Critical Minerals Are the New Energy Security

How Mining, Geopolitics, Industrial Strategy, Technology and the Energy Transition Are Reshaping Global Supply Chains

Research Monograph and Strategic White Paper

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This monograph examines critical minerals as a system of linked geological, industrial, financial, technological, environmental, social and geopolitical dependencies. It treats mineral security as a full value-chain question rather than a contest over deposits alone. The report combines current institutional evidence, peer-reviewed research, comparative mineral data, structured scenarios and a proposed research framework for future empirical testing.

Abstract

Critical minerals now sit at the intersection of energy security, industrial competitiveness, digital infrastructure, defence capability, climate policy and development strategy. The shift does not mean minerals function like oil. Fossil fuels are consumed continuously, while most minerals are embodied in long-lived assets. Mineral disruption therefore acts mainly through the cost, timing and location of new industrial capacity, replacement equipment and manufacturing output. That distinction changes the logic of security policy.

The central finding of this monograph is that geological abundance is a weak proxy for secure supply. Security depends on the entire chain between a resource and a qualified industrial input. Exploration, financing, permitting, mine construction, water and power, beneficiation, refining, chemical conversion, specialised equipment, process knowledge, logistics, trade rules, customer qualification, social legitimacy, recycling and substitution all shape the final outcome. The International Energy Agency reports that critical-mineral demand continues to grow strongly across all scenarios. Under its 2026 Stated Policies Scenario, aggregate demand approaches twice current levels by 2040. Lithium rises more than threefold. Copper adds about seven million tonnes of demand. Refining concentration is even more consequential. Excluding rare earths, the average share held by the top refining country reached 72 percent in 2025, up from 70 percent in 2023. (International Energy Agency, 2026b, 2026f)

Trade intervention has moved from theoretical risk to observed disruption. OECD analysis finds that export restrictions on critical raw materials increased fivefold from 2009 to 2024. About 16 percent of global critical-raw-material trade faced at least one export restriction during 2022 to 2024. Exposure was far higher for cobalt, manganese, graphite and rare earths. (Organisation for Economic Co-operation and Development, 2026) The IEA reports that the number of mineral tariff codes subject to Chinese export controls tripled since 2023. Policy actions by other producers, including the Democratic Republic of the Congo, Zimbabwe and Mozambique, have also altered supply expectations. (International Energy Agency, 2026b)

This study develops three contributions. First, it synthesises current market evidence and peer-reviewed criticality research into an eight-domain Mineral Security System Framework covering geology, project execution, processing, logistics and trade, technology and knowledge, finance and markets, environmental and social legitimacy, and circularity and adaptation. Second, it presents a structured scenario architecture for 2026 to 2040 that separates demand shocks, supply shocks, policy shocks, technological change, environmental disruption and compound events. Third, it proposes a research agenda and testable propositions for universities, policy institutes, mining companies and industrial researchers.

The report does not treat a single scenario as a prediction. It treats scenarios as stress tests. It also does not assume that the fastest route to more supply is always the most resilient route. Low-cost supply, geographically diverse supply, environmentally credible supply and politically stable supply are related goals, yet they are not identical. The practical research challenge is to determine where redundancy, inventory, substitution, recycling, local processing, long-term contracts and public risk sharing produce the largest resilience gain relative to economic cost.

Keywords: critical minerals, energy security, mineral criticality, supply-chain resilience, mining, refining, geopolitics, industrial policy, export controls, copper, lithium, nickel, cobalt, graphite, rare earths, recycling, social licence, energy transition, strategic materials.

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Executive Synthesis

The global economy is becoming more mineral intensive in several strategic systems at the same time. Electrification expands the need for copper, aluminium and electrical equipment. Batteries increase demand for lithium, graphite, nickel, manganese and selected phosphates. Permanent magnets depend on neodymium, praseodymium, dysprosium and terbium. Semiconductors and optical systems draw on gallium, germanium, indium, tantalum, silicon and other specialised inputs. Aerospace and defence require high-performance alloys and minerals such as tungsten, titanium, cobalt and rare earths. Nuclear expansion adds pressure across uranium mining, conversion and enrichment. AI infrastructure and data centres add another demand layer through power systems, cooling, semiconductors and large volumes of electrical equipment. (International Energy Agency, 2026c, 2026a)

The first strategic error is to interpret this shift only as a mining problem. The second is to interpret it only as a demand problem. Mineral security is a systems problem. A deposit has no strategic value until it becomes economic, permitted, financed, built, processed, transported and accepted by a qualified customer. A refinery without feedstock is insecure. A mine without power, water or export infrastructure is insecure. A diversified mine portfolio with a single-country refining bottleneck is insecure. A technically sound project without durable community legitimacy is also insecure. Recent academic work increasingly supports a multidimensional approach to criticality and resilience rather than a single concentration metric. (Arya et al., 2026; Mammadli et al., 2026; Schicho & Tercero Espinoza, 2026)

The third error is to treat concentration as a static map. Concentration is dynamic. It changes when technology changes, when a government introduces export controls, when prices collapse and investment stops, when a refinery reaches commercial qualification, when conflict closes a maritime route, or when recycling volumes increase. The IEA's 2026 evidence shows that concentration in refining continued to rise for most minerals in 2025, while rare earths provided a limited example of diversification through new United States projects and higher Malaysian output. (International Energy Agency, 2026b)

The fourth error is to equate self-sufficiency with resilience. Few industrial economies possess every relevant mineral, processing technology and manufacturing capability. Autarky would impose high economic costs and still leave technology, equipment or chemical dependencies unresolved. A more useful concept is portfolio resilience. The portfolio includes multiple supply jurisdictions, multiple processors, long-term contracts, strategic inventories, recycling, material substitution, product redesign, transparent data and contingency arrangements. The precise mix differs by mineral because copper, lithium, graphite, gallium and uranium do not share the same market structure.

The fifth error is to assume that resource-rich countries will automatically capture more value from the transition. Local processing creates economic opportunity only where power, infrastructure, capital, technology, market access, skills and governance support competitive production. Indonesia's nickel strategy shows how export restrictions and downstream investment reshape production patterns, while World Bank analysis also highlights the need for stronger domestic linkages if downstreaming is to generate broad productivity and employment gains. (World Bank, 2026; World Trade Organization, 2022) Latin America provides a different example. The IEA estimates that the region refines only about one-fifth of the key energy minerals it mines, excluding lithium, despite its large resource base. (International Energy Agency, 2026d)

The sixth error is to treat ESG as a reputational overlay. Environmental and social conditions alter project schedules, costs and continuity. Water stress, biodiversity loss, land conflict, tailings risk, labour conditions, Indigenous rights and weak benefit sharing affect security of supply because they affect whether projects operate. Peer-reviewed research documents substantial biodiversity, water, labour and social-conflict exposure in mineral supply chains. (Aska et al., 2025; 'Assessing the Social and Environmental Impacts of Critical Mineral Supply Chains for the Energy Transition in Europe', 2024; 'Critical Mineral Mining in the Energy Transition', 2024; Sefa-Nyarko, 2026)

The seventh error is to treat recycling as an immediate substitute for mining. Secondary supply is strategically important, yet timing matters. End-of-life material volumes lag the first major deployment wave. The IEA estimates average recycling rates across key energy minerals might rise from around 10 percent today to close to 20 percent by 2040 under current policy settings. Battery recycling capacity itself is concentrated, with China accounting for more than three-quarters of global pretreatment capacity and 90 percent of material-recovery capacity. (International Energy Agency, 2026b) Recycling improves resilience only where collection, processing, qualification and market demand for recovered material also exist.

The eighth error is to assume that substitution eliminates risk. Technology changes usually shift risk from one material set to another. The growth of lithium iron phosphate batteries reduces cobalt and nickel intensity while increasing the importance of lithium, graphite, phosphate processing and LFP manufacturing capability. Sodium-ion batteries reduce exposure to lithium, yet introduce dependence on hard carbon and a still concentrated manufacturing base. (International Energy Agency, 2026a) Substitution therefore belongs inside portfolio analysis rather than outside it.

The ninth error is to ignore price-cycle dynamics. Mineral markets repeatedly move between shortage fears and oversupply. Low prices improve affordability for downstream users, while simultaneously weakening the investment pipeline required years later. The IEA reports that critical-mineral investment declined 9 percent in 2025. Battery-metal capital spending fell by more than 20 percent and lithium-company spending fell around 40 percent, even as long-term demand remained strong. Public-finance commitments in advanced economies rose to about USD 65 billion in 2025, though the IEA notes a gap between commitments and disbursement. (International Energy Agency, 2026b)

The tenth error is to overlook small markets with large economic leverage. Gallium, germanium, tungsten, antimony and magnet rare earths represent smaller tonnage and market value than copper, yet their strategic importance is high because substitution is difficult in selected uses and processing is concentrated. USGS analysis of China's 2023 mineral industry found that China produced 74 of 77 tracked mineral commodities, ranked first globally for 39, and supplied as much as 98 percent of world gallium production in the dataset. (Chung et al., 2026) The IEA estimates that full implementation of expanded rare-earth controls could place USD 6.5 trillion of annual downstream production outside China at risk. (International Energy Agency, 2026b)

The central thesis of this monograph is therefore narrower and stronger than the phrase "minerals are the new oil". Critical minerals are becoming strategic industrial infrastructure. Their security depends less on owning the largest deposit than on maintaining a resilient system that converts resources into dependable industrial function.

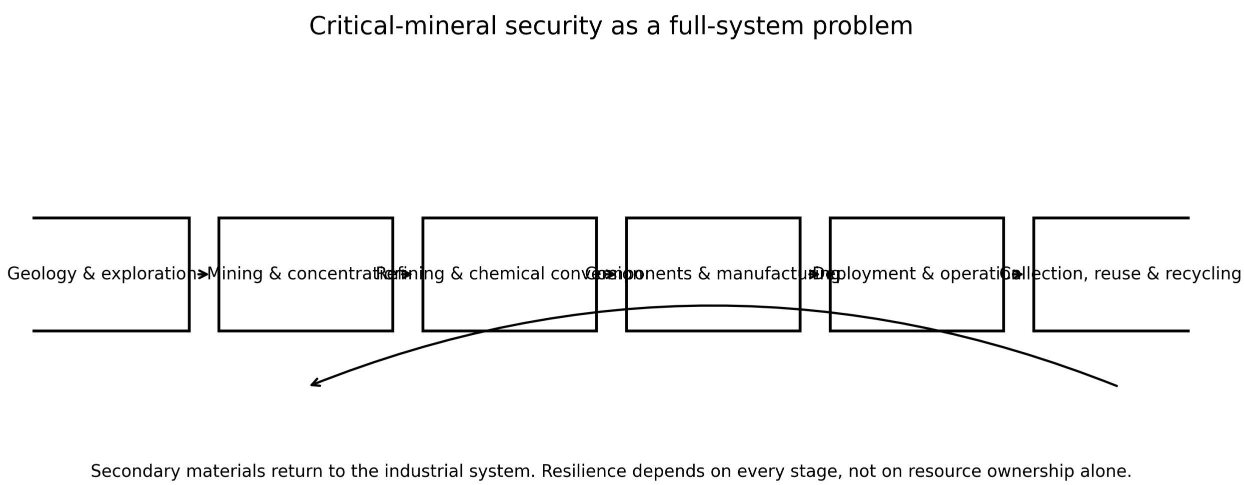

Figure 1: Critical-mineral security spans the full chain from geology to recycling.

Part I. Research Foundations

Chapter 1

Introduction

1.1 The research problem

Critical-mineral security has moved from a specialist topic in mining economics into a cross-disciplinary question spanning energy systems, industrial organisation, international trade, economic geography, environmental science, political economy and corporate risk. This change reflects three simultaneous developments. Demand is rising. Supply chains are concentrated. Governments increasingly treat selected minerals as strategic inputs rather than ordinary commodities. (International Energy Agency, 2026c; Organisation for Economic Co-operation and Development, 2026; UN Trade and Development, 2026)

A rigorous study therefore needs to answer a more difficult question than "Will there be enough minerals?" The relevant question is: under what technical, economic, political, social and environmental conditions will mineral resources become reliable industrial supply at acceptable cost and acceptable risk?

That question has no universal answer. Criticality is perspective-dependent. The United States, European Union and other jurisdictions publish different lists because their economic structures, industrial dependencies, domestic resources, strategic priorities and methodologies differ. The United States final 2025 list contains 60 minerals. The European Union distinguishes between critical and strategic raw materials and sets specific 2030 benchmarks for extraction, processing and recycling. (European Commission, 2024; U.S. Geological Survey, 2025) Academic reviews also show that criticality assessment changes with the actor, system boundary and purpose of analysis. (Mammadli et al., 2026; Schicho & Tercero Espinoza, 2026)

This report therefore uses the term "critical mineral" as a contextual category. A mineral becomes critical when high economic or strategic importance combines with meaningful exposure to disruption and limited short-run adaptation. The exposure might arise from geological concentration, refining concentration, trade restrictions, weak substitution, long project lead times, by-product dependence, social conflict, environmental constraints, infrastructure deficits, market opacity or technology concentration.

1.2 Why the oil analogy is incomplete

The phrase "critical minerals are the new oil" is rhetorically effective but analytically weak if taken literally. Oil is a continuously consumed fuel. A supply interruption quickly affects transport, industry and power systems because existing assets require a constant flow of fuel. Most critical minerals are embodied in equipment. Once copper is installed in a grid or rare-earth magnets are installed in a motor, the equipment keeps operating during a new-supply interruption.

Mineral disruption therefore acts through a different channel. It constrains new manufacturing, replacement equipment, inventory, project economics and the speed of capacity expansion. The distinction matters for emergency policy. Oil security places heavy weight on immediate fuel stocks and demand restraint. Mineral security places greater weight on strategic inventories for selected materials, diversified processing, alternative product designs, recycling, substitution, qualification of alternate suppliers and project pipelines. IRENA has emphasised the difference between fossil-fuel dependency and mineral dependency. (International Renewable Energy Agency, 2023)

The analogy also breaks down because "critical minerals" represent dozens of markets with different chemistries and industrial structures. Copper is a large and mature commodity market. Gallium is a small by-product market. Lithium has several deposit types and conversion routes. Graphite includes natural and synthetic material. Rare earths involve multiple elements and technically demanding separation and magnet manufacturing. Uranium security extends beyond mining into conversion, enrichment and fuel fabrication. Treating these as one commodity class obscures the mechanisms that matter.

1.3 Research objectives

This monograph has six objectives.

1. Establish a defensible conceptual definition of mineral security that extends beyond resource ownership.
2. Compare the demand, supply, processing and risk structures of the principal mineral systems relevant to energy, digital infrastructure, advanced manufacturing and defence.
3. Examine how trade restrictions, producer-country policy, industrial strategy and alliances are changing supply-chain geography.
4. Integrate environmental, social and climate risks into supply-security analysis rather than treating them as separate disclosure topics.
5. Develop a structured scenario architecture for 2026 to 2040 that allows institutions to stress-test exposure without presenting one forecast as inevitable.
6. Define a research agenda that supports future quantitative work by universities, scientific institutions, governments and industry.

1.4 Research questions

The report is organised around twelve research questions.

RQ1. Which stages of the mineral value chain create the greatest concentration risk: mining, refining, chemical conversion, component manufacturing or equipment supply?

RQ2. How does criticality differ when assessed from the perspective of a producer economy, processor economy, manufacturing economy or import-dependent economy?

RQ3. How do project lead times and commodity-price cycles interact to create delayed shortages?

RQ4. Which minerals pose the greatest risk because they combine concentration, limited substitution and high downstream economic leverage?

RQ5. How do export controls and resource-nationalist policies alter global investment, prices and industrial geography?

RQ6. Under what conditions does domestic processing create durable value for mineral-rich economies?

RQ7. How large a contribution is recycling likely to make before 2040, and where does recycling itself introduce new concentration risk?

RQ8. Does technology substitution reduce system risk or shift the point of dependency?

RQ9. How do water stress, biodiversity, climate hazards and social legitimacy alter the effective supply curve?

RQ10. Which policy instruments create resilience at the lowest economic cost, and which merely move risk between jurisdictions or stages?

RQ11. Which early-warning indicators provide useful lead time before a mineral disruption becomes an industrial disruption?

RQ12. What research gaps prevent reliable comparison across minerals and countries?

Chapter 2

Literature, Concepts and Criticality Theory

2.1 Criticality as a relational concept

Criticality is not an intrinsic geological property. Copper does not possess a fixed criticality score independent of the system that uses it. A material's criticality depends on the function it performs, the availability of substitutes, the concentration and governance of supply, the time available to adapt, inventories, market size, price elasticity, trade relationships, processing capability and the economic damage caused by disruption.

Schicho and Tercero Espinoza show that criticality methodologies have developed from different actor perspectives and system boundaries. Supply risk is central across most frameworks, while the measurement of economic importance and consequences differs materially. (Schicho & Tercero Espinoza, 2026) Mammadli and co-authors identify 49 key impact factors across economic, market, technical, sociopolitical, geopolitical and environmental categories. Their work also links criticality to multiple stages of the mineral life cycle rather than to extraction alone. (Mammadli et al., 2026)

Earlier USGS work provides an important foundation. McCullough and Nassar developed an early-warning methodology using supply risk, production growth and market dynamics. (McCullough & Nassar, 2017) The strength of such methods is comparability. Their limitation is compression. A single score risks hiding whether a material is vulnerable because of mine concentration, refinery concentration, by-product dependence, trade restrictions, water stress or qualification barriers. For strategy, the mechanism matters as much as the score.

2.2 Concentration metrics and their limits

The most common concentration measures are the concentration ratio and the Herfindahl-Hirschman Index. A top-three concentration ratio reports the share held by the three largest suppliers. The HHI sums the squares of supplier shares, placing greater weight on dominant suppliers. Governance-adjusted versions multiply country concentration by political or governance indicators.

These measures remain useful, yet they do not capture the complete system. A market might appear diversified at the mining stage while almost all refining occurs in one country. A market with several suppliers might still depend on a single specialised equipment vendor. A low-concentration market might also face high substitution barriers and long qualification times.

The report therefore treats concentration as one family of indicators within a larger system model.

2.3 Resilience, robustness and adaptability

Three concepts require separation.

Robustness is the capacity to continue operating through a shock without major reconfiguration. Strategic inventories provide robustness.

Resilience is the capacity to absorb disruption and restore function within an acceptable period. Multiple qualified suppliers and flexible logistics support resilience.

Adaptability is the capacity to change technology, material intensity, product design or business architecture when the previous system becomes structurally unattractive. Battery chemistry change is an example.

A secure system needs all three. A stockpile without alternate supply routes buys time but does not solve structural dependency. Diversified mining without alternate refining routes also provides limited protection. A substitute material that requires years of redesign and certification offers long-run adaptability but weak short-run resilience.

Recent resilience literature argues for more integrated risk assessments across upstream and downstream stages. A 2025 systematic review found upstream disruptions dominate existing research while downstream gaps remain. ('A Systematic Review of Resilience in the Critical Minerals Supply Chains Needed for the Low-Carbon Energy Transition', 2025) Arya, Ellefmo and Aasly similarly propose a multi-pillar approach that varies according to whether an economy is primarily a producer, processor or importer. (Arya et al., 2026)

Chapter 3

Methodology and Evidence Discipline

3.1 Evidence hierarchy

The report uses a three-tier evidence hierarchy.

Tier 1: official statistical and policy sources. These include the IEA, USGS, OECD, UN Trade and Development, World Bank, IMF, European Commission, United Nations, WTO and official government policy documents. Tier 1 sources provide the main basis for numerical claims and descriptions of current policy.

Tier 2: peer-reviewed scientific literature. Peer-reviewed work informs criticality theory, environmental and social risk, resource nationalism, recycling, supply-chain resilience and methodological limits.

Tier 3: company, industry and market evidence. This category is used sparingly for context where official or peer-reviewed sources do not capture emerging operating conditions. The final report avoids relying on unsupported market commentary for central quantitative claims.

3.2 Cut-off date and temporal discipline

The evidence cut-off is 17 September 2026. Current-state statements refer to evidence available by that date. Forward-looking values are identified as projections, scenarios, announced-project pipelines or analytical cases. This distinction is essential because a projected 2035 shortfall is not the same as a current physical shortage.

The report also distinguishes among resources, reserves, production, production capacity and announced projects. A geological resource is not equivalent to a commercially recoverable reserve. A reserve is not equivalent to operating capacity. Announced capacity is not equivalent to commissioned capacity. Each transition involves technical, financial, regulatory and market risk.

3.3 Quantitative comparability

Mineral data differ by unit, product form and stage. Lithium might be reported as metal content or lithium carbonate equivalent. Graphite supply might refer to natural flake graphite, synthetic graphite or battery-grade spherical material. Rare-earth analysis might refer to total rare-earth oxide or only magnet rare earths. Nickel markets distinguish Class 1, nickel sulphate, ferronickel, nickel pig iron and intermediate products. This report keeps source definitions visible and avoids merging incompatible measures.

3.4 Scenario method

The scenario analysis uses six independent axes:

1. Demand intensity.
2. Project delivery and supply expansion.
3. Trade openness or fragmentation.
4. Technology and substitution.
5. Circularity and secondary supply.
6. Environmental, social and physical disruption.

A scenario is a coherent combination of assumptions across those axes. The analysis does not assign probabilities. Probability ranking would create false precision because the relevant political, technological and project variables are deeply uncertain. The value of the method lies in identifying failure mechanisms, transmission channels and response options.

3.5 Proposed analytical framework

This study proposes an eight-domain **Mineral Security System Framework**, abbreviated MSSF. It is intended as a research structure rather than a validated index.

Domain	Core question	Example indicators
Geological security	Is sufficient ore or feedstock technically available?	resources, reserves, grade, depletion, by-product dependence
Project execution	Will projects reach production on schedule and budget?	lead time, permitting, capex, infrastructure, workforce
Processing security	Is refining and conversion capacity diversified and qualified?	top supplier share, HHI, utilisation, technology barriers
Logistics and trade	Does material move reliably across borders and routes?	export restrictions, shipping routes, border risk, inventories
Technology and knowledge	Are process know-how, equipment and intellectual property diversified?	equipment vendors, patents, skilled labour, qualification time
Finance and markets	Does the market support investment through the cycle?	prices, volatility, financing cost, offtake quality, public support
Environmental and social legitimacy	Is production durable under ecological and societal constraints?	water stress, biodiversity, labour risk, FPIC, conflict, tailings

Domain	Core question	Example indicators
Circularity and adaptation	How quickly does the system reduce primary dependence?	recycling, reuse, substitution, material efficiency, product redesign

A later chapter develops a proposed geometric-mean formulation for future empirical testing. The geometric form reflects the idea that severe weakness in one domain might dominate total system performance. No scores in this edition are presented as validated measurements.

