TRILATERAL ENERGY SECURITY COMMITTEE

Critical Minerals Deep Dive: Securing the Battery Supply Chain

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Trilateral Energy Security Committee (TESC)

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Executive Summary

Secure critical mineral access has become inseparable from national and economic security. The emerging consensus is that critical mineral supply chains should be treated as strategic infrastructure rather than purely commercial markets, and resilience through geographic and processing diversification must take precedence over efficiency alone. In this report, the TESC examines the global battery materials supply chain, heavily reliant on critical minerals and important for both the growing global electric vehicle and energy storage systems markets, through a dual-methodology lens—Petri map analysis combined with the Cluster & Factor Analysis Framework (CFAF)—to identify where the U.S., Japan, and Republic of Korea (hereafter referred to as South Korea) (together, the Triad) can most effectively coordinate investment to reduce dependence on China across critical mineral value chains.

While our Petri map analyses show high levels of vulnerability due to lack of market share diversification, they also show that there are several practical areas where costs are lower to pursue coordinated investment to reduce reliance on single providers. The CFAF complements the Petri-map findings and shows that for nearly all minerals, the strongest opportunities for coordinated action lie in midstream processing, chemical conversion, refining, specialty materials, active material synthesis, and electrode fabrication—rather than upstream extraction or final battery assembly. These stages depend less on geology and more on technical capability, infrastructure, policy support, and trilateral complementarity.

Our report recommends that the Triad pursue a distributed specialization model rather than full national self-sufficiency. Policy levers include harmonized ESG, labor, and traceability standards that function as non-tariff resilience measures; preferential procurement tied to those standards; direct government capital cost CAPEX support and temporary price stabilization; diversity purchasing requirements; and accelerated approvals. Through these policy levers, the U.S. would contribute financing scale and chemical processing capability, Japan high-purity materials expertise and long-term resource security planning, and South Korea its battery manufacturing strength and cell and module integration. We propose a ROK-U.S.-Japan recycling alliance that could aggregate feedstock and return battery-grade material as an early proof-of-concept of our suggestions. We also posit that other allies such as Australia and Canada will be essential upstream resource partners, contingent on streamlined permitting and faster project approvals that meet allied environmental and labor standards.

Introduction

The global energy transition and the race for advanced manufacturing dominance have elevated critical minerals from a private-sector concern to a matter of national and economic security. As the Triad works to reduce dependencies on adversarial supply chains, particularly China's commanding position across extraction, processing, and manufacturing, the need for strategic coordination has never been greater. The TESC has worked to move beyond traditional supply-chain analyses and generalized calls for supply chain diversification that often focus on geopolitical vulnerability or industrial capability in isolation. In its recent research study, "Critical Minerals Supply Chian Security: A Framework for Trilateral Investment Coordination" (the FTIC Report), the TESC used a dual-methodology approach that combined Petri map analysis and cluster and factor analysis. This analysis revealed process-level vulnerabilities in the supply chains and evaluated structural conditions to determine where value-chain stages can realistically emerge at a competitive scale through Triad collaboration.

This report expands upon the analytical frameworks in the FTIC Report through a focused study on the global battery supply chain. First, it provides greater insight and utilization of Petri map analysis by implementing new layers, including cost and time elements. Second, it executes the CFAF with mineral-specific case studies, focusing on critical minerals that are relevant to battery supply chains. Through combined interpretation of these two methods, we demonstrate how these tools can be used to inform investment prioritization, policy implementation, and Triad coordination.

This report does not attempt to fully quantify battery cost gaps or project-finance outcomes. However, it uses supply-chain mapping, cost-focused Petri analysis, and expert-informed qualitative insights to identify where coordinated investment, bankable offtake structures, demand aggregation, and risk-reduction tools may most effectively improve allied battery-material competitiveness.

Battery Supply Chain Context

Batteries are the foundation for the Energy Storage System (ESS) and the electric vehicle (EV) sectors. Advancement of the ESS sector is necessary to mitigate renewable energy intermittence as electricity demand grows alongside increased AI data center infrastructure development, which will require countries to increase output of all available energy sources. Global uptake of electric vehicles EVs is also growing, driven by cost reductions and emission policy goals. These two sectors are dependent on robust critical mineral supply chains and technology advancement in the battery industry. Beyond EVs and grid-scale ESS, battery demand is also expanding into smaller high-performance applications, including drones and portable defense systems, further linking battery material security to broader industrial and national-security priorities. Altogether, battery supply chains are made up of intricate webs of value streams, requiring a multi-layered analysis, such as ours, to uncover valuable insight.

EV vs. ESS

While EVs will remain a major driver of battery demand, the ESS sector also offers greater long-term certainty and strategic value. The EV market is increasingly saturated, highly competitive, and vulnerable to consumer demand fluctuations, making new market entry difficult. In contrast, ESS demand is being structurally driven by grid modernization and the rapid expansion of AI data centers, which require reliable backup power and load-balancing capacity. The International Energy Agency (IEA) projects that electricity demand from AI-optimized data centers will more than quadruple by 2030, significantly increasing the need for large-scale battery storage solutions (ADIPEC, 2025). Consequently, ESS-oriented battery supply chains may provide the Triad with a more stable and policy-supported demand environment than EV manufacturing alone.

Secure Supply Chains are a Public Good

Critical mineral supply chains should be viewed not merely as commercial ecosystems, but as strategic infrastructure essential to national security. These materials underpin advanced defense systems, semiconductors, energy infrastructure, and emerging AI technologies, making supply disruptions a direct threat to economic and military readiness. U.S. defense officials have repeatedly emphasized that resilient critical mineral supply chains are vital to maintaining defense production capacity and reducing vulnerability to adversarial coercion (Vergun, 2025). As a result, diversification efforts should be approached as a public-good investment requiring coordinated action between governments, defense institutions, and private industry. Much like energy security in previous decades, critical mineral security is increasingly becoming a prerequisite for long-term state resilience and industrial competitiveness.

Diversification

Reducing concentration risk within critical mineral supply chains is paramount given the growing instability of the global geopolitical environment. Many key mineral flows currently depend on narrow geographic corridors or politically volatile regions, exposing downstream industries to substantial disruption risk. Recent tensions involving Iran and the Strait of Hormuz have demonstrated the vulnerability of critical maritime chokepoints, where disruptions to shipping lanes can rapidly affect global energy, manufacturing, and mineral markets. UN Trade and Development (UNCTAD) recently warned that continued instability in the Strait of Hormuz could generate broad economic disruption through rising transportation costs and constrained trade flows (UNCTAD, 2026). At the same time, Indonesia's growing dominance in global nickel production—supported by export bans and state-led industrial policy—has increased dependence on a single country for a key battery input (Utamawati & Yusuf, 2026). Likewise, overreliance on Chinese refining and processing capacity continues to present strategic vulnerabilities for the Triad and their allies. These risks demonstrate that supply chain efficiency alone can no longer serve as the primary organizing principle for industrial strategy. Instead, resilience through diversification must become a central objective. For the Triad, this means prioritizing geographically distributed sourcing, allied processing capacity, and coordinated investment strategies that reduce exposure to single points of failure across the value chain.

Analytical Framework

This report reapplies and builds upon two structured analytical frameworks, established in our previous FTIC Report, 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 stage archetypes, spanning the lifecycle from exploration through downstream integration and applicable across multiple mineral families. These stage archetype structures provide a stable reference point for identifying structural dependencies and assessing where trilateral industrial strengths can complement one another rather than duplicate effort. For the FTIC Report, we used generic stage archetypes, but in this report, we analyze mineral specific stages that map to the 18 generic ones.

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.

Petri Map Analysis Framework

Our Petri map analysis focuses on nine key minerals: graphite (both natural and synthetic), lithium, cobalt, nickel, manganese, lanthanum, lead, and zinc. These minerals are commonly used in the production of major battery types, including lithium-ion batteries, lithium-iron phosphate (LFP) batteries, solid-state batteries, nickel cobalt aluminum (NCA) batteries, nickel manganese cobalt (NMC) batteries, zinc-manganese dioxide (alkaline) batteries, nickel-metal hydride (NiMH) batteries, lead-acid batteries, silver oxide zinc batteries. From raw materials to downstream processing of each mineral type, we use Petri maps to illustrate critical areas of chokepoints and barriers from two key perspectives: Market Share and Costs.

Market Share Petri Map

The market share (MS) Petri map of battery materials **(Figure 1)**, which was previously developed and shared in our FTIC Report, 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.

From this Petri map perspective, China controls key areas in every segment. In the upstream segment, China dominates 79% of global natural graphite mining, approximately 60% of petroleum coke and pitch required for artificial (synthetic) graphite, and 57.2% of lanthanum production. 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 the global supply of lanthanum carbonate refinement, for which the U.S. and Japan account for nearly three-quarters of production. 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 industries. Even when mining occurs elsewhere, this concentration creates chokepoints in midstream processing and component manufacturing.

