TRILATERAL ENERGY SECURITY COMMITTEE

Critical Minerals Supply Chain Security: A Framework for Trilateral Investment Coordination

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The Trilateral Energy Security Committee (TESC) is a collaborative effort led by experts from the Hamm Institute for American Energy, Oklahoma State University Global (OSU Global), the Korea Energy Economics Institute (KEEI), and the Institute of Energy Economics, Japan (IEEJ). The TESC's goal is to assess holistically the current state of energy resources, dependence, and vulnerabilities, to address the energy security risks impacting South Korea, Japan, and the U.S., and provide policy recommendations to help mitigate those risks.

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Executive Summary

This report examines the security of critical mineral supply chains with a focus on coordinated action by the United States, Japan, and South Korea (the "Triad"). Critical minerals have become a binding constraint on energy security, advanced manufacturing, and technological competitiveness. As demand accelerates for critical products and components like batteries, semiconductors, and high-performance magnets, supply chains that were once treated as commercial inputs now carry clear strategic and national security implications. For the Triad, the challenge is shared in that each economy depends heavily on imported critical mineral inputs and all face acute exposure to concentration risks, particularly regarding China's highly concentrated market share across key processing and manufacturing sectors of critical minerals.

To identify areas where meaningful, coordinated intervention is possible, this report integrates two analytical frameworks. First, mineral-specific Petri map analysis, which traces materials through detailed process steps, revealing technical dependencies and chokepoints that are obscured in aggregate trade data. Second, an adapted multi-stage Cluster and Factor Analysis, which evaluates a value chain of 18 generic stage archetypes against 8 structural factors. Together, these frameworks shift the policy debate from generalized diversification toward defensible, process-level investment priorities.

The Petri map analysis shows consistent patterns across battery, semiconductor, and magnet supply chains. Even where upstream extraction occurs outside of China, midstream conversion, purification, and advanced material production remain highly concentrated, often at levels exceeding 70-90 percent global share. These chokepoints expose allied downstream manufacturing to coercive risk and supply disruption, even where the Triad retains significant strengths.

The Cluster & Factor Analysis Framework (CFAF) clarifies why apparent vulnerabilities persist. Upstream stages are largely immobile and geology-bound, limiting the scope for trilateral self-sufficiency and pointing instead toward coordinated investment and offtake arrangements with aligned resource-rich partners. Downstream stages benefit from existing allied manufacturing excellence and competitive ecosystems but remain hostage to insecure midstream inputs. The midstream segment emerges as the principal intervention opportunity as these stages are not geology-bound, align with existing allied capabilities in chemicals, materials science, and precision manufacturing, and they exhibit high potential for coordinated specialization across the Triad.

Ultimately, this report provides a structured framework for identifying where trilateral coordination is both necessary and feasible. It establishes a foundation for subsequent mineral-specific analysis and for translating strategic intent into coordinated project pipelines that would enhance allied security and resilience in the global supply chain before vulnerabilities become crises.

Introduction

The global race for energy security and advanced manufacturing dominance has elevated critical minerals from an industrial concern to a matter of national and economic security. As the U.S., Japan, and South Korea (the "Triad") work to reduce dependencies on China's commanding position across extraction, processing, and manufacturing, the need for strategic coordination has never been greater. Traditional supply-chain analyses often focus on either geopolitical vulnerability or industrial capability in isolation. This report integrates both dimensions through a dual-methodology approach, using Petri Map analysis to generate a detailed, mineral-specific process map that reveals technical dependencies, chokepoints, and opportunities for intervention across each value chain and a Cluster & Factor Analysis Framework (CFAF) to guide systematic evaluation of structural conditions that determine where value chain stages can realistically emerge, scale, and remain competitive. Together, these methodologies enable industry and government stakeholders to move beyond generalized calls for "supply-chain diversification" toward precise, defensible investment priorities grounded in industrial reality.

Strategic Context

The concentration of critical mineral processing and manufacturing capabilities presents acute strategic vulnerabilities for allied economies. China's dominance extends across multiple value chain stages including refining operations for rare earth elements, lithium conversion to battery-grade compounds, graphite purification, and the manufacturing of permanent magnets, battery cells, and solar panels (Kim, 2025). Recent export restrictions on gallium, germanium, and graphite have demonstrated how quickly mineral dependencies can become instruments of coercive leverage, as they are crucial to key security supply chains for the U.S. and its allies (Y. G. Kim, 2025). China can use this monopoly as a negotiation tactic to reduce tariffs on China or give it an edge in the development of key technologies.

Each nation has launched major industrial policy initiatives in recent years to combat the lack of diversification in the market: the U.S. Inflation Reduction Act and Infrastructure Investment and Jobs Act, initially projected to mobilize hundreds of billions in clean-energy investments; Japan's Green Transformation (GX) strategy linking decarbonization with industrial renewal; and South Korea’s push to consolidate its position as a global battery and semiconductor manufacturing hub (Volta Foundation, 2025). Yet these parallel efforts risk duplicating efforts without substantially reducing vulnerability. Given the converging pressures, the Triad should avoid competitive fragmentation and instead coordinate to capitalize on complementary strengths and build robust, interdependent supply chains.

Supply-chain fragility is seen differently across the Triad, creating both risks and opportunities for coordination. The U.S. remains highly import-dependent for a broad range of critical minerals, with 100% net import reliance for 12 of the 50 minerals designated as "critical" in the 2022 list (Amgott, 2025). China serves as the leading supplier for many of these minerals and exerts dominant influence in processing and refining, especially of rare-earth elements. China controls nearly half of global rare-earth reserves and over 60% of mining but processes close to 90% of them (Baskaran, 2024). Japan's supply-chain vulnerability emerges from near-complete dependence on foreign mineral supplies combined with legacy over-reliance on China for rare-earths and related processing. Experience provides stark illustration of this vulnerability. In 2010, China's export restrictions on rare-earth elements to Japan caused a strategic shock

(Nishimura, 2025), and despite subsequent diversification efforts, Japanese data show that imports from China for certain rare earths rose to 79.6% in the first half of 2024 (Maekawa Yusuke, 2024). South Korea also remains among the most import-dependent advanced economies, with import-dependency rates for six critical minerals exceeding 70%, including natural graphite (98.7%), manganese sulfate (97.7%), lithium (95.2%), rare-earth oxides (95.1%), cobalt oxide (70.7%), and nickel hydroxide (72.1%) (Cheon-gu, 2025). This dependence continues to grow, with South Korea's purchases of 37 critical minerals from China reaching $7.03 billion in 2023, over three times the value recorded in 2018 (Jun-ho & Yeon-hae, 2025). South Korea's small domestic mine base produces less than one percent of global output, further constraining self-sufficiency (Korea Times, 2024).