3.6 Research propositions

The analysis advances twelve propositions for future testing.

P1. Midstream concentration predicts industrial disruption better than mine concentration for minerals requiring complex refining or separation.

P2. Price declines raise medium-term security risk when project lead times exceed the investment cycle.

P3. Export controls have larger downstream effects in small markets with low substitutability than in large markets with liquid inventories.

P4. Diversification of mining without diversification of refining yields limited resilience gains.

P5. Social conflict is an endogenous supply variable rather than an external ESG variable.

P6. High-quality infrastructure and low-cost power are stronger predictors of successful producer-country value addition than mineral endowment alone.

P7. Recycling meaningfully reduces primary demand only after sufficient end-of-life stock becomes available and collection rates rise.

P8. Technology substitution changes the composition of mineral risk more often than it removes mineral risk.

P9. Strategic stockpiles deliver the highest resilience value for low-volume, high-leverage materials with long qualification times.

P10. Public finance generates stronger diversification where it addresses a bankability gap rather than supporting structurally uncompetitive operating costs indefinitely.

P11. Transparent traceability lowers some supply risks only when data are comparable, verified and connected to procurement decisions.

**P12. The most resilient systems combine redundancy, adaptability and social legitimacy rather than maximising any single dimension.

Part II. Demand, Supply and the Architecture of Dependence

Chapter 4

From Energy Security to Industrial-System Security

4.1 A broader security concept

Traditional energy-security analysis asks whether an economy has reliable, affordable access to fuels and electricity. Mineral security widens the question. Electricity, digital infrastructure, transport electrification and advanced manufacturing all depend on physical equipment. Equipment depends on metals, chemicals, magnets, semiconductors and engineered materials. Those materials depend on supply chains that begin with geology but extend through many transformation stages.

The transition therefore changes the location of vulnerability. In a fossil-heavy system, vulnerability often sits in fuel supply, import routes and storage. In an electrified system, more vulnerability shifts into the capital stock and the supply chains that manufacture it. This does not remove fuel-security concerns. It adds a materials layer to them.

The IEA now treats critical minerals as relevant not only to clean energy but also to high-tech manufacturing, AI and digital systems, aerospace and defence. (International Energy Agency, 2026c) This wider framing matters because demand growth from one sector might persist even when another slows. A weaker electric-vehicle market, for example, would reduce one source of battery demand, yet electricity grids, storage, data centres, electronics and defence procurement might keep pressure on selected minerals.

4.2 Four forms of dependency

Mineral dependency has at least four forms.

Volume dependency arises when an economy requires large physical quantities. Copper is the clearest example because grids, motors, transformers, buildings and industrial equipment use it at scale.

Chokepoint dependency arises when small material volumes support high-value systems. Gallium, germanium and selected rare earths fit this pattern.

Capability dependency arises when the constraint is not ore but technical know-how, specialised equipment, patents, chemical conversion or quality control. Graphite purification and rare-earth magnet manufacturing illustrate this form.

Temporal dependency arises when substitution or new project development requires years. A material might have several theoretical alternatives but remain critical in the short run because redesign, testing and customer qualification take time.

These forms often overlap. A robust strategy therefore starts by identifying the type of dependency before selecting a response.

Chapter 5

Demand: Six Engines of Mineral Intensity

5.1 Electrification and electricity networks

Copper carries the largest absolute volume growth among the major energy minerals. The IEA's 2026 Outlook projects about seven million tonnes of additional copper demand to 2040 under stated policies. (International Energy Agency, 2026f) The source is not one technology. Electricity networks, renewable generation, transport electrification, industrial motors, buildings and new digital infrastructure all add demand.

Grid investment deserves special attention because transmission and distribution systems involve long-lived public or regulated assets. Unlike some consumer technologies, grid expansion is difficult to postpone indefinitely without affecting system reliability, new generation connections and industrial development. Copper and aluminium substitution is possible in some applications, yet conductor choice depends on weight, conductivity, corrosion, connection technology and system design.

The 2025 IEA mineral tables provide a useful benchmark for scale. Under the Stated Policies Scenario, total copper demand rises from 26.7 million tonnes in 2024 to 34.1 million tonnes in 2040. Secondary supply and reuse increase from 4.4 million tonnes to 8.7 million tonnes over the same period. (International Energy Agency, 2025b) The 2026 update still identifies copper as the largest volume-growth challenge and projects a 25 percent gap between base-case project supply and 2035 primary requirements. (International Energy Agency, 2026f)

5.2 Batteries and electrochemical storage

Battery demand grew by more than 35 percent in 2025 and exceeded 1.5 TWh, according to the IEA. (International Energy Agency, 2026e) This growth affects several mineral systems simultaneously, but chemistry choice changes the mix.

Lithium remains central to mainstream lithium-ion chemistries. Graphite dominates current anode materials. Nickel and cobalt remain relevant to high-nickel chemistries. Manganese appears across several cathode families. Phosphate becomes more strategically relevant as LFP gains share. The battery system therefore demonstrates why mineral risk must be technology-specific.

The shift toward LFP batteries reduces nickel and cobalt intensity but does not create a mineral-free pathway. The IEA reports that LFP batteries now account for a major share of the EV market and that LFP supply chains are more geographically concentrated than many nickel-based battery chains. (International Energy Agency, 2026a) Sodium-ion batteries create another route. They avoid lithium in the cell chemistry, yet current hard-carbon anode supply and battery manufacturing remain concentrated. Their lower energy density also limits some vehicle applications.

5.3 Permanent magnets and high-performance motors

Neodymium, praseodymium, dysprosium and terbium support permanent magnets used in wind turbines, electric motors, industrial automation, robotics and other systems. The strategic challenge lies less in raw tonnage than in separation, metal making, alloying, magnet production and process knowledge.

The IEA's 2025 benchmark placed the top three refining countries at 97 percent of magnet rare-earth supply in 2024. (International Energy Agency, 2025g) The 2026 Outlook reports some reduction in concentration through new United States projects and higher Malaysian production, yet refining remains highly concentrated. (International Energy Agency, 2026b) This provides an important policy lesson. Diversification is possible, but it requires coordinated investment across more than the mine.

5.4 Digital systems, AI and semiconductors

Digitalisation increases demand through two channels. The first is infrastructure. Data centres require power, backup systems, cooling equipment, servers, networking and electrical hardware. The second is semiconductor and electronics manufacturing. Gallium, germanium, indium, tantalum, silicon, copper and selected rare earths support different functions in these systems.

The economic leverage is large because some of these materials occupy a tiny share of final product value. The IEA's 2026 analysis identifies gallium, magnet rare earths, yttrium, graphite, tungsten, tellurium, cobalt and germanium among materials with high vulnerability scores due to supply concentration, limited substitutes and strategic use. (International Energy Agency, 2026b) These are classic chokepoint materials. Their disruption risk is not visible from market size alone.

5.5 Aerospace and defence

Aerospace and defence introduce a different form of demand. Material specifications are stringent. Qualification cycles are long. Substitution is often difficult because performance, temperature resistance, strength-to-weight ratios, radiation resistance or magnetic characteristics are central to safety and mission requirements.

This changes the meaning of inventory. A large industrial user might tolerate a delay in consumer-electronics production. A defence or aerospace system with an unqualified substitute faces a much narrower set of options. Strategic inventories and dual sourcing have greater value where qualification times exceed the duration of a plausible disruption.

5.6 Nuclear power and the fuel cycle

Nuclear supply security extends beyond uranium ore. The IEA's 2026 assessment states that the top three countries account for almost three-quarters of uranium mining and around 70 percent of conversion and enrichment capacity. (International Energy Agency, 2026b) Conversion and enrichment therefore represent midstream stages with their own concentration and investment challenges.

The nuclear example reinforces the central thesis. Owning uranium resources does not equal fuel-cycle independence. Conversion, enrichment, fuel fabrication, reactor-specific qualification and regulatory approval all matter. Next-generation reactors also introduce demand for higher-assay fuels in selected designs, adding a technology-specific supply question.

5.7 Demand is not one curve

A global mineral-demand forecast aggregates diverse end uses and assumptions. For research and corporate planning, the aggregate should be decomposed into at least five dimensions:

1. application sector,
2. technology pathway,
3. regional deployment,
4. material intensity per unit,
5. substitution and recycling.

Demand uncertainty therefore does not invalidate planning. It changes the appropriate planning method. Instead of relying on one forecast, institutions should analyse ranges and identify which assets remain strategically relevant across multiple pathways.

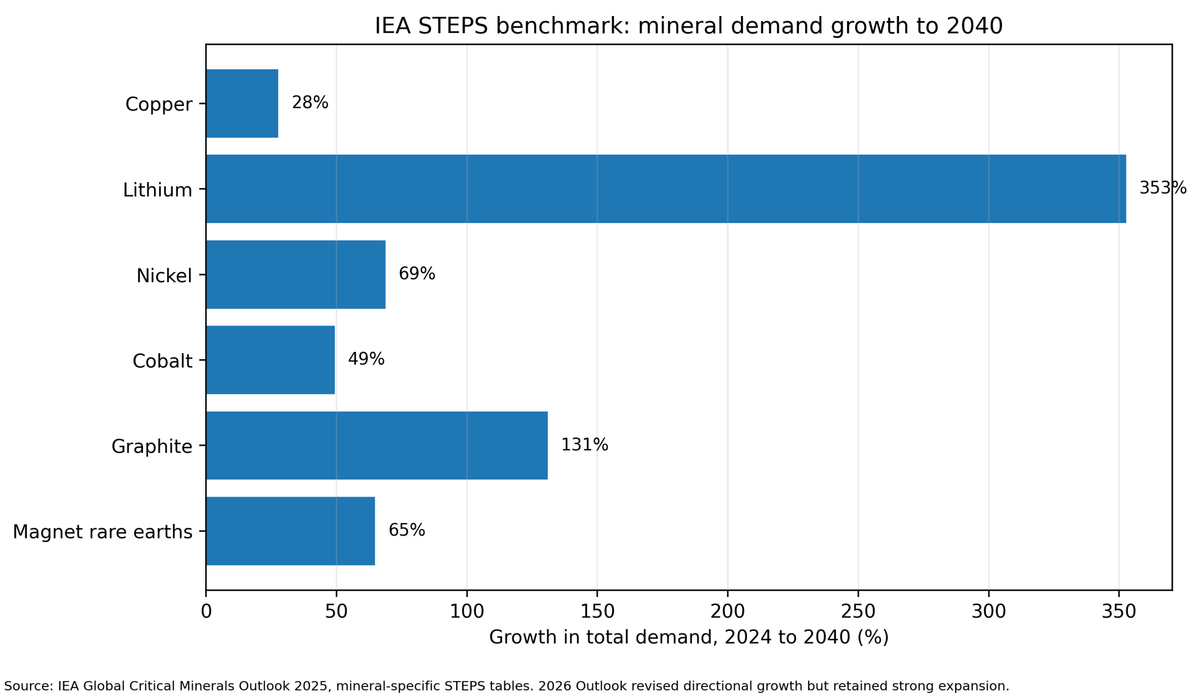

Figure 5.1: Illustrative demand growth benchmark from the IEA 2025 STEPS mineral tables.

Chapter 6

Geology, Resources, Reserves and the Supply Illusion

6.1 Resource abundance is not immediate availability

Public debate often uses “reserves” and “resources” interchangeably. They are not equivalent. A mineral resource represents a concentration with reasonable prospects for eventual economic extraction under a defined reporting framework. A reserve is the economically mineable part of a measured or indicated resource after modifying factors such as mining method, metallurgy, infrastructure, environmental conditions, legal status and economics are considered.

Even reserves are not production. Production requires capital, construction, labour, equipment, permits, power, water, roads, ports and a functioning processing route. The conversion from geological potential to industrial output therefore contains several filters.

This distinction becomes important when governments compare national resource endowments. A country might hold large resources but still import refined material for decades. Another country with limited domestic ore might control a major share of processing, component manufacturing and technology. Security analysis must therefore track control over functions rather than ownership of geology alone.

6.2 Ore grade and mineralogy matter

Two deposits containing the same metal can have different economics and environmental footprints. Ore grade determines how much rock must be moved and processed per unit of product. Mineralogy affects recovery, reagent use, tailings characteristics and processing complexity. Depth affects stripping, ventilation, energy and capital requirements. Impurities affect smelter penalties, product quality and downstream qualification.

Copper provides a useful example because declining ore grades and rising project complexity contribute to the long-term supply challenge identified by the IEA. (International Energy Agency, 2025c) The practical implication is that reserve tonnage alone does not predict future production cost or speed.

6.3 By-product dependence

Some strategic minerals are produced primarily as co-products or by-products of larger metal systems. Gallium is recovered largely from bauxite and zinc-related streams. Germanium is associated with zinc and some coal deposits. Tellurium is often recovered from copper refining. This creates a supply-response problem.

If the price of a by-product rises sharply, production does not always expand quickly because the host-metal market determines the scale of ore extraction. The bottleneck might instead be recovery technology, refinery configuration or economic incentives at the processing stage. By-product dependence therefore weakens the normal price-supply relationship.

The IEA highlights the strategic role of base-metal smelters because copper, zinc and lead processing facilities also recover several minor minerals. (International Energy Agency, 2026b) This makes smelter geography relevant to materials that do not appear in a conventional copper or zinc security assessment.

6.4 Discovery risk

Exploration has a long and uncertain pathway. Most targets do not become mines. Discovery quality matters as much as exploration spending. A period of low prices often reduces exploration budgets, while the consequences appear years later.

The IEA reports that exploration spending fell by more than 10 percent in 2025, with especially large declines in lithium and nickel exploration. (International Energy Agency, 2026b) This decline does not create an immediate shortage. It weakens the option set available in the 2030s.

Chapter 7

Project Development, Permitting and the Time Dimension

7.1 Long lead times create structural inertia

Mineral supply responds slowly because project development spans exploration, studies, engineering, approvals, financing, construction, commissioning and ramp-up. Historical IEA analysis found that major mines often require more than sixteen years from discovery to first production. The precise duration varies by mineral, deposit type and jurisdiction, yet the strategic point is stable. Demand, prices and policy move faster than mines. (International Energy Agency, 2023)

This time asymmetry creates one of the most important mechanisms in mineral security. A shortage becomes visible. Prices rise. Investment increases. New supply still takes years. When new projects eventually arrive, demand might have changed or multiple projects might enter together, creating oversupply. Prices then fall and new investment slows. The next shortage is partly created by the response to the previous one.

7.2 Permitting quality versus permitting speed

Debate often frames permitting as a choice between speed and environmental protection. The more useful question is whether approval systems are predictable, evidence-based, adequately staffed and capable of resolving conflicts early.

A fast initial approval followed by litigation, community opposition or redesign is not necessarily faster in total. A slow and opaque system also raises financing costs and reduces investment. Research should therefore measure total project-development time, variance in approval time, frequency of legal challenge, quality of baseline data and post-approval compliance rather than headline statutory timelines alone.

7.3 Infrastructure as a hidden lead time

Mine projects frequently depend on infrastructure outside the mine boundary. Roads, ports, transmission lines, generation, water systems, housing, communications and reagent supply all affect schedule and cost. Remote projects face higher risk because infrastructure development might require public-sector coordination or shared-use arrangements.

Infrastructure also shapes producer-country value addition. Refining often needs reliable power, chemicals, water, waste management and industrial logistics. A government might seek domestic processing but find that electricity cost or grid reliability makes the facility uncompetitive. Industrial strategy therefore needs to analyse the enabling system rather than only the mineral deposit.

7.4 Workforce and technical capability

Highly specialised processing sectors require metallurgists, chemical engineers, process-control specialists, maintenance teams, laboratory capability and commercial qualification expertise. The IEA's 2026 work emphasises that technology, equipment and workforce are part of diversification. (International Energy Agency, 2026b)

This creates a slow-moving form of dependency. Capital can finance a plant faster than an industrial ecosystem can accumulate experience. Training, operational learning, supplier networks and maintenance capability become part of security.

Chapter 8

The Midstream Bottleneck

8.1 Why processing often matters more than extraction

Processing and refining transform ore or concentrates into usable industrial products. For many critical minerals, this stage is more geographically concentrated than mining. The 2024 IEA data for six major energy minerals show top-three refining-country shares from 59 percent for copper to 99 percent for graphite, while mining concentration is lower for most of the same materials. (International Energy Agency, 2025b, 2025e, 2025f, 2025a, 2025d, 2025g)

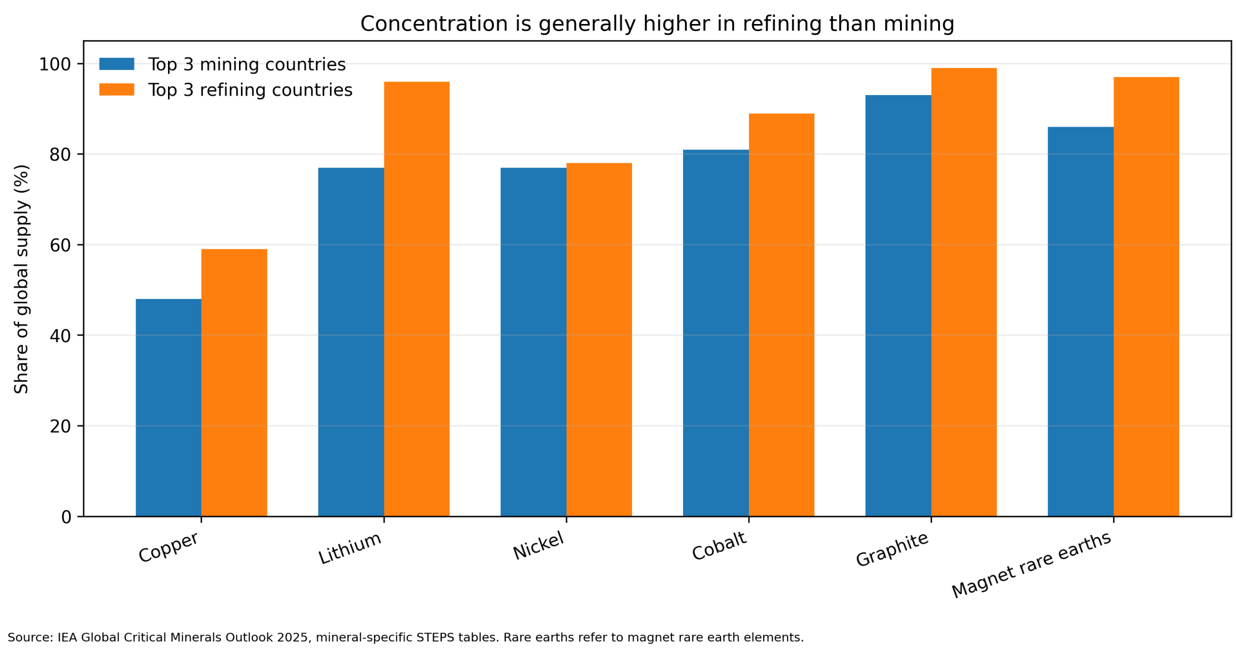

Figure 8.1: Mining and refining concentration for six major mineral systems in 2024.

The 2026 update shows further concentration. Excluding rare earths, the average share held by the top refining country rose to 72 percent in 2025. (International Energy Agency, 2026b) In manganese, nickel and graphite, almost all recent refined-supply growth came from the dominant supplier. (International Energy Agency, 2026e)

8.2 Processing is a technology system

A refinery is not only a building. It combines process flowsheets, reagent chemistry, equipment, control systems, maintenance knowledge, waste handling, quality assurance and customer relationships. Commercial success often depends on years of incremental learning.

The IEA reports notable equipment and knowledge concentration outside dominant suppliers. Battery-grade graphite processing equipment has few suppliers outside China. Ultra-high-purity gallium refining and compound-semiconductor manufacturing rely on a small number of specialised vendors. Rare-earth magnet production involves patented technologies and specialised equipment with large cost and lead-time differences across regions. (International Energy Agency, 2026b)

This suggests a research distinction between **capacity concentration** and **capability concentration**. Capacity measures installed tonnes. Capability measures the ecosystem required to operate competitively and meet customer specifications. The second is harder to quantify but often more durable.

8.3 Smelters as multi-mineral hubs

Base-metal smelters matter beyond their headline commodity. Copper, zinc and lead smelters recover or enable recovery of multiple strategic by-products and provide routes for recycled material. The IEA notes that China accounted for more than 90 percent of global copper-smelting growth since 2005, increasing its share of global capacity from about 15 percent to 50 percent by 2025. (International Energy Agency, 2026b)

This concentration matters because a decline in smelting capability outside the dominant region affects copper security and the recovery of associated minor elements. It also affects recycling, since modern smelters are important sinks for complex secondary feedstocks.

8.4 Product qualification as a barrier

A new supplier does not become a substitute the day production begins. Battery chemicals, semiconductor inputs, aerospace alloys and magnet materials require customer testing and qualification. Variations in impurity profile, particle size, morphology, magnetic performance or electrochemical behaviour might affect final product performance.

Qualification time should therefore be treated as a security variable. The relevant question is not only whether alternate production exists. It is whether alternate production is already qualified at meaningful scale.

Chapter 9

Logistics, Chemicals and Hidden Chokepoints

9.1 Mineral supply chains depend on non-mineral inputs

Mining and refining need reagents, fuel, electricity, water, explosives and consumables. A disruption in an apparently unrelated commodity therefore transmits into mineral output.

The IEA's 2026 analysis provides a useful example. Sulphur is a feedstock for sulphuric acid, which is widely used in mineral processing and fertiliser production. The Middle East supplies around one-quarter of global sulphur and a large share of seaborne trade passes through the Strait of Hormuz. Disruption in 2026 affected sulphur and acid markets, raising production costs for several mineral processes. (International Energy Agency, 2026b)

This example expands the concept of criticality. A mineral might have diversified mines but remain exposed to a concentrated chemical input. Future research should therefore model key reagents and utilities as part of the mineral network.

9.2 Maritime routes and ports

Bulk minerals and concentrates move through ports that might serve multiple commodities. Port congestion, conflict, sanctions, weather or infrastructure failure create correlated risk across minerals. The same is true for rail corridors connecting landlocked producers to export terminals.