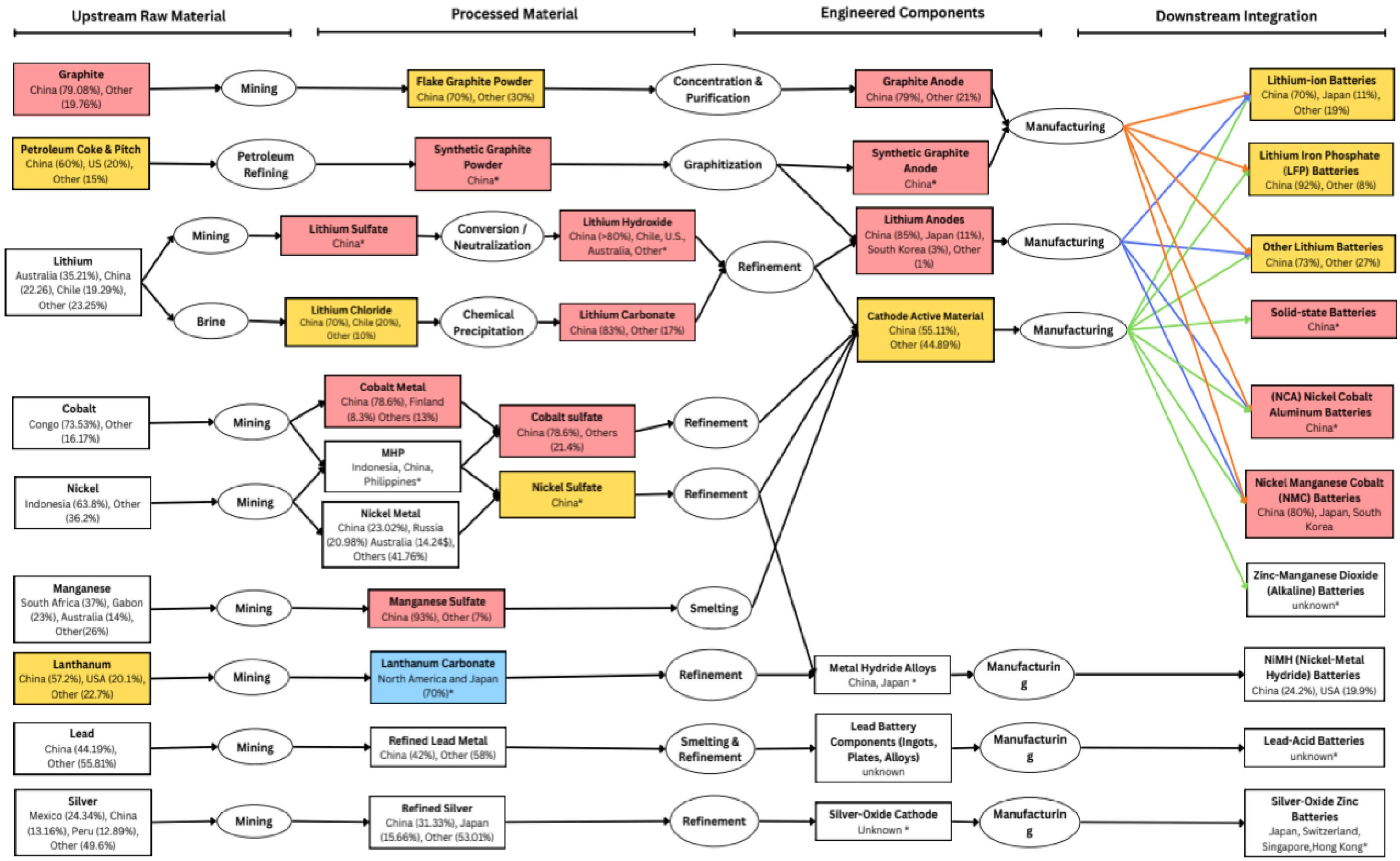


Figure 1: Market Share Petri Map (Battery Materials). ** Public Data Unavailable*

Cost-Focused Petri Map

For this report, we expand the Petri map analysis with a complementary, cost-focused (CF) analysis that visualizes various cost elements associated with critical value chains' processes. The CF Petri maps for battery materials include the same nine key minerals as the MS Petri map, but for lithium, we have mapped its three distinct sourcing pathways, which include brine, clay, and hard-rock. The CF Petri map perspective illustrates varying degrees of severity for three cost elements that make up the total anticipated expenditures required at each stage. The elements include CAPEX, operating cost (OPEX), and the facility's setup-to-production timeline (Time). CAPEX, OPEX, and Time are grouped together in hexagonal nodes that signify key processing stages within a critical mineral's value chain process. Each node is color coded to reflect the relative degree of cost severity for a given element within a stage.

The first CF map (**Figure 2)** shows that lithium, especially through its clay mining pathway, has high associated costs across its entire value chain. On the other hand, natural graphite mining associated costs are significantly lower, with CAPEX being the only high-cost element at the engineered components and downstream integration segments.

In the second CF map (**Figure 3),** nickel stands out as a value chain that offers lower costs associated with its midstream segments as its nickel metal and nickel sulfate processes are medium-cost for all three cost elements, and its mixed hydroxide precipitate or MHP (processing plant) node is low-cost for all three cost elements. However, to conduct upstream nickel mining, one would face an uphill battle of considerably high CAPEX and a longer-than-average setup-to-production time. Another value chain to consider based on the CF Petri map is cobalt, as it has at least one low-cost node at each process across its value chain. On the other hand, it does carry at least one high-cost element at each process within each of its nodes as well, typically with its OPEX costs. This may indicate that the cobalt value chain would be relatively cheaper and faster to develop but may be relatively expensive to maintain. Alternatively, there is lanthanum, which has a less complex value chain of only four process stages across its value chain, instead of up to six for both nickel and cobalt. In addition, lanthanum has no high-cost associated elements to consider at any point in its upstream and processing subsegment processes.

In the third CF map (**Figure 4),** we find that lead is the most financially viable critical mineral pathway. Its greatest challenge is that it requires up to 15 years for its setup-to-production timeline at the initial mining stage – the longest among all critical minerals listed across our Petri maps. Nevertheless, if this front-end hurdle can be overcome, the production of lead-acid batteries incurs only low-to-medium-cost elements throughout every other processing stage of its value chain.

Combined Insights

Combined interpretation of the MS and CF Petri maps allows us to identify which of the vulnerable paths is the relatively cheapest to diversify. As mentioned before, based on our MS Petri map analysis, China dominates lithium-ion battery production with 70-79% market share control at every stage of the natural graphite value chain. From this perspective alone, we would only know that this presents high-risk vulnerabilities for the Triad and its allies to secure some of the critical materials necessary for their local productions and industries. However, when layering insights are gained from the CF Petri map analysis, we learn that the overall costs associated with this value chain are relatively low. Therefore, if the Triad can coordinate its resources, in addition to capitalizing on Japan's existing competitive position in lithium-ion battery production, the entire natural graphite value chain offers one of the potentially greatest value propositions in regard to securing market control in a chain that is currently almost entirely controlled by China.

Combined analysis also points to the lanthanum and lead supply chains. From the MS Petri map, lanthanum is the only supply chain with Triad-based control over both upstream raw materials and midstream processed materials. Accordingly, the U.S. manages 20.1% of lanthanum mining, and Japan and North America collectively fulfill 70% of global lanthanum carbonate refinement. In the midstream engineered components and downstream integration segments, Japan controls a majority of metal hydride alloy production, and the U.S. manufactures 19.9% of the global supply of NiMH (nickel–metal hydride batteries. From the cost-perspective, aside from a relatively long setup-to-production timeline for midstream alloy manufacturing, every associated cost is medium-level at most. Significantly, associated CAPEX costs are low-cost for both midstream segments (metal/carbonate refinement and alloy manufacturing). Therefore, the Triad should coordinate its investments to fortify its majority control in the midstream and expand its positions across the rest of the lanthanum value chain.

Lead's value stream does not immediately stand out in the MS Petri map, as public data on its midstream engineered components and downstream integration processes are unknown or unavailable. However, strategic opportunities present themselves upstream, as China holds minority share in both lead mining and lead metal refinement at 44.19% and 42% respectively, and no other state dominates with a clear, individual majority. Our third CF Petri map (**Figure 4)** denotes that the lead value chain offers consistently low-cost elements, particularly OPEX for lead mining and CAPEX for lead battery components production and lead-acid batteries manufacturing. Therefore, the Triad should prioritize lead as a long-term, cost-competitive opportunity to strengthen its position across an entire critical mineral value chain.

