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

APPENDIX A: Petri Map References

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APPENDIX B: Factor Analysis Methodology

Approach and Structure

To guide the Triad’s coordinated strategy in regard to critical-mineral value chains, this report introduces two analytical frameworks to reveal opportunities for trilateral complementarity, helping partners target high-priority stage-mineral combinations, optimize geographic configurations, and coordinate policy interventions.

To explain the analytical framework used to evaluate structural dependencies, this appendix aims to document the methodology with clarity and precision, to provide a reproducible scoring system that future analysts and research partners can apply consistently, and to support transparent communication of how insights were derived for policy, industry, and trilateral stakeholders.

This appendix provides the interpretive bridge between raw structural scoring and downstream insight generation (e.g., investment hypotheses, trilateral cooperation pathways, or policy coordination opportunities). This appendix defines the scoring system itself; analytical insights derived from the scores appear elsewhere in the report.

Stage Archetype Outline

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 Applicaple - the stage does not exist for the factor

Factor Based Framework Outline

A. Foundational Conditions (Cluster “Emergence” Factors

- 1. Resource & Input Advantage
- 2. Related Variety & Technological Proximity
- 3. Anchor Firms & Institutional Thickness

B. Catalytic Conditions (Cluster “Acceleration” Factors)

- 4. Business Environment Strengths
- 5. Policy Commitment & Strategic Alignment
- 6. Market Structure & Local Rivalry

C. Security & Resilience Conditions

- 7. Geopolitical & Supply-Chain Risk Exposure
- 8. Trilateral Complementarity Potential

Methodological Principles

Our methodology is a structural system that evaluates inherent stage characteristics to derive insights into evident value chains. It does not make empirical arguments in regard to real-world capabilities, policy performances, or firm-level behaviors.

Our scoring system assumes no prior technical or mineral-specific knowledge, thereby being designed for non-subject matter experts. Through our scoring system, we are able evaluate structural dependencies across stages of the crucial mineral value chain—not performance, competitiveness, or mineral-specific chemistry. The methodology uses a standardized 18-stage generic framework spanning Upstream, Midstream, and Downstream activities across any given value chain. These stages provide a mineral-agnostic backbone so that different critical mineral systems can be compared using a structural lens that is easily understood and accessible to the common user. Some or all of these 18-stages are scored across 8 Structural Factors that describe what makes that stage feasible, competitive, and structured, regardless of geography. Each factor tests a different dimension of structural dependency, and each factor is scored independently.

Not all structural factors are applicable across the full value chain; where this is the case, stages receive an NA (Not Applicable) score. For example, Factor 1 (Resource & Input Advantage) is scored only for upstream stages (1–4), where dependence on geology and extraction conditions can be assessed generically; beyond this point, inputs become mineral-specific and are therefore marked NA. By contrast, Factors 2, 3, 4, 7, and 8 are scored across all 18 stages because they evaluate cross-cutting structural conditions that can shape outcomes independent of mineral type. These applicability rules ensure that composite scores reflect only structurally meaningful signals at the generic stage level and serve as a baseline reference for subsequent mineral-specific analysis.

The Eighteen-Stage Framework Summaries

Stage 1: Geological Survey & Resource Assessment

This stage is about identifying and characterizing where critical minerals are in the ground. It includes desktop geological studies, mapping, geophysical surveys, sampling, and early resource estimates. The output is information: geological models, resource maps, and preliminary assessments of whether there might be an economically interesting deposit. No mining occurs yet, this is knowledge-building, not extraction. Time horizons are long, uncertainty is high, and risk capital is typically modest but speculative. The work is heavily dependent on access to land and existing geological knowledge, and it can be shaped by public geological surveys, national geological agencies, and early-stage exploration firms. The stage sets the foundation for everything else but does not itself "move material."

Stage 2: Exploration & Permitting

Here, the company drills, samples, and models the deposit in much greater detail, while also beginning the regulatory, land-access, and social license process. This includes resource definition drilling, preliminary economic assessments, baseline environmental studies, and early engagement with local communities and regulators. The goal is to move from "maybe something is here" to "we understand what's here and whether it might be mineable." Permiong overlays technical work with policy, environmental, and social constraints. Timelines can be long and politically sensitive. Exploration still does not produce saleable product; it reduces uncertainty and sets the stage for major capital allocation decisions in mining.

Stage 3: Extraction / Mining

This is the physical removal of ore or brine from the ground. It includes open-pit or underground mining, well fields for brines, in-situ leaching where applicable, and all the associated mining infrastructure: pits, ramps, haul roads, dewatering, and on-site safety systems. The output is ore, concentrate-ready material, or mineral-bearing brine. Mining is highly capital-intensive and tightly tied to the deposit's geology and location. It is also where many ESG issues come to the surface: land disturbance, tailings, worker safety, and community impacts. The economics of the entire chain open hinge on productivity and cost at this stage.

Stage 4: Beneficiation / Ore Concentration

Beneficiation upgrades run-of-mine ore into a higher-grade concentrate by removing gangue (waste) material. Typical processes include crushing, grinding, flotation, gravity separation, magnetic separation, and basic classification. For brine-based systems, analogous steps might be early-stage preconcentration or impurity removal before more advanced processing. This stage reduces the volume and increases the value per ton, making downstream transport and processing more efficient. Its design is strongly influenced by ore mineralogy and impurity profiles. It often sits near the mine to avoid hauling large volumes of waste rock.

Stage 5: Metallurgical Processing

Metallurgical processing converts ore or concentrate into intermediate products using thermal or combined thermal–chemical routes. This includes smelting, roasting, calcination, and other high-temperature processes that change mineral phases and separate valuable metals from waste. These plants can be located at or away from the mine, depending on energy, regulatory, and logistics considerations. This stage often defines the emissions profile and energy intensity of the chain. It requires significant capital and technical expertise, and its design is highly mineral-specific. Process choices here strongly influence what later chemical conversion and refining steps look like.

Stage 6: Chemical Conversion / Hydromet Processing

Chemical conversion uses solutions, reagents, and hydrometallurgical methods to dissolve, separate, and recover metals or compounds from concentrates or roasted material. Typical operations include leaching, solvent extraction, ion exchange, precipitation, and crystallization. The outputs are intermediate chemical products suitable for further refining or specialty production. This stage is deeply chemistry-dependent and open highly integrated with environmental controls because of reagents, effluents, and waste streams. Process design varies significantly by mineral system and impurity profile, and relatively small changes in feed composition can have large impacts on performance and cost.