Supply-chain maps should therefore include transport nodes and route alternatives. A country-level concentration metric misses the possibility that several nominally independent suppliers use the same chokepoint.

9.3 Inventory and stockpiles

Inventory converts time into resilience. It does not create new supply, but it gives manufacturers time to qualify alternatives, change production schedules or negotiate new routes.

The economic case differs by mineral. Stockpiling copper at scale is expensive because of volume and working capital. Stockpiling small quantities of high-leverage strategic materials might be comparatively cheap. The IEA estimates that the net annual cost of stockpiling eleven high-risk materials for countries outside the dominant supplier is below USD 900 million. (International Energy Agency, 2026b)

This figure does not mean stockpiling is always the preferred response. Storage conditions, obsolescence, quality degradation, market distortion and release rules matter. It does show why inventory analysis should be mineral-specific rather than ideological.

Part III. Comparative Mineral Systems

Chapter 10

Comparative Mineral Baseline

10.1 Six major energy-mineral systems

A comparative view reveals why a single criticality score is insufficient. The six mineral systems below differ sharply in market size, demand growth, concentration, recycling potential, price formation and downstream use. The figures are drawn from the IEA's 2025 mineral-specific tables and represent the Stated Policies Scenario for demand. They are used here as a consistent benchmark rather than as a prediction. (International Energy Agency, 2025b, 2025e, 2025f, 2025a, 2025d, 2025g)

Mineral system	2024 demand	2040 demand	Approx. growth	Top-three share, mining / refining
Copper	26,717 kt	34,137 kt	28%	48% / 59%
Lithium	205 kt Li	928 kt Li	353%	77% / 96%
Nickel	3,371 kt	5,689 kt	69%	77% / 78%
Cobalt	221 kt	330 kt	49%	81% / 89%
Graphite	4,766 kt	11,010 kt	131%	93% / 99%
Magnet rare earths	91 kt	150 kt	65%	86% / 97%

Principal strategic exposures

- **Copper:** large absolute volume, grid dependence, long project lead times and smelting concentration.
- **Lithium:** rapid battery-demand growth, conversion concentration and price-cycle investment risk.
- **Nickel:** Indonesian concentration, battery-chemistry uncertainty and class/quality constraints.
- **Cobalt:** DRC concentration, by-product economics, battery substitution and export-policy exposure.
- **Graphite:** extreme natural-graphite and anode-processing concentration, plus qualification barriers.
- **Magnet rare earths:** separation and magnet-manufacturing concentration, export controls and limited substitution in high-performance uses.

The comparison produces four immediate observations. First, the largest growth rate does not identify the largest system risk. Lithium grows fastest in the benchmark, yet copper's enormous absolute volume means a modest percentage gap translates into millions of tonnes. Second, refining concentration is equal to or greater than mining concentration for every system in the table. Third, material criticality depends on end use. A small volume of dysprosium or gallium might have a larger strategic effect than a much larger tonnage of a common industrial mineral if substitution is weak and the downstream sector has high economic value. Fourth, the adaptation route differs by mineral. Copper security depends heavily on new mines, recycling, grid design and material efficiency. Cobalt security is strongly influenced by battery chemistry. Graphite security depends on anode-grade purification, coating, spheronisation and qualification, not merely natural-flake production.

10.2 A mineral-system typology

For research purposes, mineral systems can be grouped into five archetypes.

1. **Large-volume structural minerals.** Copper and aluminium fit this category. Security is shaped by absolute tonnage, mine depletion, infrastructure, scrap availability and large capital requirements.
2. **Battery chemicals.** Lithium, nickel, cobalt, graphite, manganese and phosphate compounds are exposed to rapid technological change and automotive demand cycles.
3. **Magnet systems.** Rare earths combine geological supply with technically difficult separation and highly concentrated magnet manufacturing.
4. **Strategic minor metals.** Gallium, germanium, indium, tellurium, antimony and similar materials often have small markets, by-product supply and large downstream leverage.
5. **Nuclear fuel-chain materials.** Uranium differs because mining is only one stage in a chain that includes conversion, enrichment and fuel fabrication.

This typology is more useful than a universal ranking because it identifies the mechanism through which risk emerges.

Chapter 11

Copper: The Volume Constraint

11.1 Strategic role

Copper is foundational to electrification because of its electrical and thermal conductivity, durability and mature industrial ecosystem. It is used in grids, transformers, motors, renewable generation, charging infrastructure, buildings, industrial equipment, data centres and conventional infrastructure. Substitution with aluminium is possible in some applications, yet the engineering trade-offs differ by conductor size, weight, connection design, corrosion behaviour and installation conditions.

The IEA's 2025 STEPS benchmark increases copper demand from about 26.7 Mt in 2024 to 34.1 Mt in 2040. (International Energy Agency, 2025b) The 2026 project assessment continues to identify copper as one of the clearest long-run supply concerns. The IEA estimates a base-project-pipeline gap of roughly 25 percent against projected 2035 requirements, improved from about 30 percent in its previous assessment. (International Energy Agency, 2026b) A project-pipeline gap is not a forecast of physical shortage. It measures the difference between expected supply from currently announced projects and scenario demand, leaving room for additional projects, substitution, recycling, demand change and project acceleration.

11.2 Why copper is difficult to diversify rapidly

Copper's challenge is scale. A new graphite, gallium or rare-earth project might materially change a relatively small market. The same project scale barely moves the copper balance. Large copper mines require complex geology, extensive infrastructure, major capital expenditure and long development periods. Declining grades in several mature districts add pressure because more material must be moved and processed per tonne of recovered copper.

The system also depends on smelting and refining. The IEA reports that China accounted for more than 90 percent of the increase in global copper-smelting capacity since 2005, raising its share of global capacity from around 15 percent to around 50 percent by 2025. (International Energy Agency, 2026b) This means mine diversification alone does not fully diversify refined supply.

11.3 Scrap and secondary supply

Copper has one of the strongest recycling advantages among critical minerals. It can be recycled repeatedly with limited loss of functional properties. The IEA's 2025 benchmark increases secondary supply from around 4.4 Mt in 2024 to 8.7 Mt in 2040. (International Energy Agency, 2025b) Yet scrap supply is constrained by product lifetimes, collection efficiency, trade, sorting and the economics of recovery. A transmission cable installed today might remain in service for decades. Recycling therefore cannot instantly respond to a large new demand wave.

11.4 Research questions for copper

Copper research should distinguish between mine supply, concentrate quality, smelter capacity, refined cathode, fabrication and scrap. Useful empirical questions include whether smelter concentration materially changes regional inventory behaviour, how declining ore grades affect energy and water intensity, how much grid-design optimisation reduces copper intensity, and which scrap-policy changes deliver the largest additional recoverable tonnage without restricting efficient global recycling trade.

Chapter 12

Lithium: Rapid Growth, Volatile Economics

12.1 Strategic role

Lithium is central to contemporary rechargeable battery systems because of its electrochemical properties. It is used across lithium-ion chemistries for electric vehicles, stationary storage, consumer electronics and other applications. Lithium demand is therefore highly sensitive to battery deployment, chemistry, pack size, recycling, energy-density improvements and the pace of vehicle electrification.

The IEA's 2025 STEPS benchmark rises from 205 kt of lithium demand in 2024 to 928 kt in 2040. (International Energy Agency, 2025e) This is the fastest percentage growth among the six major mineral systems compared in this report.

12.2 Resource diversity versus conversion concentration

Lithium occurs in hard-rock deposits, continental brines, clay-hosted resources and other settings. This geological diversity offers more potential supply routes than public debate sometimes suggests. The bottleneck is often conversion into battery-grade lithium carbonate or lithium hydroxide, followed by qualification within cathode supply chains.

Top-three refining concentration was 96 percent in the IEA's 2024 dataset. (International Energy Agency, 2025e) The key distinction is therefore between extracting a lithium-bearing material and producing a qualified battery chemical. Brine chemistry, impurity management, reagent supply, water use and plant performance affect both economics and environmental outcomes.

12.3 Price cycles and project timing

Lithium demonstrates the investment paradox. High prices encourage project announcements and expansion. Rapid supply growth then pushes prices down. Lower prices help battery manufacturers, yet they weaken the financial case for marginal projects. The IEA reports that lithium-company capital spending fell by around 40 percent in 2025 and lithium exploration declined sharply. (International Energy Agency, 2026b) A low-price period therefore contains the seeds of a later supply constraint if demand continues growing and investment remains depressed.

This does not imply a future shortage is inevitable. Lithium technology is dynamic. Direct lithium extraction, new brine projects, hard-rock expansions, recycling and alternative battery chemistries might alter the balance. Scenario work needs to test multiple price and technology pathways.

12.4 Water and community considerations

Lithium projects have different water profiles. Brine operations in arid basins raise questions about hydrology, freshwater use, brine extraction and ecosystem effects. Hard-rock mining has conventional mining impacts including waste rock, tailings, energy and processing. Generalising one environmental profile across all lithium production is therefore scientifically weak. Site-specific hydrogeology and cumulative basin-level effects matter.

Chapter 13

Nickel: Concentration Meets Technology Uncertainty

13.1 Strategic role

Nickel serves stainless steel, superalloys, plating and batteries. Battery demand increased the strategic attention given to nickel, especially high-purity material suitable for cathode production. Yet the market remains dominated by non-battery uses, and battery chemistry is changing rapidly.

The IEA's 2025 STEPS benchmark increases nickel demand from roughly 3.37 Mt in 2024 to 5.69 Mt in 2040. (International Energy Agency, 2025f) Top-three mining and refining shares were about 77 percent and 78 percent respectively in 2024.

13.2 Indonesia's transformation of the market

Indonesia's rapid production growth has changed global nickel economics. IMF analysis notes that the country's share of world nickel production reached around 60 percent in 2024 after major investment in downstream processing following the 2020 nickel-ore export ban. (World Bank, 2026) The strategy attracted smelting, stainless-steel and battery-related investment. It also created intense debate about trade rules, environmental performance, energy inputs and domestic value capture. The WTO panel in DS592 found elements of Indonesia's nickel export restrictions and domestic-processing requirement inconsistent with relevant GATT obligations, with the dispute later entering the appeal process. (World Trade Organization, 2022)

The important analytical lesson is not whether one policy model should be copied. It is that a producer-country industrial strategy can reshape global supply faster than geology alone would predict.

13.3 Class and quality matter

Nickel is not one homogeneous industrial product. Different feedstocks and processes produce ferronickel, nickel pig iron, matte, mixed hydroxide precipitate, sulphate and Class 1 metal. Battery supply therefore depends on conversion pathways and impurity control. A headline increase in nickel tonnes does not automatically translate one-for-one into battery-grade supply.

13.4 Chemistry risk

Lithium iron phosphate batteries reduce nickel use relative to nickel-rich chemistries. Sodium-ion systems reduce it further. At the same time, high-nickel chemistries retain advantages in selected applications where energy density matters. Nickel security analysis therefore needs a technology-weighted demand model rather than extrapolation from electric-vehicle unit growth alone.

Chapter 14

Cobalt: Policy Exposure and Substitution

14.1 Strategic role and concentration

Cobalt is used in batteries, superalloys, hard metals, catalysts and other specialised applications. Its strategic profile is shaped by geographic concentration, by-product supply and substitution. The Democratic Republic of the Congo dominates mined cobalt, while refining remains concentrated elsewhere. The IEA's 2024 dataset places top-three mine concentration at 81 percent and refining concentration at 89 percent. (International Energy Agency, 2025a)

The IEA's 2025 STEPS benchmark increases demand from 221 kt in 2024 to 330 kt in 2040. (International Energy Agency, 2025a) Growth is lower than lithium or graphite because battery manufacturers have reduced cobalt intensity in several chemistries and LFP batteries use no cobalt in the cathode.

14.2 Export policy as a market variable

The DRC demonstrates how policy can materially alter supply expectations. The country suspended cobalt exports in 2025 and later shifted toward a quota system. IEA policy records indicate a 2026 quota framework with a total allocation of 96,600 tonnes, including a base monthly allocation structure. (International Energy Agency, 2026h) The DRC also announced a strategic-reserve mechanism covering cobalt, coltan and germanium. (International Energy Agency, 2026g)

The 2026 IEA outlook reports a widened projected cobalt gap beyond 25 percent in its 2035 base-project assessment, partly reflecting the quota policy. (International Energy Agency, 2026b) Again, this should be read as a scenario gap, not as an unavoidable physical shortage.

14.3 Responsible sourcing and artisanal mining

Cobalt has been a focal point for research on artisanal and small-scale mining, child labour, traceability, occupational safety and livelihood dependence. These issues show why supply-security analysis should avoid a false choice between excluding high-risk regions and accepting poor practices. Blanket disengagement might reduce formal buyer exposure while worsening livelihoods or shifting material into less transparent channels. Better research examines formalisation, traceability, pricing, cooperative structures, enforcement, livelihood alternatives and company purchasing practices.

Chapter 15

Graphite: Anode Security Is a Processing Question

15.1 Natural and synthetic graphite

Graphite is essential to most commercial lithium-ion battery anodes. Battery supply uses both natural and synthetic graphite. They are not perfect substitutes because performance, cost, energy intensity and manufacturing routes differ.

The IEA's 2025 STEPS benchmark increases graphite demand from 4.77 Mt in 2024 to 11.01 Mt in 2040. (International Energy Agency, 2025d) Top-three mining concentration was 93 percent and refining concentration 99 percent in the 2024 dataset, the highest among the six benchmarked systems.

15.2 The hidden stages of anode production

Battery-grade natural graphite requires more than mining flake graphite. It must be purified, shaped, coated and qualified. Synthetic graphite requires petroleum or coal-derived feedstock, high-temperature processing and substantial energy. The IEA's 2026 work highlights both capacity and equipment concentration in battery-grade graphite processing. (International Energy Agency, 2026b)

This makes graphite a textbook example of why mine announcements overstate diversification. A mine outside the dominant region contributes to security only if purification, spheronisation, coating, logistics and customer qualification also exist or are credibly contracted.

15.3 Export-control exposure

Graphite entered the modern export-control debate before several rare-earth measures. The IEA estimates that a complete disruption of battery-grade graphite supply from the dominant supplier could place more than USD 300 billion of annual downstream production outside that supplier at risk. (International Energy Agency, 2026b) The estimate is a stress-test measure of downstream exposure rather than a forecast of realised economic loss.

Chapter 16

Rare Earths and Permanent Magnets: Small Tonnes, System-Level Leverage

16.1 The rare-earth system

Rare earth elements are a group of chemically similar elements with diverse applications. For energy and strategic systems, particular attention falls on neodymium and praseodymium for high-performance permanent magnets, with dysprosium and terbium used to improve performance at higher temperatures. Rare earths are not geologically rare in the everyday sense. The difficulty lies in finding economically attractive deposits, separating closely related elements, managing waste and building competitive magnet manufacturing.

The IEA's 2025 benchmark for magnet rare earths rises from 91 kt in 2024 to 150 kt in 2040. (International Energy Agency, 2025g) The top-three mining share was 86 percent and refining share 97 percent in 2024. Concentration extends further downstream into metal, alloy and permanent-magnet production.

16.2 Export controls and industrial exposure

China introduced export controls in April 2025 covering several rare-earth-related items including samarium, gadolinium, terbium, dysprosium, lutetium, scandium and yttrium-related products. (Ministry of Commerce of the People's Republic of China, 2025) The IEA reports subsequent expansion of control measures, with some implementation later suspended temporarily. (International Energy Agency, 2026b)

The potential economic leverage is large because permanent magnets sit inside automotive, industrial, renewable-energy, robotics, consumer-electronics and defence systems. The IEA estimates that full implementation of expanded controls could expose around USD 6.5 trillion of annual downstream production outside China. (International Energy Agency, 2026b) This value does not represent the rare-earth market itself. It represents downstream activity whose production might depend on affected inputs.

16.3 Diversification challenge

Diversification is difficult at several stages. Separation requires specialised chemistry and waste handling. Metal and alloy production require technical expertise. Magnet manufacturing depends on process knowledge, equipment, patents, quality control and customer qualification. The IEA estimates roughly USD 60 billion of investment over the next decade would be needed to diversify magnet rare-earth supply chains. (International Energy Agency, 2026b)

The research implication is clear: counting mines is an incomplete measure of resilience. A robust rare-earth indicator should separately measure mining, separation, metal/alloy, magnet manufacturing, equipment dependence and qualified customers.

Chapter 17

Manganese, Phosphate and Aluminium: Large Systems with Different Security Logic

17.1 Manganese

Manganese is a mature bulk commodity used primarily in steel, while high-purity manganese products are important for several battery chemistries. The security issue is therefore a conversion issue as much as a mining issue. Battery-grade manganese sulphate has different purity requirements from metallurgical ore. As battery chemistries evolve, high-purity conversion capacity and feedstock qualification deserve separate tracking.

OECD analysis identifies manganese among the commodities with high exposure to export restrictions, with roughly 70 percent of exports in the monitored period subjected to at least one restrictive measure. (Organisation for Economic Co-operation and Development, 2026) This makes trade policy relevant even where geological supply appears broad.

17.2 Phosphate

Phosphate is strategically unusual because fertiliser demand competes with emerging battery demand through lithium iron phosphate chemistry. The principal global security concern remains food-system dependence on phosphate fertilisers, yet rapid LFP growth adds a new demand pathway. Battery production requires high-purity phosphoric acid and battery-grade iron phosphate, so raw phosphate-rock reserves do not directly translate into battery supply.

Future research should therefore analyse cross-sector competition between agriculture and batteries, the energy intensity of purification, recycling of phosphorus, and whether battery-grade supply materially tightens fertiliser markets under different LFP penetration scenarios.

17.3 Aluminium and bauxite

Aluminium is not scarce in geological terms, yet its supply chain is electricity-intensive and linked to bauxite mining, alumina refining and smelting. Grid decarbonisation, power prices, carbon policy and geopolitical energy shocks therefore affect aluminium competitiveness. Aluminium also provides partial substitution for copper in transmission and selected electrical uses.

This makes aluminium a strategic adaptation material. Its security value rises when copper prices rise or grid expansion accelerates, yet greater substitution transfers demand toward aluminium smelting, conductor design and connection technology. Substitution therefore moves rather than eliminates system pressure.

Chapter 18

Strategic Minor Metals: Gallium, Germanium, Tungsten, Antimony, Tellurium, Indium and Tantalum

18.1 Why small markets matter

Strategic minor metals often receive less attention because their tonnage is small. This is a mistake. Their importance is determined by function, concentration and substitutability rather than volume alone. They appear in semiconductors, high-frequency electronics, fibre optics, infrared systems, photovoltaics, advanced alloys, cutting tools, capacitors, defence systems and specialised chemicals.

USGS analysis of China's mineral industries found that China produced 74 of 77 tracked mineral commodities in 2023 and ranked first globally for 39. Its share reached as high as 98 percent for gallium in the study dataset. (Chung et al., 2026) Separate research on US exposure to foreign trade restrictions identifies gallium, germanium, graphite, rare earths and tungsten among high-risk minerals. (Moon et al., 2025)

18.2 Gallium

Gallium is commonly recovered as a by-product of alumina and zinc processing. Supply therefore does not respond directly to gallium price alone. High-purity gallium and compound-semiconductor production add further technical concentration. Applications include gallium arsenide and gallium nitride devices used in communications, power electronics, radar and other high-performance systems.

Research should separate primary gallium recovery, refining purity, wafer and epitaxy capacity, and end-use design flexibility. A country might possess bauxite but lack any meaningful gallium-recovery or semiconductor capability.

18.3 Germanium

Germanium is associated with zinc processing and selected coal sources. It is used in fibre optics, infrared optics, solar cells and specialised electronics. Like gallium, by-product dependence limits short-run supply elasticity. Recycling from manufacturing scrap and end-of-life optical equipment can improve resilience, yet collection is challenging because germanium is often dispersed in small quantities.

18.4 Tungsten

Tungsten's exceptional hardness and high melting point support cemented carbides, cutting tools, high-temperature applications and defence uses. USGS reporting for 2025 notes continued Chinese dominance and sharp price increases after export-control changes. (U.S. Geological Survey, 2026) Substitution is possible in selected applications but often involves performance trade-offs.

18.5 Antimony

Antimony is used in flame retardants, lead alloys, ammunition, semiconductors and other applications. Market concentration and its role in defence-related supply chains have increased policy attention. The research challenge is data quality. Smaller markets often have less transparent inventories, pricing and end-use statistics than copper or nickel.

18.6 Tellurium and indium

Tellurium is often recovered from copper refinery slimes and is used in cadmium telluride photovoltaics and thermoelectric applications. Indium is associated with zinc processing and used in indium tin oxide, displays and selected semiconductor applications. Both illustrate the dependence of minor-metal supply on base-metal smelters and refinery-recovery circuits.

18.7 Tantalum

Tantalum supports high-performance capacitors, aerospace alloys and chemical equipment. Supply chains have long been connected with responsible-minerals due-diligence frameworks because of production in central Africa and historical conflict-financing concerns. Tantalum shows how traceability requirements can reshape trading structures and how social-governance risk becomes inseparable from security of supply.

Chapter 19

Uranium and the Nuclear Fuel Chain

19.1 Mining is only the first stage

Uranium security differs from battery and magnet minerals. Mined uranium must move through conversion, enrichment and fuel fabrication before use in most commercial reactors. Concentration therefore needs to be measured at each stage.

The IEA's 2026 critical-minerals analysis notes that the top three countries account for almost three-quarters of uranium mining, while a similarly concentrated group controls a large share of conversion and enrichment capacity. (International Energy Agency, 2026b) The importance of enrichment technology means that mine diversification alone cannot guarantee nuclear-fuel security.

19.2 Inventory and contracting

Nuclear fuel differs from gas because utilities typically hold inventories and contract years in advance. Reactor fuel represents a relatively small share of electricity-generation cost, which gives utilities more ability to pay a security premium for diversified supply. Long contracting cycles also mean market stress might appear in term-contract prices before it appears in immediate physical shortages.

19.3 Advanced reactors and future demand

Advanced reactor deployment could change uranium demand, enrichment requirements and fuel specifications. High-assay low-enriched uranium has different enrichment needs from conventional light-water-reactor fuel. Scenario analysis therefore needs to connect reactor technology, enrichment capacity and policy rather than extrapolating uranium mine demand alone.