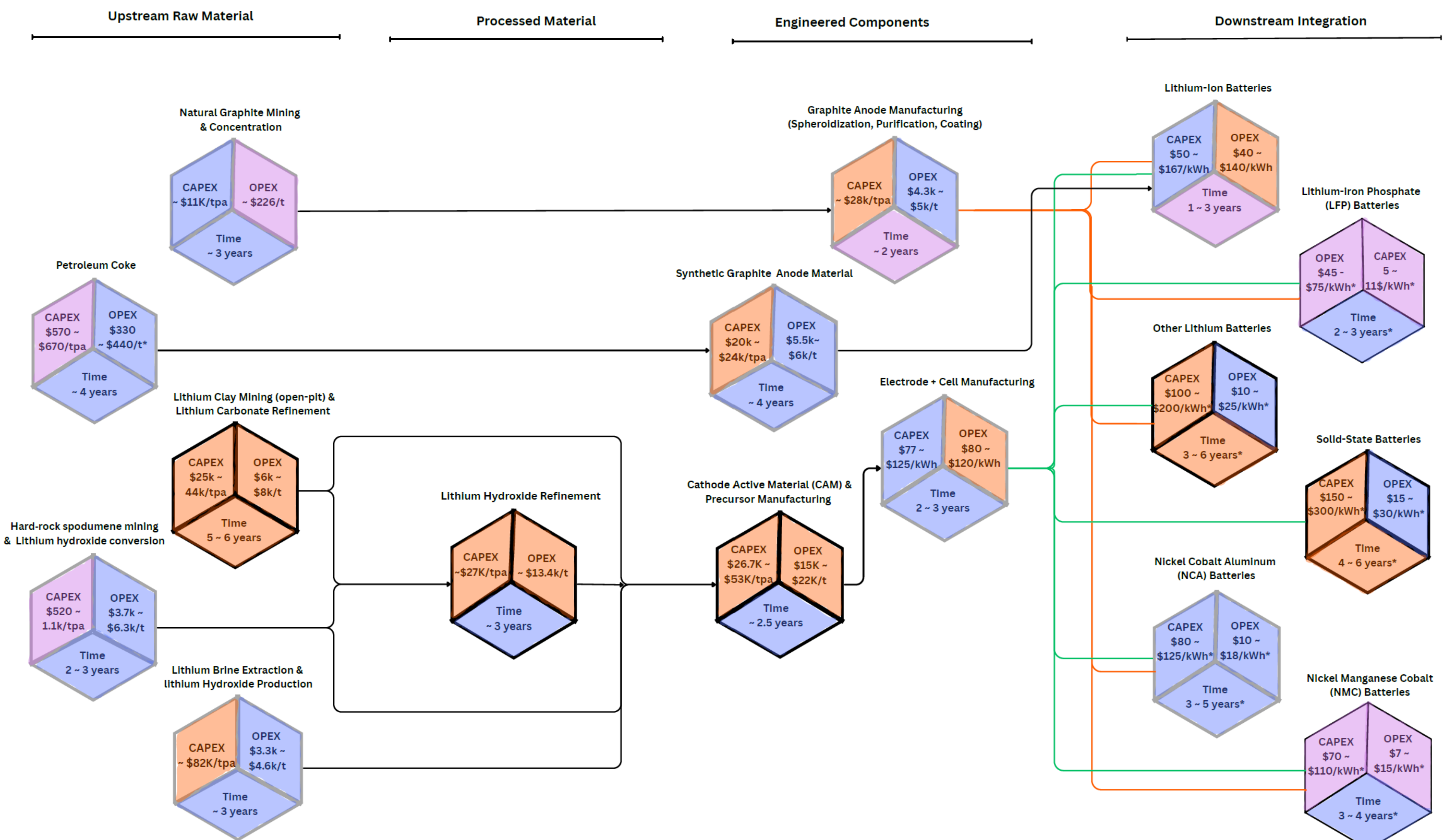


Figure 2: Cost-Focused Petri Map – Part A*. Orange = High, Blue = Medium, Purple = Low. Black Outline = High, Gray Outline = Medium. * Data Imputed.*

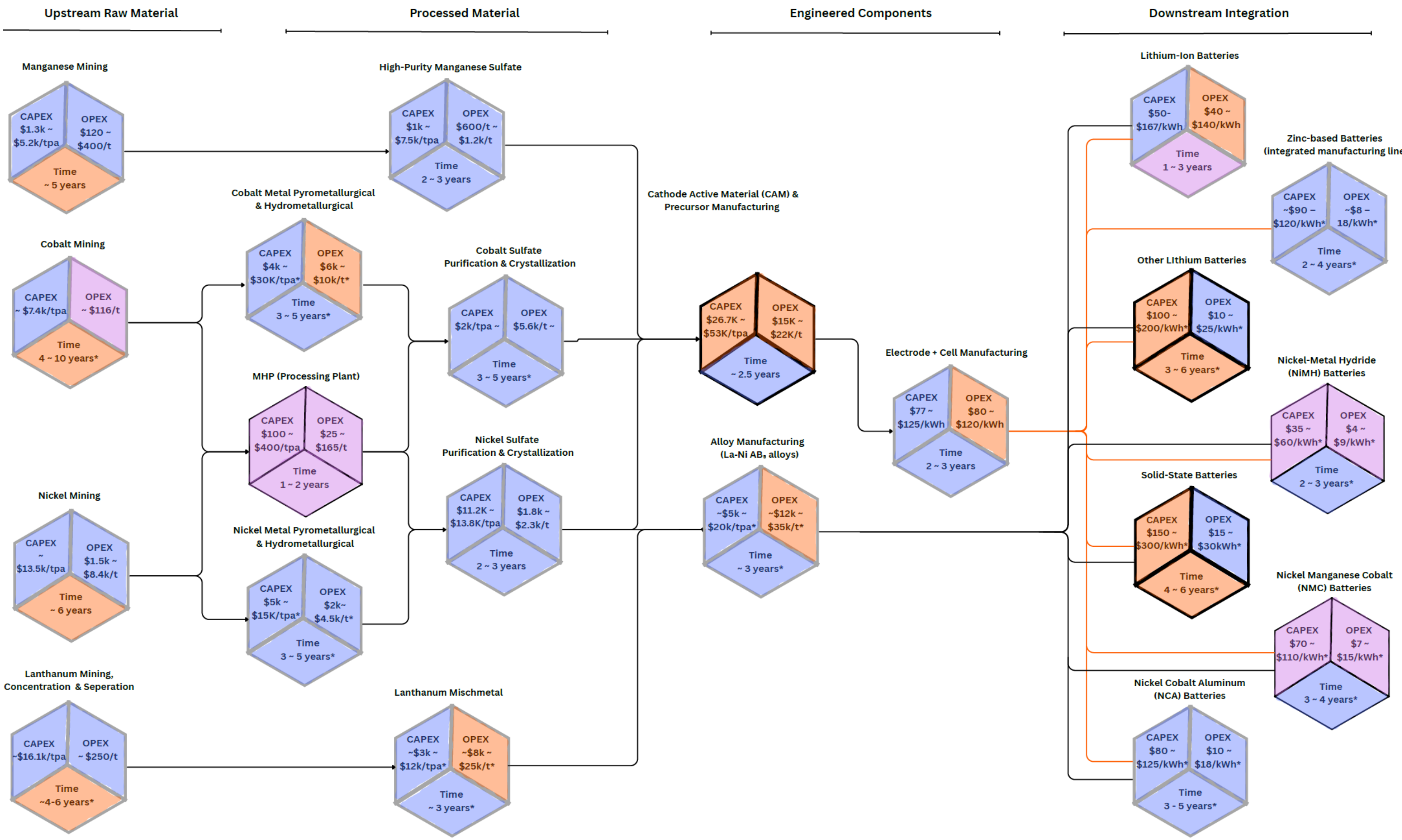
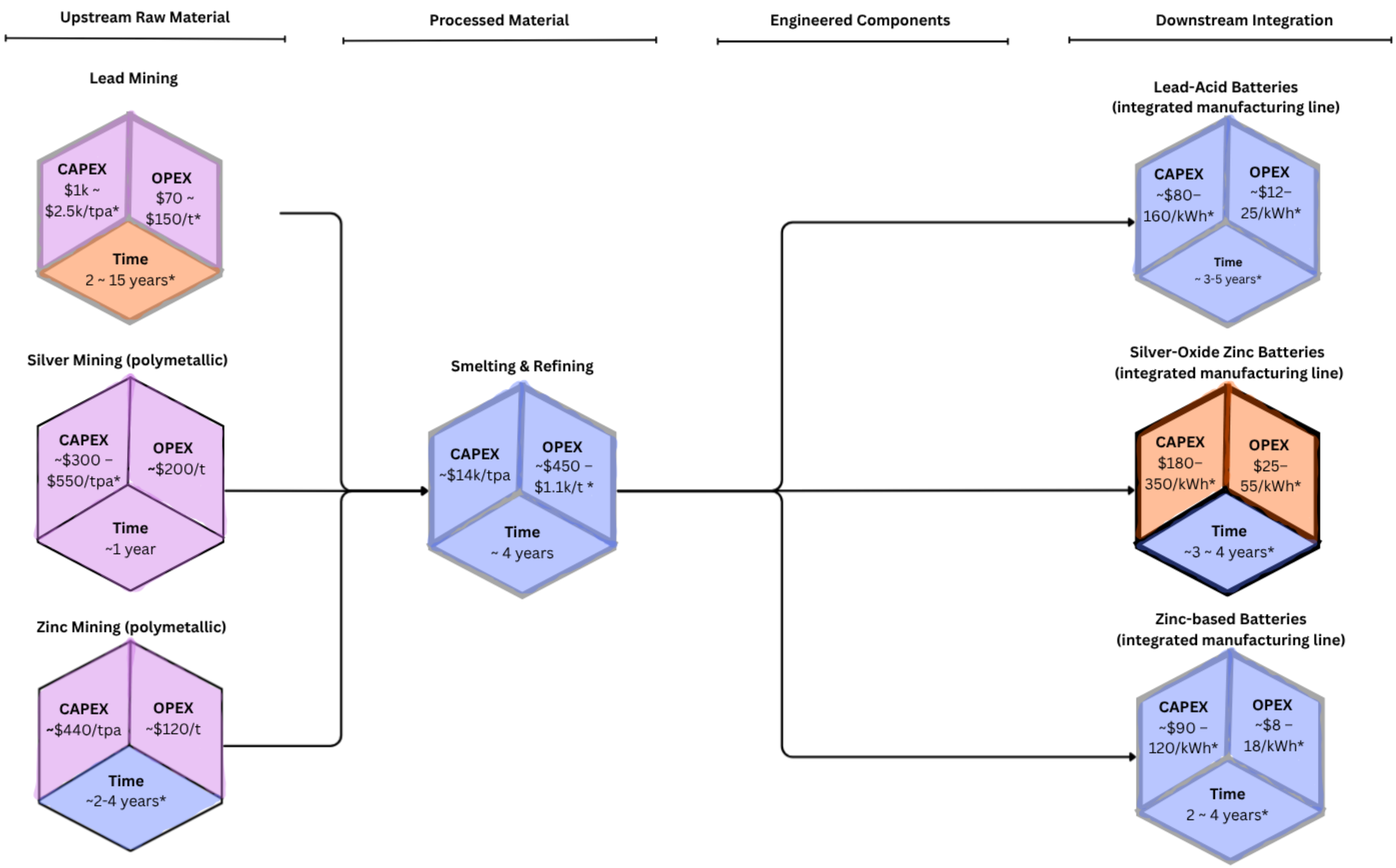