Stage 7: Purification & Refining

Purification and refining take intermediate solutions or solids and bring them to high-purity products that meet tight specifications. Operations may include recrystallization, advanced filtration, final impurity removal, electrowinning, or electrorefining. The emphasis is on achieving consistent purity, not just recovering the metal. These facilities may be located closer to demand centers or infrastructure rather than mines, especially when feedstocks can be transported as concentrates or intermediate chemicals. The business model often moves from bulk tonnage to higher value-per-ton products, with quality control and analytical capabilities becoming central.

Stage 8: Specialty Oxide / Metal / Salt Production

This stage turns refined materials into specialized oxides, metals, salts, or compounds tailored for specific applications: magnet-grade rare-earth oxides, high-purity salts, special metal forms, etc. The focus is on composition, particle characteristics, and performance in particular downstream uses. Producers operate close to end-use specifications and may collaborate with downstream OEMs to co-develop materials. The market is more differentiated than bulk commodity refining, and technical service to customers becomes part of the value proposition.

Stage 9: Alloying & Powder / Material Preparation

Alloying and powder preparation combine metals and other elements into engineered alloys or powders with specific mechanical, magnetic, or electrical properties. This may include melting, casting, atomization, milling, and controlled heat-treatment, as well as surface treatments or coatings. The stage translates pure or specialty materials into forms that can be directly used in components or advanced manufacturing processes (e.g., powder metallurgy, additive manufacturing, magnet pressing). Process control and consistency are critical, and intellectual property may reside in compositions and processing routes.

Stage 10: Active Material Synthesis

Active material synthesis produces the functional materials that directly participate in energy storage, magnesium, catalysis, or other core device functions (e.g., bakery cathode powders, magnet powders, functional oxides). Processes open involve co-precipitation, calcination, doping, and careful control of microstructure and particle morphology. This is one of the most technically demanding parts of many modern value chains because small differences in processing can translate into big differences in device performance, lifetime, and safety. Producers typically work closely with downstream manufacturers and may be heavily qualified by specific OEMs.

Stage 11: Component Fabrication — Structural & Functional Materials

At this stage, active and structural materials are turned into tangible components—plates, foils, housings, frames, substrates, or non-magnetic mechanical pieces that will be used in devices or modules. Processes can include rolling, stamping, machining, forming, coating, and bonding. The main constraints are manufacturing capabilities, quality, cost, and integration with supply chains. Materials may be metals, ceramics, polymers, or composites. These components must meet mechanical, thermal, and sometimes environmental standards.

Stage 12: Component Fabrication — Magnetic & Alloy Components

Here, magnet and specialized alloy components are produced from powders or alloys prepared upstream. Steps include pressing, sintering, machining, magnetization (for magnets), and precision finishing. Mechanical tolerances, magnetic performance, and reliability are critical. These components are open custom-designed for specific motors, generators, actuators, or other systems. OEM qualification, IP, and process know-how are major differentiators. While they depend on critical minerals, the plants themselves are not tied to ore bodies.

Stage 13: Substrate & Wafer Processing

This stage produces highly engineered substrates and wafers that serve as platforms for devices or circuits. It can include semiconductor wafers, ceramic substrates, or other precision-engineered surfaces requiring ultra-clean processing, tight flatness and thickness control, and specific thermal or electrical properties. Operations involve slicing, polishing, cleaning, deposition of base layers, and sometimes doping or patterning. Facilities are capital-intensive and demand rigorous process control and cleanroom environments.

Stage 14: Electrode / Submodule Fabrication

This stage assembles active materials, binders, current collectors, and other components into functional sub-units—electrodes, coils, or other submodules. In bakeries, this includes slurry mixing, coating, drying, calendaring, cutting, and sometimes partial stacking or winding. The performance of the final device is heavily influenced by quality at this level: uniform coatings, defect rates, adhesion, porosity, and other parameters maker. Facilities increasingly resemble high-throughput, precision manufacturing lines.

Stage 15: Device / Cell Manufacturing

This stage produces complete cells or devices: bakery cells, capacitors, magnet subassemblies, or other units that can be tested and sold. It combines submodules, seals them, introduces electrolytes or other active media, and performs formation and initial testing. The result is a discrete product with a serial number and performance spec. Device/cell plants are open large, capital-intensive factories located near end markets, skilled labor, and supporting ecosystems. Here, manufacturing maturity, automation, defect reduction, and integration into OEM qualification processes strongly shape competitiveness.

Stage 16: Module / Pack / Magnet Assembly

Modules and packs combine individual devices or cells plus structural, thermal management, electrical interconnections, and safety systems into higher-level units. For magnets, this may be rotor assemblies; for bakeries, modules and packs; for power electronics, integrated assemblies. The work involves mechanical assembly, wiring, busbars, cooling systems, sensors, control electronics, and safety features. Design complexity and custom engineering increase, and systems integration capabilities become a differentiator.

Stage 17: System Integration

System integration embeds packs, modules, or magnet assemblies into final systems: vehicles, grid storage units, turbines, industrial drives, or defense platforms. This includes mechanical integration, control algorithms, power electronics, and full-system performance validation. Most of the value here comes from system-level design, software, integration engineering, and certification for specific use cases. The underlying critical minerals are "several layers deep" in the supply chain by this point.

Stage 18: Final Testing & Certification

This stage performs final testing, certification, and quality assurance at the product or system level. It may involve safety testing, performance characterization, lifetime and reliability testing, and formal certification to regulatory or industry standards (UL, IEC, automotive standards, etc.). Testing and certification are essential for market access, warranties, and risk management. While some testing is embedded in earlier stages, this final stage ensures that devices, modules, or systems meet defined specifications and external requirements.

The Eight Structural Factors

Each value-chain stage is evaluated using a set of eight structural factors that capture the underlying conditions shaping where critical mineral activities can plausibly emerge, how they can scale, and how resilient they are to disruption over time. The factors are grouped to reflect foundational prerequisites, catalytic enablers, and security- and resilience-related constraints. Together, they provide a disciplined, comparative lens for assessing structural dependencies at the stage level and for identifying where coordinated trilateral action is most likely to be feasible and durable.

