disruption with the tradeoff of high-upfront material investment.**

While energy storage and generation have received much attention there has been fewer studies of the supply chain risks in other parts of the grid. The transmission and distribution (T&D) infrastructure required to carry power to end users is highly mineral-intensive. In many respects the vulnerabilities are more immediate: large power transformers depend on grain-oriented electrical steel and copper windings; overhead transmission lines rely on aluminum and copper conductors; substations and switching equipment require copper, silicon carbide power electronics, and nickel alloys. The extended lead times for large transformers show how supply constraints in mineral-intensive T&D equipment can become system-wide bottlenecks, slowing grid expansion from the point of generation through delivery to end users (Wood Mackenzie, 2025).

Battery energy storage systems, increasingly central to grid reliability, add a further layer of mineral dependency, with graphite, lithium, cobalt, nickel, and fluorine at the cell level, and aluminum and copper in the balance-of-system components. EVs, though not grid infrastructure, draw on the same supply chains and compete for the same materials, amplifying demand pressure.

Securing mineral supply chains is not a challenge unique to the clean energy problem, it is a challenge to the entirety of the U.S. electricity system and economy. Fossil fuel generation, nuclear plants, and conventional grid infrastructure also depend on copper, nickel, and other critical materials for electrification of field equipment and high-heat components. Energy system modernization accelerates and concentrates these dependencies but does not create them from scratch. Annex I maps the specific material dependencies of each major energy technology in detail.

2.4 The Critical Mineral Supply Chain

Understanding where risk concentrates requires understanding the supply chain structure. The critical mineral supply chain spans six broad stages: extraction and mining; concentration and beneficiation (upgrading ore into concentrates); refining and chemical processing (producing high-purity metals, oxides, or battery-grade chemicals); materials and component manufacturing (turning refined inputs into magnets, cathodes, conductors, and alloys); system integration and deployment; and, increasingly, recycling and recovery. Figure 2 shows how these stages group into upstream extraction, midstream processing and materials manufacturing, and downstream deployment and recovery.

Risk is not uniformly distributed across these stages. As Section III details, the greatest constraints in today's critical mineral supply chain are predominantly within midstream steps that rely on specialized industrial capacity to convert raw ore into the high-purity forms that energy technologies require. **Many minerals are geologically available across multiple regions; it is the processing infrastructure to unlock that availability that is concentrated, technically complex, and slow to build.**

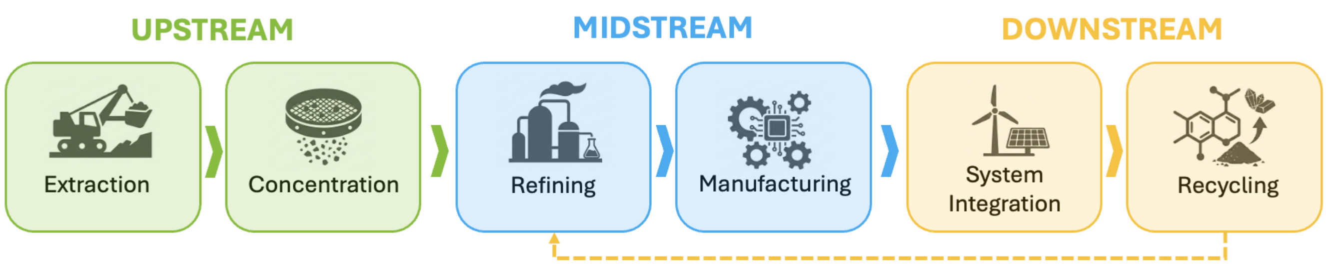

FIGURE 2 — ***Critical mineral supply chain for energy technologies.***

III. Where the System Is Vulnerable

Supply chain vulnerability in critical minerals is not uniformly distributed. It concentrates at specific intersections of geography, industrial capacity, and market structure. Five risks are introduced and discussed, each distinct in its causes and implications but collectively defining why the supply chains underpinning U.S. energy infrastructure are more fragile than they appear.

3.1 Geographic Concentration of Extraction

Many of the Electric Eighteen are mined in a small number of countries, creating single points of failure susceptible to political decisions, conflict, export restrictions, or regulatory shifts. Figure 3 highlights these geographical chokepoints. The Democratic Republic of the Congo accounts for roughly 70% of global cobalt mine production. China dominates magnesium and graphite. South Africa and Zimbabwe account for 81% of platinum metal mining (USGS, 2026). When production is this concentrated, a single disruption can move global prices and constrain supply with limited ability to reroute in the near term. Note that iridium is excluded from Figure 3 because it is recovered primarily as a by-product of platinum-group-metal and nickel-copper production, while iron ore, an input to electrical steel, and quartz, an input to silicon production, are excluded because they are not designated as critical minerals.

Geographic concentration at the extraction stage is the most visible layer of supply chain risk, but it is rarely the decisive one. Reserves of most critical minerals are distributed more broadly than current production figures suggest. The gap between what is in the ground and what reaches the market is largely a function of investment, permitting, and infrastructure, not geology.

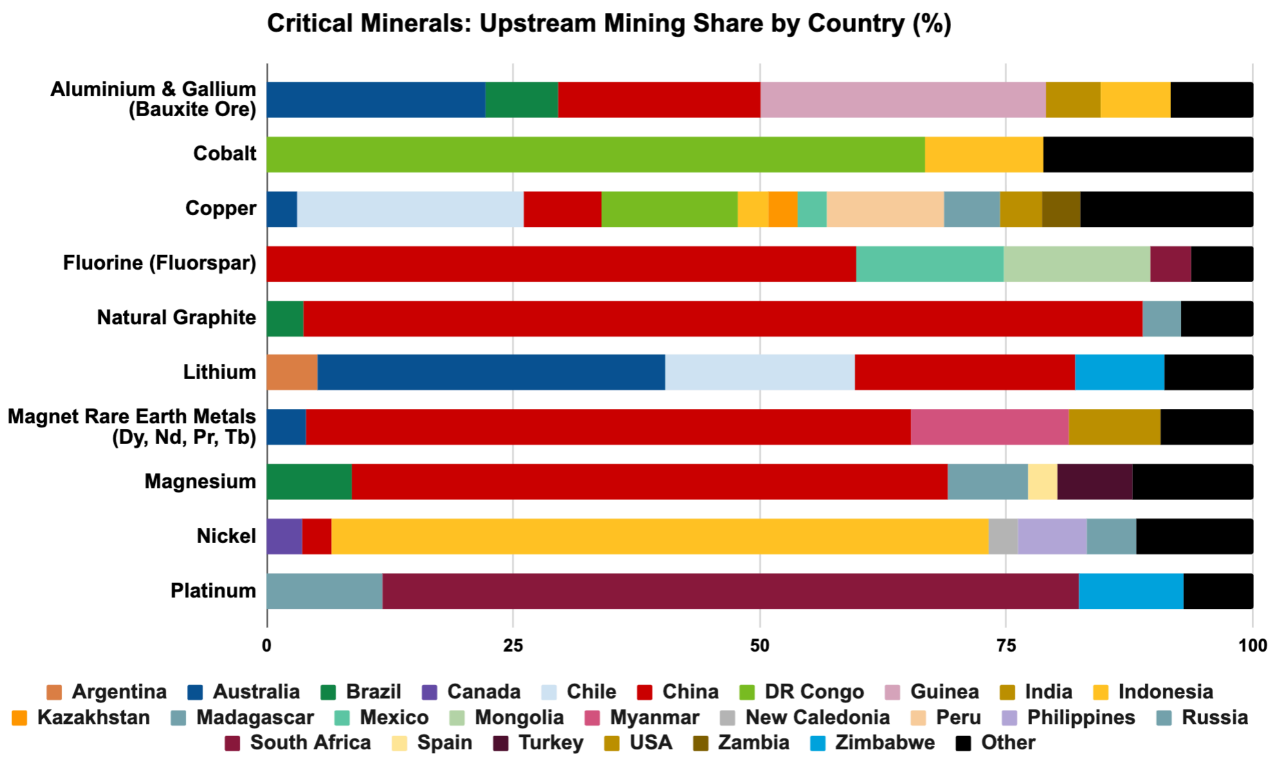

FIGURE 3 — ***Upstream mining production share by country for key Electric Eighteen materials****. Data sources: Dokua Sasu (2024); IEA (2025b);); NRC (2024); USGS (2026). All countries with less than 3% mine share aggregated into 'Other.' Figures are estimates and do not represent a single year; sources from 2023–2026. Figure source: ASU Laboratory for Energy And Power Solutions.*

3.2 Midstream Processing Bottlenecks

Most binding constraints in critical mineral supply chains are not at the mine; they are in the midstream steps for refining and manufacturing. Many minerals are geologically available across multiple continents, but the specialized industrial capacity to convert ore into battery-grade chemicals, magnet-grade rare earths, or semiconductor-grade silicon is concentrated in very few facilities globally. **Building new processing capacity requires not only capital but also regulatory approvals, technical expertise, and long-term offtake commitments. None of these materialize quickly, and the combination creates a structural bottleneck that geographical diversification alone cannot resolve.**

Some of the Electric Eighteen are not even primary mine products but rather obtained only through the processing of other ores. Iridium is recovered as a by-product of nickel and platinum-group metal refining. Gallium is extracted from bauxite ore during aluminum smelting. These materials have no independent mine supply; their availability is entirely contingent on the processing of other commodities. Geographic concentration of processing has increased across nearly all critical minerals, as shown in Figure 4. Indonesia leads nickel processing, South Africa dominates platinum-group metals, and China remains the dominant refiner or outright monopolist for the remainder of metals as a result of heavy investments in processing infrastructure over the last two decades (IEA, 2025). Comparable country-level midstream production data were not available for electrical steel, fluorine, or silicon carbide, so these materials are not included in the figure.