Figure 3: Cost-Focused Petri Map – Part B. *Orange = High, Blue = Medium, Purple = Low. Black Outline = High, Gray Outline = Medium. * Data Imputed.*



*** Estimated value using co-pilot and Chat GPT due to public data unavailable**

**** Precise per-project cost figures vary widely by location, scale, and production method, so real industrial projects typically require detailed engineering estimates**

Figure 4: Cost-Focused Petri Map – Part C. *Orange = High, Blue = Medium, Purple = Low. Black Outline = High, Gray Outline = Medium. * Data Imputed.*

Cluster & Factor Analysis Framework

This study 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. Building on cluster theory developed by Michael Porter and refined by Christian Ketels (Ketels, 2017), the approach extends traditional cluster concepts to reflect the distinctive structure of critical mineral value chains.

Traditional cluster analysis examines how competitive industries concentrate geographically through supplier networks, institutions, and market demand within relatively bounded regions. Critical mineral supply chains differ because they are fragmented across geographies, with stages concentrated in different countries due to geology, technology, regulation, and geopolitical constraints. The central question is therefore not whether one region can anchor an entire cluster, but which value-chain stages can serve as strategic footholds within a coordinated, multi-country system.

To address this challenge, the analysis uses an adapted multi-stage CFAF, purpose-built for critical minerals. Rather than treating the value chain as a single unit, the framework disaggregates it into 18 stage archetypes spanning the lifecycle from exploration through downstream integration. These archetypes provide a consistent structural backbone for comparing multiple mineral families while remaining grounded in process-level realities. Not every stage applies to each mineral and for mineral specific analysis, non-applicable stages are not scored.

Each value-chain stage is evaluated using a factor-based structural scoring approach. Eight structural factors capture the conditions that shape where and how critical mineral activities can emerge, scale, and remain resilient. Together, they assess foundational prerequisites, catalytic enablers, and security-related constraints to identify where coordinated trilateral action is most likely to be effective.

Each factor is assessed through standardized diagnostic questions and scored on a Yes / No / Unknown basis to determine structural dependence, rather than country-specific performance, firm capability, or current market outcomes. Diagnostic results are then converted mechanically into composite scores based on the percentage of Yeses. And presented in a stage-by-factor heat map.

To structurally evaluate where trilateral coordination is both feasible and strategically necessary, we have applied the CFAF to all nine critical minerals in the battery supply chain (including two variations of graphite and three distinct mining sources for lithium). The results are presented in **Figure 5**.

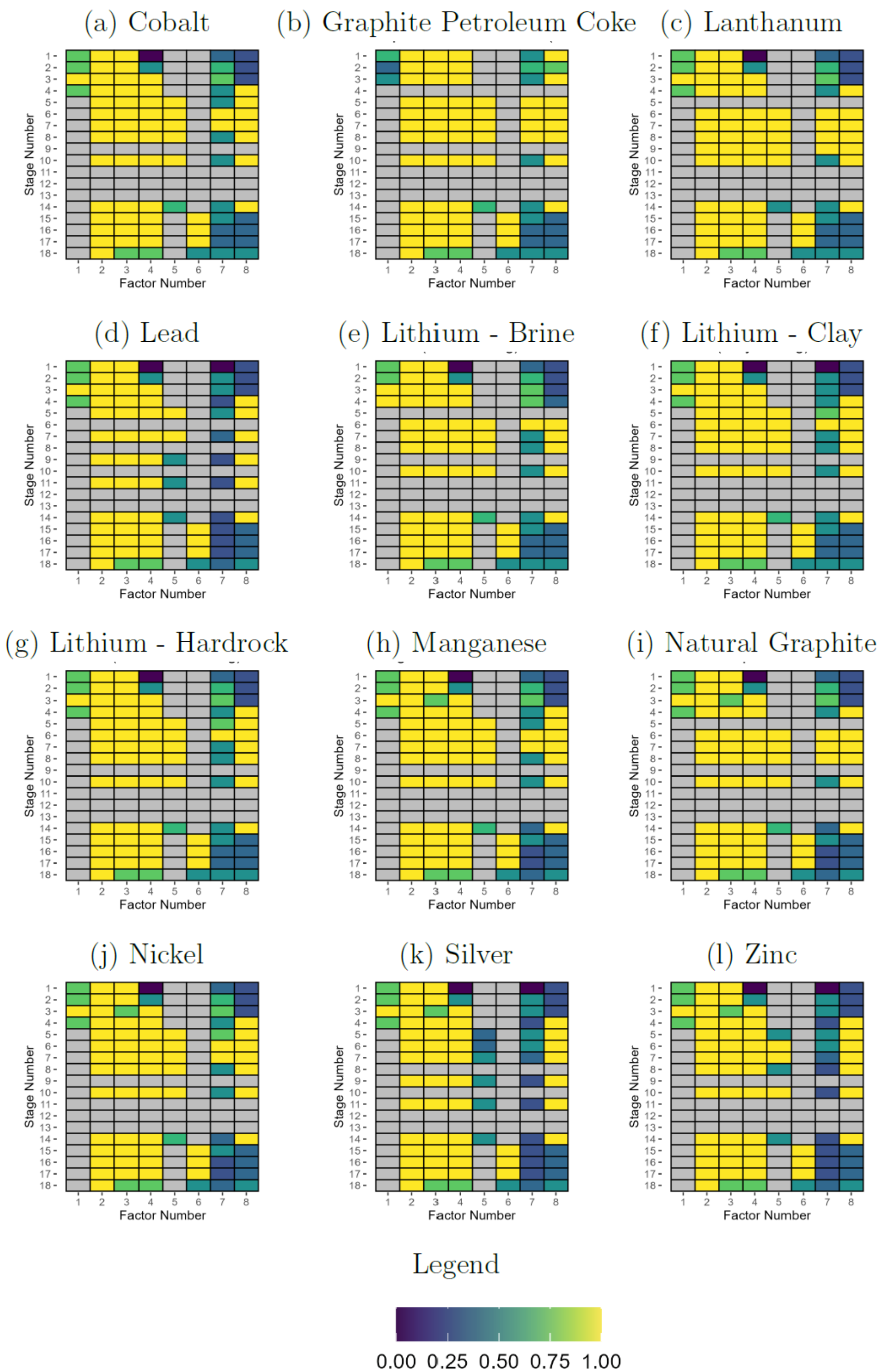


Figure 5: Battery Critical Minerals Heat Maps. *Higher values indicate higher structural dependence.*

CFAF Results – Battery Materials

Natural Graphite

Natural graphite is resource-dependent through mining and beneficiation, but its most important strategic leverage appears in purification, specialty carbon material production, active material synthesis, and electrode fabrication. These stages show high technical, institutional, policy, geopolitical, and complementarity scores, making them central to supply-chain resilience. The key vulnerability is not simply graphite extraction, but the conversion of mined graphite into battery-relevant, high-purity carbon materials that partner economies could coordinate around.