Part IV. Geopolitics, Trade and Industrial Strategy

Chapter 20

Trade Restrictions and Geoeconomic Fragmentation

20.1 Export restrictions are now a material market variable

Critical-mineral trade has entered a period in which access cannot be analysed solely through price and transport cost. OECD data show a fivefold increase in export restrictions on critical raw materials between 2009 and 2024. During 2022 to 2024, around 16 percent of global trade in monitored critical raw materials faced at least one export restriction. Exposure was substantially higher for selected materials, including cobalt, manganese, natural graphite and rare earth elements. (Organisation for Economic Co-operation and Development, 2026)

The motivations for restrictions differ. Governments use export taxes, quotas, licensing, domestic-processing requirements and prohibitions to pursue revenue, industrial development, environmental objectives, domestic supply security or national-security goals. These instruments have different economic effects. An export tax changes relative prices. A quota caps volume. A licensing regime creates administrative uncertainty and information requirements. A domestic-processing rule attempts to shift value addition toward the producer country. A prohibition can remove material from international markets entirely.

Research should therefore avoid treating all restrictions as equivalent. A useful database should code instrument type, coverage, duration, exemptions, enforcement intensity, stated objective and downstream response.

20.2 Fragmentation risk

The IMF has modelled an illustrative fragmentation scenario in which critical-mineral trade between geopolitical blocs is disrupted. Its analysis found that such fragmentation could reduce investment in renewable energy and electric vehicles by as much as 30 percent by 2030 relative to an unfragmented world. (International Monetary Fund, 2023) This is not a forecast. It demonstrates how trade barriers can amplify mineral concentration by preventing nominally available resources from reaching users.

The mechanism is important. A global market pools supply and demand. Fragmented markets divide that pool. A mineral might be adequately supplied globally while one bloc faces shortage and another surplus. Price signals then become less efficient because material cannot move freely to the highest-valued use.

20.3 Security versus efficiency

Globalisation historically rewarded concentrated production when one region possessed lower costs, better infrastructure, stronger supplier networks or greater scale. Security policy asks whether the efficiency gain from concentration remains worth the disruption risk.

This creates a portfolio problem rather than a binary choice. Full autarky is expensive and often geologically impossible. Total dependence on one supplier creates vulnerability. The practical design variable is the degree of diversification worth paying for. The answer depends on the material's strategic value, substitution options, inventory cost, market size, lead time and likelihood of disruption.

Chapter 21

China and the Midstream Question

21.1 Production and processing depth

China's role in critical minerals extends far beyond domestic mining. USGS analysis shows broad production across dozens of mineral commodities. The IEA documents especially strong positions in refining, battery materials, rare-earth separation, permanent magnets, graphite anodes and several strategic minor metals. (Chung et al., 2026; International Energy Agency, 2026b)

This position developed through a combination of resource endowment, industrial policy, infrastructure, processing expertise, large domestic demand, integrated manufacturing and accumulated operational learning. Any analysis that reduces the position to one policy variable misses the industrial-system effect.

21.2 Export controls

China's Ministry of Commerce announced controls in April 2025 on several rare-earth-related products and technologies. (Ministry of Commerce of the People's Republic of China, 2025) The IEA reports that the number of mineral tariff codes subject to Chinese export controls tripled since 2023 and that further measures expanded during 2025, with selected implementation later suspended for a defined period. (International Energy Agency, 2026b)

The research significance is twofold. First, an export-control announcement changes behaviour before physical supply changes. Firms accelerate inventory purchases, seek alternate suppliers and redesign procurement. Second, licensing regimes generate uncertainty because buyers must assess approval timing and end-use requirements.

21.3 What diversification requires

Diversification away from concentrated processing is harder than building nominal plant capacity. New producers need feedstock, utilities, chemicals, equipment, technical staff, environmental approvals, process yield, customer qualification and competitive operating economics. The IEA estimates refining capital costs outside the dominant supplier can be 20 percent to more than 150 percent higher, with operating costs averaging around 50 percent higher across selected materials. (International Energy Agency, 2026b)

This cost gap explains why market forces alone may reproduce concentration even after governments identify the risk. Research should measure the sources of the gap: energy, labour, capital, equipment, scale, permitting, feedstock, environmental compliance, financing cost or learning curve. Different causes require different responses.

Chapter 22

Producer-Country Industrial Strategy

22.1 The shift from extraction to value capture

Resource-rich economies increasingly seek a larger share of value beyond mining. UNCTAD's 2026 review of critical-mineral partnerships identifies a rapid increase in agreements since 2022, while warning that many partnerships remain more focused on extraction and access than on local value addition, technology transfer and skills. (UN Trade and Development, 2026)

The development logic is clear. Ore exports generate royalties, taxes and foreign exchange. Processing, services, manufacturing and technology create additional employment, capability and industrial spillovers. Yet downstreaming is not automatically welfare-enhancing. A domestic refinery with high energy cost, poor logistics and permanent subsidy requirements might destroy value that could have been captured through other sectors.

A rigorous producer-country strategy therefore asks four questions. Which value-chain stages are technically feasible? Which are economically competitive? Which produce meaningful domestic spillovers? Which create excessive fiscal or environmental cost?

22.2 Indonesia as a case study

Indonesia's nickel strategy illustrates the scale of structural change a producer country can induce. The 2020 ore-export ban helped redirect investment toward domestic processing, while strong demand from stainless steel and batteries supported rapid capacity growth. World Bank and IMF analysis document the resulting expansion in processed exports and industrial investment. (World Bank, 2026)

The strategy also generated trade disputes and raised questions about energy intensity, environmental impacts, local linkages and exposure to one commodity cycle. (World Trade Organization, 2022) For research purposes, Indonesia should therefore be treated as a natural experiment in downstreaming rather than as proof of a universal policy model.

Useful outcome variables include domestic value added, productivity, wages, employment quality, fiscal revenue, electricity demand, emissions, local supplier development, technology transfer and sensitivity to nickel prices.

22.3 Democratic Republic of the Congo

The DRC has used export policy and quota mechanisms to influence cobalt-market conditions. (International Energy Agency, 2026h) Its strategic-reserve initiative also signals a desire to manage selected mineral resources more actively. (International Energy Agency, 2026g)

The DRC case raises a different set of research questions from Indonesia. Cobalt is largely a by-product of copper mining, artisanal mining plays a material social role, and downstream conversion occurs largely outside the country. Policy therefore interacts with livelihood, traceability, copper economics, refining geography and battery-chemistry substitution.

22.4 Latin America

Latin America holds a major share of global copper mine production and approximately one-quarter of lithium supply in the IEA's 2026 assessment, yet the region refines a much smaller share of the key energy minerals it mines, excluding lithium. (International Energy Agency, 2026d) The IEA estimates an analytical case in which greater local refining could support around USD 220 billion of economic value by 2035. (International Energy Agency, 2026d)

The opportunity is heterogeneous. Chile and Peru have mature copper sectors. Argentina is expanding lithium. Brazil possesses a broad mineral base and industrial capacity. Smaller jurisdictions differ in power cost, infrastructure, institutional quality and project pipelines. Regional analysis should therefore avoid presenting Latin America as one mineral system.

22.5 Africa

Africa's role spans cobalt, copper, manganese, graphite, platinum-group metals, bauxite, lithium, rare earth prospects and several strategic minor minerals. The policy debate often focuses on the continent's resource endowment, yet the more important research question is value-chain position.

Processing requires reliable electricity, transport corridors, water, finance, industrial skills and access to customers. Cross-border infrastructure might be more economically rational than duplicating small facilities in each state. Regional economic communities therefore represent an important unit of analysis for mineral industrialisation.

Chapter 23

Alliances and Resilience Policy

23.1 European Union Critical Raw Materials Act

The European Union's Critical Raw Materials Act sets 2030 benchmarks under which domestic extraction should reach at least 10 percent of annual EU consumption of strategic raw materials, processing 40 percent and recycling 25 percent. It also seeks to limit dependence on a single non-EU country to no more than 65 percent of annual needs at the relevant processing stage. (European Commission, 2024)

These benchmarks provide a measurable diversification framework. Their academic value lies in allowing ex post evaluation. Researchers can track whether capacity actually develops, what public and private cost is incurred, whether concentration declines, and whether environmental and social performance changes as production geography shifts.

23.2 G7 Critical Minerals Resilience and Production Alliance

The 2026 G7 declaration established a non-binding Critical Minerals Resilience and Production Alliance focused on diversification, information sharing, project finance, stockpiles and emergency coordination. (Group of Seven, 2026b) The annex includes objectives related to reducing excessive dependence in rare-earth and permanent-magnet supply chains. (Group of Seven, 2026a)

Such arrangements create a new category of mineral governance between open global trade and purely national policy. Their effectiveness will depend on whether coordination produces real projects, qualification, offtake and inventory, or mainly declarations.

23.3 Minerals Security Partnership

The Minerals Security Partnership and associated finance network seek to coordinate investment in projects aligned with responsible-supply and diversification goals. (U.S. Department of State, 2024b, 2024a) These initiatives should be studied as financing institutions as much as diplomatic arrangements. Relevant questions include whether public participation reduces financing cost, accelerates project completion, improves environmental standards or redirects capital toward projects that would otherwise remain uneconomic.

Chapter 24

Stockpiles, Offtake Agreements and Strategic Procurement

24.1 Stockpiles as time buffers

A stockpile is a bridge, not a source. It buys time during a disruption. Its value is therefore highest for materials where a modest physical volume supports high downstream value and where alternate supply requires months rather than years to qualify.

A stockpile policy requires decisions on material form, purity, location, ownership, rotation, release conditions and market interaction. Stockpiling ore when industry needs battery-grade chemical is ineffective. Storing a material that degrades or becomes technologically obsolete carries another risk.

24.2 Long-term offtake

Long-term contracts can support new projects by providing predictable revenue. For buyers, they secure volume. Yet fixed or formula-linked contracts can become uneconomic when spot prices fall. Offtake also creates counterparty concentration if buyers secure supply from one new source without building redundancy.

The important research question is whether offtake should be analysed as a financing instrument, a security instrument or both. Project-level data on contract duration, price formula, floor and ceiling provisions, take-or-pay terms, ESG requirements and force-majeure clauses would materially improve empirical research.

24.3 Price floors and contracts for difference

Where diversified production has structurally higher cost, policy designers have considered price floors, premiums or contracts for difference. These mechanisms transfer part of price risk from producers to governments or customers. They can accelerate investment, yet they also create fiscal exposure and the risk of supporting high-cost production after technology changes.

Academic evaluation should compare resilience gained per unit of public expenditure rather than judging such tools by ideology. Metrics might include concentration reduction, emergency substitution capacity, domestic value added, carbon intensity and fiscal cost.

Part V. Economics, Finance and Market Structure

Chapter 25

The Mineral Investment Cycle

25.1 Why commodity cycles create security risk

Mineral investment follows prices with long lags. A price spike improves project economics and expands exploration. Because new mines take years to develop, supply often arrives after the initial scarcity signal. If many projects enter simultaneously, prices weaken. Lower prices then curtail investment, setting up the next tightening cycle.

This dynamic is especially severe when demand grows structurally while supply investment is cyclical. The IEA reports that total critical-mineral investment fell 9 percent in 2025 despite continued long-term demand growth. Battery-metal capital spending fell by more than 20 percent. Lithium-company spending declined around 40 percent. Exploration spending fell more than 10 percent, with large reductions in lithium and nickel. (International Energy Agency, 2026b)

The resulting research problem is intertemporal. Today's low prices benefit consumers. Tomorrow's security depends partly on investment decisions made during today's low-price period.

25.2 The option value of undeveloped projects

A permitted but undeveloped project has strategic value because it shortens response time. Conventional valuation might assign little value to idle capacity or dormant permits if current prices do not justify construction. A resilience framework assigns option value to projects that could be accelerated during a shock.

This concept deserves formal modelling. A project portfolio could be valued as a set of real options under uncertainty in prices, demand, policy and technology. The strategic option value would depend on remaining development time, permit status, infrastructure, financing readiness and product qualification.

Chapter 26

The Security Premium

26.1 Cost is not the same as value

Diversified supply is often more expensive than incumbent supply because the incumbent region benefits from scale, established infrastructure, lower equipment cost, supplier ecosystems and learning. The IEA documents capital and operating cost disadvantages for new refining capacity outside dominant suppliers. (International Energy Agency, 2026b)

The difference can be interpreted as a security premium. Buyers or governments pay more to reduce the probability or consequence of disruption. The economic challenge is deciding when the premium is rational.

A simple expected-loss framework is useful:

[Expected disruption cost = P(D) ×L(D)]

where (P(D)) is the probability of disruption and (L(D)) is the economic loss conditional on disruption. Diversification is economically attractive when its incremental cost is lower than the reduction in expected disruption cost, adjusted for uncertainty and risk tolerance.

This formula is conceptually simple but empirically difficult. Disruption probabilities are not stationary, loss estimates depend on substitution and inventory, and political events are not independent. Scenario analysis is therefore required alongside expected-value calculations.

26.2 Downstream leverage

The security premium can be small relative to the value of final goods. The IEA estimates critical minerals account for roughly one-quarter of battery-cell cost but only around 3 percent of average electric-vehicle price, while rare earths represent about 40 percent of magnet cost but less than 1 percent of vehicle price. (International Energy Agency, 2026b) This cost structure means a large increase in a small mineral input does not always translate into a proportionate increase in final-product price.

The implication is not that mineral prices are unimportant. It is that firms might rationally pay a higher input price for secure supply where the input represents a small share of final value and disruption would stop production entirely.

Chapter 27

Market Opacity, Pricing and Information Risk

27.1 Transparent versus opaque markets

Copper trades in deep, liquid markets with widely observed benchmark prices. Several minor minerals trade through bilateral contracts, dealer assessments or thin spot markets. Inventory data might be incomplete. Product specifications vary. Small transactions can move quoted prices substantially.

Opacity creates security risk because firms struggle to distinguish genuine scarcity from temporary price dislocation. It also complicates financing. Banks and investors prefer transparent prices, standard specifications and liquid hedging markets.

27.2 Benchmark risk

A benchmark price can become disconnected from project economics if it represents a different product, location or quality. Battery-grade lithium hydroxide, technical-grade carbonate, spodumene concentrate and brine economics are linked but not identical. Nickel prices on major exchanges might not fully reflect all intermediate products. Graphite grades and flake sizes differ significantly.

Research should therefore avoid using one quoted price as a complete measure of market health. Project margins need product-specific realised prices, freight, payability, treatment charges, penalties and conversion cost.

Chapter 28

By-Product Economics and Supply Elasticity

A by-product metal's supply curve is linked to the economics of its host metal. If gallium recovery depends on alumina production, gallium price cannot induce more bauxite mining unless the host system also supports expansion. The relevant response might be to install recovery circuits at existing plants rather than open a new mine.

This creates three research variables: host-metal production, recovery rate and recovery-capacity utilisation. Strategic policy focused only on new mining will miss the lower-cost opportunity of increasing recovery from existing flows.

Tellurium, indium, germanium, rhenium and several platinum-group or minor elements exhibit variants of this structure. A comprehensive material-flow database should therefore track co-production relationships.

Chapter 29

Public Finance and Risk Sharing

29.1 The rise of public commitments

The IEA estimates public-finance commitments for critical minerals in advanced economies reached around USD 65 billion in 2025, more than four times the 2023 level, while warning that actual disbursement lags announcements. (International Energy Agency, 2026b) This expansion reflects the financing difficulty of high-capital projects exposed to volatile commodity prices and competition from incumbent supply.

29.2 Additionality

The main research question for public finance is additionality. Would the project have proceeded without public support? If yes, public funding might simply replace private capital. If no, researchers should ask whether the project provides measurable public benefits through resilience, technology, environmental performance or regional development.

Useful evaluation metrics include private capital mobilised per public dollar, time to financial close, construction completion, cost overruns, production achieved, concentration reduction and repayment performance.

Chapter 30

Corporate Finance and Bankability

Mining projects require long-duration capital before revenue begins. Lenders and investors therefore evaluate reserve confidence, technical design, permits, commodity price, offtake, political risk, construction risk and management capability.

Critical-mineral projects add newer risks. Technology might change before the asset repays capital. A government might alter trade policy. An incumbent supplier might cut prices and reduce margins for new entrants. Downstream customers might require long qualification periods.

Bankability therefore depends increasingly on integrated contracts. A mine linked to a refinery and a long-term buyer is easier to finance than an isolated project exposed to an uncertain spot market. This integration improves financing while potentially reducing market flexibility. The trade-off deserves empirical study.

Part VI. Environmental, Social and Physical-System Constraints

Chapter 31

Environmental Performance as Supply Security

31.1 From externality to continuity risk

Environmental impacts are often discussed as externalities separate from mineral security. In practice, environmental performance affects permitting, litigation, financing, community acceptance and operating continuity. Water shortage can stop production. Tailings failure can close a mine and reshape regulation across a jurisdiction. Biodiversity conflict can delay approval. Extreme weather can damage transport and power.

Peer-reviewed literature documents significant environmental pressure associated with mineral extraction, including land-use change, water use, waste, emissions and biodiversity effects. (Aska et al., 2025; 'Critical Mineral Mining in the Energy Transition', 2024; 'Metal Mining Is a Global Driver of Environmental Change', 2025) A 2025 review in *Nature Reviews Earth & Environment* notes that crude metal-ore extraction rose from about 2.7 Gt in 1970 to 9.4 Gt in 2022, while international supply chains connect much of extraction to distant consumption. ('Metal Mining Is a Global Driver of Environmental Change', 2025)

31.2 Ore grades and footprint

Lower ore grades generally require more material movement, crushing, grinding and waste generation per unit of metal, although technological improvements can offset some effects. The relationship is deposit-specific. Researchers should therefore measure energy and water intensity per unit of payable product rather than assume a uniform decline.

31.3 Tailings and waste

Tailings facilities are long-life infrastructure whose risk extends beyond mine closure. Mineral-transition scenarios that increase mining volume also increase the importance of tailings governance, paste or dry-stack technologies where appropriate, water recovery, geotechnical monitoring and closure funding.

A supply-chain resilience model should include catastrophic tailings risk because one failure can produce company-level shutdowns, jurisdiction-wide regulatory change and broad social opposition.

Chapter 32

Water

32.1 Water quantity

Mining competes for water with agriculture, ecosystems and communities in several mineral regions. Water risk is especially material in arid copper and lithium provinces. Physical water availability, legal allocation, infrastructure and social legitimacy all matter.

The correct unit of analysis is often the watershed or basin, not the mine. Multiple projects might each appear manageable in isolation while creating cumulative stress together. Basin-level hydrological modelling should therefore be linked with mineral-demand scenarios.

32.2 Water quality

Acid mine drainage, salinity, metals, process reagents and sediment can create long-duration water-quality risks. Processing technologies also produce distinct effluent profiles. Water-security research should distinguish withdrawal, consumption and discharge quality rather than use one aggregate water metric.

Chapter 33

Biodiversity and Land Use

Mining overlaps with biodiversity-rich areas in several jurisdictions. A 2025 review synthesises evidence on direct habitat loss, fragmentation, pollution and indirect development effects associated with mining. (Aska et al., 2025) A 2026 causal study examining roughly 3,000 energy-transition-mineral projects found sustained forest loss in surrounding areas over time, underscoring the need to analyse indirect as well as direct land effects. (Quan & Tan-Soo, 2026)

Biodiversity risk is not measured adequately by hectares disturbed. Habitat quality, ecosystem uniqueness, species vulnerability, connectivity and restoration feasibility matter. Research needs spatially explicit data linking deposits, protected areas, Key Biodiversity Areas, Indigenous lands and planned infrastructure.

Chapter 34

Climate Risk and Energy Intensity

34.1 Transition emissions

Mineral production consumes energy and produces greenhouse-gas emissions. The emissions profile depends on ore grade, mining method, haulage, processing route and electricity mix. Nickel production using coal-intensive power can carry a materially different footprint from hydropower-based processing. Aluminium smelting is similarly sensitive to power source.

This creates a feedback loop. Minerals support decarbonisation technologies, while mineral production itself must decarbonise if the net climate benefit is to be maximised. Corporate comparisons should therefore use product-level emissions intensity with consistent system boundaries.

34.2 Physical climate risk

Climate change affects mining through heat stress, drought, extreme rainfall, wildfire, flooding, storms and infrastructure disruption. A project designed around historical rainfall might face different tailings and water-management conditions over a multi-decade life.

Physical-risk analysis should therefore be integrated into reserve and project economics. If climate adaptation requires additional water storage, drainage, cooling or road reinforcement, those costs affect supply competitiveness.

Chapter 35

Human Rights, Labour and Social Licence

35.1 Social legitimacy as infrastructure

A mine depends on legal permission and social relationships. Formal permits alone do not guarantee uninterrupted operation. Community conflict can halt roads, delay construction, create legal challenges or raise security risk. Social performance therefore has measurable supply consequences.

Research on critical minerals increasingly treats social licence and subnational governance as components of criticality. (Sefa-Nyarko, 2026) The United Nations Secretary-General's Panel on Critical Energy Transition Minerals likewise places human rights, benefit sharing, environmental stewardship and justice within responsible mineral development. (United Nations Secretary-General's Panel on Critical Energy Transition Minerals, 2024)

35.2 Indigenous Peoples and free, prior and informed consent

Many mineral deposits overlap with Indigenous territories or areas of cultural significance. Rights frameworks, national law and community expectations differ by jurisdiction. Researchers should avoid reducing engagement to a project milestone. Consent, consultation, benefit agreements, cultural heritage and grievance mechanisms operate through the project life cycle.

35.3 Labour

Critical-mineral supply chains include large industrial mines, contractors, processing plants and artisanal operations. Occupational safety, wages, freedom of association, migrant labour and contractor management affect operational stability and responsible-sourcing claims.

A 2024 analysis of social and environmental risks in European critical-mineral supply chains identifies exposure to modern slavery and water scarcity in parts of the upstream system. ('Assessing the Social and Environmental Impacts of Critical Mineral Supply Chains for the Energy Transition in Europe', 2024) Such findings should be interpreted as risk exposure requiring due diligence, not as proof that every supplier in a country exhibits the same practice.

Chapter 36

Artisanal and Small-Scale Mining

Artisanal and small-scale mining provides livelihoods to millions of people across commodities including cobalt, tantalum, tin and gold. It is often associated with informality, safety risks, environmental damage, child labour or conflict financing, yet it also supports household income where formal employment is limited.