Factor 1: Resource & Input Advantage

- Factor 1 evaluates whether a value-chain stage structurally depends on geological endowment, raw material presence, or location-specific inputs that cannot be easily relocated. This factor identifies stages where resource location, ore quality, raw feedstock availability, or unique natural conditions fundamentally shape where the stage can feasibly operate. This factor is the primary determinant of which stages are resource-constrained rather than policy- or capability-constrained. It asks: "Is this stage structurally tied to the physical location of raw material sources or immobile inputs?"

Factor 2: Related Variety & Technological Proximity

- Factor 2 evaluates whether a value-chain stage structurally depends on adjacency to other industries with similar technologies, supplier networks, engineering capabilities, or transferable skills. In cluster theory, this is often referred to as related variety — the technological and skill proximity between industries. This factor evaluates structural technological adjacency, not national capability, not firm-level specialization, and not mineral-specific process chemistry.

It asks: "Does this stage structurally require adjacency to other industrial capabilities in order to develop efficiently and competitively?"

Factor 3: Institutional Thickness

- Factor 3 evaluates whether a value-chain stage structurally depends on a dense ecosystem of institutions — including engineering firms, certification bodies, testing labs, industrial associations, research institutions, workforce training systems, and regulatory bodies — to operate effectively, scale, and maintain quality. In cluster theory, "institutional thickness" refers to the depth, diversity, and interconnectedness of enabling institutions.

It asks: "How essential is a strong institutional ecosystem to the successful development of this stage, independent of geography or mineral?"

Factor 4: Business Environment Sensitivity

- Factor 4 evaluates the structural dependence of a stage on broad business-environment conditions—such as energy availability, logistics, utilities, permitting throughput, and operational stability. It captures cross-cutting industrial enablers, not country-specific advantages, real-world operating costs, or policy performance.

It asks: "To what extent is this stage structurally sensitive to business-environment conditions that vary by location, even when not tied to geology or policy incentives?"

Factor 5: Policy Commitment & Strategic Alignment

- Factor 5 evaluates whether a midstream stage is structurally sensitive to policy intervention, industrial strategy, and long-term alignment with government priorities in ways that can alter its feasibility, competitiveness, or security outcomes. It captures whether the stage requires strategic policy to emerge, is shaped by long-term regulatory certainty, depends on cross-border policy coordination, is heavily influenced by industrial policy choices, or exhibits public-good characteristics (e.g., environmental risk, national security relevance).

It asks: "Does this stage fundamentally rely on durable, multi-year policy commitment to be competitive or viable?"

Factor 6: Market Structure & Local Rivalry

- Factor 6 evaluates whether the feasibility and competitiveness of a downstream stage structurally depend on market competition, local rivalry, and the presence of demanding customers. This factor captures whether a downstream manufacturing stage benefits from cross-firm rivalry, lead-firm pressure, quality-driven competition, presence of demanding downstream integrators, iterative improvement cycles, customer-supplier co-development, cluster-style competition among peer firms. This factor evaluates structural dependency, not actual competitive conditions.

It asks: "Does this downstream stage structurally require strong local rivalry or competition to drive performance, innovation, and manufacturing excellence?"

Factor 7: Geopolitical & Supply-Chain Risk Exposure

- Factor 7 evaluates whether a value-chain stage is structurally exposed to geopolitical concentration, single-country dominance, chokepoint risks, or adversarial leverage that is independent of any specific mineral or location. This factor assesses where, in principle, a stage is inherently vulnerable to reliance on race institutional capabilities, reliance on scarce equipment or reagents, global concentration patterns, governance risk, transport or maritime chokepoints, and adversarial control of upstream or midstream segments.

It asks: "Is this stage inherently prone to geopolitical concentration or strategic vulnerability, regardless of where it is located?"

Factor 8: Trilateral Complementarity Potential

- Factor 8 evaluates whether a value-chain stage is structurally suited to productive division of labor, burden-sharing, or complementary specialization across the U.S., Japan, and South Korea. This factor does not score how strong or weak any country is today. Rather, it examines whether the nature of the stage itself makes it conducive to distributed production, coordinated investment, cross-border specialization, shared infrastructure or knowledge, and interoperability across allied systems. This factor evaluates structural complementarity potential, not current capability distributions or geopolitical alignment.

It asks: "Does this stage, by its inherent characteristics, naturally lend itself to trilateral collaboration and complementary advantage?"

Scoring Logic

Diagnostic Scoring Logic (Y/N/U)

Each factor is evaluated using a small set of structural guiding questions designed to test whether a given value-chain stage inherently depends on the condition represented by that factor. The purpose of diagnostic scoring is to assess structural dependence, not current performance, national capability, or firm-level outcomes.

For each guiding question, scorers assign one of three values:

- **Y (Yes)** — The stage exhibits a clear structural dependency on the condition tested by the question, based on generic stage characteristics.
- **N (No)** — The stage does not structurally depend on the condition; its viability or operation is not meaningfully shaped by that factor.
- **U (Unknown)** — The dependency cannot be determined from the generic stage structure alone, or the answer would require mineral-specific, country-specific, or process-specific knowledge.

The U category is intentional and analytically important. It signals where generalist structural logic is insufficient and where interpretation must be deferred or escalated, rather than inferred or assumed. Diagnostic scoring therefore prioritizes discipline and transparency over completeness.

Composite Scoring Logic (H/M/L/U)

Once diagnostic Y/N/U values are assigned across the guiding questions for a factor, they are converted into a single composite structural score. The composite score summarizes the degree of structural dependence a stage has on that factor and enables consistent comparison across stages and factors.

Composite scores are classified as:

- ***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.*

The composite score is the value used in cross-factor summaries, heat maps, and downstream analysis. Importantly, composite scores are rule-based transformations of the diagnostic layer—not subjective judgments—and must not be manually adjusted. This ensures consistency, reduces interpretive drift, and preserves the integrity of the structural assessment. Scoring was machine-assisted using a custom analytical model developed in ChatGPT 5.2.