Graphite Petroleum Coke (GPC)

For graphite petroleum coke (or synthetic graphite), the front end depends on feedstock sourcing, characterization, and qualification rather than fixed mineral deposits. The clearest action zone is the processing-to-active-material segment, where technological capability, institutional support, business environment sensitivity, policy relevance, geopolitical exposure, and trilateral complementarity are all high. Downstream cell, module, and system stages remain technically intensive but show weaker complementarity. Overall, GPC is most strategically relevant where petroleum coke is transformed into specialty carbon and active battery materials.

Lithium (Brine Mining)

Lithium from brine mining is strongly shaped by resource geography at the survey, permitting, brine pumping, and pre-concentration stages. After that, the chain becomes much more actionable: chemical conversion, refining, specialty chemical production, active materials, and electrode fabrication show high technical, institutional, policy, and complementarity scores. The key takeaway is that brine resources are location-bound, but much of the value-added processing and battery material production can be coordinated across partner economies.

Lithium (Clay Mining)

Lithium from clay mining follows a similar pattern, but with emphasis on ore preparation and processing after extraction. The upstream stages remain tied to deposit location, while metallurgical processing, hydromet conversion, refining, specialty chemicals, and active materials become the main areas of actionability. Geopolitical risk is moderate and highest around chemical conversion, while complementarity is strong through electrode fabrication. The strongest opportunity is, therefore, in coordinated development of processing and battery material capacity rather than mining itself.

Lithium (Hard-rock Mining)

Hard-rock lithium is geology-bound through extraction and beneficiation, but its strategic actionability rises sharply in metallurgical processing, chemical conversion, refining, specialty chemicals, active materials, and electrode fabrication. These stages are less dependent on mine location and more dependent on industrial capability, infrastructure, policy support, and technical ecosystems. Geopolitical risk is highest around conversion, while complementarity is strong across the processing-to-battery materials chain. This makes hard-rock lithium most actionable after concentration, especially in conversion and materials production.

Cobalt

Cobalt shows sharper upstream vulnerability than lead, with extraction and early processing exposed to both resource dependence and geopolitical risk. Once the chain moves into beneficiation, hydromet processing, refining, specialty salts, active materials, and electrode fabrication, resource dependence falls away while technical, institutional, policy, and complementarity factors remain strong. This makes cobalt especially actionable in the midstream-to-battery materials segment, where strategic exposure and partner-country coordination potentially overlap.

Nickel

Nickel's upstream stages remain tied to deposits and mining conditions, but the main strategic actionability emerges in metallurgical processing, hydromet conversion, refining, specialty salt production, active materials, and electrode fabrication. Geopolitical risk is highest in conversion and refining, while complementarity remains strong through the battery materials stages. This suggests that nickel coordination should focus less on extraction itself and more on processing, refining, and production of battery-grade nickel inputs.

Manganese

Manganese shows upstream dependence in survey, permitting, extraction, and beneficiation, but the stronger strategic opportunity lies in processing, refining, specialty salt production, active materials, and electrode fabrication. Policy commitment and technical capability are especially important across this midstream-to-materials segment. Geopolitical risk is highest in chemical conversion and refining, while complementarity is strong from beneficiation through electrode stages. Overall, manganese is most actionable where ore moves into refined and battery-grade material forms.

Lanthanum

Lanthanum is resource-exposed at the mining and early concentration stages, but the major leverage point shifts quickly into chemical conversion, refining, specialty oxide production, alloying, and active material synthesis. These stages combine high technical requirements, policy dependence, geopolitical exposure, and partner complementarity. That makes lanthanum most actionable in the midstream materials-conversion segment, where coordinated investment could reduce strategic exposure while building distributed processing and specialty-material capacity.

Lead

For lead, the strongest opportunities appear beyond the geology-bound front end. Upstream stages remain resource-dependent, especially extraction, but midstream and downstream activities show consistently high technological, institutional, and business-environment dependence. Processing, refining, alloying, fabrication, and manufacturing stages are therefore more actionable because they can build on existing industrial capabilities across partner economies. Geopolitical risk is generally moderate to low, so the main opportunity is less about relieving an acute chokepoint and more about strengthening distributed industrial capacity and downstream integration.

Silver

Silver shows a more moderate strategic-risk profile than many battery minerals. Its upstream stages are resource-dependent, but processing, refining, alloying, component fabrication, and downstream manufacturing show high technical and institutional relevance. Policy dependence and geopolitical risk are comparatively lower, so the opportunity is mainly industrial rather than chokepoint driven. Silver is most actionable in the processing-to-fabrication segment, where partner economies can strengthen refining, materials preparation, and component integration.

Zinc

Zinc's front end is tied to resource geography, but the strongest coordination potential lies in metallurgical processing, chemical conversion, refining, specialty oxide/metal production, active material synthesis, and electrode fabrication. Geopolitical risk is generally manageable compared with more concentrated mineral chains, while complementarity remains strong across the midstream and materials stages. The main takeaway is that zinc offers practical opportunities to deepen processing, specialty-material, and downstream capacity rather than resolve a severe geopolitical bottleneck.

CFAF Analysis

Patterns

There are four clear patterns from the collective results of all twelve heat maps. The first pattern that emerges is that the strongest strategic opportunities are generally not in the upstream segment, but in the midstream processing and engineering stages where resource dependence falls away and industrial, technical, policy, and partner-country coordination factors become most important. Most of these minerals echo the same trend; the upstream stages – geological survey, exploration/permitting, extraction, and sometimes beneficiation – are constrained by geology and deposit location. These stages matter, but they are harder to relocate or coordinate because they depend on where the resource in question exists. Once the value chain moves into the midstream stages – metallurgical processing, chemical conversion, purification/refining, specialty chemical or material production, active material synthesis, and electrode/component fabrication – the constraint shifts away from fixed resource geography and toward industrial capability, infrastructure, institutional expertise, regulatory capacity, and policy support. That is where coordinated action becomes more feasible.

A second pattern is that technological proximity, institutional thickness, and business environment sensitivity are consistently high across nearly all midstream and downstream stages. This suggests that these supply chains are not just about having mineral reserves; they require dense industrial ecosystems, specialized processing know-how, permitting and regulatory capacity, skilled labor, infrastructure, and reliable commercial conditions. In practical terms, whether the members of the Triad or any of their allies control the relevant raw resources, any state with strong technological processes, research support, manufacturing, and quality-control/operational capabilities can play an important role.

The third pattern is that geopolitical risk is highest around conversion, purification, refining, and specialty material production, rather than extraction. This is especially clear for cobalt, natural graphite, GPC, lanthanum, lithium, manganese, and nickel. This means that these processing and early-production stages often hold capacities that are inherently prone to global concentration, appear as chokepoint risks, or are technically difficult to replicate. That makes them both strategically vulnerable and important targets for intervention.

A fourth pattern is that trilateral complementarity is usually strongest from beneficiation or processing through active material synthesis and electrode/submodule fabrication. This means the heat maps are pointing toward a distributed model: one partner may contribute upstream leadership with feedstock or intermediate materials, and another may manage downstream integration involving advanced manufacturing, assembly, and certification, while the third facilitates midstream coordination in the chemical processing or refining stages that bridges trilateral complementarity across all segments. Ultimately, this signifies that battery materials value chains do not need to be fully localized in one country to become more resilient.

Additional Findings and Takeaways

There is also a useful distinction between minerals. Cobalt, nickel, lithium, manganese, natural graphite, GPC, and lanthanum show stronger strategic urgency in midstream and stages because they combine technical intensity, policy relevance, geopolitical exposure, and high complementarity. Lead, silver, and zinc look somewhat less chokepoint-driven; their opportunity is more about strengthening industrial capacity, refining, fabrication, and downstream integration than ensuring political and strategic alignment or resolving a severe geopolitical bottleneck.