These vulnerabilities are primarily due to a lack of global investment diversification, leading to limited domestic mining capacity and midstream processing infrastructure across all three nations. Given the time lag required to build and scale processing and refining capacity, vulnerabilities may persist in the near-term. Initial actions with partners outside of the Triad include Japanese investments in Australia's Lynas rare earth operations (Meredith & Butts, 2025) and the U.S.'s framework to coordinate with Australia, announced in October 2025.

The overlapping critical minerals identified across the Triad's national priority lists spanning battery minerals, permanent magnet metals, and semiconductor materials represent the basis for a strategic alignment opportunity (G.-P. Kim, 2025; Mineral Resources Program, 2025). These materials underpin advanced electronics, defense applications, electric vehicles, and renewable energy systems, where allied technological leadership depends on secure material access. Our approach seeks to capture this strategic opportunity at both a broad and granular level by applying two distinct analytical frameworks to the critical minerals' domain.

Analytical Framework

This report applies two structured analytical frameworks to guide trilateral coordination across critical-mineral value chains. To ground the analysis in process-level reality, the study employs Petri mapping, which represents how materials move through specific physical and chemical transformation steps within each value chain. This process-technology lens is paired with a factor-based analytical framework, which evaluates where structural dependencies, chokepoints, or coordination requirements arise at the stage archetype level, rather than through aggregate trade flows or country-level capabilities.

Petri maps visualize materials as they move through four broad segments—Upstream raw materials, Midstream processed materials and Midstream engineered components, and Downstream integration. To enable systematic comparison across minerals, a factor-based framework then maps these detailed process flows onto a common structural backbone of 18 generic stage archetypes, spanning the lifecycle from exploration through downstream integration and applicable across multiple mineral families. This generic stage archetype structure provides a stable reference point for identifying structural dependencies and assessing where trilateral industrial strengths can complement one another rather than duplicate effort.

Crucially, the framework separates structural viability from current capabilities. This distinction allows the analysis to focus on not only where gaps exist today but also where coordinated investment or policy action could be structurally feasible and durable over time, independent of present-day production patterns.

Introduction to Petri Maps: Revealing Process-Level Dependencies

Petri maps are process diagrams that trace how raw materials are transformed into finished products across value chains. The term "Petri map" reflects a biological analogy: just as a Petri dish reveals microorganism interactions invisible to the naked eye, these maps expose dependencies that aggregate supply-chain data obscures. For critical minerals analysis, this granularity proves essential because strategic vulnerabilities and intervention opportunities often reside not in mining or final manufacturing, the most visible stages, but in midstream processing steps that require specific technical capabilities, reagent supplies, environmental controls, or equipment that only a few facilities worldwide possess.

Petri maps were originally designed to analyze single, end-use products for one firm, highlighting chokepoints or limited supplier diversity. We adapted this approach to map entire product groups. Instead of firms as actors, we aggregate countries involved in each process as the actor but separately list their market shares. Unlike high-level supply-chain diagrams that emphasize trade flows between countries or companies, Petri maps operate at the process-technology level, detailing physical and chemical transformations, required inputs, intermediate outputs, and critical dependencies at each stage.

The data for the Petri maps in this study came from a range of government and non-government official websites, such as the U.S. Geological Survey (USGS), the International Energy Agency (IEA), and the U.S. Department of Energy (DOE). Our approach began by identifying three major categories of critical minerals (battery materials, semiconductor materials, and permanent magnet materials) as defined by the USGS 2025 critical mineral list. From this broader list, we selected only those minerals that directly contribute to the production of key downstream technologies such as lithium-ion batteries and conventional semiconductors. According to USGS criteria, these minerals represent the most essential inputs for manufacturing final energy and electronic products.

To create a consistent structure, we adopted the U.S. Department of Energy (DOE) framework for organizing the stages of critical mineral supply chains into four broad categories: (1) upstream raw materials, (2) processed materials, (3) engineered components, and (4) final end-use products. The mapping flows from raw critical minerals positioned at the upstream end and final technologies placed at the downstream integration end. We worked in both directions, upstream and downstream, to identify the intermediate stages of processed materials and engineered components through a review of a combination of engineering literature, industry analyses, and market research.

Upstream raw material data was sourced primarily from the USGS 2025 Mineral Commodity Summaries, which provided 2024 World Production Capacity data. From those data, the market share by country was calculated. For the midstream and downstream data, we used secondary research from engineering publications and market intelligence platforms. We noted with an asterisk when data was not publicly available.

Critical mineral supply chains are not simple linear flows. A battery-grade lithium compound, for instance, may pass through 8-12 distinct process steps, each requiring specific technical capabilities, regulatory approvals, and input materials. Our intention with the modified Petri maps is to reveal the stages controlled by single countries or firms, adjacency opportunities where existing industrial capabilities (chemicals, metallurgy, semiconductor processing) can be leveraged, modularity potential showing which stages can be geographically separated without performance loss, technical barriers where specialized equipment, proprietary know-how, or extreme purity requirements limit replication, and environmental constraints that may require stringent controls to responsibly control hazardous pollutants and waste.

Industry Cluster and Factor Analysis: Identifying Strategic Solutions

This study also applies an adapted industry cluster analysis framework to evaluate where robust critical mineral supply chains can be developed and sustained in support of economic resilience and national security objectives. The approach builds on foundational cluster theory developed by Michael Porter and subsequent refinements by Christian Ketels (Ketels, 2017), but extends these concepts to reflect the distinctive characteristics of critical mineral value chains.

Traditional cluster analysis focuses on how competitive industries concentrate geographically through interrelated factors—such as supplier networks, institutions, and market demand—within relatively bounded regions. Critical mineral supply chains, however, differ in important ways. They are inherently fragmented across geography, with different stages concentrated in different countries due to geological endowments, process technologies, regulatory requirements, and geopolitical constraints. As a result, the analytical question is not whether a single region can anchor an entire cluster, but which specific stages of a value chain can serve as strategic footholds within a coordinated, multi-country system.

To address this challenge, the analysis employs an adapted multi-stage Cluster & Factor Analysis Framework (CFAF), purpose-built for critical minerals. Rather than treating the value chain as a single unit, the framework disaggregates it into 18 generic stage archetypes, spanning the full lifecycle from exploration through downstream integration. These stage archetypes provide a common structural backbone that can be applied consistently across multiple mineral families, enabling systematic comparison while remaining grounded in process-level realities.