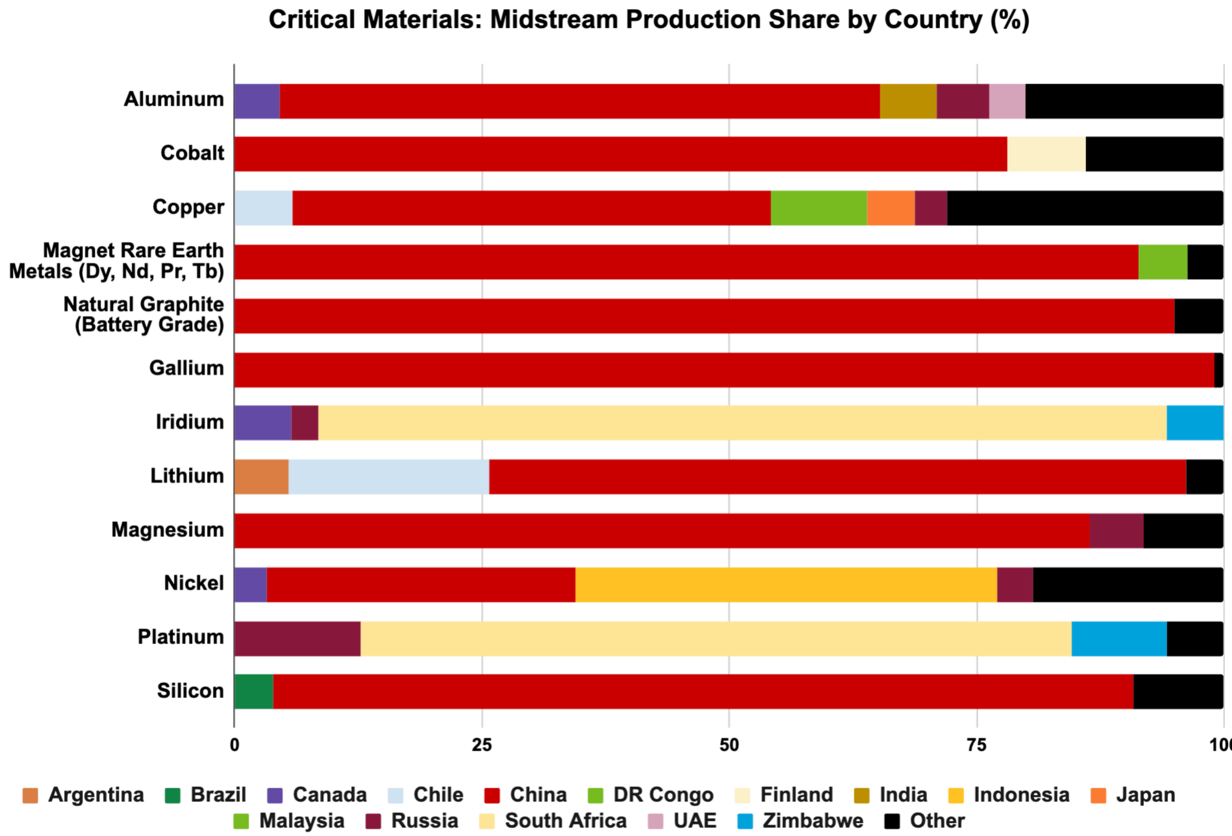

FIGURE 4 — *Midstream refining and processing share by country for key Electric Eighteen materials.* *Data sources: European Commission (2024); IEA (2025b); SFA Oxford (2026;);USGS (2026). All countries with less than 3% processing share aggregated into 'Other.' Figures are estimates and do not represent a single year. Figure source: ASU Laboratory for Energy And Power Solutions.*

The gap between where minerals are mined and where they are processed is starkly visible in Figure 5. This depicts mining-to-processing pathways for key Electric Eighteen materials, showing the countries in which raw ore is extracted and the countries to which that ore flows for refining into market-ready materials. Outside China, very few nations have the processing capacity to handle the minerals extracted within their own borders. **Resource wealth in the ground does not translate to supply chain independence without midstream investment.**

Once a mineral is processed and becomes a commodity it becomes harder to track how the original source of ore shows up in end-use goods. Processed materials are aggregated and then bought, sold, and traded in bulk. Once processed, a material may move through component manufacturing in one country, sub-assembly in another, and final integration in a third before reaching the U.S. market. China's dominance of polysilicon production illustrates the point: despite controlling over 80% of global solar module manufacturing, direct U.S. solar imports from China fell to near zero by 2024 as trade restrictions took effect (IEA, 2022; USITC, 2024). Nonetheless, the underlying processing dominance remained intact with Chinese-processed material flowing through Southeast Asian assembly operations before re-entering global markets, including the U.S. (USITC, 2024). A similar dynamic occurs with magnet rare-earth supply chain in which Neodymium Iron Boron (NdFeB) magnet manufacturing is overwhelmingly concentrated in China regardless of where wind turbines or EV motors are finally assembled (IEA, 2026b). What constrains energy sector growth is not where components are assembled, but rather who controls the material at the processing stage.