So, the overall takeaway is that the best targets for coordinated Triad action are the stages where geology matters less but capability, policy, and security matter more—especially processing, chemical conversion, purification/refining, specialty material production, active material synthesis, and electrode/component fabrication. These are the recurring calls to action across the critical mineral heat maps for battery materials.

Implications/Policy Recommendations

The combined Petri map and cluster and factor analyses results reflect that the highest-value opportunities for the U.S., Japan, and South Korea lie where four conditions overlap: adversarial market-share concentration, manageable cost barriers, structural actionability, and clear trilateral complementarity. In practical terms, this means that the strongest opportunities are not concentrated only in upstream mining or downstream manufacturing, but in the midstream segments where materials are converted into battery-relevant inputs. This is where the Triad has the strongest ability to coordinate investment, technology, resources, and production. For long-term success, the triad should also pursue a coordinated procurement strategy to sustain the minimum scale needed for cost-efficiency and return on investment.

The priority minerals identified in this report should be understood through two related but distinct lenses: industrial necessity and actionability. From a battery-industry perspective, lithium, cobalt, natural graphite, and synthetic graphite carry the greatest strategic importance because of their cost share, technical relevance, and dependence on Chinese-controlled supply chains. Minerals such as lanthanum and lead may present more actionable or lower-cost opportunities in specific value-chain segments, but they should not be interpreted as replacing lithium, cobalt, or graphite as the highest-priority battery materials for trilateral cooperation.

The Petri map analysis identifies where market concentration and cost feasibility intersect. China's control across natural graphite, lithium conversion, cobalt sulfate, manganese sulfate, graphite anodes, lithium anodes, and multiple downstream battery categories creates acute exposure for allied battery industries. However, variance across the associated cost profiles must be interpreted carefully. For example, while the natural graphite value chain appears relatively more accessible compared with more cost-intensive pathways, this does not mean that graphite is a low-barrier market. Graphite is a relatively low-priced material, so even small absolute cost differences can create large competitiveness gaps. China's low midstream processing costs, established scale, and qualification advantages make graphite difficult to enter even where public subsidies are available. For this reason, natural graphite should be treated as strategically urgent but commercially challenging despite the lower relative costs.

Lanthanum and lead also highlight different ways the maps can reveal opportunities. Lanthanum stands out because the Triad already has a stronger position in parts of the value chain, especially in lanthanum carbonate refinement, and the cost profile appears manageable. The policy goal should be to protect and expand this existing advantage. Lead is less defined by an immediate China-centered chokepoint, but its value chain has relatively low-to-medium cost barriers after mining. This makes it a practical case for strengthening distributed industrial capacity across refining, components, and battery manufacturing. However, all opportunities revealed by the maps should be framed as complementary to, rather than substitutes for, the higher-priority battery materials that dominate cost, performance, and supply-chain risk in the battery industry.

The CFAF results reinforce and sharpen the conclusions from the maps. Across natural graphite, synthetic graphite, lithium, cobalt, nickel, manganese, and lanthanum, the strongest policy-relevant action zones occur in processing, chemical conversion, purification and refining, specialty material production, active material synthesis, and electrode or submodule fabrication. These stages depend less on resource location and more on technical capability, infrastructure, skilled labor, regulatory certainty, and policy support. These are areas where the Triad can coordinate effectively if governments and industry align early.

These insights collectively show that the Triad should not measure supply-chain resilience only by access to mines or final battery factories. Mining access is necessary, and downstream manufacturing strength is valuable, but the decisive vulnerability lies in the middle of the chain. Without secure processing and engineered-material capacity, downstream battery production remains dependent on external or highly concentrated inputs. Potential projects should be evaluated based on four criteria: whether they reduce a major chokepoint, whether the cost profile is manageable, whether the stage can realistically be developed outside China, and whether the project uses the different strengths of the U.S., Japan, South Korea, and trusted resource partners like Australia. In applying these criteria, policymakers should balance feasibility with industrial necessity so that lower-barrier projects do not crowd out materials that are more difficult but more central to battery competitiveness and national security.

Cooperation Model

The Triad should not seek to build every part of every value chain in each country. That would likely lead to under-scaled projects, fragmented demand, and higher costs. Instead, the Triad should pursue distributed specialization model where each country focuses on the stages where it has the strongest capabilities, while still creating shared supply-chain security through cross-border material flows, common standards, and coordinated demand. It would also have room to include partnerships with trusted allies to faithfully fill in gaps.

This model also provides a practical basis for demand aggregation, but aggregation should be targeted carefully. Interview findings suggest that aggregation is most feasible where product specifications can be standardized or narrowed enough to create a tradable market, rather than at highly bespoke downstream stages such as certain cathode active materials, precursor cathode active materials, or cell-level products. EV, ESS, defense, and infrastructure demand from public agencies and major corporate buyers could therefore be pooled or coordinated around commodifiable upstream and midstream materials, recycling feedstocks, and ESS-related material demand. This would help translate broad supply-chain resilience goals into bankable project pipelines that can attract private capital.

Demand aggregation should also be tied to the operating scale required for priority facilities to reach competitive unit costs. Rather than aggregating demand in the abstract, participating governments and firms should identify the minimum efficient scale for a jointly supported refining, smelting, processing, or recycling facility, estimate the utilization rate needed to minimize unit costs, and secure offtake commitments sufficient to support that threshold over a fixed period. Volumes could then be allocated among participants based on their financial, technological, operational, or procurement contributions. This structure would make offtake more meaningful because it would be directly connected to facility utilization, unit-cost reduction, and project bankability.

Under the proposed framework, the U.S. can contribute scale, financing tools, defense and infrastructure demand, and chemical-processing capability. Japan can contribute high-purity materials expertise, fine chemicals, quality control, and a stronger model for long-term resource security planning. South Korea can contribute strategic midstream refining capabilities alongside its established strengths in battery manufacturing, cell and module integration, recycling demand, and major private-sector battery firms. Recent investment activity in the U.S. illustrates how Korean industrial capacity could support allied midstream processing and refining outside China. For example, Korea Zinc, the world's largest zinc smelting company, announced in December 2025 that it has partnered with the U.S. to build a state-of-the-art critical minerals smelter in the U.S. with a total planned investment of $7.4 billion (including $6.6 billion in capital expenditures) (Korea Zinc, 2025). In consideration of including key partnerships, Australia should be considered as an effective upstream ally because of its resource base, mining expertise, and potential to support allied supply chains if permitting and approvals can move quickly enough (Critical Minerals Office, 2023).

The first practical test of this cooperation framework could be a ROK-U.S.-Japan recycling alliance. Recycling should be treated as a top priority because it offers the Triad an opportunity to demonstrate economic viability in a market where supply aggregation, standards, logistics, and downstream qualifications are just as important as technology. A successful recycling alliance would create a valid sample for a working model that proves allied battery material systems can aggregate feedstock, process material at competitive quality, and return battery-relevant inputs into regional supply chains. This model would be particularly valuable because recycling can reduce exposure to upstream resource constraints while building midstream capabilities in black mass processing, refining, precursor recovery, and active-material reintegration. Because recycling feedstocks can potentially be aggregated across firms and jurisdictions, a recycling alliance could also serve as a proof of concept for broader demand aggregation before the model is extended to more complex upstream or midstream materials.

However, the recycling alliance should not focus only on collecting black mass or manufacturing scrap. It must also address the cost gap in post-treatment processing. Chinese firms have been allowed to import black mass, and material can continue to flow toward China if Chinese post-treatment processing remains significantly cheaper than allied alternatives. A ROK-U.S.-Japan recycling alliance should therefore include mechanisms to offset processing-cost differences, support Korean and allied post-treatment capacity, and keep recycled feedstock within trusted supply chains.

This recycling alliance should also be paired with a broader benchmarking of the Japanese model. Japan's approach is instructive because it treats strategic mineral security as a national-security issue, not just company-level procurement concern (JOGMEC). Government support beginning at the feasibility-study stage lowers early project risk before private capital is willing to enter. The Triad should adopt this government-backed approach that would jointly support feasibility studies, coordinate due diligence, and help secure bankable offtake arrangements before projects reach final investment decisions. This would reduce early risk and make private investment more likely.