Once this generic stage architecture is established, the framework evaluates each value chain stage using a factor-based structural scoring approach. Each stage is assessed across eight structural factors designed to capture the conditions that shape where and how critical mineral activities can emerge, scale, and remain resilient over time. Together, these factors assess foundational prerequisites, catalytic enablers, and security-related constraints, providing a structured lens for comparing stages and identifying where coordinated trilateral action is most likely to be effective.

Cluster & Factor Analysis Framework (CFAF)[1]

Foundational Conditions (Cluster Emergence)

These factors assess the basic prerequisites for a stage to emerge.

1. *Resource & Input Advantage* — evaluates whether a stage is structurally anchored to specific geological resources, feedstocks, or immobile natural inputs that constrain where it can be located.
2. *Related Variety & Technological Proximity* — assesses whether a stage depends on adjacency to other industries with overlapping process technologies, suppliers, or transferable technical skills.

3. *Institutional Thickness* — examines the degree to which a stage structurally relies on dense institutional support, such as certification systems, engineering ecosystems, specialized workforce pipelines, or research infrastructure.

Catalytic Conditions (Cluster Acceleration)

These factors capture conditions that shape the ability of a stage to scale, upgrade, or remain competitive over time.

4. *Business Environment Strengths* — evaluates a stage's structural sensitivity to cross-cutting industrial conditions such as infrastructure reliability, energy access, logistics, and operational stability.
5. *Policy Commitment & Strategic Alignment* — assesses whether a stage structurally depends on sustained regulatory clarity, long-term policy alignment, or public-sector risk management to operate at scale.
6. *Market Structure & Local Rivalry* — examines whether competition, customer proximity, and iterative design-manufacturing feedback loops structurally influence performance and innovation.

Security & Resilience Conditions

These factors evaluate structural vulnerabilities and opportunities for coordinated risk mitigation across allied economies.

7. *Geopolitical & Supply-Chain Risk Exposure* — assesses whether a stage is inherently prone to global concentration, chokepoint risks, or dependence on scarce capabilities that create strategic vulnerability.
8. *Trilateral Complementarity Potential* — evaluates whether a stage is structurally divisible or modular in ways that enable complementary specialization and distributed execution across partner economies.

Each factor is evaluated using standardized diagnostic questions and scored on a Yes / No / Unknown (Y/N/U) basis to reflect whether a given stage exhibits a structural dependency on that factor. Importantly, this scoring assesses structural dependence rather than country-specific performance, firm-level capability, or current market outcomes. Once diagnostic Y/N/U values are assigned across the guiding questions for a factor, composite scores of High / Medium / Low / Unknown (H/M/L/U) are generated mechanically from the diagnostic inputs using a fixed rule set, summarizing the degree of structural dependence that a stage has on that factor, ensuring consistency and transparency.

Mineral-specific interpretation is intentionally deferred in this report. The structural scoring framework is designed so that differences in chemistry, process pathways, and equipment requirements can be incorporated in subsequent analyses without altering the baseline scores. This sequencing preserves analytical discipline while preparing the groundwork for future mineral-specific studies.

The results of the factor analysis are synthesized visually using a stage-by-factor heat map (**Table 1**), which highlights patterns of structural dependence, vulnerability, and complementarity across the value chain.[2]

Stage ID	Stage Archetype Name	Segment	F1	F2	F3	F4	F5	F6	F7	F8
1	Geological Survey & Resource Assessment	Upstream	H	L	L	L	NA	NA	L	L
2	Exploration & Permitting	Upstream	H	L	L	L	NA	NA	L	L
3	Extraction / Mining	Upstream	H	L	L	L	NA	NA	L	L
4	Beneficiation / Ore Concentration	Upstream	H	M	L	L	NA	NA	L	L
5	Metallurgical Processing	Midstream	NA	H	H	H	H	NA	H	U
6	Chemical Conversion / Hydromet Processing	Midstream	NA	H	H	H	H	NA	H	U
7	Purification & Refining	Midstream	NA	H	H	H	H	NA	H	U
8	Specialty Oxide / Metal / Salt Production	Midstream	NA	H	H	H	H	NA	H	U
9	Alloying & Powder/Material Preparation	Midstream	NA	H	H	M	M	NA	U	H
10	Active Material Synthesis	Midstream	NA	H	H	H	U	NA	U	H
11	Component Fabrication — Structural & Functional Materials	Midstream	NA	H	H	M	L	NA	L	H
12	Component Fabrication — Magnetic & Alloy Components	Midstream	NA	H	H	M	L	NA	L	H
13	Substrate & Wafer Processing	Midstream	NA	H	H	H	H	NA	H	H
14	Electrode / Submodule Fabrication	Midstream	NA	H	H	H	M	NA	U	H
15	Device/Cell Manufacturing	Downstream	NA	H	H	H	NA	H	L	H
16	Module / Pack / Magnet Assembly	Downstream	NA	H	H	M	NA	H	L	H
17	System Integration	Downstream	NA	H	M	M	NA	L	L	H
18	Final Testing & Certification	Downstream	NA	H	H	H	NA	L	L	H

H	High - Strong Structural dependence, indicated by multiple reinforcing dependencies
M	Medium - Partial or conditional dependence, where the factor matters but is not determinative
L	Low - Minimal structural dependence; the stage is largely independent of the factor
U	Unknown - Insufficient structural evidence to determine dependence
NA	Not Applicable - the stage does not exist for the factor

Table 1: Stage Archetypes

Taken together, this integrated cluster and factor-based framework is designed to surface opportunities for trilateral complementarity by identifying value chain stages where coordinated investment or policy action is most likely to be structurally viable. By combining a fixed structural backbone with disciplined factor scoring, the methodology enables partners to assess relative strengths, identify potential footholds across the value chain, and evaluate alternative geographic configurations without relying on mineral-specific assumptions. Because the approach is transparent, rule-based, and repeatable, it provides a consistent foundation for subsequent, more targeted analyses and supports the development of coherent, actionable guidance for trilateral industrial coordination.