Appendix C: Structural Scoring Rationales

Factor 1: Resource & Input Advantage

Q1 — Geological or Raw Material Anchoring

Is this stage typically located near a specific physical resource (ore body, brine field, mineral deposit, metallurgical-grade feedstock)?

Q2 — Dependency on Ore Quality or Unique Feedstock Attributes

Does the stage require specific ore grades, impurity profiles, or in-situ feedstocks that determine locational feasibility?

Q3 — High Transport Burden for Raw Materials

Is it generally uneconomical or impractical to transport raw inputs to distant locations due to bulk, weight, hazard, or degradation?

Q4 — Immobile Natural Inputs (Optional)

Does the stage require natural conditions that cannot be relocated (e.g., geothermal brines, hydropower, dry-air conditions)?

(Optional; use only when clear.)

Stage 1 — Geological Survey & Resource Assessment

- Answers: Y, Y, N, U
- Q1–Q2 are Yes because this stage depends structurally on proximity to the resource body and direct access to primary geological inputs. Q3 is No since operational feasibility is not shaped by intermediate feedstock characteristics, and Q4 is U where exposure to external input substitution cannot be generically determined.

Stage 2 — Exploration & Permitting

- Answers: Y, Y, N, U
- Q1–Q2 are Yes because exploration requires direct access to in-situ resource characteristics and location-specific geological signals. Q3 is No because intermediate feedstock properties do not drive feasibility, while Q4 is U due to uncertain generic exposure to input flexibility or substitution.

Stage 3 — Extraction / Mining

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes due to strong structural anchoring to ore-body characteristics, physical accessibility, and dependence on naturally occurring resource attributes. Q4 is U because the degree of exposure to alternative input structures cannot be inferred generically.

Stage 4 — Beneficiation / Ore Concentration

- Answers: Y, Y, Y, U

- Q1–Q3 are Yes because beneficiation feasibility is structurally tied to ore mineralogy, grade distribution, and inherent physical properties of the resource. Q4 is U because potential substitutability or diversification of input materials is not structurally evident at the generic stage level.

**Note: Factor 1 only addresses Stage Archetypes 1-4*

Factor 2: Related Variety & Technological Proximity

Q1 — Process Adjacency

Does this stage structurally rely on industries with similar process technologies (thermal, chemical, mechanical) or specialized industrial equipment that enable its operation? *(Note: Do not consider generic equipment – e.g., trucks, pumps, steel structures – as adjacency.)*

Q2 — Engineering & Supplier Ecosystem Proximity

Does the stage structurally benefit from co-location with engineering firms, component suppliers, or technical services that specialize in similar industrial processes? *(Note: Do not score based on any specific mineral's flowsheet or refining pathway.)*

Q2 — Supplier & Equipment Overlap

Does the stage rely on suppliers, equipment types, or engineering services commonly used across multiple industrial sectors?

Q3 — Workforce & Skills Proximity

Is there a workforce whose skills transfer readily from related industries to this stage (chemical engineers, metallurgists, precision machinists, materials scientists)?

Q4 — Knowledge & Innovation Spillovers (Optional, Use Only When Clear)

Does innovation in adjacent industries materially benefit this stage (through materials development, process improvements, or equipment evolution)?

(Q4 is optional and should only be scored when innovation spillovers are structurally obvious. Do not infer a Y/N based on mineral- or country-specific R&D ecosystems.)

Stage 1 — Geological Survey & Resource Assessment

- Answers: N, N, N, U
- Q1–Q3 are No because surveying relies on geological expertise, not adjacency to industrial process, supplier, or skills ecosystems; innovation spillovers (Q4) are not structurally evident.

Stage 2 — Exploration & Permitting

- Answers: N, N, N, U
- Q1–Q3 are No because drilling and permitting are field-based activities dominated by geology and regulatory processes, not adjacent industrial capabilities; Q4 remains unclear.

Stage 3 — Extraction / Mining

- Answers: N, N, N, U
- Q1–Q3 are No because mining depends on geology and onsite operations rather than technological adjacency to other industries; Q4 not structurally determinable.

Stage 4 — Beneficiation / Ore Concentration

- Answers: Y, N, N, U
- Q1 is Yes because beneficiation shares process technologies (e.g., crushing, milling) with other bulk-material industries; Q2–Q3 are No since supplier and skills adjacency is helpful but not structurally required.

Stage 5 — Metallurgical Processing

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes due to inherent dependence on thermal/chemical process equipment, engineering-services ecosystems, and transferable skilled labor typical of large-scale processing industries.

Stage 6 — Chemical Conversion / Hydromet Processing

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because this stage fundamentally relies on chemical-process industries, specialized engineering suppliers, and transferable chemical/materials skills.

Stage 7 — Purification & Refining

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes given deep adjacency to chemical, metallurgical, and precision purification technologies, along with supplier and workforce ecosystems.

Stage 8 — Specialty Oxide / Metal / Salt Production

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because producing specialty materials depends structurally on advanced chemical-processing capabilities, specialized equipment suppliers, and relevant skilled labor.

Stage 9 — Alloying & Powder / Material Preparation

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes as alloying and powder preparation strongly depend on metallurgical, thermal, and precision-process industries, supplier networks, and transferable technical skills.

Stage 10 — Active Material Synthesis

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes due to adjacency with advanced chemical, materials-engineering, and process-control industries, requiring shared equipment and specialized skills.

Stage 11 — Component Fabrication — Structural & Functional

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because fabrication uses industrial equipment, supplier networks, and precision-manufacturing skills common to multiple related sectors.

Stage 12 — Component Fabrication — Magnetic & Alloy Components

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes since magnetic/alloy component production depends structurally on metallurgical, machining, and advanced-manufacturing adjacencies.

Stage 13 — Substrate & Wafer Processing

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because this stage requires sophisticated equipment, precision-engineering suppliers, and high-skill industrial workforces found in related process industries.

Stage 14 — Electrode / Submodule Fabrication

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes due to structural reliance on adjacent precision manufacturing, coating, and process-control ecosystems.

Stage 15 — Device / Cell Manufacturing

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because cell/device manufacturing requires strong adjacency to advanced manufacturing sectors, equipment suppliers, and transferable workforce capabilities.