Australia's role should be integrated into this model at the front end. For mineral streams where Australia has geological or mining advantages, the Triad should pursue coordinated offtake, equity participation, credit-enhancement tools, and processing partnerships that connect Australian upstream production to U.S., Japanese, and Korean midstream and downstream capacity. However, upstream access alone will not be sufficient. If project approvals take too long, allied capital will remain unable to respond at the speed required by the strategic environment. Australia and the Triad should therefore coordinate on faster approval pathways for projects that meet agreed environmental, labor, and security standards. However, streamlining should not mean weakening environmental safeguards but should mean clearer timelines, parallel reviews, predictable requirements, and faster decisions for strategically significant projects.

For raw material linkages with Australia, Canada, and other trusted partners to become commercially durable, the central question is not only whether supply can be secured, but whether the resulting processed output can be produced at a competitive unit cost for the buyer. Aggregated offtake tied to efficient facility utilization, paired with credit enhancement and targeted public support, may therefore be one of the most practical tools for connecting allied upstream resources to downstream battery-material demand.

Harmonization – Standards, Non-Tariff Measures, and Market Formation

The Triad should also use standards and sustained quality as a strategic instrument. Chinese dominance in many battery material stages is not only a function of scale, but also of cost structures shaped by state support, environmental externalities, and uneven labor and regulatory burdens. If allied producers are required to meet higher environmental, labor, and governance expectations while competing directly against lower-cost materials produced under different conditions, market forces alone will continue to favor concentrated supply chains.

Although this report does not decompose the full cost gap between Korean and Chinese battery producers, the analysis and interview findings suggest that part of the competitiveness challenge is structural rather than purely operational. The gap is tied to upstream input prices, midstream scale, energy and operating costs, processing concentration, qualification timelines, regulatory asymmetry, and fragmented product specifications. For this reason, standards and market-formation tools should be understood not only as compliance measures, but also as mechanisms for narrowing the competitive gap between trusted allied suppliers and lower-cost incumbent producers.

Alongside of coordinated investments, the U.S., Japan, South Korea, and Australia should harmonize ESG criteria, labor standards, traceability requirements, environmental regulations, technical specifications, quality bands, qualification requirements, and quality standards for battery materials. Properly designed, these standards would serve several purposes at once. They would reduce compliance uncertainty for firms operating across allied markets, create a shared definition of trusted battery materials, support responsible mining and processing, increase the feasibility of demand aggregation by narrowing specification differences where possible, and function as non-tariff barriers against dumped or underpriced materials that do not meet comparable standards. These measures should be framed not as protectionism, but as resilience standards that reflect the real security, environmental, and social costs of battery material supply.

At the same time, standards should be designed carefully so they do not simply shift compliance and verification costs to battery manufacturers. Differentiated ESG, labor, traceability, environmental, and quality requirements will only strengthen trusted supply chains if they are paired with clear market benefits, such as procurement preferences, tax incentives, credit support, tariff preferences, or eligibility for public financing. Without these complementary measures, higher standards could increase overhead costs across the allied battery value chain without meaningfully improving competitiveness against lower-cost incumbent suppliers.

Such standards should be linked directly to procurement eligibility, public financing, tax incentives, and strategic stockpile purchases. The IEA identifies standards-based incentives, demand-side structures, public procurement channels, strategic reserves, and qualification approaches as policy mechanisms that can support diversified mineral supplies (IEA, 2025). In this model, materials that meet Triad-plus-allies standards should receive preferential treatment in government-supported projects, while materials that fail to meet traceability, labor, environmental, technical, qualification, or quality thresholds should be excluded from public procurement and ineligible for premium incentives. Over time, this would create a differentiated market in which trusted supply chains receive a security premium, allowing allied producers to compete on resilience and quality rather than price alone.

The same caution applies to price-floor mechanisms. While price floors can improve the commercial viability of new allied projects, they may also raise input costs for battery manufacturers unless paired with compensatory tools. For this reason, price stabilization should be combined with demand aggregation, public procurement, tariff or tax preferences, and time-limited support mechanisms that help firms absorb the cost of participating in trusted supply chains while new capacity reaches scale.

Role of Government

Governments will need to act as market makers during the early stage of supply chain development. Many of the priority stages identified in the analysis require high upfront investment, long qualification timelines, and protection from price volatility. Private firms are unlikely to carry that risk alone, especially when competing against established and subsidized Chinese producers.

Government support should be designed around bankability, not simply purchase volume. Offtake commitments can help demonstrate future demand, but the scale of those commitments alone may have limited effect on financing costs if the participating firms are not viewed as sufficiently creditworthy. In battery material value chains, financing conditions often depend more heavily on the credit profile of the counterparties involved and on whether project risks are allocated to entities capable of absorbing them. For this reason, government agencies, development finance institutions, export credit agencies, and investment banks may be most valuable when they serve as credit backstops or credit enhancers, reducing counterparty and project-finance risk rather than relying solely on large offtake commitments.

At the same time, aggregated offtake can become more powerful when it is structured around efficient plant scale. If participating countries and firms commit enough demand to support the utilization level required for a jointly backed refining, smelting, or processing facility to minimize unit costs, offtake can provide a clearer revenue base for debt financing. Under this framework, governments could aggregate ESS procurement, public infrastructure demand, or other strategic battery-material demand over a fixed period, while participating firms receive volume allocations based on their investment, technology, operational role, or procurement contribution. Adjustment mechanisms would also be needed if participants fail to take committed volumes, so that the project's revenue stability is preserved. We propose six steps for successful government support that follow these motivating guidelines.

First, governments should provide direct CAPEX support. Midstream processing, refining, recycling, and engineered-material facilities often require substantial infrastructure investment before revenues are proven. The U.S. Department of Energy exemplifies this support through its substantial investment in manufacturing, processing, refinancing, and advanced batteries to reduce business and country risks in mineral projects from 2021 to 2024 (DOE, 2024). Such support in the form of grants, low-cost loans, loan guarantees, tax credits, or public equity participation should be used for projects that address major chokepoints and meet allied standards. This support should be tied to clear milestones, including production targets, bankable offtake arrangements, rigorous technical and commercial due diligence, environmental compliance, and technology protection requirements. Because government support inevitably requires some degree of project selection, public agencies should prioritize projects based on demonstrated technical capability, OEM qualification potential, execution capacity, and fit with identified supply-chain chokepoints rather than strategic appeal alone.

Second, governments should provide temporary price stabilization. A price floor, contract-for-difference model, strategic reserve purchase, or guaranteed offtake price could help new projects survive the early market-formation period. This support should not be permanent. It should be designed with a clear phase-out schedule as facilities reach commercial scale, qualification is completed, and private demand becomes self-sufficient. This will help to prevent strategically necessary capacity from being destroyed before it has time to mature. Interview findings suggest that a roughly five-year stabilization window may be appropriate for some priority midstream and battery-material projects, giving firms enough time to finance, construct, qualify, and begin scaling production before competing fully against incumbent suppliers.

Third, governments should implement diversity purchasing requirements. These are stronger than simple local-content rules because they focus directly on reducing concentration risk. Public procurement, battery incentives, and ESS deployment programs should require that a growing share of battery material inputs come from a diversified set of trusted suppliers, with limits on overreliance on any single country, firm, or processing route. This would reward resilient supply chain design rather than simply relocating dependency from one bottleneck to another. While temporary price floors can help bridge early-stage cost gaps, diversity purchasing requirements are likely to be the more durable policy tool because they create long-term demand for non-concentrated supply even after direct subsidies phase down.

Fourth, the Triad should develop a coordinated strategic stockpiling mechanism. Recent disruptions and instability around major maritime chokepoints underscore the need for physical reserves of selected battery-relevant minerals and processed materials. Because critical minerals differ significantly in chemical properties, shelf life, storage requirements, and downstream usability, stockpiling should not be treated as a generic warehousing exercise. The Triad should prioritize usable, standardized, and relatively shelf-stable forms of material that can be integrated into industry supply chains, rather than stockpiling materials that degrade quickly, lack common specifications, or cannot be readily qualified by downstream users. The U.S., Japan, and South Korea should explore mechanisms for shared planning, compatible inventory standards, and, where appropriate, joint or regionally coordinated storage arrangements for materials most exposed to disruption risk. South Korea and Japan, given their geographic proximity and existing industrial demand, could also explore shared storage or joint management facilities to strengthen regional resilience.

Fifth, governments should accelerate approval pathways for qualified critical battery-material projects. Critical battery material projects cannot take too long to permit if they are meant to reduce near-term supply chain security risk. If permitting and review processes stretch beyond timelines, allied projects will fail to offset Chinese concentration before vulnerabilities deepen. Therefore, governments should create accelerated approval pathways for critical battery material projects that meet high environmental and labor standards. This is especially important in Australia's upstream role, where resource potential must be matched by timely development, but it also applies to U.S., Japanese, and Korean midstream processing and downstream manufacturing projects. The goal should be clearer rules, predictable timelines, parallel reviews, and faster decisions for projects that meet high environmental and labor requirements.