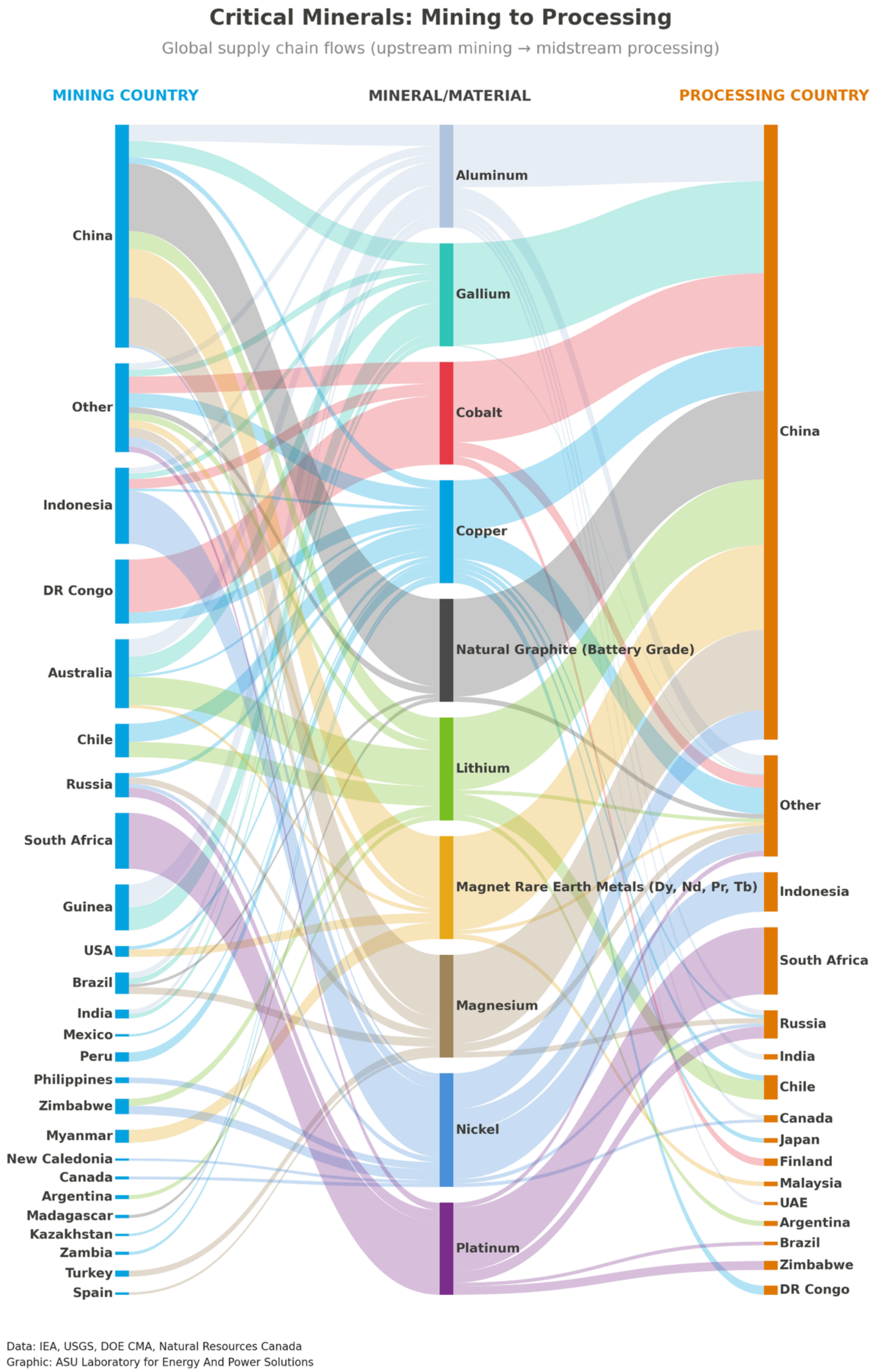

FIGURE 5 — *Mining-to-processing flow for key Electric Eighteen materials*. *Data sources: Dokua Sasu (2024); European Commission (2024); IEA (2025b); NRC (2024); SFA Oxford (2026); USGS (2026). All countries with less than 3% processing share aggregated into 'Other.' Figures are estimates and do not represent a single year; sources from 2023–2026. Figure source: ASU Laboratory for Energy And Power Solutions.*

3.3 Long Lead Times and Permitting Lag

Even where the geology is favorable and the investment case is clear, critical mineral supply chains cannot respond quickly to demand signals. The timeline from discovery to production for a new mine typically spans ten to fifteen years, encompassing exploration, feasibility studies, environmental review, permitting, construction, and commissioning. For processing facilities, the timeline is shorter but still measured in years, not months. This structural lag means that supply-side responses to reach today's demand growth will not materialize until the mid-2030s at the earliest. This mismatch is already visible in copper, where a projected 30% supply deficit by 2035 reflects a decade of underinvestment compounded by declining ore grades and a near-collapse in new resource discoveries (IEA, 2025).

Permitting is more complex and lengthier in countries with robust environmental laws, democratic governance, and community consultation requirements. In the United States, complex, multi-agency permitting processes can significantly delay major mining projects, with some individual projects taking more than a decade to secure approval (U.S. GAO, 2024). Projects in frontier markets face different but similarly serious barriers: inadequate transport and energy infrastructure, community opposition rooted in well-documented histories of extraction without equitable sharing of revenues, and political risk premiums that make private financing prohibitive without sovereign backing (IEA, 2025). Cobalt mining in the DRC, rare earth production in Myanmar, and lithium development across indigenous Andean territories have numerous and well-documented concerns around labor conditions, land rights, and environmental harm (ILO, 2024; OHCHR, 2023; UN, 2025). Any credible supply chain diversification strategy must address these constraints rather than externalize them.

The practical implication is that market signals alone cannot solve the lead time problem. Even sustained high prices do not compress a ten-year permitting and construction cycle. **Policy innovation must occur through streamlined permitting frameworks, sovereign-backed financing, and long-term offtake commitments that give developers the certainty they need to proceed.** This is needed for materials supply responses to meet the deployment timelines of energy infrastructure rather than the slower deployment timelines for mining and processing facilities.

3.4 Co-Product Dependence

Three critical materials — gallium, iridium, and cobalt — are recovered as by-products of production processes and not mined directly. This creates a structural vulnerability that is fundamentally different from the concentration and lead time risks described above. The supply of co-products cannot respond to demand signals independent of the primary commodity demand signal.

Gallium is recovered as a by-product of alumina refining, making its supply structurally coupled to aluminum production decisions rather than to demand of manufacturing solar cells or power electronics (USGS, 2025). Iridium is one of the scarcest elements in the earth's crust and is recovered primarily as a by-product of nickel and platinum-group metal refining, and its supply is tethered to the production economics of platinum, palladium, and rhodium (USGS, 2025). For example, even if iridium demand surged due to rapid scaling of proton exchange membrane (PEM) electrolyzers, producers cannot simply increase iridium output, they can only increase it by increasing primary platinum-group metal production, which is governed by entirely different market dynamics. Cobalt, recovered almost entirely alongside copper and nickel, is subject to the same structural decoupling of supply from demand.

This coupling makes co-product materials among the most difficult to secure. Price signals that would ordinarily attract new supply have limited effect when the material has no independent production pathway. **The processing dependence on another good combined with limits on supply chain capacity mean that co-product shortfalls can appear suddenly and are slow to resolve.** For technologies that depend on these materials and have limited substitution options, such as PEM electrolyzers for iridium or thin-film solar for gallium, the risk is structural rather than cyclical.

3.5 Chinese Processing Monopoly Risks

The four vulnerabilities above describe structural features of the market: where minerals sit, where capacity was built, how long it takes to build more, and how supply is coupled across commodities. Each would exist regardless of who held the dominant position. The fifth risk differs in kind because the midstream concentration described in Section 3.2 is not distributed across several industrial economies but consolidated, across almost every critical material category simultaneously, in a single state that has demonstrated both the capability and the willingness to use that position as an instrument of policy. A bottleneck held by many actors is an economic constraint; a bottleneck held by one is strategic leverage.

China does not hold the largest reserves of most critical minerals, but it does hold the most processing infrastructure. Over two decades of patient, state-backed investment, China built the processing capacity, technical expertise, and integrated supply chain relationships that convert raw ore into the high-purity, energy-ready forms that modern power systems require. That infrastructure cannot be replicated quickly, and it operates at a scale and cost structure that private markets in other countries have found very difficult to compete with.

The numbers are stark. China processes over 90% of global battery-grade graphite, maintains 85% of cathode active materials, and 98% of lithium iron phosphate (LFP) battery-cell production (IEA, 2025a; IEA, 2025b). China also controls approximately 94% of permanent magnet manufacturing, such as the neodymium-iron-boron magnets that are essential for wind turbine generators and EV traction motors (IEA, 2025c). China has a near complete monopoly of primary gallium with 99% of production and dominates the production of rare earth elements (REEs), silicon, and magnesium (USGS, 2026). For modern energy system components such as battery storage, solar PV, wind generation, and electric vehicles, the conversion of raw materials into energy-ready components runs overwhelmingly through Chinese industrial facilities.

This concentration has increasingly functioned as strategic leverage for China. It restricted exports of rare-earth extraction, separation, and magnet-manufacturing technologies in late 2023, then imposed licensing controls in 2025 on selected medium and heavy rare earths, related compounds, and permanent magnets (IEA, 2025d). These measures sharply reduced exports and created procurement bottlenecks for manufacturers dependent on Chinese magnet supply, including EV producers and some wind-equipment manufacturers (IEA, 2026b). NdPr oxide prices also rose substantially in 2025, although the increase reflected several factors, including constrained feedstock supply and broader market uncertainty, rather than direct controls on NdPr alone (Onstad & Lv, 2025). When a dominant processor imposes export controls or suppresses spot prices, the effects cascade through supply chains with limited ability to substitute or reroute.

The future of abundant energy and a modern grid requires urgent actions to develop and secure mineral supply chains. The concentration of processing by a single actor is not a permanent feature of the global economy, but it is the result of investment decisions made over decades, and it can be changed by strategic decisions made now, as described in Section IV.

IV. Strategic Recommendations

The vulnerabilities detailed in Section III are structural and have built up over decades of underinvestment and geographic concentration. They will not self-correct on the timelines that energy infrastructure presently requires, but they can be addressed through immediate and targeted actions. Meeting projected U.S. and allied demand for critical minerals in energy and advanced technology manufacturing will require more than $25 billion in additional investment by 2030 (SAFE, 2025). This investment gap will not be met by U.S. businesses operating against state-backed competition.

The following five strategic recommendations to address this gap are mutually reinforcing to create supply chain resilience, as shown in Figure 6. Financing refining in allied nations creates the projects that price floors make investable; price floors attract the institutional capital that scales allied production; technical standards ensure that allied production is commercially integrated with Western supply chains from the outset; circularity reduces the primary supply requirements that all three of the above are trying to secure; and alternative technologies and manufacturing processes could eliminate some risks altogether. Each recommendation strengthens other and the whole.