Stage 16 — Module / Pack / Magnet Assembly

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes as assembly depends on mechanical, electrical, and systems-engineering adjacencies, along with shared suppliers and skilled labor.

Stage 17 — System Integration

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes due to structural reliance on engineering, electronics, and systems-manufacturing ecosystems and overlapping supplier networks.

Stage 18 — Final Testing & Certification

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because advanced test and certification processes depend on specialized equipment, engineering services, and technical skillsets found in related industries.

**Note: Factor 2 addresses all Stage Archetypes, 1-18*

Factor 3: Institutional Thickness

Q1 — Certification, Standards & Testing Requirements

Does this stage require product certification, quality testing, regulatory approvals, or adherence to formal technical standards?

Q2 — Engineering & EPC Ecosystem Dependence

Does this stage require product certification, quality testing, regulatory approvals, or adherence to formal technical standards?

Q3 — Workforce & Skill Formation Dependency

Does the stage require highly trained, institutionally developed professionals (chemical engineers, metallurgists, materials scientists, precision manufacturing engineers)?

Q4 — Research & Innovation Institutions (Optional)

Is this stage reliant on research labs, universities, or technical institutes for process innovation, validation, or problem-solving?

(Q4 is optional and should only be scored when institutional research dependence is

structurally obvious. Do not infer a Y/N based on mineral-specific behavior)

Stage 1 — Geological Survey & Resource Assessment

- Answers: N, N, N, U
- Q1–Q3 are No because surveying relies on geological expertise and fieldwork rather than certification bodies, EPC firms, or institutionally produced technical labor. Q4 is unclear because research dependence is not structurally required.

Stage 2 — Exploration & Permitting

- Answers: N, N, N, U
- Q1–Q3 are No since exploration and permitting rely on field operations and regulatory processes rather than deep institutional engineering or testing ecosystems. Q4 is not structurally evident.

Stage 3 — Extraction / Mining

- Answers: N, N, N, U
- Q1–Q3 are No because daily mining operations depend primarily on onsite operational capability rather than dense institutional ecosystems. Q4 is uncertain as research institutions are not structurally required for routine extraction.

Stage 4 — Beneficiation / Ore Concentration

- Answers: N, N, N, U
- Q1–Q3 are No because beneficiation uses established processes with moderate technical oversight but does not inherently require certification bodies, EPC ecosystems, or advanced institutional skill pipelines. Q4 not structurally determinable.

Stage 5 — Metallurgical Processing

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because metallurgical facilities require engineered plant design, compliance oversight, and institutionally trained professionals to operate and maintain thermal/chemical processes. Q4 is not uniformly required across all variants.

Stage 6 — Chemical Conversion / Hydromet Processing

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes due to strong structural reliance on formal standards, EPC design, and institutionally trained chemical-process professionals. Q4 remains uncertain without assuming mineral-specific innovation needs.

Stage 7 — Purification & Refining

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because refining depends on strict QC standards, engineered process systems, and skilled technical labor produced through institutional pathways. Q4 is not universally obligatory across all refining archetypes.

Stage 8 — Specialty Oxide / Metal / Salt Production

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes since producing specialty materials requires certifications, engineered systems, and advanced skills, all embedded in institutional ecosystems. Q4 remains unclear generically.

Stage 9 — Alloying & Powder / Material Preparation

- Answers: N, Y, Y, U
- Q1 is No because alloying/powder steps do not inherently require certification bodies; Q2–Q3 are Yes because specialized engineering services and technical workforce pipelines are structurally necessary. Q4 is not universally required.

Stage 10 — Active Material Synthesis

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because synthesis demands stringent standards, engineered process control, and institutionally trained materials/chemical professionals. Q4 is uncertain without assuming mineral-specific R&D needs.

Stage 11 — Component Fabrication — Structural & Functional

- Answers: N, Y, Y, U
- Q1 is No because fabrication does not universally require product certification; Q2–Q3 are Yes due to reliance on precision-engineering firms and skilled technical labor. Q4 is not structurally mandated.

Stage 12 — Component Fabrication — Magnetic & Alloy Components

- Answers: N, Y, Y, U

- Q1 is No because certification requirements are not uniformly essential at this stage; Q2–Q3 are Yes because specialized engineering and skilled labor ecosystems are structurally required. Q4 remains unclear.

Stage 13 — Substrate & Wafer Processing

- Answers: Y, Y, Y, Y
- Q1–Q3 are Yes due to extreme institutional dependence on standards, EPC design, and highly specialized workforce; Q4 is Yes because R&D institutions are structurally integral to process innovation and control.

Stage 14 — Electrode / Submodule Fabrication

- Answers: N, Y, Y, U
- Q1 is No since certification is not inherently required at the submodule level; Q2–Q3 are Yes as engineered production systems and skilled labor pipelines are structurally needed. Q4 is not universally necessary.

Stage 15 — Device / Cell Manufacturing

- Answers: N, Y, Y, U
- Q1 is No because certification becomes more relevant later in final testing; Q2–Q3 are Yes owing to engineered manufacturing lines and institutionally trained technical workforce. Q4 stays uncertain.

Stage 16 — Module / Pack / Magnet Assembly

- Answers: N, Y, Y, U
- Q1 is No because core certification occurs downstream; Q2–Q3 are Yes because assembly requires engineering support ecosystems and skilled labor. Q4 is unclear.

Stage 17 — System Integration

- Answers: N, Y, N, U
- Q1 is No since system integration is not structurally tied to certification bodies at this stage; Q2 is Yes because engineering-services ecosystems are necessary; Q3 is No because skills are less specialized than midstream chemical/materials stages. Q4 is undetermined.

Stage 18 — Final Testing & Certification

- Answers: Y, Y, Y, Y
- Q1–Q3 are Yes because certification, engineering oversight, and specialized technical labor are structurally essential; Q4 is Yes because testing/validation infrastructure fundamentally relies on institutional research and standards bodies.

**Note: Factor 3 addresses all Stage Archetypes, 1-18*

Factor 4: Business Environment Sensitivity

Q1 — Cost Sensitivity

Is the stage highly sensitive to energy, labor, or input costs in a way that materially affects feasibility?

Q2 — Infrastructure Dependence

Does the stage depend on sophisticated or high-capacity infrastructure (utilities, ports, pipeline networks, specialized transport)?