Key Findings and Strategic Implications

Petri Maps

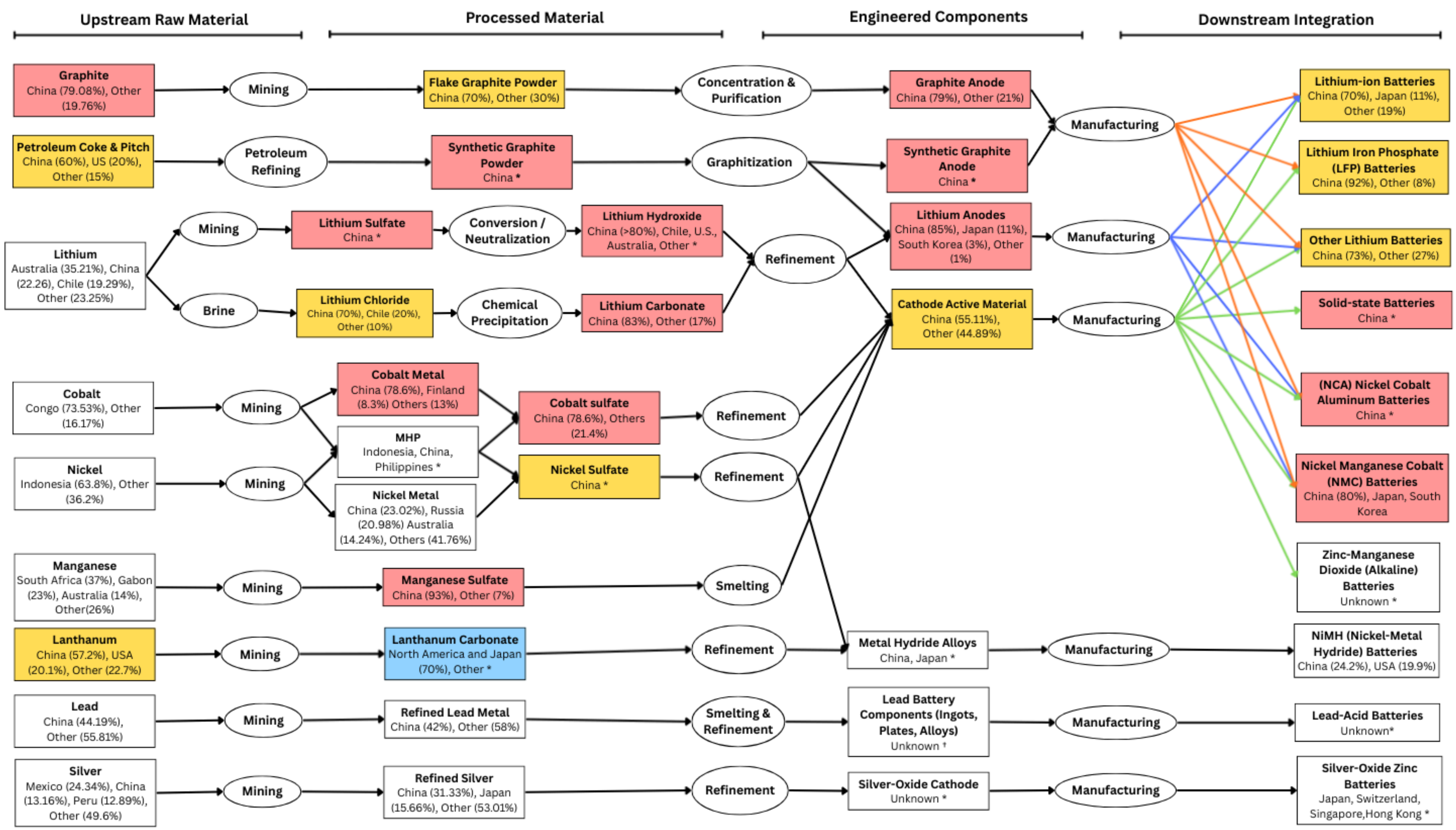
Battery Materials Petri Map

The Petri map of battery materials (**Figure 1**) focuses on eight key minerals: graphite, lithium, cobalt, nickel, manganese, lanthanum, lead, and silver. These minerals are commonly used in the production of major battery types, including lithium-ion batteries, solid-state batteries, nickel–cobalt–aluminum (NCA) batteries, zinc–manganese dioxide (alkaline) batteries, nickel–metal hydride (NiMH) batteries, lead-acid batteries, and silver–oxide zinc batteries. From raw materials to downstream processing of each mineral type, the map identifies critical chokepoints by illustrating supply concentrations: red indicates heavy dependence (over 75%) on major competitors like China, yellow reflects moderate concentration and medium risk (50% to 75%), no color signals low concentration in competitor countries, and blue represents areas where the Triad or its allies hold a favorable competitive position across the supply chain.

In the Petri map analysis, upstream raw material subsegment, China dominates two major mineral stages: In the upstream raw material subsegment, China dominates 79% of global natural graphite mining, indicating a high-risk chokepoint; approximately 60% of petroleum coke and pitch required as raw materials for artificial (synthetic) graphite; and over 57.2% of lanthanum production, indicating medium-risk chokepoints. We divide the midstream segment into two subsegments—processed materials and engineered components—to reflect distinct process pathways and capability requirements. In the midstream processed materials subsegment, China has positioned itself as the most influential producer, accounting for approximately 83% of global lithium carbonate output, 78.6% of cobalt metal, 78.6% of cobalt sulfate, and about 93% of global manganese sulfate production. Other processed materials such as flake graphite powder, lithium chloride, and nickel sulfate are also dominated by China, which holds roughly 70% of global production. One exception is that the U.S. and Japan account for roughly 70% of the global supply of lanthanum carbonate refinement. China also holds a strong position in the midstream engineered components subsegment that includes battery-material manufacturing, producing approximately 79% of the world's graphite anodes and about 85% of lithium anodes. It maintains medium-level dominance in cathode active materials (around 55%). In the downstream integration stage, the final stage of the Petri map, China is the global leader in producing solid-state batteries, nickel-cobalt-aluminum (NCA) batteries, and nickel manganese cobalt batteries. Although Japan holds a competitive position in lithium-ion battery production, China continues to dominate lithium-ion and overall battery manufacturing, accounting for more than 70% of global output.

The high degree of Chinese control over these critical processing and manufacturing steps creates significant vulnerabilities for the U.S., Japan, and South Korea. Disruptions or supply restrictions at these chokepoints could severely impact the ability of allied nations to secure the materials necessary for their domestic battery and electric vehicle industries. Even when mining occurs elsewhere, this concentration creates chokepoints in midstream processing and component manufacturing.

Battery Materials



***Public Data Unavailable**
† Data Not Found

Figure 1: Battery Minerals Petri Map[3]

Semiconductor Materials Petri Map

The Petri map on Semiconductor materials (**Figure 2**) focuses on seven key minerals: Arsenic, Gallium, Germanium, Hafnium, Indium, Silicon, and Silver. These upstream raw materials were identified using the USGS 2025 U.S. Critical Minerals list, whereas the midstream and downstream integration was identified using the U.S. DOE 2022 Semiconductor Supply Chain report. Like the Battery Material Petri map, China controls many of the important steps in production. In the upstream section, China dominates three of the seven listed materials—Gallium at 98%, Germanium at 93%, and Silicon at 84%, respectively. These concentrations represent potential chokepoints in the midstream segment. The Petri map highlights two midstream areas where China's upstream advantages create potential chokepoints: Gallium Nitride and Indium Phosphide. It should be noted that much of the country-specific data on midstream segment processes is not publicly available at this time, and therefore the figures may be understated.