FIGURE 6 — ***Five strategic recommendations for supply chain resilience and their reinforcing relationships.***

4.1 Financing Allied Refining Capacity

Over the next decade, resource-rich nations will need to build substantial midstream refining capacity to process the minerals beneath their soil. The core challenge is not the absence of viable projects, it is that midstream refining ventures in frontier markets are commercially nonviable without sovereign backing: political risk is too high, offtake is too uncertain, and the cost of capital is prohibitive for private investors moving alone.

The U.S. government has financing institutions suited to this task: the U.S. Trade and Development Agency (USTDA), the U.S. International Development Finance Corporation (DFC), and the Export-Import Bank (EXIM), which is financing Project Vault, the strategic critical minerals reserve announced in February 2026 (EXIM, 2026). The Millennium Challenge Corporation (MCC) offers a complementary instrument: grant-funded compacts conditioned on governance reforms that can enable the transport, power, and institutional foundations on which mineral projects depend. These domestic tools are complemented internationally by the Forum on Resource Geostrategic Engagement (FORGE), launched at the February 2026 Critical Minerals Ministerial as the successor to the Minerals Security Partnership, to coordinate policy and project-level action on critical mineral supply chains (U.S. DOS, 2026). Together these institutions span the full project lifecycle: bilateral trade coordination, grant-funded feasibility studies and technical assistance to prepare projects for investment, first-loss equity and concessional debt to crowd in private capital, political risk insurance to address sovereign exposure, and export credit to finance the equipment and construction that build the facilities themselves.

Capital alone, however, does not carry a project to production. Frontier-market ventures also depend on conditions no balance sheet can substitute for: sound technical design, credible feasibility assessment, a workable regulatory and permitting strategy, community engagement, and the social license to operate. Without these prerequisites, even well-financed often projects fail to reach production (SAFE, 2025). This is why the earliest-stage instruments in the toolkit are often the most consequential, and why USTDA's project-preparation role precedes and enables DFC and EXIM investment downstream.

The Lobito Corridor build-out represents a good example of early-stage assistance that established local partnerships and de-risked follow-on investment. As shown in Figure 7, this corridor connects cobalt and copper production in the DRC and Zambia to Atlantic export infrastructure. USTDA provided $13.2 million in technical assistance grants across the region, including environmental and social impact assessments for the Zambia rail extension that prepared the project for financing and helped secure local governmental approval and a social license to operate (USTDA, 2024). DFC financing then supported rehabilitation of a brownfield mineral port in Lobito and approximately 1,300 kilometers of rail line to the Angolan border. The investment is projected to increase Lobito's freight capacity tenfold to 4.6 million metric tons annually while reducing critical mineral transport costs by up to 30% (DFC, 2025). The same sequence can be repeated for rare earth separation in sub-Saharan Africa, lithium conversion in the Andes, or graphite processing in Southeast Asia, with each project adding a node to a growing network of allied industrial capacity.

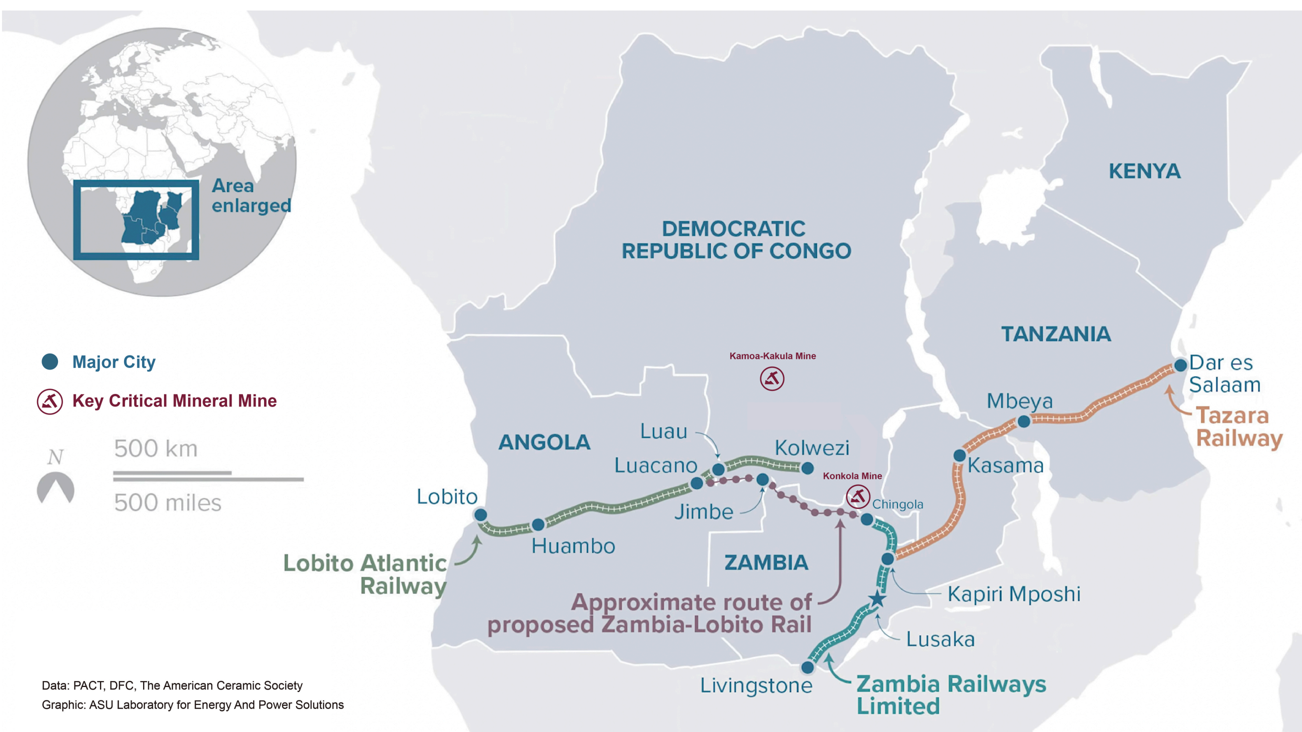

FIGURE 7 — ***The Lobito Corridor DFC-financed rail rehabilitation connecting DRC and Zambia copper-cobalt production to the Atlantic port of Lobito, Angola.*** *Figure source: ASU Laboratory for Energy And Power Solutions. Figure reproduced from PACT (2026) and McDonald (2024).*

4.2 Establishing Price Floors for Critical Minerals

For some minerals, the obstacle is not access to capital but the inability to price it. A pension fund, infrastructure investor, or sovereign wealth fund will not commit ten-year capital to a rare earth separator or cobalt refinery when the price floor is effectively set by a competitor's political decisions. This is the fundamental market failure at the heart of supply chain vulnerability for a specific class of minerals, and it has a direct policy solution.

Price floors convert volatile commodity exposure into something closer to a government-backed infrastructure asset. When a government provides a guaranteed minimum price, through direct offtake commitments or through make-whole payments if spot prices fall below a threshold, it effectively underwrites the revenue certainty that institutional investors need to model a return. The mechanism requires no ongoing expenditure if markets remain above the floor. It only kicks-in when market prices fall below the floor, thereby providing the certainty that allows private capital to move into an otherwise risky or speculative market.

This instrument is most powerful where it is most needed, specifically in thin, illiquid markets where Chinese state-backed producers actively suppress prices to exclude competitors. Rare earths, cobalt, and gallium are the clearest cases. These minerals markets have extreme processing concentration, where price discovery outside China is structurally weak, and a single actor's output decisions can move global prices regardless of underlying demand fundamentals. The Pentagon's 2025 establishment of a ten-year price floor of $110 per kilogram for NdPr oxide demonstrates how to keep U.S. rare earth processing operations solvent against Chinese oversupply (MP Materials, 2025). The Center for Strategic and International Studies (CSIS) has made a parallel case for cobalt, where prices fell nearly 60% between 2022 and 2025 as Chinese producers flooded the market, shuttering the only U.S. cobalt mine in the process (Baskaran & Schwartz, 2025).

Price floors may not be the best instrument where the binding constraint is not market manipulation but geology, permitting lag, or commodity scale. For large, globally traded markets such as copper and lithium with broad price discovery and many producers, the decisive barriers are mine development timelines and processing investment, not strategic price suppression. Those constraints respond better to the financing and standards instruments.

The next step for price floors is coordination rather than universalization. The FORGE framework and its 15 core signatory bodies can align price floors for the minerals where market distortion is the demonstrated barrier. This creates a multilateral demand signal that no single producer can undercut and that no single government bears alone. An allied price floor regime also carries diplomatic weight. For resource-rich nations deciding between U.S. and Chinese partnership, a revenue guarantee offers what Beijing's model cannot: protection from the price suppression that has repeatedly stranded producer-country investments. Establishing that architecture early would anchor allied mineral supply relationships for decades.