A security strategy that excludes artisanal material without considering livelihood effects can displace rather than solve risk. Formalisation, traceability, access to finance, safety support, transparent buying centres and enforcement against criminal exploitation are research areas with both social and supply implications.

Chapter 37

Benefit Sharing and Development Legitimacy

The durability of mineral supply is partly determined by whether host communities and producer countries perceive fair benefits. Fiscal revenue, employment, local procurement, infrastructure and community investment shape this perception.

Benefit sharing requires more than spending. Researchers should measure distribution, durability and opportunity cost. A road that serves both a mine and surrounding communities has a different development effect from a short-term donation. Skills programmes that lead to certified employment differ from training without labour-market demand.

The scientific challenge is to connect social outcomes with project continuity. Longitudinal data on grievances, protests, legal challenges, local employment, procurement, trust and operating disruption would improve understanding of the social determinants of supply security.

Part VII. Circularity, Substitution and Technology Change

Chapter 38

Recycling and Secondary Supply

38.1 Recycling changes the long-run supply equation

Primary mining remains necessary under all major transition pathways because demand is growing faster than end-of-life material becomes available. Recycling nevertheless becomes increasingly important as the installed stock of batteries, vehicles, grids, electronics and renewable equipment ages.

The IEA estimates average recycling rates across key energy minerals rise from roughly 10 percent today to close to 20 percent by 2040 under current policy settings. (International Energy Agency, 2026b) This contribution is material, yet it should not be misread as a 20 percent reduction in mining for every mineral. Recycling rates, collection efficiency, process yield and product lifetimes differ substantially.

38.2 The stock-and-flow constraint

Recycling depends on historical deployment. If a material is locked into a twenty-year asset, it cannot become end-of-life feedstock for two decades. Rapidly growing technologies therefore face a period in which scrap supply is structurally smaller than demand.

A proper circularity model uses dynamic material-flow analysis. It tracks annual product sales, material intensity, lifetime distributions, collection rates, processing yield and secondary-product quality. Static recycling percentages hide these time lags.

38.3 Manufacturing scrap versus end-of-life scrap

Manufacturing scrap becomes available immediately and is often cleaner and easier to recycle. End-of-life scrap appears after the product's service life and is more heterogeneous. Early battery-recycling economics often rely heavily on manufacturing scrap because the first large generation of electric-vehicle batteries has not yet reached retirement at scale.

This distinction matters for capacity planning. A recycling plant designed around temporary manufacturing scrap could face feedstock change as factories improve yield and end-of-life volumes later grow.

38.4 Concentration in recycling

Circularity does not automatically diversify supply. The IEA reports that China holds more than three-quarters of global battery pretreatment capacity and about 90 percent of material-recovery capacity. (International Energy Agency, 2026b) A circular supply chain can therefore reproduce the concentration of a primary supply chain.

Research should measure secondary-supply concentration separately from primary-supply concentration.

Chapter 39

Battery Recycling Technology

39.1 Pyrometallurgy

Pyrometallurgical routes use high-temperature processes to recover valuable metals. They are robust to mixed feed and can integrate with existing metallurgical infrastructure, though energy use is high and lithium or aluminium recovery can be lower without additional steps.

39.2 Hydrometallurgy

Hydrometallurgical processes use leaching and separation chemistry to recover lithium, nickel, cobalt, manganese and other constituents. They can achieve high recovery rates but require careful reagent management, wastewater treatment and feed preparation.

39.3 Direct recycling

Direct recycling seeks to preserve or restore cathode material rather than break it down fully into constituent metals. Recent research highlights its potential for lower energy use and greater retention of material value, while also identifying challenges involving feed separation, chemistry changes, contamination and product qualification. ('Scaling Direct Recycling of Lithium-Ion Batteries Toward Industrialization', 2025)

The strategic implication is that recycling technology is itself an innovation race. A country possessing scrap but lacking competitive recovery technology might export the secondary resource and retain little value.

Chapter 40

Circular Mining and Mine-Waste Recovery

Mine waste, tailings and smelter residues contain residual metals that were uneconomic or technically unrecoverable when first processed. Higher prices, improved technology and demand for strategic by-products might turn selected waste streams into resources.

A growing literature on circular mining examines reprocessing, waste reduction, water recovery and recovery of critical minerals from existing material. (Cotrina-Teatino & Marquina-Araujo, 2025) The opportunity is site-specific. Old tailings might contain valuable metals, but geotechnical disturbance, acid-generating material, permitting and processing cost can outweigh benefits.

A useful research inventory would map historical waste facilities against modern critical-mineral grades, mineralogy, environmental liability and infrastructure. Reprocessing projects that both recover minerals and reduce legacy environmental risk have a different social value from projects that create new disturbance solely for marginal metal recovery.

Chapter 41

Substitution

41.1 Substitution is functional, not elemental

Substitution should be analysed at the function level. A material performs a technical function such as conducting electricity, storing charge, resisting heat or producing magnetic force. A substitute must meet enough of those functional requirements at acceptable cost.

Copper can be substituted with aluminium in selected conductors. Cobalt can be reduced or eliminated in some battery chemistries. Rare-earth permanent magnets can be replaced in some motors by induction or ferrite-based designs. Gallium arsenide can be replaced by silicon or other semiconductors in some applications. Each substitution changes performance, weight, efficiency, design or manufacturing requirements.

41.2 Substitution creates second-order demand

Reducing one mineral often raises another. LFP batteries reduce nickel and cobalt but still require lithium, graphite, iron and phosphate-based materials. Sodium-ion batteries reduce lithium dependence but increase demand for sodium-ion-specific cathode materials and hard carbon. Aluminium substitution reduces copper intensity but increases aluminium demand and might alter system size.

A resilience model should therefore use a substitution matrix rather than a binary substitution score. Each technology pathway should map which minerals fall, which rise, and what new manufacturing dependencies appear.

Chapter 42

Battery Chemistry Pathways

42.1 LFP

Lithium iron phosphate has expanded rapidly because of cost, safety and cycle-life advantages. Its growth reduces exposure to nickel and cobalt. The IEA's 2026 EV analysis documents the expanding role of LFP in global battery markets. (International Energy Agency, 2026a)

LFP does not eliminate mineral risk. It preserves lithium and graphite demand and creates stronger links to purified phosphates and LFP manufacturing. Its lower energy density relative to some nickel-rich chemistries also affects pack design and application suitability.

42.2 Nickel-rich chemistries

Nickel-rich cathodes remain relevant where high energy density is valuable. They maintain demand for nickel and selected cobalt inputs, though manufacturers continue reducing cobalt intensity. Their future share depends on vehicle segment, raw-material prices, safety, charging, pack design and policy.

42.3 Sodium ion

Sodium-ion technology reduces dependence on lithium and can use more widely available raw materials. Commercial deployment is growing, especially in lower-range mobility and stationary storage. Yet industrial capacity remains concentrated and hard-carbon anodes create their own supply considerations.

42.4 Solid-state systems

Solid-state batteries cover several technology families rather than one chemistry. They might change demand for lithium metal, graphite, silicon, nickel or other materials depending on design. Forecasts that treat "solid state" as one material substitution are therefore too coarse.

Chapter 43

Permanent-Magnet Alternatives

Rare-earth-free motors include induction, switched-reluctance and ferrite-magnet designs. These can reduce exposure to neodymium, praseodymium, dysprosium and terbium, but trade-offs might appear in efficiency, noise, size, control systems or manufacturing complexity.

The market response to rare-earth disruption might therefore be application-specific. High-performance aerospace or defence applications might have limited substitution. Some vehicle platforms can redesign motors. Industrial users might accept larger equipment. Scenario models should assign different substitution elasticities by end use.

Chapter 44

Material Efficiency and Product Design

The cheapest tonne of mineral is often the tonne not required. Material efficiency can reduce intensity through higher-voltage grids, improved conductor design, thinner foils, higher battery energy density, smaller vehicle batteries, shared mobility, longer product life or modular repair.

Efficiency is often overlooked because mineral forecasts multiply technology units by current material intensity. A better model makes material intensity endogenous. It falls or rises with price, engineering and regulation.

At the same time, rebound effects matter. Cheaper or more efficient technology can increase total adoption. A 20 percent reduction in copper intensity per unit does not reduce total copper demand if deployment grows 50 percent.

Chapter 45

Digital Traceability, Data and AI

45.1 Traceability

Digital traceability systems seek to document origin, custody, processing and ESG attributes. Technologies include interoperable databases, product passports, chain-of-custody systems and selected blockchain applications. The strategic value lies less in the technology label than in data quality and governance.

A traceability system is useful only if identity is preserved, audits are credible and incentives discourage false reporting. Mass-balance systems suit some commodities while segregated chains suit others. Researchers should assess traceability by error rate, coverage, verification cost and decision usefulness.

45.2 AI in exploration and processing

Machine learning is increasingly applied to geological targeting, core logging, process control, predictive maintenance and ore sorting. These applications might improve discovery probability, recovery and energy efficiency. They do not remove geological uncertainty or metallurgical testing.

A research agenda should quantify whether AI materially shortens discovery-to-resource timelines or mainly improves targeting efficiency. Similar evaluation is needed for autonomous equipment and sensor-based sorting.

Part VIII. Scenario Architecture, 2026-2040

Chapter 46

Scenario Method

46.1 Why scenarios rather than predictions

The period to 2040 contains uncertainty in technology, policy, prices, geopolitics, climate and demand. No responsible research document can enumerate every conceivable event. It can, however, map the principal classes of shocks, define transmission mechanisms and combine them systematically. This report therefore uses a broad scenario universe rather than claiming exhaustive prediction.

Each scenario is evaluated across six dimensions:

1. **Trigger:** the event or structural change that begins the scenario.
2. **Transmission:** the mechanism through which the trigger affects mineral supply or demand.
3. **Exposure:** the minerals, geographies and sectors most affected.
4. **Time horizon:** immediate, medium term or structural.
5. **Observable signals:** indicators suggesting that the scenario is developing.
6. **Adaptation:** options available to governments, companies and technology users.

Scenarios are grouped into demand, supply, trade-policy, technology, environmental-social, logistics, finance and compound shocks. They are stress tests, not probability forecasts.

Chapter 47

Demand Scenarios

47.1 D1. Faster-than-expected electrification

Trigger. Electric-vehicle sales, heat pumps, renewable deployment and industrial electrification exceed baseline scenarios.

Transmission. Battery and grid demand rises simultaneously, increasing lithium, graphite, copper, aluminium and selected nickel demand. Manufacturing equipment and power infrastructure add second-order mineral demand.

Signals. EV penetration above policy scenarios, stronger grid capital expenditure, accelerated renewable auctions, falling battery costs and rapid charging build-out.

Adaptation. Accelerated recycling, material efficiency, supplier qualification, longer-term procurement and prioritisation of high-value applications during tightness.

47.2 D2. Grid supercycle

Trigger. Electricity demand from AI data centres, industrial electrification, cooling and transport forces rapid transmission and distribution investment.

Transmission. Copper and aluminium demand rises, with pressure on transformers, electrical steel and specialist equipment. Grid connection queues shift from generation bottlenecks to equipment bottlenecks.

Signals. Transformer lead times, conductor prices, utility capex, data-centre interconnection requests and national transmission plans.

Adaptation. Aluminium substitution where technically suitable, advanced conductors, grid optimisation, transformer standardisation, refurbishment and recycling.

47.3 D3. AI and data-centre acceleration

Trigger. Compute demand grows faster than expected.

Transmission. Additional electricity infrastructure, backup power, cooling, semiconductors and construction increase demand for copper, aluminium, silicon, gallium, rare earths and battery materials.

Signals. Data-centre power purchase agreements, grid requests, semiconductor fab utilisation and hyperscaler capex.

Adaptation. More efficient compute, location choices based on grid capacity, closed-loop electronics recycling and longer hardware life.

47.4 D4. Defence rearmament cycle

Trigger. Governments sustain higher procurement of aerospace, missiles, communications, sensors and munitions.

Transmission. High-performance alloys, rare earths, gallium, germanium, tungsten, antimony, titanium and other speciality materials tighten, even where tonnage is small.

Signals. Multi-year procurement budgets, defence-production contracts, inventory targets and export-control expansion.

Adaptation. Strategic inventories, recycling of manufacturing scrap, alternate material qualification and capacity investment.

47.5 D5. Nuclear expansion

Trigger. Large reactors, life extensions and advanced-reactor programmes expand faster than baseline.

Transmission. Uranium, conversion, enrichment and fuel-fabrication demand rises. Selected zirconium and speciality-metal demand also increases.

Signals. Final investment decisions, reactor construction starts, enrichment contracts and uranium term contracting.

Adaptation. Diversified fuel-cycle contracting, inventory and investment in conversion and enrichment.

47.6 D6. Transition slowdown

Trigger. Slower economic growth, policy change, high financing costs or consumer resistance reduces clean-energy deployment.

Transmission. Battery-metal demand falls below investment assumptions. Prices weaken, projects are deferred and exploration declines.

Signals. Lower EV sales, cancelled renewable auctions, project write-downs and reduced capital expenditure.

Adaptation. Flexible project staging, lower-cost technologies, multi-market product strategies and preservation of high-quality projects through downturns.

Chapter 48

Supply and Project Scenarios

48.1 S1. Copper project underdelivery

Trigger. Major projects are delayed by permitting, construction, grade or infrastructure problems.

Transmission. The projected copper pipeline gap widens. Refined inventories fall and prices rise, affecting grids and manufacturing.

Signals. Repeated schedule slippage, capex inflation, lower mine guidance and declining treatment charges indicating concentrate tightness.

Adaptation. Scrap recovery, debottlenecking, brownfield expansion, aluminium substitution and demand efficiency.

48.2 S2. Lithium oversupply persists

Trigger. Supply expansions continue while EV demand grows more slowly.

Transmission. Prices remain low, high-cost projects close and exploration contracts.

Signals. Inventory accumulation, producer curtailments, project deferrals and lower exploration budgets.

Adaptation. Preserve strategic projects through staged development, reduce cost and avoid assuming current low prices persist indefinitely.

48.3 S3. Lithium tightness returns abruptly

Trigger. Several projects are cancelled during a low-price period, followed by faster demand growth.

Transmission. Limited spare capacity causes rapid price increases and downstream contract renegotiation.

Signals. Multi-year decline in capital spending, low inventories, strong battery demand and delayed new supply.

Adaptation. Long-term contracts, recycling, chemistry diversification and strategic project finance.

48.4 S4. Nickel structural oversupply

Trigger. Indonesian capacity keeps expanding while LFP captures greater battery share.

Transmission. Prices remain depressed, non-Indonesian projects struggle to finance and global supply concentration rises as higher-cost producers exit.

Signals. Persistent margin compression, mine closures outside Indonesia and continued capacity additions.

Adaptation. Product differentiation, low-carbon premiums where markets support them, diversified end uses and disciplined capacity investment.

48.5 S5. Cobalt quota tightening

Trigger. DRC quotas become more restrictive or enforcement strengthens.

Transmission. Cobalt availability tightens, prices rise and substitution toward lower-cobalt chemistry accelerates.

Signals. quota announcements, export data, inventory drawdowns and cathode redesign.

Adaptation. Recycled cobalt, chemistry shift, long-term contracts and improved recovery from copper-cobalt operations.

48.6 S6. Major mine disruption

Trigger. Geotechnical failure, strike, political instability, flood, fire or tailings event closes a large mine.

Transmission. Impact depends on the mine's global market share, inventories and substitution. Concentrated markets respond more strongly.

Signals. Operating alerts, emergency declarations, transport interruption and force-majeure notices.

Adaptation. Inventory, diversified contracts and pre-qualified alternate supply.

48.7 S7. Processing-plant failure

Trigger. Fire, equipment failure, cyberattack or environmental shutdown affects a major refinery or chemical converter.

Transmission. Upstream ore remains available but downstream usable product tightens.

Signals. plant outages, force majeure, unusual treatment charges and regional price spreads.

Adaptation. spare conversion capacity, tolling agreements, alternate specifications and inventory.

Chapter 49

Trade and Policy Scenarios

49.1 P1. Expanded rare-earth export controls

Trigger. Licensing broadens across additional rare-earth products, technologies or magnets.

Transmission. Manufacturers outside the dominant supplier face delayed or reduced access. Inventory rises and product redesign accelerates.

Signals. regulatory announcements, licence delays, customs data and magnet price spreads.

Adaptation. alternative separation and magnet capacity, strategic inventories, recycling and motor redesign.

49.2 P2. Graphite licensing tightens

Trigger. Export approvals for battery-grade graphite become more restrictive.

Transmission. Anode supply tightens even where natural graphite mines remain available elsewhere.

Signals. licence processing times, anode inventories and non-Chinese qualification announcements.

Adaptation. synthetic graphite, diversified purification, natural-graphite projects linked to anode plants and recycling.

49.3 P3. Producer-country export bans expand

Trigger. More resource-rich economies require domestic processing before export.

Transmission. Near-term raw-material availability falls while domestic-processing investment increases. Projects face new policy risk.

Signals. legislative proposals, export taxes, local-content rules and refinery investment agreements.

Adaptation. joint ventures, regional processing hubs, contractual stabilisation and scenario-based capital allocation.

49.4 P4. Trade fragmentation into blocs

Trigger. Sanctions, reciprocal controls or geopolitical alignment restricts cross-bloc mineral trade.

Transmission. Global balance splits into regional balances, producing simultaneous surplus and shortage.

Signals. tariff escalation, sanctions lists, investment screening and government procurement restrictions.

Adaptation. multi-region sourcing, inventory, flexible product specifications and recycling.

49.5 P5. Coordinated diversification succeeds

Trigger. Public finance, offtake and permitting support bring non-dominant projects online at scale.

Transmission. concentration declines, security premiums narrow and suppliers compete on quality and ESG as well as price.

Signals. financed projects reaching commissioning, customer qualification and sustained utilisation.

Adaptation. Buyers rebalance portfolios without abandoning efficient incumbents.

49.6 P6. Policy reversal after price collapse

Trigger. Governments withdraw support because mineral prices fall and projects appear uneconomic.

Transmission. diversification projects are cancelled, restoring dependence on dominant low-cost supply.

Signals. subsidy withdrawal, budget cuts and project write-offs.

Adaptation. policy designs linked to resilience metrics rather than spot price alone.

Chapter 50

Technology Scenarios

50.1 T1. LFP dominance

Trigger. LFP gains a much larger share of global EV and storage markets.

Transmission. nickel and cobalt demand falls relative to baseline while lithium, graphite and phosphate-chain importance rises.

Signals. chemistry shares, cathode capacity announcements and vehicle-platform choices.

Adaptation. nickel and cobalt producers diversify end markets; phosphate and graphite chains expand.

50.2 T2. Sodium-ion breakthrough

Trigger. Sodium-ion reaches competitive energy density and cost across mass-market vehicles and storage.

Transmission. lithium demand growth moderates. Hard carbon and sodium cathode materials expand.

Signals. commercial cell costs, cycle life, energy density and large OEM commitments.

Adaptation. lithium projects stress-test lower demand while battery manufacturers diversify chemistry.

50.3 T3. Solid-state commercialisation

Trigger. A solid-state design scales successfully.

Transmission. Material demand shifts according to the winning chemistry, potentially increasing lithium metal, silicon or nickel while reducing graphite in some designs.

Signals. validated cycle life, manufacturing yield and multi-GWh plant commitments.

Adaptation. Avoid single-chemistry forecasts; maintain flexible processing capability.

50.4 T4. Rare-earth-free motor adoption

Trigger. induction, switched-reluctance or ferrite motor designs improve enough to gain broad market share.

Transmission. magnet rare-earth demand falls relative to baseline while copper, electrical steel or power-electronics requirements might change.

Signals. OEM platform announcements, motor efficiency and cost data.

Adaptation. magnet producers diversify into high-performance applications and recycling.

50.5 T5. Direct recycling scales

Trigger. Direct cathode recycling achieves robust commercial qualification across chemistries.

Transmission. secondary material retains more value and energy use falls. Primary demand growth moderates over time.

Signals. commercial yields, OEM qualification and long-term feedstock contracts.

Adaptation. integrate recyclers with manufacturers and design batteries for disassembly.

50.6 T6. Material-intensity breakthrough

Trigger. engineering cuts mineral use per unit across batteries, grids or magnets faster than expected.

Transmission. demand scenarios fall without reducing service delivered.

Signals. conductor designs, battery Wh/kg, thinner foils, magnet loading and product redesign.

Adaptation. producers update long-run demand assumptions and prioritise lowest-cost assets.

Chapter 51

Environmental and Social Scenarios

51.1 E1. Water-constrained mining district

Trigger. prolonged drought or regulatory reallocation reduces industrial water availability.

Transmission. mine throughput falls, projects add desalination or water-recycling infrastructure, costs rise.

Signals. reservoir levels, basin allocations, community conflict and water tariffs.

Adaptation. desalination where viable, dry processing, recycling, basin cooperation and project sequencing.

51.2 E2. Tailings disaster

Trigger. major tailings failure at a large operation.

Transmission. local production stops and regulators globally tighten design and assurance requirements.

Signals. incident reports, emergency orders and insurance changes.

Adaptation. independent review, modern monitoring, closure funding and portfolio-wide assurance.

51.3 E3. Biodiversity permitting reset

Trigger. new scientific evidence, litigation or regulation tightens biodiversity requirements.

Transmission. projects in high-value ecosystems face redesign, delay or rejection.

Signals. new protected areas, legal decisions and lender standards.

Adaptation. early spatial screening, avoidance, alternative infrastructure routes and better baseline data.

51.4 E4. Social conflict closes a corridor

Trigger. community protests or political grievances block a major mining road, railway or port.

Transmission. several nominally separate mines lose access simultaneously.

Signals. grievance escalation, local election tensions and repeated transport interruption.

Adaptation. benefit-sharing, alternate routes, inventory and continuous stakeholder engagement.

51.5 E5. Carbon-border differentiation

Trigger. buyers or jurisdictions apply stronger carbon-intensity requirements to minerals.

Transmission. low-carbon producers gain market access or premiums while high-carbon production faces cost.

Signals. procurement standards, carbon-border rules and product-level emissions reporting.

Adaptation. renewable power, electrification, methane control, process innovation and verified product footprints.

Chapter 52

Logistics and Infrastructure Scenarios

52.1 L1. Maritime chokepoint closure

Trigger. conflict, accident or security event disrupts a major shipping route.

Transmission. freight cost rises and mineral, reagent and equipment delivery slows. Exposure depends on route concentration.

Signals. shipping insurance, vessel diversions and port congestion.