Reviewing the downstream integration segment, we identified two broad groups of semiconductors: conventional and wide bandgap semiconductors. Conventional semiconductors include materials such as silicon (Si) and germanium (Ge), while wide bandgap semiconductors include silicon carbide (SiC), gallium nitride (GaN), gallium arsenide (GaAs), and indium phosphide (InP). For many of the engineered components associated with these more specific semiconductor types, detailed production data are not publicly available. However, we were able to identify several key statistics: South Korea maintains a slight lead in silicon wafer production with a market share of 22%, followed closely by Taiwan at 21%, China at 18%, and Japan at 15%; the U.S. leads GaN epitaxial layer production with 34.3% of the market, though additional country-level data was restricted; and SiC epitaxial wafer production is led by China at 48%, followed by the U.S. at 25% and Japan at 14%. Overall, China holds a slight advantage across the semiconductor supply chain, yet several countries remain competitive and close behind. A more complete understanding of these dynamics that underpin much of the industry landscape would require access to proprietary data.

Magnet Materials Petri Map

Permanent magnets are widely used in motors because they enhance efficiency, including at lower operating speeds. Their ability to provide consistent torque, reduced heat generation, compact size, and cost-effectiveness makes them well-suited for high-efficiency industrial applications. Permanent magnets exist in several forms, such as ceramic, flexible, injection-molded, and Alnico, but the types relevant to the U.S. Geological Survey's 2025 list of Rare Earth Elements (REEs) are Neodymium-Iron-Boron (NdFeB) magnets and Samarium-Cobalt (SmCo) magnets. These magnets are produced by combining major elements with specific REEs, identified in the USGS 2025 list, to enhance magnetic performance and durability. The Petri map for these processes is presented in **Figure 3**.

Mapping the supply chain for permanent magnets is a complex process, as none of the REEs used in their production occur in pure form in nature. Instead, they are derived from nine primary mineral sources: euxenite, fergusonite, polycrase, blomstradine, xenotime, monazite, gadolinite, ion-adsorption clays, and bastnasite. Extracted from these primary mineral sources are five key REEs: dysprosium, terbium, praseodymium, neodymium, and samarium. China maintains overwhelming market share in this upstream stage, producing approximately 95% of global dysprosium, 70% of terbium, 70% of praseodymium, 80% of neodymium, and 60% of samarium.

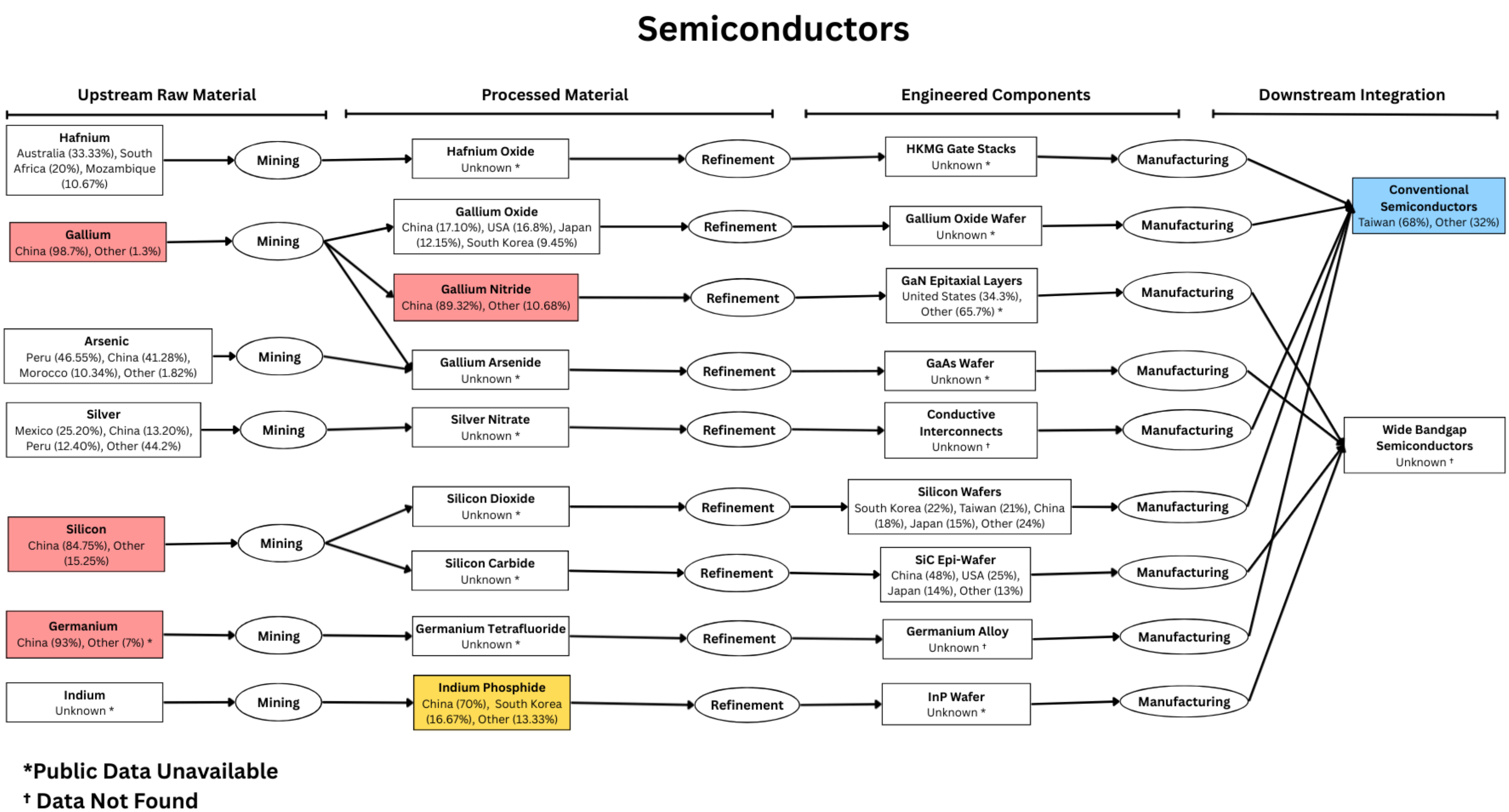


Figure 2: Semiconductor Minerals Petri Map[4]