4.3 Technical Standards Diplomacy

When a critical mineral refinery is built in Namibia, the Philippines, or Peru, it is built to someone's technical specifications, and who sets those specifications shapes downstream decisions from the equipment procured, the quality of grades produced, the environmental standards applied, and the long-term compatibility of output with end-use manufacturers. A facility financed and constructed under a single country's terms defaults to that country's standards. When China has dominated project finance and construction, the technical and commercial architecture of the facility and supply chain has followed accordingly.

That dynamic is beginning to change. Through FORGE, the G7's Roadmap to Promote Standards-Based Markets, and the bilateral critical minerals frameworks signed in 2025–2026, the U.S. and its partners have built the policy architecture for a standards-aligned supply network (NRC, 2025). The task now is to make that architecture operational at the project level by deploying technical assistance for facility design, operator training, quality certification, and environmental compliance so that allied-financed infrastructure produces to common manufacturing specifications from the outset. A DFC-financed lithium hydroxide plant in Argentina that defaults to Chinese equipment and process standards at the design stage is a missed opportunity that cannot be corrected after the fact.

A refinery built to allied standards, using allied-sourced equipment, producing output certified to allied quality benchmarks will create a supply chain that is structurally oriented toward the Western market. As allied refining capacity scales, a critical mineral supply network follows, and that network will be compatible, auditable, and insulated from the provenance risks that manufacturers, investors, and regulators seek to avoid. **The window is now: the buildout of allied processing capacity is just beginning, and standards embedded in first-generation facilities will shape supply chain architecture and the energy dominance for decades.**

4.4 Circularity and Secondary Supply

Critical minerals circularity is becoming increasingly important to commercialize and master. **The energy technologies now being deployed at scale are not just consumers of critical minerals, they are future stockpiles of them.** Battery storage systems, solar PV installations, wind turbines, and transmission infrastructure embed large quantities of lithium, cobalt, copper, REEs, and other critical materials into assets that will operate for decades before reaching end-of-life. Figure 8 illustrates how recovery potential varies significantly across asset types: wires, cables, and lead-acid batteries sit in the high-salvage, fast-circularity quadrant and are near-term recovery priorities, whereas solar panels, wind turbine blades, and lithium-ion batteries require more deliberate policy intervention to capture their mineral value at end-of-life. Without recovery facilities and infrastructure, those materials are processed once, at great cost, embedded into grid assets, and then lost. Circularity can become a compounding secondary supply that is controlled domestically.

The scale of the opportunity is significant. Under IEA projections, recycling could reduce new mine development needs by 40% for copper and cobalt, and by 25% for lithium and nickel by 2050 (IEA, 2024). The market value of recycled energy transition minerals is projected to reach $200 billion annually by mid-century. Yet the U.S. and Europe are not on track to capture that value. Announced recycling capacity, for instance, covers only 30% of available EV battery feedstock by 2040 (IEA, 2024). Without deliberate policy intervention, the minerals embedded in the next generation of U.S. grid infrastructure will exit the domestic supply chain entirely. Without the uptake of recycling, capital requirements for mining and extraction would need to be approximately 30% higher through 2040 (IEA, 2024).

The electric utility sector has traditionally followed a linear model to build, operate, then discard, which places persistent pressure on primary supply while foregoing the potential advantages of recovery. **Continued investment in historical practices alone will not prepare the U.S. to meet the mineral needs for the electric grid in 2040 and 2050.** Unlocking the circularity opportunity requires action at three levels: federal procurement standards should mandate design-for-recyclability in energy equipment; the DFC and EXIM financing mechanisms proposed for allied refining capacity should be extended to recovery infrastructure, particularly battery recycling and rare earth separation facilities; and the FORGE framework should incorporate circularity metrics into its supply chain assessments, treating domestic and allied secondary supply as a quantifiable offset to primary production requirements.

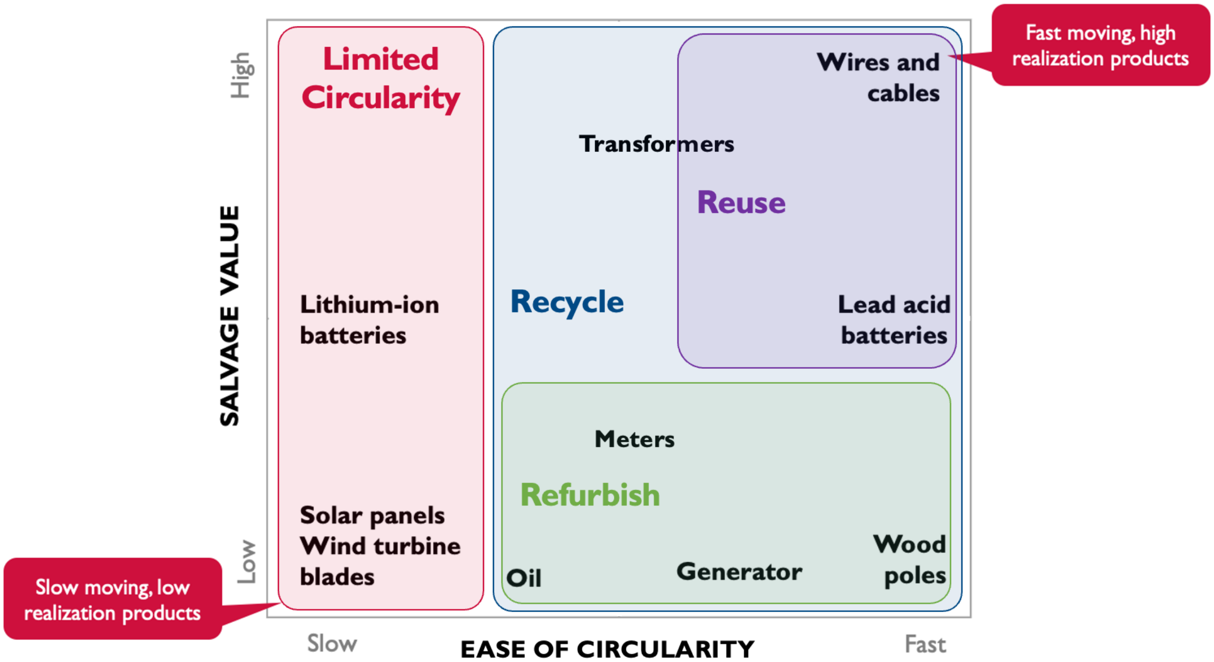

FIGURE 8 — *Illustrative circularity pathways for energy sector assets for the relationship between salvage value and ease of recovery.* *Source: Chaturvedi et al. (2023). Figure source: ASU Laboratory for Energy And Power Solutions.*

4.5 Alternative Technologies and Materials

Supply chain vulnerabilities can also be mitigated by avoiding use of critical minerals when possible. New energy storage technologies are showing promise. LFP cathode chemistry eliminates cobalt and nickel entirely (U.S. DOE, 2023). Sodium-ion batteries go further still and contain no lithium (U.S. DOE, 2023). Other storage technologies are also on the rise in commercial and pre-commercial applications such as flow batteries, iron-air, zinc-based batteries, thermal energy storage, compressed gases, gravity storage, and more.

Materials substitution is also advancing in electric motors and generators. Researchers demonstrated in 2024 that motor designs using samarium-iron-nitrogen (SmFeN) magnets — which require significantly less critical rare earth content than conventional NdFeB designs — can achieve comparable or improved performance with lower overall motor mass and volume (Critical Materials Innovation Hub, 2024).

None of these substitutions are expected to completely displace critical minerals. Looking again to energy storage, the market will continue to increase in lithium-ion batteries even as this demand compounds security, economic, and geopolitical risks. **Meaningful substitution at scale requires sustained public investment in materials R&D and deliberate policy choices to prioritize supply chain resilience over narrow cost optimization** (DOE, 2023). Processing of materials and production of energy components may then shift towards U.S. based manufacturing, and at cost-competitive rates. The substitution pathway represents a class of intervention that reduces primary mineral demand structurally, rather than simply rerouting it through allied supply chains.