Adaptation. alternate routes, regional inventory and supplier diversification.

52.2 L2. Sulphur and sulphuric-acid shock

Trigger. disruption in sulphur supply or seaborne trade.

Transmission. acid prices rise, affecting copper, lithium, cobalt, nickel, rare-earth and fertiliser processes.

Signals. Middle East export data, acid prices and refinery outages.

Adaptation. acid recovery, alternative reagents where feasible and supply contracts.

52.3 L3. Grid failure at processing hub

Trigger. power shortage or system instability constrains a refining cluster.

Transmission. processing output falls despite available ore.

Signals. industrial curtailment notices, power-price spikes and reserve-margin decline.

Adaptation. dedicated generation, storage, grid reinforcement and geographic diversification.

52.4 L4. Cyberattack on industrial control systems

Trigger. cyber intrusion disrupts mine, refinery, port or utility controls.

Transmission. physical production halts, safety systems activate and restart takes time.

Signals. threat intelligence, anomalies and sector incidents.

Adaptation. network segmentation, offline backups, incident exercises and manual-safe operation.

Chapter 53

Finance and Market Scenarios

53.1 F1. Commodity-price collapse

Trigger. oversupply or demand slowdown cuts prices below incentive levels.

Transmission. projects defer, exploration falls, high-cost mines close and future concentration increases.

Signals. negative free cash flow, capex cuts and junior-finance withdrawal.

Adaptation. balance-sheet resilience, staged projects and countercyclical strategic finance.

53.2 F2. Financing-cost shock

Trigger. global interest rates or risk premiums rise sharply.

Transmission. long-duration projects become uneconomic despite favourable commodity prices.

Signals. higher project-finance margins, falling equity valuations and delayed final investment decisions.

Adaptation. stronger offtake, blended finance and capital discipline.

53.3 F3. Incumbent price response

Trigger. dominant low-cost suppliers increase output or cut prices as diversified competitors enter.

Transmission. new projects lose margins before reaching scale, threatening diversification.

Signals. rapid output increases, prolonged price below new-project cost and refinery underutilisation.

Adaptation. long-term contracts, differentiated products and resilience-linked procurement.

53.4 F4. Speculative inventory cycle

Trigger. fear of restrictions drives stockpiling beyond immediate industrial need.

Transmission. spot prices spike, physical availability tightens temporarily, then reverses when inventories are released.

Signals. imports exceeding consumption, warehouse accumulation and widening spot-term spreads.

Adaptation. transparent inventory data and disciplined procurement.

Chapter 54

Compound Shock Scenarios

Single-variable scenarios are useful for diagnosis. Real crises often combine shocks. The following compound cases test interactions that create nonlinear effects.

54.1 C1. Rare-earth controls plus defence-demand surge

A broadening of export controls occurs at the same time as aerospace and defence procurement accelerates. Inventories tighten quickly because strategic users compete with automotive and industrial buyers. Magnet prices rise, yet the larger risk is unavailable qualified material. Firms with alternate motor designs gain flexibility in commercial applications, while defence and aerospace users with stringent specifications have fewer substitution options.

The scenario tests whether inventory policies prioritise applications based on system importance rather than willingness to pay alone. It also tests whether non-dominant magnet plants have qualified feedstock and customers before the shock.

54.2 C2. Copper underinvestment plus grid supercycle

Several years of low mining investment are followed by rapid grid construction driven by data centres, renewables and electrification. Major new mines face delay. Scrap supply grows but cannot close the gap immediately because installed copper remains in service.

The result is a sustained price signal rather than a short spike. Utilities redesign conductor choices and increase aluminium use where technically appropriate. Equipment manufacturers face working-capital pressure. The scenario illustrates why a large, mature market can be more difficult to rebalance than a small specialist market.

54.3 C3. Lithium project cancellations plus EV acceleration

Low lithium prices lead to project cancellations and exploration decline. Two years later, EV demand accelerates, inventories are low and new conversion capacity lacks feedstock. Prices rebound sharply.

The scenario tests whether buyers use the low-price period to secure long-term supply or assume low prices are permanent. It also tests whether governments and lenders distinguish cyclical weakness from structural obsolescence.

54.4 C4. Nickel oversupply plus carbon differentiation

Nickel remains oversupplied globally, but automotive buyers introduce stricter product-level emissions requirements. The market separates into low-cost high-carbon tonnes and higher-cost lower-carbon material.

This creates a two-dimensional market. Price alone no longer determines competitiveness. The outcome depends on whether customers pay for verified emissions performance and whether trade rules recognise product carbon intensity consistently.

54.5 C5. DRC cobalt quota plus artisanal-supply disruption

Formal export quotas tighten while artisanal production is disrupted by regulation, conflict or financing constraints. Cobalt prices rise faster than expected. Battery manufacturers accelerate LFP adoption and cobalt thrift.

The scenario tests the speed of chemistry substitution against the speed of supply adjustment. It also demonstrates how policy and social conditions can reinforce one another.

54.6 C6. Maritime chokepoint closure plus sulphur shortage

A major maritime route closes while sulphur supply tightens. Freight costs rise across mineral concentrates, while sulphuric-acid-dependent processing faces an additional input-cost shock.

The shock is correlated across commodities that appear unrelated. It tests whether supply-chain maps include reagents and transport routes rather than only mines and refineries.

54.7 C7. Tailings disaster plus permitting reset

A catastrophic tailings event causes a major mine closure and triggers stricter regulatory reviews worldwide. Existing projects face additional studies and new projects are delayed.

The immediate physical loss is smaller than the long-term regulatory effect. The scenario tests the system-wide consequence of low-probability, high-impact operational failure.

54.8 C8. Trade fragmentation plus recession

Geopolitical blocs restrict mineral trade at the same time as global growth slows. Demand falls, which initially masks the cost of fragmentation. Investment declines. When growth returns, regional supply deficits emerge because projects were cancelled during the recession.

This sequence demonstrates why near-term market balance can hide long-run vulnerability.

54.9 C9. Recycling breakthrough plus primary-price collapse

Direct recycling or another high-yield recovery technology scales faster than expected just as new mines enter production. Primary mineral prices fall. High-cost mines close and exploration falls.

The transition is positive for circularity but destabilising for primary producers. The long-run system depends on whether secondary supply is sufficiently large and reliable to replace the lost primary option value.

54.10 C10. AI demand surge plus power-system constraint

Data-centre expansion raises mineral demand while simultaneously competing with mines and refineries for electricity. Processing projects in power-constrained regions face delayed grid connections or high prices.

The demand source therefore also constrains supply. This is a systems feedback absent from simple mineral-demand forecasts.

54.11 C11. Producer-country downstreaming plus incumbent price response

Several resource-rich countries mandate or incentivise local processing. New plants are announced. Incumbent processors expand capacity or lower prices, weakening new-project economics.

The scenario tests whether downstreaming strategies are resilient to competitive response. Facilities backed by cheap power, integrated feedstock and customer contracts survive. Politically attractive but structurally high-cost projects struggle.

54.12 C12. Extreme weather plus cyberattack

Flooding or storm damage disrupts physical infrastructure while a simultaneous cyberattack affects logistics or process control. Recovery is slower because emergency teams must manage both physical and digital failure.

The scenario tests whether continuity plans assume independent shocks. Critical infrastructure often becomes most vulnerable when multiple systems fail together.

Chapter 55

Scenario Matrix

Scenario family	Immediate horizon	Medium-term horizon	Structural horizon	Typical leading indicator
Demand acceleration	price and inventory	capex and capacity	redesign of supply chains	technology deployment, utility capex
Supply delay	spot tightness	project acceleration	substitution and new districts	project schedules, treatment charges
Export controls	licensing and stockpiling	supplier qualification	geographic restructuring	legal notices, customs data
Technology substitution	product redesign	capacity reallocation	demand mix change	chemistry and platform shares
ESG constraint	operating disruption	permitting changes	location shift	grievances, water, litigation
Logistics shock	freight and delay	route diversification	infrastructure investment	freight rates, port throughput
Finance shock	project deferral	pipeline weakening	concentration change	funding spreads, capex, exploration
Compound shock	nonlinear	cross-sector	structural reconfiguration	correlated indicators

The matrix is designed as a research template. Institutions can assign quantitative probabilities and loss distributions if they possess sufficient data. This monograph does not do so because the evidence base is too heterogeneous for defensible universal probabilities.

Part IX. A Mineral Security System Framework

Chapter 56

Conceptual Framework

56.1 Purpose

Existing criticality methods often combine economic importance with supply risk. This is useful, yet it can compress distinct mechanisms into one score. The Mineral Security System Framework proposed here expands the diagnostic layer before any aggregation occurs.

The framework contains eight domains:

1. **G - Geology and primary resource:** reserves, resources, ore grade, depletion, by-product dependence and discovery pipeline.
2. **P - Project execution:** permitting, infrastructure, capital intensity, construction capability, workforce and lead time.
3. **R - Refining and processing:** concentration, technology, product purity, equipment, utilisation and customer qualification.
4. **L - Logistics and trade:** transport nodes, trade restrictions, tariffs, maritime routes, chemical inputs and inventories.
5. **T - Technology and knowledge:** intellectual property, specialist equipment, operating know-how, substitution and manufacturing capability.
6. **F - Finance and markets:** price transparency, volatility, bankability, public support, offtake and market depth.
7. **E - Environmental and social legitimacy:** water, biodiversity, tailings, climate, labour, rights, community acceptance and governance.
8. **C - Circularity and adaptation:** recycling, secondary supply, material efficiency, substitution, repair and product redesign.

The framework is intentionally broader than a national critical-mineral list. It can be applied to one mineral, one country, one company or one downstream product.

56.2 Domain indicators

Each domain should be measured with multiple indicators rather than one proxy. An illustrative research design is shown below.

Domain	Example indicators	Unit or method
G	reserve concentration, production concentration, reserve life, grade trend, by-product share	HHI, %, years, trend

Domain	Example indicators	Unit or method
P	median project lead time, permit variance, capex intensity, infrastructure gap	years, coefficient of variation, USD/t
R	top-country share, top-three share, plant utilisation, qualified alternate capacity	%, HHI, tonnes
L	export-restriction exposure, route concentration, inventory days, reagent concentration	%, HHI, days
T	supplier concentration for equipment, patents, substitution elasticity, qualification time	share, index, months
F	price volatility, market liquidity, financing spread, capex trend, public/private leverage	statistical measures
E	water stress, biodiversity overlap, social conflict, labour risk, carbon intensity	spatial and operational metrics
C	collection rate, recycling yield, secondary share, substitution readiness, material-intensity trend	%, index, trend

56.3 Normalisation

Indicators measured in different units require normalisation before aggregation. Researchers might use min-max scaling, percentile ranks, distance-to-threshold methods or empirically estimated risk functions. The choice materially affects results and should be disclosed.

A simple orientation places all indicators on a 0 to 1 scale where 1 represents strong resilience and 0 represents severe vulnerability. A concentration measure, for example, would be inverted after normalisation because higher concentration reduces resilience.

56.4 A proposed Mineral Security System Resilience score

For empirical testing, this monograph proposes a weighted geometric aggregation:

$$MSSR = \prod_{i=1}^{8} x_i^{w_i}$$

subject to:

$$\sum_{i=1}^{8} w_i = 1, \qquad 0 < x_i \leq 1$$

where (x_i) is the normalised resilience score for each domain and (w_i) is its weight.

The geometric mean is proposed because severe weakness in one domain should reduce the overall score more strongly than under a simple arithmetic average. A mineral with excellent geology but no viable processing route should not receive a high security score merely because resource abundance offsets processing weakness numerically.

This formula is a research proposition, not a validated index. Weights should be estimated or stress-tested rather than selected to produce a desired ranking.

56.5 Actor-specific weights

Weights differ by actor.

A **producer economy** might assign greater weight to project execution, environmental legitimacy and market access.

A **manufacturing economy** might weight processing, trade, technology and inventory more heavily.

A **mining company** might emphasise geology, project execution, finance and social legitimacy.

An **OEM** might emphasise qualified processing, logistics, technology substitution and recycling.

The same mineral can therefore have different security scores for different actors without contradiction.

Chapter 57

Network Representation

57.1 From linear chain to network

Mineral supply chains are networks, not simple lines. One mine can feed several refiners. One refinery can blend concentrates from multiple countries. One smelter can recover multiple minor metals. One port can serve several mines. One equipment supplier can serve many processing plants.

Graph theory provides tools to identify nodes whose failure creates disproportionate disruption. Nodes can be mines, refineries, ports, reagent plants, equipment suppliers or manufacturing clusters. Edges represent material, technology, finance or transport relationships.

Important network measures include:

- **degree centrality**, which measures direct connections;
- **betweenness centrality**, which identifies nodes lying on many paths;
- **eigenvector centrality**, which weights connections to other important nodes;
- **community structure**, which identifies regional clusters;
- **network robustness**, which measures performance after node removal.

A refinery with modest capacity might have high betweenness if it connects several mining regions with a specialised customer base. Conventional market-share statistics would miss this role.

Chapter 58

Shock-Adjusted Resilience

A static MSSR score can be paired with scenario shocks. Let (s_j) represent the severity of scenario (j) on a 0 to 1 scale and (a_{ij}) represent the exposure of domain (i) to that scenario. A scenario-adjusted domain score can be represented conceptually as:

$$x'_{ij} = x_i(1 - a_{ij}s_j)$$

The post-shock MSSR becomes:

$$MSSR_j = \prod_{i=1}^{8} (x'_{ij})^{w_i}$$

This formulation is illustrative. Empirical work would need nonlinear response functions, inventory buffers, substitution and recovery time. Its value lies in forcing researchers to state how a shock reaches each domain.

Chapter 59

Recovery Time as a Security Metric

Most criticality indices focus on the probability of disruption. Recovery time deserves equal attention. Two supply chains with the same disruption probability can have different resilience if one recovers in weeks and the other takes years.

Recovery time includes:

1. inventory drawdown period;
2. time to qualify an alternate supplier;
3. time to restart a failed facility;
4. time to construct replacement capacity;
5. time to redesign a product;
6. time to obtain permits and finance.

A useful composite risk measure is therefore **time-to-functional-recovery**, defined as the time required to restore an agreed percentage of downstream service after a specified disruption.

Chapter 60

Research Validation Strategy

The proposed framework should be validated through multiple methods.

60.1 Historical event studies

Researchers can examine export controls, mine disruptions, refinery outages and trade disputes. Price, inventory, trade flow and downstream production changes before and after each event provide evidence on transmission.

60.2 Panel-data models

Country-mineral panels can test whether concentration, governance, water stress, trade restrictions and investment explain production volatility or project delay.

60.3 Survival analysis

Mine-development databases can be used to estimate the probability and timing of projects reaching production. Explanatory variables might include commodity price, jurisdiction, ownership, capex, infrastructure, permit status and social conflict.

60.4 Input-output modelling

Input-output tables and supply-use data can estimate downstream economic exposure to mineral disruption. This approach is especially useful for minor minerals whose market value is small relative to dependent industries.

60.5 Network simulation

Supply-network models can remove major nodes and estimate the effect on reachable capacity, transport cost and customer qualification.

60.6 Monte Carlo simulation

Uncertain variables such as demand growth, project delay, recovery rate and trade-policy shocks can be sampled from distributions. The output should be a distribution of supply outcomes rather than one deterministic gap.

60.7 System-dynamics modelling

System dynamics can capture feedback between price, investment, project lead time, recycling, substitution and demand. It is suited to the cyclical mechanisms described earlier.

Part X. Early-Warning System

Chapter 61

A Research Dashboard for Mineral Stress

A useful early-warning system tracks variables before a shortage reaches headline prices. The dashboard below groups 48 indicators by mechanism. Institutions should adapt thresholds to each mineral rather than impose one universal alarm level.

Category	Indicator	Suggested frequency	Interpretation
Demand	EV sales by chemistry	monthly/quarterly	battery-material direction
Demand	grid capex	quarterly/annual	copper, aluminium, equipment demand
Demand	data-centre power requests	quarterly	infrastructure demand acceleration
Demand	renewable additions	monthly/quarterly	copper, rare earths, aluminium
Demand	defence procurement	quarterly/annual	strategic minor-metal exposure
Demand	nuclear construction starts	annual	uranium-chain demand
Supply	mine production guidance	quarterly	near-term primary supply
Supply	refinery utilisation	monthly/quarterly	processing tightness
Supply	project schedule slippage	quarterly	medium-term pipeline risk
Supply	capex revisions	quarterly	project viability
Supply	exploration budgets	annual	long-term option set
Supply	reserve replacement	annual	depletion risk
Supply	treatment/refining charges	weekly/monthly	concentrate/refining balance
Supply	unplanned outages	real time	acute disruption
Trade	export-control notices	real time	policy risk
Trade	licence approval time	monthly	administrative restriction
Trade	customs volumes	monthly	actual flow change

Category	Indicator	Suggested frequency	Interpretation
Trade	regional price spreads	daily/weekly	market fragmentation
Trade	tariffs and sanctions	real time	trade friction
Logistics	freight rates	daily/weekly	transport stress
Logistics	port throughput	monthly	corridor performance
Logistics	chokepoint transit	daily	route risk
Logistics	sulphur/acid prices	weekly/monthly	reagent pressure
Inventory	exchange stocks	daily/weekly	visible buffer
Inventory	producer inventories	quarterly	hidden supply pressure
Inventory	OEM inventory days	internal/monthly	downstream resilience
Finance	project-finance spreads	monthly/quarterly	bankability
Finance	mining equity issuance	monthly	capital access
Finance	junior exploration funding	monthly/quarterly	future pipeline
Finance	public disbursement	quarterly	policy implementation
Technology	battery chemistry share	monthly/quarterly	demand substitution
Technology	recycling yield	quarterly/annual	secondary-supply quality
Technology	material intensity	annual	engineering adaptation
Technology	alternate supplier qualification	quarterly	resilience capacity
Technology	patents/process announcements	quarterly	capability shift
ESG	water-stress indicators	monthly/seasonal	operating risk
ESG	community grievances	monthly	social continuity risk
ESG	strikes/protests	real time	operational risk
ESG	tailings alerts	real time	catastrophic risk
ESG	biodiversity litigation	quarterly	permitting risk
ESG	product carbon intensity	annual/quarterly	market access

Category	Indicator	Suggested frequency	Interpretation
Climate	extreme-weather forecasts	seasonal	physical disruption
Climate	flood/drought indices	monthly	asset exposure
Circularity	scrap collection	quarterly/annual	secondary feedstock
Circularity	recycling capacity	quarterly	recovery capability
Circularity	secondary material price	weekly/monthly	circular-market balance
Policy	strategic stockpile changes	quarterly/annual	buffer policy
Policy	permitting reform/standards	quarterly	project-timeline shift

Chapter 62

Signal Interpretation

An early-warning dashboard should avoid false precision. A single signal rarely proves a shortage. Stronger warnings come from correlated indicators.

For example, rising lithium prices alone might reflect speculation. Rising prices combined with falling inventories, high conversion utilisation, accelerating EV sales, project delays and stronger term contracts is a more credible stress signal.

The dashboard should therefore use signal clusters. One method assigns each indicator a normalised deviation from its historical range, then tests whether several indicators within the same mechanism cross thresholds together.

A second method uses machine learning to identify historical patterns preceding price or supply disruptions. Such models require careful validation because mineral markets have limited event histories and structural change can make old relationships unstable.

Chapter 63

Data Governance

The weakest link in many critical-mineral studies is inconsistent data. Definitions change across agencies. Mine production may be reported as ore, concentrate, contained metal or refined product. Capacity is often confused with production. Announced capacity is confused with commissioned capacity. Resources are confused with reserves.

A university-grade dataset should record:

- original source and retrieval date;
- physical unit and conversion method;
- product form and purity;
- geographic boundary;
- whether data represent production, capacity, reserves or resources;
- whether figures are observed, estimated or modelled;
- revision history;
- confidence score.

Reproducibility requires preservation of raw source data where licensing permits and scripts for every transformation.

Part XI. Implications by Actor

Chapter 64

Governments and Public Institutions

64.1 Define the security objective before selecting the instrument

Mineral policy often begins with a preferred instrument such as a subsidy, stockpile, export restriction or tax credit. A more rigorous process begins with the failure mode.

If the problem is excessive processing concentration, mine subsidies might not solve it. If the problem is long supplier-qualification time, an inventory buffer and qualification programme might deliver more resilience than new mining. If the problem is a lack of competitive project finance, offtake or credit support might matter more than geological exploration.

Public policy analysis should therefore follow a sequence:

1. identify the vulnerable industrial function;
2. map the complete supply chain;
3. identify the dominant failure mode;
4. estimate the consequence and recovery time;
5. compare instruments by cost, resilience gain and side effects;
6. set measurable exit or review conditions.

64.2 Instrument families and trade-offs

64.2.1 Geological information and exploration support

Public geoscience lowers information costs and supports exploration. Its benefit is broad because data can be used by multiple firms. The limitation is time. New discoveries rarely solve immediate supply pressure.

64.2.2 Permitting reform

Predictable, well-resourced permitting can reduce uncertainty. Speed without adequate environmental and social analysis risks later litigation or conflict. The measurable objective should be predictable total project-development time with credible safeguards.

64.2.3 Direct grants, loans and guarantees

Public finance lowers cost of capital and can support projects exposed to strategic price competition. Fiscal risk rises if the project is technically weak or technology changes. Additionality and repayment performance should be disclosed.

64.2.4 Tax incentives

Tax credits can reward domestic production or processing while allowing firms to choose projects. They can also create windfall benefits for activity that would have occurred anyway. Evaluation requires a counterfactual.

64.2.5 Strategic stockpiles

Stockpiles improve short-term resilience for selected high-leverage materials. Carrying cost, product degradation and release governance limit their value. They are poorly suited to very bulky commodities where storage requirements become large.

64.2.6 Public procurement

Government purchasing can create demand for responsibly produced or diversified material. This works best where the government is a material buyer, such as defence or infrastructure. Procurement standards need enough flexibility to avoid excluding nascent suppliers through overly narrow specifications.

64.2.7 Price floors and contracts for difference

These instruments protect projects from low prices and can reduce the risk of incumbent price competition. They transfer downside risk to taxpayers or buyers. Transparent trigger levels and duration are therefore important.

64.2.8 Trade restrictions

Export or import restrictions can promote domestic objectives or respond to security concerns. They can also reduce global market efficiency, invite retaliation and raise downstream cost. Their effects depend on market share and availability of substitutes.