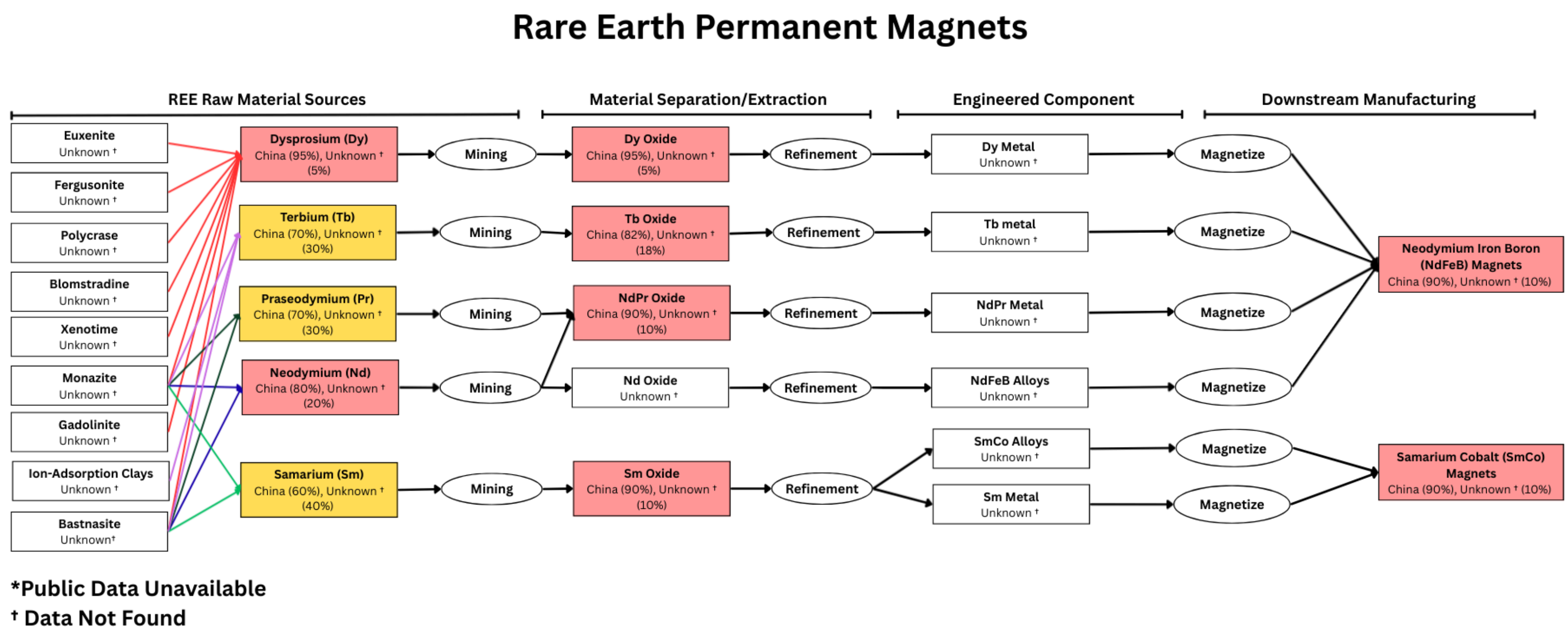


Figure 3: Rare Earth Permanent Magnets Petri Map[5]

This control of the market continues throughout the midstream processing stage, where REEs are converted into oxides such as dysprosium oxide, terbium oxide, NdPr oxide (a neodymium–praseodymium mixture), and samarium oxide. Across raw material extraction, metal production, and separation processes, China controls an estimated 90-95% of the global supply chain.

Following oxide production, these materials are refined into individual metals (Dy, Tb, Sm) and alloys (NdPr, NdFeB, SmCo). Publicly available data on the exact production shares and locations for this step remain limited. The final stage involves magnet fabrication, where the refined materials are processed into finished NdFeB and SmCo permanent magnets. China also leads this stage, with roughly 90% of global production capacity. On both ends of the supply chain, China is a dominant stakeholder at the moment with public data largely unavailable for the engineered components of the map.

Cluster & Factor Analysis Framework Applied to Generic Value Chain Stage Archetypes

To interpret the results of the Cluster and Factor Analysis, the 18 generic value chain stages are organized into three segments that reflect fundamentally different structural logics: the upstream segment, where geology determines location; the midstream segment, representing the most promising intervention opportunity; and the downstream segment, where existing strengths can be leveraged.

These segments differ in their sources of constraint, policy leverage, and coordination potential. Structuring interpretation at the segment level provides a clear bridge between the factor-based scores and strategic insights, helping focus attention on where trilateral coordination is structurally feasible and most likely to produce durable impact.

The Upstream Segment: Where Geology Determines Location

The upstream segment covering the stage archetypes of geological survey, exploration, mining, and initial ore processing are fundamentally constrained by geological reality. Mining cannot happen where minerals do not exist, regardless of policy support or industrial capability. This geological anchoring explains why this segment's stage archetypes show minimal dependency on the technological capabilities, institutional infrastructure, or business conditions that prove decisive elsewhere in the value chain.

The U.S. possesses significant undeveloped reserves but faces permitting challenges extending timelines to 7-10 years. Japan has virtually no viable domestic deposits and South Korea produces less than 1% of global output through their key mines. While policy coordination on permitting reform and environmental standards could accelerate development, geological constraints suggest that for trilateral supply chain security, upstream strategy should include joint equity investments in mining projects within aligned nations, such as Australia, Canada, Chile, and Indonesia, combined with coordinated due diligence standards and shared offtake agreements that ensure reliable supply to all three partners.

The Midstream Segment: The Most Promising Intervention Opportunity

The midstream segment, spanning chemical processing, refining, purification, and advanced materials production, presents the opposite situation. These ten stage archetypes are not strictly bound by geology, although financial costs of transport may be prohibitive for certain inputs. In many cases, they can be located anywhere with appropriate infrastructure, yet they are currently concentrated overwhelmingly in China, which controls 70-90% of global capacity in rare earth refining, lithium chemical conversion, and specialty compound production.

What makes midstream stages both vulnerable and contestable is their unique factor profile. Unlike upstream operations tied to ore bodies, many midstream facilities require sophisticated technological capabilities that all three Triad nations possess through adjacent industries. For example, the U.S. has deep chemical engineering expertise, Japan operates world-class fine chemicals sectors, and South Korea's petrochemical and battery industries provide relevant process knowledge. These existing capabilities captured in chemical processing plants, metallurgical facilities, and materials science institutions can be redirected toward critical mineral applications.