V. Supply Risk and Mitigation Summary

For decision-makers, the practical question is not whether critical mineral risks exist, but which risks attach to which technologies, and what can be done about each. Table 2 consolidates analyses from Sections III and IV. Each major energy technology is listed along with corresponding critical mineral and material dependencies, structural risk categories, vulnerabilities, and recommendations to address the vulnerabilities. Vulnerabilities shown are those most distinctive to each technology; shared mineral-specific constraints apply across rows. More details of how each critical mineral and material are used by technology is provided in Annex I. Several cross-cutting findings emerge from Table 2:

- **Chinese processing monopoly as a structural risk.** Chinese processing dominance appears as a primary vulnerability across battery storage, solar PV, wind, electric vehicles, and fuel cells. This concentration means a single actor's policy decisions can simultaneously constrain multiple energy technology supply chains.
- **Co-product dependence as a less tractable risk.** Gallium and iridium cannot be independently scaled regardless of price signals or investment levels. Technologies that depend on them, including CIGS/GaAs solar technologies for gallium and PEM electrolyzers for iridium, face structural exposure that allied refining finance alone cannot resolve.
- **Copper's permitting lag as the broadest-reaching vulnerability.** Of all mineral risks, copper's projected supply deficit cuts across the broadest range of technologies, from transmission infrastructure to nuclear to oil and gas. Unlike mineral risks that are technology-specific, this deficit will apply simultaneous pressure across the sector.
- **Hydropower, geothermal, and oil and gas at the lower end of mineral exposure.** These sectors require no technology-specific mineral intervention and benefit indirectly from broader copper diversification efforts. This finding underscores that mineral risk is not uniformly distributed across the energy system but concentrated in the clean energy technologies presently being deployed at the greatest scale and speed. Oil and gas, however, remain vulnerable to disruptions in fuel supply, even where mineral exposure is comparatively limited.
- **The most acute dependencies coincide with the longest deployment horizons.** Technologies with the least substitutable mineral dependencies, hydrogen and fuel cells for iridium, wind for magnet rare earths, also carry the longest deployment timelines. The window for building alternative supply infrastructure remains narrow but has not yet closed.

Table 2 — *Critical Material Supply Risk and Strategic Response by Energy Technology.* *Data Sources: Baskaran & Schwartz (2025); U.S. DOE (2023); Home, 2026; IEA (2025b); Li & Du (2026); Nickel Institute (2021a); Nickel Institute (2021b); USGS (2026); Wood Mackenzie (2025)*

Technology	Critical Minerals or Materials	Risk Category	Major Vulnerabilities	Recommendations
Battery Storage (e.g., anode, cathode, electrolyte, separator, inverters)	Graphite, Cobalt, Lithium, Nickel, Aluminum, Fluorine	China processing monopoly Domestic capacity gap / Import reliance	China processes a vast majority of battery-grade graphite. China refines a majority of global cobalt and produces over 90% of precursor cathode active materials. Lithium carbonate futures spiked after Zimbabwe's February 2026 export ban accelerated an existing rally. DRC instability and export quotas risk disrupting cobalt supply. Nickel processing concentrated in Indonesia and China.	**Rec. 1** Finance battery-grade graphite and lithium hydroxide processing in allied nations. **Rec. 2** Price floors for cobalt to unlock institutional capital. **Rec. 4** Mandate requirements for design-for-recyclability in BESS procurement; scale battery recycling. Improve aluminum recovery from available assets. **Rec. 5** Invest in alternative energy storage technologies.

Technology	Critical Minerals or Materials	Risk Category	Major Vulnerabilities	Recommendations
			Fluorine supply concentrated in Chinese fluorspar mining and HF conversion.	
Transmission & Distribution (e.g., conductors, transformers, protective devices)	Copper, Electrical Steel, Silicon Carbide (SiC), Nickel, Aluminum	Mining / permitting lag Domestic capacity gap / Import reliance China processing monopoly	Decade-long U.S. permitting lag for copper mines. Four-year transformer lead times due to electrical steel scarcity. SiC supply chains concentrated among a small number of global producers. Nickel alloys for grid hardware face Indonesian and Chinese processing concentration. Geopolitical and processing monopoly risks to aluminum supply.	**Rec. 1** Support allied copper processing in Chile and Peru; expand electrical steel capacity with Japan, South Korea, and domestic producers. **Rec. 3** Embed U.S. electrical steel and SiC specs in allied infrastructure projects. **Rec. 4** Expand transformer copper recovery; treat T&D end-of-life equipment as secondary copper stockpile. Improve aluminum recovery from available assets.
Solar PV (e.g., cells, panels, cabling, fuses/breakers, inverters and power electronics)	Silicon, Silicon Carbide, Gallium, Aluminum, Copper	China processing monopoly Co-product dependency Mining / permitting lag	The energy sector competes with the chemical industry for metal-grade silicon. Gallium is a by-product of aluminum smelting, supply cannot be scaled independently. China controls most silicon and primary gallium production.	**Rec. 2** Price floors for gallium to incentivize by-product recovery investments. **Rec. 3** Establish allied gallium quality standards; embed in allied-financed smelter upgrades. **Rec. 4** Improve aluminum recovery from available assets.
Onshore/ Offshore Wind (e.g., motors, generators, turbines)	Neodymium, Praseodymium, Dysprosium, Terbium, Copper, Electrical Steel	China processing monopoly Domestic capacity gap / Import reliance Mining/permitting lag	China holds a majority of permanent magnet manufacturing. NdPr oxide prices spiked in early 2026 amid export controls, quota constraints, and structural supply deficit. Magnet-grade REE separation infrastructure remains limited outside China.	**Rec. 1** Finance REE separation and NdFeB magnet facilities in sub-Saharan Africa, Australia, allied Southeast Asia. **Rec. 2** Extend NdPr price floor model across magnet rare earths via allied coordination. **Rec. 3** Embed Western magnet-grade separation standards in first-generation allied facilities. **Rec. 4** Recover REE content from decommissioned wind turbine magnets. **Rec. 5** Invest in alternative magnet technologies

Technology	Critical Minerals or Materials	Risk Category	Major Vulnerabilities	Recommendations
Electric Vehicles (e.g., battery cells, motors, structural material)	Lithium, Cobalt, Nickel, Neodymium, Praseodymium, Dysprosium, Terbium, Copper, Silicon, Gallium, Magnesium, Fluorine, Electrical Steel, Aluminum	China processing monopoly Domestic capacity gap / Import reliance Co-product dependency	REE magnets face the same bottleneck as wind. Lithium supply shocks detailed under Battery Storage.	**Rec. 1** Finance cobalt and lithium processing in the DRC/Zambia corridor and lithium hydroxide conversion near Andean deposits. **Rec. 2** Allied price floors for cobalt to crowd in private capital. **Rec. 3** Establish allied gallium quality standards; embed in allied-financed smelter upgrades. **Rec. 4** Mandate EV battery design-for-recyclability; scale recycling to recover lithium, aluminum, cobalt, and nickel. **Rec. 5** Invest in alternative magnet technologies and alternative energy storage technologies.
Nuclear (e.g., generators, casings, reactors)	Copper, Nickel, Electrical Steel	Mining/permitting lag Domestic capacity gap / Import reliance	Subject to the same copper, nickel, and electrical steel supply constraints.	**Rec. 1** Support diversified copper and nickel refining and expand domestic and allied electrical-steel and nuclear-grade alloy manufacturing capacity.
Oil & Gas (e.g., pipelines, platforms, cabling)	Copper, Nickel	Mining/permitting lag Domestic capacity gap / Import reliance	Lower mineral intensity than clean energy technologies. Copper and nickel dependencies for electrification of field equipment and processing infrastructure.	**Rec. 1** Sector benefits indirectly from broader copper supply diversification; no sector-specific intervention required beyond baseline copper support. **Rec. 4** Recovery of copper from decommissioned oil and gas infrastructure is an underutilized circularity stream.
Electrolyzers and Fuel Cells (e.g., electrodes, catalysts, bipolar plates, stack components)	Iridium, Platinum, Nickel, Cobalt, Graphite	Co-product dependency Domestic capacity gap / Import reliance	Graphite and cobalt inputs face Chinese processing concentration; PGM refining concentrated in South Africa and Zimbabwe. Iridium, among the scarcest elements, production is fundamentally linked to PGM as a by-product.	**Rec. 1** Develop additional PGM refining and recycling capacity outside the existing southern African concentration while maintaining partnerships with incumbent producers. **Rec. 4** Prioritize recovery and recycling of platinum-group metals from PEM electrolyzers and fuel cells.
Hydropower (e.g., turbines,	Aluminum, Copper, Nickel	Mining/permitting lag	Aluminum substitution limitations if supply cannot meet demand.	**Rec. 1** Sector benefits indirectly from a broader copper supply diversification strategy.

Technology	Critical Minerals or Materials	Risk Category	Major Vulnerabilities	Recommendations
cables, generators)		Domestic capacity gap / Import reliance		**Rec. 4** Recovery of aluminum, nickel, and copper from decommissioned hydro infrastructure is an underutilized circularity stream.
Geothermal (e.g. condenser, heat exchanger, piping)	Nickel, Copper	Mining/permitting lag Domestic capacity gap / Import reliance	Lower mineral intensity than other clean energy technologies.	**Rec. 1** Sector benefits indirectly from broader copper supply diversification; no sector-specific intervention required beyond baseline copper support. **Rec. 4** Recovery of copper and nickel from decommissioned infrastructure components improves domestic supply.