Q3 — Operational Stability & EHS Requirements

Does the stage require stable operations, strict EHS compliance, or continuous-process facilities where disruptions create major losses?

Q4 — Permitting & Regulatory Throughput (Optional)

Does the stage structurally require efficient permitting or stable regulatory execution to avoid prolonged downtime or capital loss?

(Q4 evaluates structural permitting or compliance exposure, not mineral-specific regulatory regimes. Q4 is optional and should only be scored when permitting/regulatory throughput dependence is structurally obvious. Do not infer a Y/N based on country-specific policy performance, firm experience, or mineral-specific conditions.)

Stage 1 — Geological Survey & Resource Assessment

- Answers: N, N, N, U
- Q1–Q3 are No because surveying requires personnel and field tools but has minimal sensitivity to cost, environment, infrastructure, or operational stability; Q4 is unclear since permitting throughput does not structurally constrain basic surveying.

Stage 2 — Exploration & Permitting

- Answers: N, N, N, U
- Q1–Q3 are No because exploration drilling and early permitting do not rely on sophisticated infrastructure or continuous operations; Q4 is uncertain because generic permitting does not structurally determine feasibility of this stage.

Stage 3 — Extraction / Mining

- Answers: N, N, N, U
- Q1–Q3 are No since mining feasibility is dominated by geology, not business-environment cost, infrastructure, or operational stability; Q4 remains undetermined as permitting throughput affects timelines but is not structurally definitive.

Stage 4 — Beneficiation / Ore Concentration

- Answers: N, N, N, U
- Q1–Q3 are No because beneficiation uses robust but flexible processes that can operate under varied business environments; Q4 is not structurally required.

Stage 5 — Metallurgical Processing

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because metallurgy is highly sensitive to energy costs, requires industrial utilities and transport, and depends on stable operations for thermal processes; Q4 not universally obligatory.

Stage 6 — Chemical Conversion / Hydromet Processing

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes since hydromet/chemical conversion involves energy-, utility-, and stability-intensive continuous processes; Q4 remains ambiguous across all variations.

Stage 7 — Purification & Refining

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because refining is sensitive to energy/input cost stability, depends on sophisticated utilities, and requires process continuity; Q4 is not structurally clear.

Stage 8 — Specialty Oxide / Metal / Salt Production

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes given reliance on controlled environments, stable utilities, and cost-sensitive production processes; Q4 is not uniformly evident.

Stage 9 — Alloying & Powder / Material Preparation

- Answers: Y, N, N, U
- Q1 is Yes since alloy/powder production is moderately cost-sensitive; Q2–Q3 are No because infrastructure and continuous-process stability are less determinative for this archetype; Q4 ambiguous.

Stage 10 — Active Material Synthesis

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes due to high operational stability needs, controlled utilities, and cost-sensitive chemical/materials production; Q4 is not structurally universal.

Stage 11 — Component Fabrication — Structural & Functional

- Answers: Y, N, N, U
- Q1 is Yes because cost environment influences fabrication feasibility; Q2–Q3 are No since these operations typically do not require heavy infrastructure or continuous-process stability; Q4 is unclear.

Stage 12 — Component Fabrication — Magnetic & Alloy Components

- Answers: Y, N, N, U
- Q1 is Yes because fabrication steps are cost-sensitive; Q2–Q3 are No as infrastructure demands and stability constraints are moderate; Q4 is uncertain.

Stage 13 — Substrate & Wafer Processing

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because wafering requires stable high-quality utilities, precise process control, and significant operational stability; Q4 is not uniformly required even though R&D interactions exist.

Stage 14 — Electrode / Submodule Fabrication

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because submodule fabrication depends on controlled environments, reliable utilities, and stable operations; Q4 is not structurally universal.

Stage 15 — Device / Cell Manufacturing

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes as cell production requires stable utilities, controlled environments, and cost-sensitive continuous manufacturing; Q4 remains optional and unclear.

Stage 16 — Module / Pack / Magnet Assembly

- Answers: Y, N, N, U
- Q1 is Yes due to cost sensitivity; Q2–Q3 are No because assembly requires moderate infrastructure and limited continuous-process stability; Q4 is undetermined.

Stage 17 — System Integration

- Answers: Y, N, N, U
- Q1 is Yes because integration processes are influenced by cost environment; Q2–Q3 are No since infrastructure demands and stability requirements are moderate rather than foundational; Q4 is unclear.

Stage 18 — Final Testing & Certification

- Answers: Y, Y, Y, Y
- Q1–Q3 are Yes because testing/certification depends on reliable utilities, operational stability, and cost-sensitive precision facilities; Q4 is Yes since permitting/regulatory throughput is structurally necessary for certification functions.

**Note: Factor 4 addresses all Stage Archetypes, 1-18*

Factor 5: Policy Commitment & Strategic Alignment

Q1 — Regulatory Exposure vs. Structural Dependence

Does this stage structurally require significant regulatory throughput or environmental compliance to operate?

(Note: Do not score Y simply because real-world countries tightly regulate this stage.)

Q2 — Strategic Enabling Requirement

Does this stage structurally depend on long-term policy priority or strategic alignment (e.g., critical-externality risks, national security sensitivity)?

(Note: Do not score Y based on subsidies, incentives, or current industrial strategy programs.)

Q3 — Strategic or National-Security Relevance

Does this stage typically become the focus of industrial policy due to strategic vulnerability, supply-chain centrality, or national security?

Q4 — Infrastructure or Capital-Risk Sharing (Optional)

Does the stage require large-scale infrastructure or capital deployment where policy plays a structural enabling role (e.g., shared facilities, long-term commitments)?

(Q4 is optional and should only be scored when capital-risk sharing or infrastructure dependence is structurally obvious. Do not infer a Y/N from country-specific subsidies, incentives, or regulatory programs.)

Stage 5 — Metallurgical Processing

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because metallurgical operations structurally involve significant environmental compliance, strategic relevance, and capital-intensive processes that historically require policy stability; Q4 is uncertain because shared infrastructure dependence is not universally determinative across all metallurgical archetypes.