Midstream stage archetypes also require dense institutional support: specialized engineering firms to design facilities, certification bodies to validate quality, testing laboratories to ensure purity, research institutions to solve process problems, and workforce training systems to develop skilled operators. All three Triad nations maintain these institutional ecosystems, though they have underinvested in applying them to critical minerals. Additionally, midstream operations are sensitive to business conditions, including stable energy supplies, reliable utilities, and efficient permitting processes - areas where the Triad and their allies can compete if they make strategic commitments.

The vulnerability arises because midstream stages require long-term policy support to overcome market failures. Chemical refineries processing critical minerals face higher environmental compliance costs than competitors in China. Purification facilities require years to reach commercial scale while competing against established Chinese operations. Without sustained policy commitment, including capital support, regulatory certainty, and guaranteed demand, private investors cannot justify the risk. China consolidated dominance precisely because it provided this long-term support through state capital, relaxed environmental standards, and coordinated industrial planning.

However, the strategic opportunity is clear: these stages are not naturally monopolistic. They concentrate in China due to policy choices, not insurmountable advantages. Concentration creates severe chokepoint vulnerabilities - single facilities or regions control supplies essential to entire industries. Yet the same stages show high potential for allied cooperation through division of labor, with each nation specializing in stages matching its industrial strengths while trading intermediate materials to create mutual resilience. We anticipate that detailed factor analysis at the mineral-specific stage level will reveal more precisely where the best opportunities lie.

Stage Archetypes 5 through 8 - metallurgical processing, chemical conversion, purification and refining, and specialty compound production, form the highest-priority intervention cluster. These operations require extreme purity (99.999% or higher), stringent environmental controls for hazardous reagents, and sophisticated quality management. These are precisely the areas where Triad nations excel but have underinvested in critical minerals applications. As Chinese dominance deepens, technological gaps widen and market entry becomes costlier. Early coordinated investment can shape market structures before concentration solidifies further.

Stage Archetypes 9 through 14—alloying & powder preparation, active material synthesis, and component fabrication—represent a transition zone between bulk processing and precision manufacturing. These stages maintain the same freedom from geological constraints while requiring even more sophisticated technical capabilities. Their concentration patterns remain somewhat uncertain, making early positioning critical to prevent Chinese dominance from extending downstream. Stage 13—substrate and wafer processing—particularly leverages semiconductor expertise where South Korea and Japan lead globally, demonstrating how existing capabilities can be mobilized if coordination mechanisms are established.

The Downstream Segment: Leveraging Existing Strengths

The downstream zone—device manufacturing, module assembly, system integration, and final testing—presents a different situation. The Triad already possesses substantial capabilities here. South Korea leads in battery cell manufacturing, Japan excels in permanent magnet production, and the U.S. has emerging capacity in batteries and electric vehicle assembly. These stages depend neither on resource location nor on the specific chemical processing expertise that midstream stages require. Instead, downstream competitiveness derives from manufacturing excellence, with competitive pressure among firms driving continuous improvement. Companies co-locate near demanding customers like automakers, electronics firms, and defense contractors, creating tight feedback loops that accelerate innovation. The institutional requirements shift from chemical engineering and process control to manufacturing systems, quality management, and integration with complex supply chains. The challenge is not building downstream capacity that already exists but securing the feedstock supply that makes it viable. Without midstream security, downstream investments remain hostage to Chinese material supply decisions.

Investment Opportunities and Policy Coordination

The strategic rationale for coordination emerges directly from structural analysis. Midstream facilities require investments and only achieve competitive costs when operating on a commercial scale. Coordinated demand from all three nations makes projects viable; single-nation markets often cannot. Predatory pricing by Chinese firms using subsidized production to bankrupt new entrants requires collective defensive measures that isolated nations struggle to sustain. Capabilities are complementary rather than duplicative: each nation's adjacent industries and institutional strengths differ, enabling specialization that exploits advantages rather than duplicating weaknesses. Distributed production provides operational resilience; disruptions in one location are partly offset by surge production in partners, while economic interdependence strengthens alliance cohesion and credibility.

The factor patterns demonstrate that uncoordinated investment will fail. None of the three nations has natural advantages in midstream stages that guarantee success alone. All face concentration vulnerabilities requiring collective responses. Yet all possess complementary capabilities that, if coordinated, can genuinely shift strategic outcomes. The question is not whether the Triad has the capability to secure critical mineral supply chains—it does—but whether it will coordinate effectively before a crisis forces reactive, costly, and less resilient responses. The window for proactive action is narrowing as Chinese dominance deepens and technological gaps widen. The analysis points toward clear priorities: midstream processing first, advanced manufacturing second, and demand coordination third, with explicit division of labor preventing duplication while creating mutual dependencies that enhance security rather than undermine it.

Priority Investment Strategy: Midstream Processing and Advanced Manufacturing

The highest investment priority lies in establishing trilateral security for midstream chemical processing and refining stages. China currently has significant market control in these stages, but allied capabilities have genuine competitive potential. If each nation attempts complete self-sufficiency, it would produce subscale, uncompetitive facilities. Instead, the Triad should pursue a division of labor strategy that exploits complementary strengths.

The U.S. should concentrate on metallurgical processing and chemical conversion (Stage Archetypes 5-6), along with alloying, powder preparation, and structural/functional components (Stage Archetypes 9, 11). This focus leverages U.S. strengths in chemical engineering depth and environmental management infrastructure for hazardous processing steps—such as rare earth separation, acid leaching, and solvent extraction—while drawing on aerospace and defense manufacturing expertise for advanced metal forming and component production. Japan should prioritize purification, refining, and specialty compound production (Stage Archetypes 7-8), along with active material synthesis and magnetic components (Stage Archetypes 10, 12). These areas capitalize on Japan's fine chemicals industry and precision manufacturing culture to achieve extreme purity levels (99.999%+) and reinforce its leadership in permanent magnets for high-performance functional materials. South Korea should emphasize substrate and wafer processing along with electrode and submodule fabrication (Stage Archetypes 13, 14), extending its dominance in semiconductors and batteries into critical minerals applications through precision manufacturing and assembly operations that bridge midstream processing to downstream device production. By concentrating on these areas of comparative advantage, each nation strengthens its position in the global value chain, amplifies collective market influence, and reinforces strategic autonomy while reducing exposure to adversarial suppliers.