Materials within the DOE 2023 Electric Eighteen: aluminum, cobalt, copper, dysprosium, electrical steel, fluorine, gallium, iridium, lithium, magnesium, natural graphite, neodymium, nickel, platinum, praseodymium, silicon, silicon carbide, terbium.

Recommendations: Rec. 1 — Finance allied refining capacity | Rec. 2 — Price floors | Rec. 3 — Technical standards diplomacy | Rec. 4 — Circularity & secondary supply | Rec. 5 — Alternative technologies

VI. Conclusion

Energy sector growth and the increasing demand on critical minerals and materials is shifting how we view energy security. The technologies on which the U.S. electricity system increasingly depends — from utility-scale battery storage and offshore wind to high-voltage transmission and power electronics — are all dependent on minerals and materials whose supply chains are currently concentrated, constrained, contested, and in several cases actively leveraged by strategic competitors. The 2025–2026 period made this concern a reality through rare earth export controls, a sudden lithium export ban, and ongoing disruption to Gulf supply chains. Each translated into cost increases and procurement delays for energy infrastructure, and the effects compounded. These were not anomalies but rather previews of the global rewiring of supply chains for critical minerals and materials.

The five recommendations in this brief, financing allied refining capacity, establishing price floors, advancing technical standards diplomacy, building circularity into supply chain strategy, and developing alternative technologies and materials, can address structural vulnerabilities in energy system supply chains. These are not reactive measures but rather provide strategic proactive investments to restructure the supply chain using instruments the U.S. already has at its disposal. The Lobito Corridor, the MP Materials price floor agreement, and the FORGE ministerial are early evidence that the institutional pieces are moving into place. Comprehensive strategy and effort are now required to coordinate, amplify, and secure the outcomes of these isolated initiatives.

The nations that act with urgency and coordination on critical mineral supply chains will shape the terms of energy abundance and global economic leadership for decades. The U.S. has the capital markets, the allied relationships, the institutional architecture, and the technical base to lead that effort. The question is not capability; it is whether U.S. policy will meet the needs of this strategic moment.

ANNEX I: ENERGY TECHNOLOGY TO CRITICAL MATERIAL MAPPING

The table below provides a comprehensive mapping of energy technology components to their critical mineral dependencies, including the primary application for each mineral within that technology.

Technology	Critical Material	Primary Applications
Battery Storage (e.g., anode, cathode, electrolyte, separator, inverters)	Natural Graphite	Anode active material in batteries
	Nickel	Increases energy storage capacity (energy density) of cathodes
	Lithium	Essential carrier ion that shuttles between electrodes during charge and discharge
	Cobalt	Provides structural stability and high energy density in cathodes
	Aluminum	Cathode current collectors and alloying agent
	Fluorine	Used in the cathode binder material and electrolyte salt of lithium-ion batteries
Transmission & Distribution (e.g., cables, transformers, productive devices)	Copper	Preferred material for cables, busbars, and transformer windings
	Nickel	High-performance alloys for grid infrastructure requiring corrosion resistance and high-temperature strength
	Aluminum	Used in overhead transmission lines, transformer windings
	Electrical Steel	Grain-orientated electrical steel engineered for low magnetic energy losses; essential for laminated transformer cores
	Silicon Carbide	Wide-bandgap semiconductor for advanced power electronics
Solar PV (e.g., cells, panels, cabling, inverters)	Silicon	Dominant semiconductor material in crystalline-silicon photovoltaic cells; silicon semiconductor devices are also widely used in conventional inverters.
	Silicon Carbide	SiC based inverters and power electronics
	Copper	Inverters, cabling, and module interconnects
	Gallium	Semiconductor constituent in GaAs and CIGS photovoltaic technologies and in some GaN power-electronic devices
	Aluminum	Module frames, mounting structures, inverter enclosures, and rear-contact metallization in some cell architectures
Onshore/ Offshore Wind (e.g., motors, generators, turbines)	Electrical Steel	Non-grain-oriented electrical steel in generator stators and rotors; grain-oriented electrical steel in associated step-up transformers
	Copper	Wiring, subsea cabling, electrical collection systems, and generator windings
	Neodymium	Primary component of NdFeB permanent magnets used in generators. Magnet rare-earth dependence varies significantly by generator architecture; direct-drive permanent-magnet turbines generally have the greatest exposure

Technology	Critical Material	Primary Applications
	Praseodymium	Alloyed with neodymium in permanent magnets
	Dysprosium	Added to magnets to maintain high-temperature performance
	Terbium	Added to magnets to maintain high-temperature performance
Electric Vehicles (e.g., battery cells, motors, structural material)	Fluorine	Used in the cathode binder material and electrolyte salt of lithium-ion batteries
	Lithium	Essential ion carrier in battery cells
	Cobalt	Improves structural stability, energy density, and safety in cathodes
	Nickel	Key cathode component increasing battery energy density
	Neodymium	Primary magnetic element in high-performance permanent magnets
	Praseodymium	Alloyed with neodymium to enhance magnetic strength and stability
	Dysprosium	Additive improving performance of permanent magnets
	Terbium	Additive improving performance of permanent magnets
	Copper	Electrical wiring, motor windings, and busbars
	Silicon	Control semiconductors; transistors, charging stations, increasingly used in anodes
	Gallium	Utilized in advanced semiconductor materials
	Magnesium	Lightweight structural alloys reducing vehicle mass
	Aluminum	Lightweight structural alloys reducing vehicle mass
	Electrical Steel	Non-oriented electrical steel used in motors
Nuclear (e.g., generators, casings, reactors)	Electrical Steel	Generator stators and step-up transformers
	Copper	Power plant electrical systems
	Nickel	Nickel-bearing and nickel-based alloys used in steam generators, reactor internals, piping, heat exchangers and other corrosion- or heat-resistant components
Oil & Gas (e.g., pipelines, platforms, cabling)	Nickel	Stainless steels and nickel-based alloys used in corrosive, sour-service and high-temperature equipment, piping, valves and offshore components
	Copper	Power cabling, motor windings, seawater piping, heat exchangers, condensers, instrumentation, controls and electrification of production and processing facilities
Electrolyzers and Fuel Cells	Nickel	Low-cost catalyst; hydrogen storage in hydride alloys. Anode cermet material in SOFCs; low-cost catalyst in alkaline electrolyzers

Technology	Critical Material	Primary Applications
(e.g., electrodes, catalysts, bipolar plates, stack components)	Platinum	Cathode catalyst for the Hydrogen Evolution Reaction. Cathode catalyst for hydrogen evolution in PEM electrolyzers; cathode catalyst for oxygen reduction in PEM fuel cells
	Iridium	Primarily utilized in Proton Exchange Membrane (PEM) electrolyzers. Anode catalyst for oxygen evolution in PEM electrolyzers
	Natural Graphite	Bipolar plates and gas-diffusion components in many fuel-cell systems; use in electrolyzers depends on technology and electrode environment
	Cobalt	Used in some solid-oxide fuel-cell (SOFC) cathodes and under development in non-platinum-group-metal catalysts for fuel cells and electrolyzers
Hydropower (e.g., turbines, cables, generators)	Copper	Generator windings and grid interconnects
	Aluminum	High-voltage transmission cables, substation components
	Nickel	Alloying element in selected stainless-steel turbine runners, shafts and other corrosion-resistant components
Geothermal (e.g. condenser, heat exchanger, piping)	Nickel	Alloying element in corrosion- and temperature-resistant piping, heat exchangers, well components and processing equipment
	Copper	Often alloyed with nickel, used in generators, condensers, cabling

Data sources: IEA, (2025b); USGS (2026); U.S. DOE (2023); U.S. DOE (2025); Wood Mackenzie, (2025); Hayakawa, Y. (2022); P & D Northern Steels. (n.d.); Nickel Institute, 2021a; Nickel Institute, 2021b; International Wire (2025)

References and Data Sources

Baskaran, G., & Schwartz, M. (2025, December 10). *Stabilizing cobalt markets: A price floor for U.S. minerals security*. Center for Strategic and International Studies. https://www.csis.org/analysis/stabilizing-cobalt-markets-price-floor-us-minerals-security

Chaturvedi, H., Busch, R., Kemabonta, T., van Hove, E., Lanning, D., & Johnson, N. (2023). *A practical framework to enhance asset circularity for electric utilities*. Arizona State University; United States Energy Association; United States Agency for International Development.

Critical Materials Innovation Hub, Ames National Laboratory. (2024, March 4). Applicability of less-critical Sm-Fe-N magnets in motors. U.S. Department of Energy. https://www.ameslab.gov/cmi/research-highlights/applicability-of-less-critical-sm-fe-n-magnets-in-motors

Dokua Sasu, D. (2024, April 19). Global fluorspar mine production in 2023, by country. Statista. https://www.statista.com/statistics/1051717/global-fluorspar-production-by-country/

European Commission. (2024), Raw Materials Information System https://rmis.jrc.ec.europa.eu/rmp/Iridium.