Finally, governments must exercise patience. Upstream mining projects require especially long planning horizons, often extending 10–15 years or more when exploration, feasibility studies, permitting, financing, are construction are pursued before first production even starts (IEA, 2021). For these projects, government support should begin well before construction and continue through early production, rather than only after market shortages appear. Midstream processing, refining, recycling, and engineered-material projects may move faster than new mines, but they still require several years to finance, permit, construct, commission, qualify with downstream customers, integrate into procurement systems, and withstand price volatility during ramp-up. A five-year stabilization period should therefore be treated as the minimum support window for priority midstream and battery material projects once they enter the project-development and construction pipeline, while upstream mining requires at least a longer 10–15-year planning and support horizon. During this period, governments should provide subsidies, guarantees, credit enhancement, offtake support, standards alignment, and procurement commitments until private markets are strong enough to carry more of the burden.

Overall, the policy goal should be to build the right capacity in the right parts of the value chain. The Petri map and CFAF analysis show that the best opportunities are where chokepoint risk, cost feasibility, and allied capability overlap. If the U.S., Japan, and South Korea act separately, they may create fragmented projects that remain vulnerable to Chinese scale and pricing. If they coordinate, they can build a more resilient battery materials supply chain that is commercially realistic and strategically secure.

Conclusion

Battery material supply chains have become a key test case for critical mineral security because they connect energy transition, advanced manufacturing, national security, and long-term industrial competitiveness. As demand grows for electric vehicles, energy storage systems, grid modernization, and AI-related power infrastructure, secure access to battery-relevant minerals and materials will become increasingly important for the U.S., Japan, and South Korea.

At the same time, diversification of battery production and its supporting supply chains should be understood as a long-term industrial undertaking rather than a near-term substitution exercise. Building competitive capacity outside China will require durable demand, sustained public and private investment, accumulated technical expertise, and pathways for reducing production-cost gaps over time. These challenges also reinforce the value of practical collaboration with established battery producers, technology-sharing arrangements, and coordinated investment among markets that may be too small to support full supply-chain duplication independently. For the Triad, this means that resilience will depend less on isolated national buildout and more on shared scale, complementary specialization, and partnerships with resource-rich allies (IEA, 2025).

Applying Petri map analysis and the CFAF together to battery materials, our analysis shows that the main supply chain challenge is not only upstream mining and that many of the most serious vulnerabilities appear in midstream processing, engineered components, and downstream integration. China’s strong position across natural graphite to graphite anodes, lithium conversion to lithium anodes, cobalt sulfate, manganese sulfate, and battery manufacturing creates clear exposure for allied industries.

The CF Petri maps sharpen this finding by showing that not every vulnerable pathway carries the same barriers to entry. Natural graphite stands out because it combines heavy Chinese concentration with a relatively accessible cost profile. Lanthanum presents a different opportunity because the Triad already holds meaningful positions in parts of the value chain, especially refinement. Lead is less defined by an immediate chokepoint, but its relatively low-to-medium costs after mining make it a practical opportunity for strengthening distributed industrial capacity. These cases show that the best investment targets are where risk, feasibility, and allied capability overlap.

The CFAF results reinforce this conclusion. Across the battery minerals studied, the strongest areas for coordinated action generally appear after the geology-bound upstream stages. Processing, chemical conversion, purification and refining, specialty material production, active material synthesis, and electrode or submodule fabrication are repeatedly identified as the most actionable stages. These stages depend less on resource location and more on technical capability, infrastructure, institutional support, skilled labor, regulatory certainty, and long-term policy commitment.

The policy implication is direct. The Triad should treat battery material supply chains as strategic infrastructure, not only as commercial markets. Securing mines and expanding final battery manufacturing are necessary, but neither is sufficient without reliable midstream and engineered-material capacity. A coordinated project pipeline should therefore evaluate investments based on chokepoint reduction, cost feasibility, structural actionability, and trilateral complementarity.

Government support will be essential. CAPEX assistance, temporary price stabilization, diversity purchasing requirements, coordinated offtake, faster permitting for qualified projects, and harmonized ESG, labor, traceability, and environmental standards can help create a trusted market until private-sector capacity becomes commercially durable. A ROK-U.S.-Japan recycling alliance could serve as an early demonstration model, while Australia and Canada should be integrated as a key upstream partner where resource access and faster project development can support Triad supply-chain goals.

Ultimately, this report shows that battery material supply-chain resilience will depend less on full national self-sufficiency and more on coordinated specialization. The U.S., Japan, and South Korea each possess important but different capabilities. If pursued separately, their efforts may produce fragmented projects that remain vulnerable to Chinese scale, pricing, and processing dominance. If coordinated, however, those same capabilities can support a more resilient battery material system built around trusted inputs, diversified processing, shared standards, and commercially realistic investment. The next step is to move from analytical identification to project-level execution, using the Petri map and CFAF findings to guide where the Triad should invest first, where partner countries should be integrated, and where government support is necessary to turn strategic intent into durable supply-chain capacity.

References

ADIPEC. (2025, July). *IEA: Electrification, clean energy technologies, and data centre demand shaping 2025 global energy investment trends*. https://www.adipec.com/press-media/insights/2025/07/iea-electrification-clean-energy-technologies-and-data-centre-demand-shaping-2025-global-energy-investment-trends/

Critical Minerals Office. (2023, June 20). *Critical minerals strategy 2023–2030*. Department of Industry, Science and Resources. https://www.industry.gov.au/publications/critical-minerals-strategy-2023-2030

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

Japan Organization for Metals and Energy Security. (n.d.). *Financial support for Japanese companies (Metals)*. https://www.jogmec.go.jp/english/activities/metal/financial-support.html

Ketels, C. (2017, June). *Cluster Mapping as a Tool for Development*. Harvard Business School. https://www.hbs.edu/faculty/Pages/item.aspx?num=53385

Korea Zinc. (2025, December 15). *Korea Zinc Partners with the U.S. Department of War and U.S. Department of Commerce to Build a State-of-the-Art Critical Minerals Smelter in the United States with $6.6 Billion of Capital Expenditures*. https://www.koreazinc.co.kr/en/korea-zinc-partners-with-the-u-s-department-of-war-and-u-s-department-of-commerce-to-build-a-state-of-the-art-critical-minerals-smelter-in-the-united-states-with-6-6-billion-of-capital-expenditures/

International Energy Agency. (2025). *Policy mechanisms for diversified mineral supplies*. Global Critical Minerals Outlook 2025. https://www.iea.org/reports/global-critical-minerals-outlook-2025/policy-mechanisms-for-diversified-mineral-supplies

International Energy Agency. (2025, March 5). *The battery industry has entered a new phase*. https://www.iea.org/commentaries/the-battery-industry-has-entered-a-new-phase

UN Trade and Development. (2026, April 1). *Hormuz disruption deepens global economic strain across trade, prices and finance*. https://unctad.org/news/hormuz-disruption-deepens-global-economic-strain-across-trade-prices-and-finance

U.S. Department of Energy. (2024, December 19). *Department of Energy Publishes Findings on Supply Chains for Energy Sector Industrial Base and Advanced Batteries sector*. https://www.energy.gov/cmei/manufacturing/articles/department-energy-publishes-findings-supply-chains-energy-sector

Utamawati, H., & Yusuf, A. (2026, March). *How Indonesia's ban on raw nickel exports provides lessons for fiscal and economic policy in the low-carbon transition*. Centre for Economic Transition Expertise. https://cetex.org/wp-content/uploads/2026/03/Indonesia-Ban-on-Exports-of-Raw-Nickel.pdf

Vergun, D. (2025, January 10). *Securing Critical Minerals Vital to National Security, Official Says*. U.S. Department of War. https://www.war.gov/News/News-Stories/Article/Article/4026144/securing-critical-minerals-vital-to-national-security-official-says/

Endnotes

1. More information on our previous report, “Critical Minerals Supply Chian Security: A Framework for Trilateral Investment Coordination,” can be found here: https://hamminstitute.org/site-files/documents/critical_minerals_supply_chain_security.pdf
2. For more information about the Petri Map Framework, see Appendix A.
3. For further information about the Market Share Battery Materials Petri Map and the sources used to build it, see Appendix B.
4. For further information about the Cost-Focused Petri Map – Parts A, B, & C and the sources used to build it, see Appendix C.
5. For further information about the Cluster & Factor Analysis Framework (CFAF), see Appendix D.

Appendices

To maintain focus in the main report, a 56-page appendices document is provided separately that includes extensive references, detailed methods, and rationales. This material supports transparency and enables a deeper technical review of the frameworks presented in this paper.

The Appendices are available online via the QR code below or at: ***https://hamminstitute.org/site-files/documents/BatterySupplyChainAppendices.pdf***

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