Stage 6 — Chemical Conversion / Hydromet Processing

- Answers: Y, U, Y, U
- Q1 is Yes due to strong structural exposure to environmental and regulatory frameworks; Q2 is U because policy prioritization varies across chemical archetypes; Q3 is Yes because these stages often become strategic due to chokepoint relevance; Q4 is unclear without mineral-specific capital-risk detail.

Stage 7 — Purification & Refining

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because refining requires stringent regulatory oversight, frequently receives long-term industrial-strategy attention, and structurally occupies a central point of vulnerability in supply chains; Q4 is not uniformly evident across all refining models.

Stage 8 — Specialty Oxide / Metal / Salt Production

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes since specialty-material production typically incurs environmental exposure, strategic relevance, and policy-enabled industrial scaling; Q4 is indeterminate because not all archetypes require explicit public risk-sharing mechanisms.

Stage 9 — Alloying & Powder / Material Preparation

- Answers: Y, U, U, U
- Q1 is Yes as alloy/powder manufacturing involves notable compliance exposure; Q2 and Q3 are U because structural dependence on strategic policy alignment or national-security relevance cannot be determined generically; Q4 remains uncertain without capital-risk specifics.

Stage 10 — Active Material Synthesis

- Answers: U, U, U, U
- All U because the degree of regulatory exposure, strategic relevance, and capital-risk dependence varies substantially across material families, and the generic stage structure does not provide enough information to answer Q1–Q4 without mineral-specific detail.

Stage 11 — Component Fabrication — Structural & Functional

- Answers: N, N, N, U
- Q1–Q3 are No because fabrication of structural/functional components is predominantly market-driven, exhibits limited regulatory exposure, and is not structurally tied to strategic policy mandates; Q4 is unclear because large-scale public risk-sharing is not essential to feasibility.

Stage 12 — Component Fabrication — Magnetic & Alloy Components

- Answers: N, N, N, U
- Q1–Q3 are No because this stage's feasibility is driven by industrial manufacturing rather than strategic policy or environmental regulation; Q4 cannot be determined structurally.

Stage 13 — Substrate & Wafer Processing

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because wafer/substrate processing is structurally exposed to strict regulatory environments, often receives strategic policy attention, and represents a known chokepoint class; Q4 remains U since shared-infrastructure or capital-risk policies are not universally required.

Stage 14 — Electrode / Submodule Fabrication

- Answers: Y, U, U, U
- Q1 is Yes because electrode/submodule production involves regulatory compliance related to materials handling; Q2–Q3 are U because strategic relevance or policy-enabling dynamics cannot be determined generically; Q4 is uncertain without process-specific capital-risk data.

**Note: Factor 5 only addresses Stage Archetypes 5-14*

Factor 6: Market Structure & Local Rivalry

Q1 — Rivalry-Driven Performance Requirement

Does this stage structurally benefit from multiple competing firms driving quality, innovation, and price discipline?

Q2 — Customer Proximity Requirement

Does this stage improve significantly when co-located with demanding customers or system integrators?

Q3 — Iterative Design–Manufacturing Loop Dependency

Does the stage require tight, rapid feedback loops (design → prototype → test → adjust) that thrive under competitive pressure?

Q4 — Benchmarking & Standards Competition (Optional)

Is this stage structurally enhanced by global benchmarking, competitive standards, or rapid product cycles?

(Use optional Q4 only when clearly inherent to the stage.)

Stage 15 — Device / Cell Manufacturing

- Answers: Y, Y, Y, Y
- Q1–Q3 are Yes because this stage structurally benefits from strong rivalry, demanding customers, and rapid design–prototype–test iteration cycles that directly influence performance and yield. Q4 is Yes because global benchmarking and competitive product cycles are structurally integral to device/cell manufacturing excellence.

Stage 16 — Module / Pack / Magnet Assembly

- Answers: Y, Y, Y, Y
- Q1–Q3 are Yes because assembly stages depend on competitive pressure, tight customer–integrator proximity, and iterative feedback with OEMs to refine performance and reliability. Q4 is Yes since benchmarking and standards-based competition structurally enhance quality and system integration.

Stage 17 — System Integration

- Answers: N, N, N, U
- Q1–Q3 are No because system integration is structurally engineering-driven—performance derives more from design capability and system-level engineering than from local rivalry or competitive clustering. Q4 is U because benchmarking benefits are not structurally determinative and vary across integration archetypes.

Stage 18 — Final Testing & Certification

- Answers: N, N, N, N
- Q1–Q3 are No because this stage is standards- and compliance-driven rather than rivalry-driven, with quality governed by regulation rather than market competition. Q4 is No because competitive benchmarking does not structurally influence feasibility; testing depends on adherence to standards, not competition dynamics.

**Note: Factor 6 only addresses Stage Archetypes 15-18*

Factor 7: Geopolitical & Supply-Chain Risk Exposure

Q1 — Natural Global Concentration

Does this stage structurally tend to consolidate into a small number of global facilities due to intrinsic capital intensity, specialized know-how, or minimum efficient scale, independent of current geography?

Q2 — Specialized or Restricted Inputs

Does the stage require rare, restricted, or proprietary inputs (equipment, reagents, IP, catalysts) that are typically produced by a small number of firms or countries in principle?

Q3 — High Coordination or Environmental Oversight Requirements

Does the stage require stringent environmental controls, sensitive process streams, or complex coordination requirements that naturally limit global diffusion even before considering minerals or countries?

Q4 — Strategic Chokepoint Characteristics (Optional)

Is this stage inherently prone to supply-chain chokepoints (e.g., hazardous materials shipping, specialized refining circuits)?

(Q4 is optional and should only be scored when chokepoint characteristics are structurally obvious. Do not infer a Y/N from mineral-specific maritime constraints, specific country risks, or today's supply-chain configurations.)

Stage 1 — Geological Survey & Resource Assessment

- Answers: N, N, N, U
- Q1–Q3 are No because surveying is location-bound and diffuse rather than concentrated or reliant on scarce inputs; Q4 is U since chokepoint characteristics are not inherent to this information-gathering stage.

Stage 2 — Exploration & Permitting

- Answers: N, N, N, U
- Q1–Q3 are No because exploration activities occur wherever deposits are located and do not structurally concentrate globally or depend on restricted equipment; Q4 is U because no inherent chokepoint characteristics emerge.