Export-Import Bank of the United States. (2026, May 4). *EXIM announces Project Vault as Deal of the Year, advancing U.S. critical minerals security and industrial strength*. https://www.exim.gov/news/exim-announces-project-vault-deal-year-advancing-critical-minerals-security-and-industrial

Geldard, R. (2026, April 1). The Strait of Hormuz crisis affects more than just oil. Here are 9 other commodities. *World Economic Forum*. https://www.weforum.org/stories/2026/04/beyond-oil-lng-commodities-impacted-closure-hormuz-strait/

Hayakawa, Y. (2022). Electrical steel. In *Encyclopedia of materials: Metals and alloys*. Elsevier. https://www.sciencedirect.com/topics/materials-science/electrical-steel

Home, A. (2026, March 19). Iran war rattles global aluminium supply chain. Reuters. https://www.reuters.com/markets/commodities/iran-war-rattles-global-aluminium-supply-chain-2026-03-19/

International Energy Agency. (2021). *The role of critical minerals in clean energy transitions*. IEA Publications. https://www.iea.org/reports/the-role-of-critical-minerals-in-clean-energy-transitions

International Energy Agency. (2022). *Solar PV global supply chains*. https://www.iea.org/reports/solar-pv-global-supply-chains

International Energy Agency. (2024). *Recycling of critical minerals: Strategies to scale up recycling and urban mining*. IEA Publications. https://www.iea.org/reports/recycling-of-critical-minerals

International Energy Agency. (2025a). *Global EV outlook 2025: Expanding sales in diverse markets*. https://www.iea.org/reports/global-ev-outlook-2025

International Energy Agency. (2025b). *Global critical minerals outlook 2025*. IEA Publications. https://www.iea.org/reports/global-critical-minerals-outlook-2025

International Energy Agency. (2025c). *China's share in rare earth magnet production, 2024* [Chart]. https://www.iea.org/data-and-statistics/charts/china-s-share-in-rare-earth-magnet-production-2024

International Energy Agency. (2025d, October 23). *With new export controls on critical minerals, supply concentration risks become reality*. https://www.iea.org/commentaries/with-new-export-controls-on-critical-minerals-supply-concentration-risks-become-reality?utm_source=chatgpt.com

International Energy Agency. (2026a). Electricity 2026: Analysis and forecast to 2030. IEA Publications. https://www.iea.org/reports/electricity-2026

International Energy Agency. (2026b). *Rare earth elements*. https://www.iea.org/reports/rare-earth-elements

International Labour Organization. (2024, November 20). *ILO launches GALAB project in Democratic Republic of the Congo to address child labour in cobalt mining sector*. https://www.ilo.org/resource/news/ilo-launches-galab-project-democratic-republic-congo-address-child-labour

International Wire. (2025). Oil and gas market. Retrieved June 2, 2026, from https://internationalwire.com/markets/oil-gas-market/

Li, Z., & Du, X. (2026, February 25). Zimbabwe imposes immediate ban on exports of raw minerals, lithium concentrates. *Fastmarkets*. https://www.fastmarkets.com/insights/zimbabwe-imposes-immediate-ban-on-exports-of-raw-minerals-lithium-concentrates/

McDonald, L. (2024, August 28). *Video: The Lobito Corridor—inside the railway connecting mineral supply chains in Africa*. Ceramic Tech Today, The American Ceramic Society. https://ceramics.org/ceramic-tech-today/the-lobito-corridor/

MP Materials. (2025, July 10). MP Materials announces transformational public-private partnership with the Department of Defense to accelerate U.S. rare earth magnet independence [Press release]. MP Materials Corp. https://mpmaterials.com/news/mp-materials-announces-transformational-public-private-partnership-with-the-department-of-defense-to-accelerate-u-s-rare-earth-magnet-independence/

Natural Resources Canada. (2024). *Aluminum facts*. Government of Canada. Retrieved April 21, 2026, from https://natural-resources.canada.ca/minerals-mining/mining-data-statistics-analysis/minerals-metals-facts/aluminum-facts

Natural Resources Canada. (2025, October 31). *Roadmap to promote standards-based markets for critical minerals*. https://www.canada.ca/en/natural-resources-canada/news/2025/10/roadmap-to-promote-standards-based-markets-for-critical-minerals.html

Nickel Institute. (2021a, August 3). *Hot rocks: Geothermal and the role of nickel*. https://nickelinstitute.org/en/blog/2021年/august/hot-rocks-geothermal-and-the-role-of-nickel/

Nickel Institute. (2021b, June 22). Corrosion resistant alloys in pipelines. https://nickelinstitute.org/en/blog/2021/june/corrosion-resistant-alloys-in-pipelines/

Office of the United Nations High Commissioner for Human Rights. (2023, November 27). *Military coup has exacerbated already severe climate risks in Myanmar, UN experts warn*. https://www.ohchr.org/en/press-releases/2023/11/military-coup-has-exacerbated-already-severe-climate-risks-myanmar-un

P & D Northern Steels. (n.d.). Steel for the nuclear industry. Retrieved May 22, 2026, from https://pdnorthern.com/steel-for-the-nuclear-industry/

Progressive African Communities and Territories. (2026, February 4). Understanding the Lobito Corridor: Infrastructure, minerals and trade. AfricanPact. https://africanpact.org/2026/02/04/understanding-the-lobito-corridor/

Onstad, E & Lv, A. (2025, August 26). *Rare earth prices hit two-year peak after MP Materials stops China shipments*. Reuters. https://www.reuters.com/sustainability/climate-energy/rare-earth-prices-hit-two-year-peak-after-mp-materials-stops-china-shipments-2025-08-26/?utm_source=chatgpt.com

SAFE Center for Critical Minerals Strategy. (2025). *Resources for resources: Financing critical minerals supply chains.* Securing America's Future Energy. https://secureenergy.org/resources-for-resources-funding-critical-minerals-supply-chains/

SFA Oxford. (2026). *The platinum market and platinum price drivers*. Retrieved April 21, 2026, from https://www.sfa-oxford.com/platinum-group-metals/platinum-market-and-platinum-price-drivers/

United Nations. (2025). *State of the world's Indigenous peoples: Climate crisis*. United Nations Department of Economic and Social Affairs. https://digitallibrary.un.org/record/4083431

U.S. Department of Energy, Advanced Materials & Manufacturing Technologies Office. (2023, August). *2023 critical materials assessment*. Office of Energy Efficiency & Renewable Energy. https://www.energy.gov/eere/ammto/articles/2023-doe-critical-materials-assessment

U.S. Department of Energy, Office of Critical Minerals & Materials. (2025). *Critical minerals and materials strategic directive*. U.S. Department of Energy. https://www.energy.gov/cmm/critical-minerals-and-materials-program

U.S. Department of State, Office of the Spokesperson. (2026, February 4). *2026 critical minerals ministerial* [Press release]. U.S. Department of State. https://www.state.gov/releases/office-of-the-spokesperson/2026/02/2026-critical-minerals-ministerial

U.S. Geological Survey. (2025, November 6). *About the 2025 list of critical minerals*. U.S. Department of the Interior. https://www.usgs.gov/publications/methodology-and-technical-input-2025-us-list-critical-minerals-assessing-potential

U.S. Geological Survey. (2026). *Mineral commodity summaries 2026* (ver. 1.2). U.S. Department of the Interior. https://doi.org/10.3133/mcs2026

U.S. Government Accountability Office. (2024). *Critical minerals: Status, challenges, and policy options for recovery from nontraditional sources* (GAO-24-106395).

U.S. International Development Finance Corporation. (2025, December 17). *DFC CEO Ben Black signs loan agreement for Lobito Atlantic Railway, securing critical minerals for mutual U.S.–Africa benefit* [Press release]. DFC. https://www.dfc.gov/media/press-releases/dfc-ceo-ben-black-signs-loan-agreement-lobito-atlantic-railway-securing

U.S. International Trade Commission. (2024). *Crystalline silicon photovoltaic cells and modules from China: Investigation Nos. 701-TA-481 and 731-TA-1190, third review* (Publication No. 5546). https://www.usitc.gov/publications/701_731/pub5546.pdf

U.S. Trade and Development Agency. (2024). *USTDA advances Lobito Corridor development in Southern Africa.* https://www.ustda.gov/ustda-advances-lobito-corridor-development-in-southern-africa/

Wood Mackenzie. (2025). Power and distribution transformers supply deficit outlook [Press release]. Wood Mackenzie. https://www.woodmac.com/press-releases/power-transformers-and-distribution-transformers-will-face-supply-deficits-of-30-and-10-in-2025/