This specialization strengthens collective market influence and reinforces strategic autonomy rather than creating vulnerabilities. Each nation focuses on stages where it holds comparative advantages, while all three exchange intermediate products—diversifying away from China and building alliance cohesion through coordinated specialization and shared market leverage. In an example scenario where American facilities supply Japanese operations, which feed South Korean manufacturers, generating cross-border material flows that amplify resilience and competitiveness, the key innovation is designing these flows deliberately, ensuring security and reducing exposure to adversarial suppliers. A trilateral joint venture structure with equity participation from all three governments and anchor firms would pool investment risk, share technology, and establish guaranteed markets that justify commercial-scale operations and consolidate collective market power.

Critical policy coordination includes harmonized environmental standards that avoid regulatory arbitrage while ensuring responsible operations, synchronized capital deployment through aligned investment tax credits and loan guarantees, joint workforce development programs to build specialized expertise, coordinated intellectual property protection to prevent technology leakage while enabling allied knowledge sharing, and coordinated strategic reserves to stabilize prices during facility ramp-up when Chinese competitors may attempt predatory pricing. Policy requirements also include eliminating tariffs on intermediate goods moving within the Triad and automatic mutual recognition of quality certifications and environmental permits. Success requires treating midstream and advanced manufacturing investment as security infrastructure, essential regardless of short-term economics, while structuring operations to achieve long-term commercial viability.

Coordinated Demand: Procurement, Incentives, and Standards

Downstream stages offer the greatest near-term leverage because capabilities already exist. The coordination opportunity lies in creating guaranteed demand that justifies midstream investment risk. A trilateral procurement alliance coordinating government purchases like defense systems, infrastructure projects, and official vehicles would require minimum trilateral content percentages: such as 30% in Year 1, rising to 70% by Year 5, for example. This could create protected market space where midstream facilities can reach commercial scale without being undercut by Chinese predatory pricing.

Chinese domination of the supply chain was driven by market forces responding to competitive pricing. Even with joint-investment, Chinese end-consumer pricing will continue to be the lowest in the mid-term. This is a result of heavy Chinese government subsidization of the supply chain elements it controls. Therefore, the Triad will need to implement subsidy harmonization to reward trilateral supply chains with premium incentives that reflect the national security gains and goals of the three partners. Products incorporating allied-sourced materials will receive higher subsidies, faster permitting, and preferential market access across all three nations. Joint certification and testing infrastructure would establish shared facilities and unified protocols, reduce compliance costs, and create standardization that enables integrated supply chains. Engagement with end-user industries like automotive, electronics, defense, and energy would develop detailed supply chain maps and volume commitments that reduce investor uncertainty, leading to a robust, secure supply chain for critical minerals and downstream products.

Partner-Nation Mining: Securing Feedstock

Geological constraints mean upstream coordination includes other partners in addition to U.S. reserves. This should include a joint mining equity fund for stakes in projects across Australia, Canada, Chile, Indonesia, Argentina, and Zambia that pools investment, shares due diligence costs, and provides miners with certainty through coordinated offtake agreements. Shared exploration technology accelerates discovery while investment screening harmonization prevents adversarial acquisition of strategic resources. This approach accepts geological reality while ensuring allied access to essential raw materials.

Conclusion

The Triad finds itself at a defining moment to reshape global critical mineral supply chains and their impact on energy security and advanced manufacturing competitiveness. The Triad's shared exposure to concentration risks across critical value chains—especially processing, refining, and critical intermediate manufacturing—creates vulnerabilities that cannot be resolved through parallel, uncoordinated national efforts. This report's integrated approach—pairing mineral-specific Petri map chokepoint visibility with a structural, stage-archetype lens to reveal where capacity can realistically emerge and persist—shows why "diversification" must be translated into targeted, defensible investment coordination grounded in industrial reality.

Across the battery, semiconductor, and permanent magnet pathways examined, the core strategic pattern is consistent: even where upstream extraction occurs outside China, concentration in midstream processed materials and engineered components creates decisive chokepoints. The Petri map findings underscore how disruption risk is amplified by reliance on a small number of dominant processing and manufacturing nodes, while also revealing areas where allied positions are stronger and can be leveraged. At the same time, the cluster and factor interpretation clarifies that the value chain is not uniformly contestable: upstream stages remain constrained by geological anchoring, while downstream stages largely depend on manufacturing excellence and customer-driven innovation cycles that the Triad already possesses. The principal intervention opportunity in the immediate future, and therefore the central coordination challenge, sits in the midstream, where capability requirements are demanding but feasible for the Triad given adjacent industrial strengths and institutional ecosystems.

The report's structural implications are direct. Midstream security requires commercial-scale facilities and long-horizon policy support to overcome market failures and withstand subsidized competitive pressure. No single Triad market can reliably carry the scale, risk, and time-to-maturity alone; coordinated demand and synchronized capital deployment are therefore not optional add-ons but enabling conditions. The analysis also indicates that "self-sufficiency everywhere" is more likely to produce subscale, uncompetitive assets than resilient supply chains. A deliberate division-of-labor model, aligned to each nation's industrial strengths and reinforced by cross-border flows of intermediate products, offers a path to diversify away from adversarial concentration while increasing collective resilience and strategic autonomy.

From a policy and industry standpoint, the value proposition of the framework is practical: it provides a disciplined basis for prioritizing where trilateral coordination is structurally feasible, where it is strategically necessary, and where it can create durable impact. It points toward a sequenced emphasis on midstream processing first, advanced manufacturing second, and demand coordination as the mechanism that makes both investable at scale—while treating these capabilities as security infrastructure that must also meet long-term commercial viability.

Next steps are implied by the analysis itself. The report anticipates more detailed mineral-specific stage-level factor analysis to sharpen where the strongest opportunities lie, and it identifies that some midstream and engineered-component visibility—particularly in semiconductors—remains limited by non-public, proprietary data. Advancing this work will therefore depend on deepened collaboration with industry and institutional partners to refine stage-level visibility, validate competitiveness conditions, and translate the framework into coordinated project pipelines that reduce vulnerability before a crisis forces costlier, reactive responses.

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Endnotes

1. For further information about the Cluster & Factor Analysis Framework (CFAF), see Appendix B.

2. For further information about the scoring approach, see Appendix C.

3. For further information about the Battery Materials Petri Map and the sources used to build it, see Appendix A.

4. For further information about the Semiconductor Minerals Petri Map and the sources used to build it, see Appendix A.

5. For further information about the Rare Earth Permanent Magnets Petri Map and the sources used to build it, see Appendix A.

Appendices

To maintain focus in the main report, a 35-page appendices document is provided separately that includes extensive references, detailed methods, and rationales. This material supports transparency and enables deeper technical review of the frameworks presented in this paper.

The Appendices are available online via the QR code below or at:
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