64.2.9 Recycling regulation

Collection targets, recycled-content rules and producer responsibility can increase secondary supply. Poorly designed restrictions on scrap trade can reduce recycling efficiency if domestic processing capacity is insufficient.

64.3 Policy evaluation framework

Every mineral-security policy should be evaluated against at least eight questions:

1. How much does it reduce concentration?
2. How much qualified capacity does it add?
3. What is the public cost per unit of resilience?
4. How quickly does the benefit arrive?
5. What environmental and social effects occur?
6. Does the policy create international spillovers or retaliation risk?
7. Does the benefit survive low commodity prices?
8. What happens if technology changes?

This framework does not imply one policy choice. It provides a consistent way to compare choices.

Chapter 65

Producer Economies

65.1 Value addition should follow comparative capability

A resource-rich country has several routes to capture value: mining, beneficiation, refining, chemicals, components, equipment services, engineering, logistics, finance, technology, recycling and specialised professional services. Full vertical integration is not always optimal.

A country with cheap renewable electricity might have an advantage in energy-intensive refining. Another might have stronger ports and trading services. Another might specialise in geological expertise, mine technology or regional processing. Industrial strategy should identify where local capability and global demand intersect.

65.2 Infrastructure as shared capital

Mining infrastructure can create wider economic value if designed for shared use. Roads, ports, transmission and digital networks can serve communities and other industries. Shared infrastructure also reduces the risk of stranded single-project assets.

Researchers should therefore calculate infrastructure spillovers separately from direct mining value added. The result changes the social return on project-support decisions.

65.3 Local content versus capability formation

Local-content rules measure where spending occurs. Capability measures whether firms become competitive suppliers. The two are related but different. A domestic contract awarded without productivity improvement might disappear when policy support ends. A supplier that gains quality certification, technology and export customers represents a deeper capability gain.

Longitudinal studies should track firm survival, productivity, export activity and workforce skills after major mineral projects begin operation.

Chapter 66

Mining Companies

66.1 Compete on reliability, not only tonnes

Mineral producers traditionally compete on grade, cost, scale and jurisdiction. A security-focused market adds reliability, traceability, carbon intensity, product quality, logistics and social continuity.

A producer with slightly higher cost might create greater customer value if supply is low-carbon, politically diversified, consistently delivered and backed by transparent provenance. Whether customers pay for those attributes remains an empirical question and will vary by commodity.

66.2 Portfolio resilience

Mining companies should stress-test portfolios against:

- prolonged low prices;
- construction inflation;
- grid and water constraints;
- trade restrictions;
- product-specification change;
- community conflict;
- climate events;
- customer concentration;
- technology substitution.

Resilience is not equivalent to owning many projects. Projects sharing the same port, power system or buyer might be highly correlated.

66.3 Downstream integration

Vertical integration can capture value and secure market access. It also introduces processing, technology and customer risk unfamiliar to mining organisations. Joint ventures might spread risk but add governance complexity.

The right integration depth depends on the mineral. A lithium miner might benefit from conversion. A rare-earth miner without separation capability might remain exposed. A copper mine can sell concentrate into a mature global market. The optimal boundary therefore differs by market structure.

Chapter 67

Refiners and Processors

Processors occupy a strategic position because they connect heterogeneous ores to standardised industrial products. Their main security variables include feedstock diversity, process flexibility, energy, reagents, waste management, spare capacity and customer qualification.

A resilient processor does not depend on one mine or one transport corridor unless economics leave no alternative. It also develops the ability to handle varying impurity profiles, since a nominally diversified concentrate portfolio has little value if the plant can process only one narrow feed specification.

Chapter 68

Automotive, Battery and Technology Manufacturers

68.1 Move procurement upstream

Manufacturers increasingly need visibility beyond direct suppliers. A cell producer purchasing cathode material remains exposed to the mine and refinery behind it. An automaker purchasing cells remains exposed to anode processing, cathode precursors and rare-earth magnets.

Supplier mapping should therefore follow material provenance to the stage where concentration originates.

68.2 Design for material flexibility

Product architecture influences mineral risk. A vehicle platform compatible with more than one battery chemistry has greater adaptation capacity. Motors designed around only one magnet specification have less flexibility. Standardisation and modularity therefore become supply-security tools.

68.3 Qualify before the crisis

Alternate suppliers need to be tested before disruption. Qualification during a crisis is slower because laboratories, engineering teams and regulators face simultaneous pressure. The value of pre-qualification should be recognised as a resilience asset even when the supplier receives little normal volume.

Chapter 69

Investors and Lenders

69.1 Move beyond commodity price

A conventional project model uses commodity price, grade, recovery, capex and opex. Critical-mineral finance also needs policy, technology and concentration variables.

Lenders and equity investors should ask whether projected demand depends on one technology pathway, whether processing capacity is qualified, whether the product has a transparent market, and whether host-country policy might shift after prices rise.

69.2 ESG as cash-flow risk

Water, tailings, biodiversity and social conflict affect cash flow through delay, shutdown, capex and financing cost. Integrating these variables into valuation is therefore financially relevant rather than purely normative.

A useful research direction is to estimate whether projects with stronger social and environmental performance exhibit lower cost of capital or lower schedule variance after controlling for jurisdiction and project quality.

Chapter 70

Universities and Research Institutes

Universities occupy a distinctive role because mineral security crosses disciplinary boundaries. No single department contains the full problem.

A serious research programme could integrate:

- geology and economic geology;
- mineral processing and metallurgy;
- chemical engineering;
- energy systems;
- industrial ecology;
- economics and finance;
- international trade;
- political science;
- environmental science;
- hydrology;
- biodiversity science;
- Indigenous and community studies;
- data science and network analysis;
- materials science and recycling.

Interdisciplinary work is difficult because units of analysis differ. A geologist studies deposits. An economist studies markets. A political scientist studies institutions. An ecologist studies landscapes. A materials scientist studies performance. The Mineral Security System Framework provides one structure for connecting those scales.

Chapter 71

International Organisations

International institutions can improve mineral security by reducing information gaps, harmonising data definitions, supporting responsible-investment standards, financing shared infrastructure and providing forums for producer-consumer dialogue.

Their value is highest where national action produces cross-border spillovers. Trade restrictions, environmental impacts, transport corridors and regional power systems often cross borders. International data also supports smaller economies that lack specialised analytical capacity.

Part XII. Research Agenda for Universities and Scientific Institutions

Chapter 72

Priority Research Questions

The following questions are designed for theses, research centres, policy laboratories and industry-academic collaboration.

72.1 Geology and exploration

Q-R1. How does declining ore grade alter energy, water, waste and carbon intensity across major copper districts after controlling for technology improvement?

Q-R2. Which unexplored geological provinces offer the highest probability of economically meaningful diversification by 2040?

Q-R3. How much strategic value should be assigned to resources that are geologically large but lack infrastructure or processing routes?

Q-R4. Can machine learning measurably improve discovery success after controlling for exploration spend and target maturity?

72.2 Project execution

Q-R5. What variables explain the largest share of variance in discovery-to-production timelines?

Q-R6. Do predictable environmental-review systems reduce total project time even when statutory review periods are longer?

Q-R7. How often do infrastructure dependencies cause project delay relative to mine-engineering problems?

Q-R8. What is the option value of permitted but undeveloped projects during a supply shock?

72.3 Processing and technology

Q-R9. How much processing concentration is explained by energy cost, capital cost, know-how, environmental regulation, equipment supply and customer proximity?

Q-R10. Which processing stages have the longest customer-qualification periods and why?

Q-R11. How concentrated are specialist equipment and reagent suppliers relative to mineral refining capacity?

Q-R12. Which strategic by-products can be recovered economically from existing base-metal plants with modest retrofit investment?

72.4 Trade and geopolitics

Q-R13. What is the causal effect of export restrictions on price, investment and downstream substitution?

Q-R14. Do export restrictions create lasting domestic value addition or mainly redirect trade?

Q-R15. How do strategic partnerships affect project finance and realised production relative to similar projects without partnership support?

Q-R16. How much economic loss arises from mineral-market fragmentation under different levels of inventory and substitution?

72.5 Finance and market design

Q-R17. What security premium are downstream manufacturers willing to pay for geographically diversified supply?

Q-R18. Do price floors or contracts for difference lower financing cost enough to offset public fiscal exposure?

Q-R19. Which public-finance tools generate the largest private-capital mobilisation per dollar?

Q-R20. How does market opacity affect financing cost for minor-metal projects?

72.6 Circularity

Q-R21. What is the maximum technically and economically recoverable secondary supply by mineral under realistic collection rates?

Q-R22. When does direct battery recycling outperform hydrometallurgy across cost, emissions and material retention?

Q-R23. Which mine-waste deposits offer the strongest combination of critical-mineral recovery and environmental-liability reduction?

Q-R24. How do scrap-trade restrictions affect global recycling efficiency?

72.7 Environment and society

Q-R25. What is the relationship between water stress and mine-production volatility?

Q-R26. Do stronger community-benefit agreements measurably reduce disruption and legal challenge?

Q-R27. How should biodiversity value be incorporated into mine-location and infrastructure optimisation?

Q-R28. What social and economic outcomes follow formalisation of artisanal critical-mineral mining?

Q-R29. How do mine-closure liabilities affect long-term security and public finance?

Q-R30. Which product-level carbon-accounting methods are sufficiently consistent for mineral-market differentiation?

72.8 Technology substitution

Q-R31. How quickly do manufacturers substitute materials after a supply shock compared with a price shock?

Q-R32. What is the total mineral effect of widespread sodium-ion adoption after accounting for hard carbon, aluminium and grid infrastructure?

Q-R33. How would large-scale rare-earth-free motor adoption redistribute copper, steel and power-electronics demand?

Q-R34. How much material-intensity reduction is technically achievable in grids without compromising reliability?

72.9 Systems research

Q-R35. Which nodes have the highest betweenness centrality in global mineral supply networks?

Q-R36. Does a geometric multi-domain criticality index predict disruption better than concentration metrics alone?

Q-R37. What combination of inventory, diversification and substitution minimises expected loss for each mineral?

Q-R38. Which early-warning indicators provide statistically meaningful lead time before market stress?

Q-R39. How do physical climate hazards interact with social conflict and infrastructure dependency?

Q-R40. What recovery-time distributions apply to mines, refineries, ports and downstream qualification after different shock types?

Chapter 73

Research Data Architecture

A global critical-mineral research platform should integrate at least nine data layers.

1. **Geology:** deposits, resources, reserves, grade, mineralogy and ownership.
2. **Projects:** development stage, permits, capex, schedule and infrastructure.
3. **Production:** mine, refinery and component output by product specification.
4. **Trade:** bilateral flows, tariffs, restrictions, routes and ports.
5. **Markets:** prices, inventories, treatment charges, contracts and liquidity.
6. **Technology:** material intensity, chemistry, substitution, patents and qualification.
7. **Environment:** water, biodiversity, emissions, waste, climate exposure and land use.
8. **Society:** population, Indigenous territories, labour, grievances, conflict and benefit sharing.
9. **Finance:** ownership, debt, equity, public support, offtake and cost of capital.

These layers should be spatially and temporally aligned where possible. A mine coordinate without basin data, port route or refinery destination provides only partial insight.

Chapter 74

Reproducibility Protocol

Academic credibility depends on reproducibility. Future editions of this monograph or derivative studies should follow a minimum protocol.

Source preservation. Retain original institutional tables, reports and data snapshots where licensing permits.

Version control. Record retrieval date and publication version because mineral statistics are revised.

Unit discipline. Store original units and conversion equations. Distinguish contained metal, oxide, concentrate and refined product.

Scenario separation. Never mix observed data and scenario outputs in one series without labels.

Code publication. Publish analysis scripts and data dictionaries where confidentiality permits.

Uncertainty. Provide ranges, confidence intervals or sensitivity analysis when input uncertainty is material.

Conflict of interest. Disclose funding and commercial relationships.

Peer review. Subject methods, not only conclusions, to external review.

Chapter 75

Suggested Empirical Studies

75.1 Study A. The price of diversification

Construct a refinery-level dataset across lithium, nickel, graphite and rare earths. Estimate capital and operating cost as a function of geography, energy, scale, labour, regulation, equipment source and utilisation. Quantify the security premium required for non-dominant capacity to earn an acceptable return.

75.2 Study B. Social licence and project delay

Build a global dataset of mining projects with timelines and coded social-conflict events. Apply survival analysis to estimate how conflict, consultation quality and benefit agreements relate to schedule and cancellation after controlling for commodity and jurisdiction.

75.3 Study C. Mineral-network stress test

Map mine-refinery-port-manufacturer links for one mineral system. Remove nodes sequentially and measure lost reachable capacity, route cost and time to qualification. Compare results with standard concentration indices.

75.4 Study D. Recycling as a strategic reserve

Develop a dynamic stock-and-flow model for batteries by region. Estimate how much secondary lithium, nickel, cobalt and graphite becomes available under alternative vehicle lifetimes, collection rates and recycling technologies. Compare secondary supply with conventional strategic stockpiles.

75.5 Study E. Export-control event study

Use daily or weekly prices, customs flows, inventory and downstream equity data around export-control announcements. Estimate immediate and persistent market effects while separating announcement, implementation and licensing phases.

75.6 Study F. Climate-adjusted mine supply

Overlay mine production with drought, flood, heat and wildfire projections. Model expected production-at-risk under multiple climate pathways and adaptation investment levels.

75.7 Study G. By-product recovery opportunity

Map global copper, zinc, alumina and lead facilities against potential gallium, germanium, tellurium, indium and other by-product recovery. Estimate technically recoverable supply and marginal cost under retrofit scenarios.

75.8 Study H. Technology pathway portfolio

Build a mineral-demand model spanning LFP, NMC, sodium-ion, solid-state batteries, rare-earth and rare-earth-free motors, and multiple grid-conductor options. Optimise the technology portfolio for cost and mineral-risk constraints.

Part XIII. Executive and Scientific Questions and Answers

Chapter 76

Fifty Questions for Scrutiny

76.1 1. Are critical minerals literally the new oil?

No. The comparison is useful only at a high strategic level. Oil is consumed continuously as fuel, so supply interruption affects existing activity immediately. Most minerals are embodied in long-lived assets. A mineral disruption mainly constrains new manufacturing, replacement equipment and expansion. The security tools therefore differ. Oil security relies heavily on fuel inventories and demand restraint. Mineral security relies more on diversified processing, strategic inventory for selected materials, alternate supplier qualification, recycling, substitution and product redesign. (International Renewable Energy Agency, 2023)

76.2 2. Is the world running out of critical minerals?

The evidence does not support a simple geological-depletion narrative. The more immediate risks involve economically recoverable supply, project timing, processing concentration, infrastructure, trade rules and investment. Large resources can exist while markets remain tight because developing a mine and refinery takes years. Reserve figures also change with price, technology and exploration. The key distinction is between material existing in the crust and qualified industrial product available at the place and time demanded.

76.3 3. Which mineral has the greatest global security risk?

There is no scientifically defensible universal answer because criticality depends on the actor, application and time horizon. Copper has enormous absolute-volume exposure. Graphite and magnet rare earths have extreme processing concentration. Gallium and germanium have small markets but high leverage in specialist technologies. Cobalt has strong geographic concentration and policy exposure. Lithium has rapid demand growth. A serious assessment identifies the failure mechanism rather than declaring one permanent "most critical" mineral. (Mammadli et al., 2026; Schicho & Tercero Espinoza, 2026)

76.4 4. Why is processing concentration more important than mine concentration in many cases?

Ore or concentrate is not directly usable in most advanced technologies. It must be converted into refined metal, battery chemical, purified graphite, separated rare earth or another specification. Processing can therefore remain a bottleneck even when mining diversifies. The IEA's 2024 data show top-three refining shares above or equal to mining concentration across six major energy-mineral systems. (International Energy Agency, 2025b, 2025e, 2025f, 2025a, 2025d, 2025g)

76.5 5. Why cannot high prices solve shortages quickly?

Price is a signal, not instant capacity. Exploration, feasibility, permitting, financing, infrastructure, construction and commissioning take years. Processing plants also require equipment, staff and qualification. High prices encourage investment, substitution and recycling, yet the physical response is delayed. This is why mineral cycles can overshoot in both directions.

76.6 6. Is China the only source of critical-mineral concentration?

No. China holds major positions in many processing stages, graphite, rare earths and strategic minor metals. Other concentrations are equally relevant in specific markets. The DRC dominates cobalt mining. Indonesia dominates nickel growth. Selected countries dominate platinum-group metals, lithium or uranium stages. Concentration should be mapped commodity by commodity and stage by stage. (Chung et al., 2026; International Energy Agency, 2026c)

76.7 7. Does geographic diversification always improve resilience?

Not automatically. Two mines in different countries might use the same port, refinery, reagent supplier or equipment vendor. Diversification only reduces risk when the underlying failure modes are sufficiently independent. Network analysis is therefore more informative than country counts alone.

76.8 8. Does domestic production guarantee national security?

No. Domestic ore might still require foreign refining, specialist equipment, chemicals, technology or customers. Conversely, a country with little domestic ore might achieve high security through diversified imports, large inventories, domestic processing, recycling and substitution. Resource ownership is one component of security.

76.9 9. Should every country seek self-sufficiency?

Full self-sufficiency is often geologically or economically unrealistic. The policy choice is better framed as a portfolio of domestic production, trusted imports, processing, inventory, recycling, substitution and international partnerships. The efficient mix differs by mineral and strategic use.

76.10 10. What does "critical" mean scientifically?

Most criticality frameworks combine importance with disruption risk and limited adaptability. There is no universal threshold. Criticality changes with technology, geography and time. A mineral important to semiconductor production might be less important to a country without that industry. Academic literature therefore treats criticality as perspective-dependent. (Schicho & Tercero Espinoza, 2026)

76.11 11. How reliable are 2040 demand forecasts?

They are scenario outputs, not certainties. Demand depends on technology adoption, policy, economic growth, material intensity, recycling and substitution. This monograph uses IEA scenarios as benchmarks and explicitly avoids presenting them as predictions. Good planning tests multiple demand pathways.

76.12 12. What does a projected supply gap mean?

A project-pipeline gap compares projected demand with expected supply from known projects under stated assumptions. It does not mean the world will physically run short by exactly that percentage. New projects, higher prices, recycling, demand changes and substitution can close part of the gap. The figure is best read as an investment signal.

76.13 13. Why is copper a concern despite its mature market?

Copper combines broad demand with huge absolute volume and long mine-development timelines. Electrification, grids, data centres and renewable generation all require conductive material. Even moderate percentage growth translates into millions of tonnes. Recycling and aluminium substitution help, yet scaling these responses also takes time. (International Energy Agency, 2026b)

76.14 14. Why is lithium different from copper?

Lithium has much faster percentage demand growth, stronger exposure to battery chemistry and more volatile recent price cycles. Its supply includes brines and hard-rock sources, while conversion to battery-grade chemicals is highly concentrated. Copper demand is more diverse and its market far larger. Different security tools are therefore appropriate.

76.15 15. Could sodium-ion batteries remove lithium risk?

They can reduce lithium demand in applications where sodium-ion performance and cost are competitive. They do not eliminate battery-material risk. Hard carbon, cathode materials, manufacturing capability and supply-chain concentration become more important. The scale and timing of adoption remain uncertain.

76.16 16. Does LFP eliminate nickel and cobalt risk?

It reduces nickel and cobalt demand in batteries that use LFP cathodes. Nickel and cobalt retain other industrial uses, and nickel-rich chemistries remain relevant in applications requiring high energy density. LFP also preserves dependence on lithium and graphite while increasing the importance of phosphate-chain materials.

76.17 17. Why is graphite strategically important when carbon is abundant?

Battery anodes require highly specified graphite products, not generic carbon. Natural graphite must be mined, purified, shaped and coated. Synthetic graphite requires specialised feedstock and high-temperature processing. The concentration lies in industrial capability and qualification, not carbon abundance. (International Energy Agency, 2026b)

76.18 18. Are rare earths geologically rare?

Not in the simple sense implied by the name. The challenge is economic concentration, complex mineralogy, separation chemistry, waste management and downstream magnet production. High-performance magnet supply is far more concentrated than rare-earth occurrence.

76.19 19. Why do gallium and germanium matter despite small market size?

They support high-value semiconductor, optical and defence applications. Supply is concentrated and often tied to recovery as by-products of larger metal systems. Small tonnage therefore supports large downstream economic functions. Market value is not a good proxy for strategic leverage.

76.20 20. What is by-product dependence?

A by-product mineral is recovered during production of another primary commodity. Its supply responds partly to the economics of the host metal rather than its own price. A gallium price spike, for example, does not automatically cause more bauxite mining. Recovery capacity at existing plants might be the binding constraint.

76.21 21. Does recycling remove the need for new mines?

No under major current transition scenarios. Rapid demand growth occurs before enough end-of-life material becomes available. Recycling becomes increasingly important over time and can reduce primary requirements, but it does not eliminate the need for primary supply during the major build-out period. (International Energy Agency, 2026b)

76.22 22. Why is battery recycling itself a security issue?

Recovery capacity is geographically concentrated. Collection, pretreatment, hydrometallurgy and final recovery require industrial infrastructure. A country could possess large volumes of used batteries yet depend on foreign processors to recover materials. Circularity and diversification therefore need to be assessed separately.

76.23 23. Which recycling technology is best?

No universal answer exists. Pyrometallurgy handles mixed feed robustly. Hydrometallurgy can achieve high recovery of several metals. Direct recycling has potential to retain more cathode value but faces feed-separation and qualification challenges. The optimal route depends on chemistry, scale, energy, regulation and desired products. ('Scaling Direct Recycling of Lithium-Ion Batteries Toward Industrialization', 2025)

76.24 24. Does substitution solve criticality?

It reduces exposure to one material while increasing exposure elsewhere or changing performance. Good security analysis maps second-order effects. Aluminium can reduce copper use but requires more aluminium production. LFP reduces nickel and cobalt but retains lithium and graphite. Rare-earth-free motors change copper, steel and power-electronics requirements.

76.25 25. How important are export restrictions?

They are increasingly significant. OECD data show a fivefold increase in restrictions since 2009, with high exposure for several strategic materials. (Organisation for Economic Co-operation and Development, 2026) The effect depends on market share, duration, exemptions, inventory and substitution. Restrictions also influence investment long before physical shortage emerges.

76.26 26. Do export bans help producer countries industrialise?

Outcomes differ. Export restrictions can create an incentive for local processing, as Indonesia's nickel experience demonstrates. They can also raise trade disputes, create fiscal or environmental costs and fail if infrastructure or skills are weak. The correct research question is under what conditions downstreaming produces durable productivity and value addition. (World Bank, 2026; World Trade Organization, 2022)

76.27 27. What is the risk of trade fragmentation?

Fragmentation can create regional shortages even when global supply is adequate. IMF modelling shows that severe critical-mineral trade fragmentation could materially reduce investment in clean technologies relative to an unfragmented case. (International Monetary Fund, 2023) The result is illustrative rather than predictive.

76.28 28. Are strategic stockpiles economically sensible?

For some materials and applications. Stockpiles are attractive when material volume is small, downstream value is high and alternate supply takes time. They are less attractive for bulky commodities with large annual consumption. Governance, rotation, quality and release rules determine effectiveness.

76.29 29. What is a mineral security premium?

It is the additional cost paid for lower disruption risk through diversified or more reliable supply. The rational premium depends on expected loss from disruption, final-product value, substitution and inventory. A small input supporting a high-value product can justify a larger percentage premium than a bulk input.

76.30 30. Why would a buyer pay more for diversified material?

Because lost production can cost far more than the incremental input price. If a rare-earth magnet represents less than one percent of a vehicle's value but its absence stops vehicle production, reliable supply carries option value. (International Energy Agency, 2026b)

76.31 31. Could diversification itself become inefficient?

Yes. Building every stage in every country creates duplication, low utilisation and high cost. The objective is not maximum geographic dispersion. It is an economically defensible reduction of concentrated failure risk.

76.32 32. How should governments measure success?

Not by announcements alone. Relevant outcomes include commissioned and qualified capacity, concentration reduction, private capital mobilised, production reliability, environmental performance, public cost and recovery capability during stress.

76.33 33. Why distinguish capacity from production?

A plant rated for 100,000 tonnes might produce far less because of feedstock, technical problems, maintenance, market weakness or qualification. Installed capacity overstates supply if utilisation is poor. Research should report both.

76.34 34. Why distinguish resources from reserves?

Resources represent geological material with reasonable prospects for eventual extraction. Reserves are the economically mineable portion after modifying factors. Neither equals current production. Confusing these terms exaggerates immediate supply.

76.35 35. What is customer qualification?

It is the process through which a buyer verifies that material meets technical, quality and reliability requirements. Qualification can take months or longer. Alternate capacity that is not qualified might offer little immediate resilience during a shock.

76.36 36. Why are specialist equipment suppliers important?

Processing capacity depends on furnaces, separators, coating equipment, reactors, controls and other specialised systems. If only a few suppliers produce key equipment, new capacity can be delayed even when finance and feedstock exist. Capability concentration can therefore exceed commodity concentration.

76.37 37. How does ESG affect security of supply?

Water shortage, social conflict, tailings failure, labour problems, biodiversity litigation and governance failures can delay or close projects. ESG variables therefore influence physical continuity and financing, not only reputation. (Aska et al., 2025; Sefa-Nyarko, 2026)

76.38 38. Does stronger environmental regulation always reduce supply?

Not necessarily. Poorly designed or unpredictable regulation can delay projects. Strong, clear and predictable standards can reduce later conflict and legal risk. The empirical question is total project time and operating continuity, not statutory approval speed alone.

76.39 39. How should biodiversity be measured in mining analysis?

Hectares disturbed are insufficient. Researchers should consider ecosystem condition, rarity, species vulnerability, connectivity, cumulative effects and restoration feasibility. Spatial analysis linking deposits with biodiversity layers is essential.

76.40 40. How does climate change affect mineral security?

Through both physical and transition channels. Drought, flooding, heat and storms affect mines, transport and power. Carbon policy and buyer preferences affect the competitiveness of energy-intensive processing. Climate resilience therefore belongs in project economics.

76.41 41. What role do communities play in mineral security?

Projects operate in social settings. Community relationships influence access, workforce stability, legal challenge and transport continuity. Durable benefit sharing and credible grievance systems can reduce disruption risk, though their effectiveness needs more empirical research.

76.42 42. How should artisanal mining be treated?

As a livelihood and governance system, not only a compliance problem. Formalisation, traceability, safety, transparent purchasing and enforcement against exploitation can improve outcomes. Blanket exclusion can push activity into less visible channels.

76.43 43. Are critical-mineral partnerships changing markets?

They are expanding rapidly. UNCTAD identified 73 partnership agreements in its 2026 analysis, most signed since 2022. (UN Trade and Development, 2026) Their real impact should be assessed through financed projects, production, technology transfer, local value addition and trade flows rather than number of agreements.

76.44 44. What does the EU Critical Raw Materials Act seek to achieve?

It establishes 2030 benchmarks for EU extraction, processing and recycling and seeks to limit excessive dependence on a single non-EU supplier at relevant processing stages. (European Commission, 2024) The benchmarks create a basis for future empirical assessment of cost and diversification outcomes.

76.45 45. What is the significance of the G7 2026 mineral initiative?

The G7 created a non-binding framework for cooperation on diversification, finance, data, stockpiles and emergency preparedness. (Group of Seven, 2026b, 2026a) Its importance will depend on whether coordination produces operating capacity and qualified supply.

76.46 46. How should companies stress-test mineral exposure?

They should map direct and indirect suppliers, identify concentration at mine and processing stages, test export-control and outage scenarios, measure inventory days, estimate supplier-qualification time and model product redesign options. Stress tests should include compound shocks rather than one supplier failing in isolation.

76.47 47. What is the proposed Mineral Security System Resilience score?

It is a conceptual research framework introduced in this monograph. It aggregates eight resilience domains through a weighted geometric mean so that severe weakness in one domain is not easily hidden by strength elsewhere. It has not been empirically validated and should not be used as an official rating without further research.

76.48 48. Why use a geometric mean?

A geometric mean penalises bottlenecks. If processing resilience is near zero, abundant geology should not produce a high overall score. This reflects the complementarity of supply-chain stages. The method still requires validation and sensitivity analysis for weights and normalisation.

76.49 49. What evidence would falsify the central thesis of this monograph?

The thesis would weaken if future disruptions consistently showed that geological abundance alone predicted secure industrial supply, if refining and qualification bottlenecks had little effect, or if environmental, trade and technology variables failed to explain supply continuity. A research framework should be falsifiable rather than designed to confirm its premise.

76.50 50. What is the most important unanswered question?

The central unresolved question is how much resilience societies should purchase and where. Diversification, inventory, recycling and redundancy all carry cost. Too little resilience creates disruption risk. Too much creates inefficient capital and higher prices. The optimal balance differs by mineral, application and tolerance for interruption. Quantifying this balance is a major interdisciplinary research task.

Part XIV. Synthesis and Conclusions

Chapter 77

What the Evidence Supports

The evidence assembled in this monograph supports nine broad findings.

First, critical-mineral demand is rising across energy, digital, industrial and strategic systems, yet growth rates differ sharply by material and scenario. Aggregate demand approaching twice current levels by 2040 under the IEA's 2026 Stated Policies Scenario is a useful benchmark, not a certainty. (International Energy Agency, 2026f)

Second, concentration is frequently greater in refining and processing than in mining. The strategic bottleneck therefore often sits in the midstream.

Third, market size is a poor measure of importance. Small quantities of high-leverage materials can affect trillions of dollars of downstream activity.

Fourth, investment cycles generate structural risk because project lead times are much longer than price cycles. Low prices can improve present affordability while weakening future supply options.

Fifth, trade policy is now an observed driver of mineral markets. Export restrictions, quotas, licensing and strategic partnerships influence investment, inventory and technology choices.

Sixth, resource-rich producer countries increasingly seek domestic value addition. Success depends on industrial capability, infrastructure, market access, power, finance and governance rather than resource ownership alone.

Seventh, environmental and social conditions belong inside supply-security analysis because they affect project continuity, permitting and financing.

Eighth, recycling, substitution and material efficiency are essential adaptation mechanisms, but none removes the need for primary supply across all minerals and horizons.

Ninth, resilience is a portfolio property. It emerges from diversified sources, processing, inventory, contracts, technology, recycling, social legitimacy and the ability to recover after disruption.

Chapter 78

The Central Analytical Shift

The key analytical shift is from **mineral availability** to **industrial function**.

Traditional analysis asks how much copper, lithium or rare earth material exists. A security analysis asks whether the industrial function supported by the material will remain available through disruption.

That function might be electricity transmission, battery storage, magnetic torque, semiconductor switching or heat resistance. Once the function becomes the unit of analysis, a broader set of resilience options appears: alternative materials, redesigned products, spare capacity, inventory, recycling, demand efficiency and network reconfiguration.

This approach avoids two errors. It avoids assuming more mining is the only solution. It also avoids assuming technology will remove physical constraints automatically.

Chapter 79

A Research Standard for Future Work

Future critical-mineral research should meet five standards.

Stage specificity. Identify whether the data refer to mining, concentration, refining, chemicals, components or final manufacturing.

Scenario transparency. Label projections, assumptions and observed data separately.

System boundaries. State whose security is being assessed and which applications are included.

Multidisciplinary evidence. Integrate engineering, economics, trade, environmental and social data.

Reproducibility. Preserve sources, units, calculations and code.

Chapter 80

Final Perspective

Critical minerals are becoming strategic industrial infrastructure because modern energy, digital and manufacturing systems depend on them. Their importance does not make them equivalent to oil. The material, market and technological mechanics are different.

The deepest risk is not simple scarcity. It is the possibility that a complex chain fails at one of several complementary stages: project development, processing, logistics, technology, finance, environmental legitimacy or trade.

The deepest opportunity is equally systemic. Better geology, faster learning, diversified processing, transparent markets, responsible development, recycling, material efficiency and international cooperation all expand the set of available responses.

The research task for the next decade is therefore not to predict one mineral future. It is to understand which combinations of resources, technologies, institutions and industrial capabilities keep essential functions operating across many possible futures.

That is the scientific foundation of mineral security.

Appendix A. Controlled Glossary

Anode. The negative electrode in a battery during discharge. Commercial lithium-ion batteries commonly use graphite-based anodes, with growing interest in silicon blends and other materials.

Battery grade. A product specification sufficiently pure and consistent for battery manufacturing. The term is chemistry-specific and does not mean every producer meets the same universal specification.

Beneficiation. Physical or chemical upgrading of mined material before refining, such as crushing, grinding, flotation, gravity separation or magnetic separation.

By-product. A material recovered during production of another primary commodity. Supply is partly governed by the host commodity's economics.

Capacity. Maximum or nameplate output a facility is designed to produce. Capacity is not the same as actual production.

Cathode. The positive electrode in a battery during discharge. Cathode chemistry strongly influences lithium, nickel, cobalt, manganese, iron and phosphate demand.

Circularity. The set of practices that keep materials in productive use through durability, repair, reuse, remanufacturing and recycling.

Commodity concentration. The degree to which production or processing is controlled by a small number of countries or firms.

Concentrate. An upgraded mineral product produced after beneficiation and before smelting or refining.

Critical mineral. A context-dependent mineral considered economically or strategically important and exposed to meaningful supply risk or limited adaptability.

Direct lithium extraction. A family of technologies designed to selectively recover lithium from brines using adsorption, ion exchange, membranes, solvents or other processes rather than relying solely on conventional evaporation ponds.

Direct recycling. Battery recycling intended to preserve or restore active materials rather than fully converting them back to basic chemical constituents.

Downstream. Later stages of a value chain, including components, manufacturing and final products.

Export control. A legal restriction requiring licensing, limiting volume or prohibiting export of selected goods or technologies.

Feedstock. Material entering a processing facility.

Ferrite magnet. A lower-cost permanent magnet based on iron oxide and ceramic materials, used in some applications as an alternative to rare-earth magnets.

Free, prior and informed consent. A rights-based process associated particularly with Indigenous Peoples in which consent is sought before activities affecting rights or territories proceed, under applicable legal and normative frameworks.

Geological resource. A concentration of material with reasonable prospects for eventual economic extraction under a recognised reporting framework.

Grade. Concentration of valuable material within ore or another feedstock.

Hard carbon. A non-graphitisable carbon material used especially in sodium-ion battery anodes.

Herfindahl-Hirschman Index. A concentration metric calculated from squared market shares. Higher values indicate greater concentration.

Hydrometallurgy. Extraction and purification using aqueous chemistry, often involving leaching, solvent extraction, precipitation or ion exchange.

Industrial policy. Government measures intended to influence the structure, capacity or competitiveness of industries.

Inventory days. The number of days normal consumption can be supported by available inventory under stated assumptions.

LFP. Lithium iron phosphate, a lithium-ion cathode chemistry containing no nickel or cobalt in the cathode active material.

Material intensity. Quantity of a material required per unit of technology, capacity or service.

Midstream. Processing stages between extraction and final manufacturing, including refining, chemical conversion and selected precursor production.

Mineral reserve. The economically mineable portion of a measured or indicated mineral resource after relevant modifying factors are applied.

Mineral resource. A concentration of material with reasonable prospects for eventual economic extraction, classified according to confidence under an applicable code.

NMC. Nickel-manganese-cobalt family of lithium-ion cathode chemistries.

Offtake agreement. Contract under which a buyer agrees to purchase future production under defined terms, often supporting project finance.

Ore grade. Concentration of a target commodity in mined material before beneficiation.

Permanent magnet. A material that retains magnetisation without continuous electrical input. High-performance neodymium-iron-boron magnets are important in selected motors, wind turbines and electronics.

Processing concentration. Geographic or corporate concentration in refining, purification, chemical conversion or other intermediate transformation.

Project pipeline. Set of announced, planned, financed, under-construction and operating projects expected to contribute future supply.

Pyrometallurgy. High-temperature metallurgical processing such as roasting, smelting or converting.

Qualification. Customer testing and approval required before a material or component is accepted for commercial use.

Rare earth elements. A group of 17 elements consisting of the lanthanides plus scandium and yttrium. Their industrial uses differ substantially.

Recovery rate. Share of valuable material successfully recovered from feedstock through mining, processing or recycling.

Refining. Processing that converts intermediate material into a higher-purity product suitable for downstream use.

Resilience. Ability of a system to withstand, adapt to and recover from disruption while maintaining an agreed level of function.

Resource nationalism. Government intervention intended to increase domestic control, revenue or value capture from natural resources.

Secondary supply. Material supplied from recycling, reuse, recovery from waste or other non-primary sources.

Security premium. Incremental cost accepted to reduce exposure to disruption through diversification, inventory or other resilience measures.

Social licence. Informal societal acceptance or legitimacy associated with a project or company, distinct from formal legal permits.

Spheronisation. Processing of natural graphite into rounded particles suited for lithium-ion battery anodes.

Strategic stockpile. Inventory held to support continuity during disruption rather than normal commercial operation alone.

Substitution. Replacement of a material, component or technology with another that performs a similar function.

Supply elasticity. Responsiveness of supply to a change in price or other incentives.

Tailings. Finely ground waste and process water remaining after valuable minerals are separated from ore.

Treatment charge. Fee paid to a smelter or refiner to process concentrate, often serving as a market indicator of concentrate availability relative to processing capacity.

Upstream. Early stages of a value chain including exploration, mining and initial concentration.

Value chain. Connected stages through which material moves from resource to processed input, component, product, use and end-of-life recovery.

Appendix B. Evidence Hierarchy and Source Audit

80.1 Evidence hierarchy used

This monograph prioritises sources in the following order for quantitative claims:

1. official statistical or technical agencies such as USGS;
2. major intergovernmental organisations such as IEA, OECD, UNCTAD, IMF and the World Bank;
3. primary government laws, regulations and policy announcements;
4. peer-reviewed academic literature;
5. official company disclosures for project-specific facts;
6. reputable secondary analysis where primary evidence is unavailable.

Peer-reviewed work is prioritised for theory, methods and causal interpretation. Institutional sources are prioritised for current market statistics because academic publication lags fast-moving mineral data.

80.2 Evidence cut-off

The evidence cut-off for this edition is 17 September 2026. Sources published after that date are not represented. Fast-moving policy measures, prices and project status should therefore be rechecked before the report is used for an operational decision.

80.3 Observed versus modelled evidence

Observed data include reported production, trade measures, project announcements, current capacity and historical statistics.

Modelled evidence includes IEA demand scenarios, project-pipeline gaps, IMF fragmentation analysis and analytical value-add cases. These are labelled in the text as scenarios, estimates or analytical cases rather than presented as observed future facts.

80.4 Current versus historical evidence

Several older sources remain in the bibliography because they define methods or provide historical evidence. The World Bank's 2020 mineral-intensity analysis is treated as historical scenario work, not as a current 2026 forecast. McCullough and Nassar's 2017 work is used for criticality methodology. Current market claims rely primarily on 2025 and 2026 data.

80.5 Source conflicts

Where credible sources differ, differences can arise from product definitions, time periods, units, conversion assumptions or whether capacity and production are mixed. This edition avoids averaging conflicting figures without understanding those differences.

Future researchers should retain source-specific series before harmonisation.

Appendix C. Methodological Limitations

No global critical-mineral study eliminates uncertainty. The principal limitations of this monograph are listed below.

Data lag. Mine and trade statistics often appear months after the reporting period.

Commercial confidentiality. Refining yields, contracts, inventories and customer qualification are frequently private.

Product heterogeneity. One commodity name can contain multiple grades, chemical forms and specifications.

Capacity ambiguity. Announced, nameplate, commissioned and sustainable capacity are different concepts.

Political uncertainty. Trade controls and industrial policies can change quickly.

Technology uncertainty. Battery, motor, semiconductor and recycling technologies are evolving.

Scenario uncertainty. Long-term demand depends on policy, economics and technology. No single scenario is treated as a forecast.

Environmental data gaps. Site-level water, biodiversity and waste data are inconsistent across jurisdictions.

Social measurement. Community trust, social licence and rights impacts are difficult to compare across cultures and legal systems.

Network opacity. Exact mine-to-refinery-to-OEM connections are often confidential or change through commodity trading.

Price opacity. Several minor metals lack deep transparent markets.

Index design. The MSSR formulation is conceptual and requires empirical validation before use as an operational rating.

These limitations are not reasons to avoid analysis. They identify where confidence should be lower and where research effort has the greatest value.

Appendix D. Falsifiability and Audit Tests

A research document should state what evidence would challenge its conclusions.

The central systems thesis should be reconsidered if:

1. processing concentration does not predict disruption or adaptation after controlling for mine concentration;
2. supplier qualification proves negligible in major disruptions;
3. environmental and social variables show no measurable relationship with project delay or continuity;
4. diversified supply portfolios do not recover faster after shocks;
5. recycling and substitution fail to alter primary-demand exposure as expected;
6. network metrics add no explanatory value beyond national market shares;
7. the proposed MSSR fails to predict historical supply stress better than simple concentration metrics.

These tests provide a pathway from conceptual framework to empirical science.

Appendix E. Suggested Open and Institutional Data Sources

US Geological Survey Mineral Commodity Summaries. Annual production, reserves and market information across a broad set of minerals. (U.S. Geological Survey, 2026)

International Energy Agency Critical Minerals Data Explorer and outlooks. Demand, supply, concentration, project pipelines and policy analysis for major energy minerals. (International Energy Agency, 2025c, 2026c)

OECD Inventory of Export Restrictions on Industrial Raw Materials. Structured trade-restriction data. (Organisation for Economic Co-operation and Development, 2026)

UN Comtrade. Bilateral merchandise trade data by product code.

UNCTAD. Trade, development and partnership analysis relevant to producer-country value addition. (UN Trade and Development, 2026)

World Bank. Commodity markets, governance, development and country studies.

IMF. Macroeconomic and trade-fragmentation analysis.

European Commission Raw Materials Information System. EU-focused material and supply-chain information.

National geological surveys. Deposit, reserve, production and geoscience data.

Satellite and geospatial datasets. Land cover, forest loss, water, climate hazard and infrastructure data suitable for spatial mineral-risk analysis.

Company technical reports. Reserve, resource, metallurgy, capex, schedule and environmental information, subject to jurisdiction-specific disclosure rules.

Appendix F. Publication Audit

80.6 Scope audit

This edition covers geology, project development, processing, trade, geopolitics, finance, markets, environmental science, social legitimacy, circularity, technology substitution, actor-specific strategy, scenarios, early-warning indicators and future research.

It includes thirty-four single-factor scenarios across demand, supply, policy, technology, ESG, logistics and finance, plus twelve compound-shock scenarios. The scenario architecture is deliberately broad rather than claiming to enumerate every conceivable event.

It includes fifty scrutiny questions and forty research questions.

80.7 Quantitative audit

All major current quantitative claims are tied to cited institutional sources. Scenario values are labelled as scenarios or analytical estimates. The report does not convert IEA or IMF model outputs into forecasts.

The six-mineral comparative table uses a consistent IEA 2025 data source to reduce cross-source comparability problems.

80.8 Conceptual audit

The report distinguishes:

- resources from reserves;
- reserves from production;
- capacity from production;
- mine concentration from refining concentration;
- observed data from scenarios;
- geological availability from industrial availability;
- primary from secondary supply;
- material substitution from functional substitution;
- price risk from physical availability risk.

80.9 Political and policy audit

Government policies are described as instruments with documented objectives, observed effects or analytical trade-offs. The report does not rank political systems, governments or electoral choices. Policy options are evaluated against measurable criteria rather than partisan preference.

80.10 Academic audit

The report includes peer-reviewed work from mineral economics, energy research, resource policy, industrial ecology, environmental science and climate research. Institutional data and peer-reviewed literature are used for different purposes and are not treated as interchangeable.

80.11 Original contribution audit

Original analytical contributions are explicitly identifiable and should not be mistaken for established external indices. These include:

1. the eight-domain Mineral Security System Framework;
2. the conceptual MSSR geometric aggregation;
3. the shock-adjusted domain formulation;
4. recovery time as an explicit security metric;
5. the 48-indicator early-warning architecture;
6. the integrated scenario taxonomy;
7. the actor-specific weighting concept;
8. the research validation programme.

These elements are proposed for testing, replication and critique.

80.12 Final quality statement

This monograph is designed as a research foundation rather than a final scientific consensus. It uses current evidence available at the cut-off date, marks uncertainty, separates external evidence from original analysis and defines empirical tests that could support or reject its propositions.

For academic citation, researchers should cite the original institutional or peer-reviewed source for source-specific facts and cite this monograph only for its synthesis, scenario architecture and original analytical framework.

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