Stage 3 — Extraction / Mining

- Answers: N, N, N, U
- Q1–Q3 are No as mining is determined by dispersed geology, not geopolitical concentration or specialized inputs; Q4 is U because mining does not structurally create transport or coordination chokepoints at this generic level.

Stage 4 — Beneficiation / Ore Concentration

- Answers: N, N, N, U

- Q1–Q3 are No because beneficiation capacity scales broadly and does not depend on rare equipment or centralized capabilities; Q4 is U since inherent chokepoint features are not structurally evident.

Stage 5 — Metallurgical Processing

- Answers: Y, U, Y, U
- Q1 is Yes because metallurgical plants tend to concentrate due to scale and capital intensity; Q2 is U because dependence on specialized inputs varies; Q3 is Yes owing to stringent oversight and coordination demands that naturally limit global diffusion; Q4 remains U.

Stage 6 — Chemical Conversion / Hydromet Processing

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes due to intrinsic concentration pressures, specialized/restricted inputs, and strong environmental/coordination requirements that limit global dispersal; Q4 is U because chokepoint characteristics differ across conversion archetypes.

Stage 7 — Purification & Refining

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes since refining is structurally prone to global concentration, relies on rare technological capabilities, and requires sensitive multi-stage oversight; Q4 is U because chokepoint features vary by process type.

Stage 8 — Specialty Oxide / Metal / Salt Production

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because specialty-material production tends to consolidate in capability-intensive hubs requiring scarce equipment and stringent process control; Q4 is U absent universally inherent chokepoint traits.

Stage 9 — Alloying & Powder / Material Preparation

- Answers: U, U, U, U
- All U because the extent of concentration, restricted inputs, or inherent chokepoint risk cannot be determined generically without mineral-specific or technology-specific information.

Stage 10 — Active Material Synthesis

- Answers: U, U, U, U
- All U because structural geopolitical vulnerability cannot be inferred generically; concentration patterns and restricted-input dynamics differ significantly across synthesis archetypes.

Stage 11 — Component Fabrication — Structural & Functional

- Answers: N, N, N, U
- Q1–Q3 are No because component fabrication is broadly replicable and not structurally dependent on rare inputs or concentrated capabilities; Q4 is U as inherent chokepoints are not evident.

Stage 12 — Component Fabrication — Magnetic & Alloy Components

- Answers: N, N, N, U
- Q1–Q3 are No because this stage can be geographically diversified and does not inherently rely on rare or restricted inputs; Q4 is U without clear chokepoint characteristics.

Stage 13 — Substrate & Wafer Processing

- Answers: Y, Y, Y, Y
- Q1–Q4 are Yes because substrate/wafer processing structurally concentrates due to extreme technological exclusivity, reliance on restricted equipment, high coordination burdens, and inherent chokepoint characteristics in process architecture.

Stage 14 — Electrode / Submodule Fabrication

- Answers: U, U, U, U
- All U because structural chokepoint tendencies, concentration behaviors, and restricted-input dependencies cannot be inferred generically across submodule archetypes.

Stage 15 — Device / Cell Manufacturing

- Answers: N, N, N, U
- Q1–Q3 are No because cell/device assembly is replicable and not inherently subject to geopolitical concentration or restricted inputs; Q4 is U because any chokepoint traits are not structurally universal.

Stage 16 — Module / Pack / Magnet Assembly

- Answers: N, N, N, U
- Q1–Q3 are No as assembly processes distribute easily and lack intrinsic scarcity or concentration drivers; Q4 is U due to absence of clear chokepoint characteristics.

Stage 17 — System Integration

- Answers: N, N, N, U
- Q1–Q3 are No because system integration is engineering-driven and not concentrated by structural geopolitical constraints; Q4 is U since chokepoint traits are not inherent.

Stage 18 — Final Testing & Certification

- Answers: N, N, N, U
- Q1–Q3 are No because testing and certification are standards-driven and widely replicable; Q4 is U because no inherent chokepoint dynamics emerge from the generic stage structure.

**Note: Factor 7 addresses all Stage Archetypes, 1-18*

Factor 8: Trilateral Complementarity Potential

Q1 — Structural Modularity & Fragmentation Potential

Can this stage be structurally divided across multiple locations without degrading performance, requiring co-processing, or creating integration risk?

(Note: Do not consider mineral-specific flowsheet variants or country-level ecosystem distribution when scoring.)

Q2 — Complementary Capability Requirements

Does successful execution of this stage structurally require diverse technical capabilities (chemical, thermal, mechanical, materials-science) that tend to be distributed across different industrial ecosystems in principle?

(Note: Do not consider mineral-specific flowsheet variants or country-level ecosystem distribution when scoring.)

Q3 — Interoperability & Standardization Potential

Does this stage produce intermediates that are naturally standardizable, tradeable, or compatible across producers without requiring co-located sequential processing?

Q4 — Multi-Stage Co-Processing Flexibility (Optional)

Can this stage be structurally co-located or separated from adjacent stages without dependency on mineral-specific flowsheets or national industrial ecosystems?

(Optional; score only when the stage is inherently flexible. Do not infer Y/N from real-world chemical hubs, semiconductor clusters, or battery ecosystems.)

Stage 1 — Geological Survey & Resource Assessment

- Answers: N, N, N, U
- Q1–Q3 are No because surveying is geology-anchored and cannot be modularized, shared, or standardized across multiple locations; Q4 is U because fragmentation flexibility is not structurally relevant.

Stage 2 — Exploration & Permitting

- Answers: N, N, N, U
- Q1–Q3 are No because exploration and permitting must occur at the deposit and involve localized regulatory processes, offering no structural modularity or interoperable outputs; Q4 is U due to minimal relevance of co-processing flexibility.

Stage 3 — Extraction / Mining

- Answers: N, N, N, U
- Q1–Q3 are No because extraction is fixed to ore location and cannot be divided or complemented across actors; Q4 is U since integration flexibility is not applicable to this resource-anchored stage.

Stage 4 — Beneficiation / Ore Concentration

- Answers: N, N, N, U
- Q1–Q3 are No because beneficiation is structurally tied to the mine site and not divisible or compatible with cross-location staging; Q4 is U due to limited modularity potential.

Stage 5 — Metallurgical Processing

- Answers: U, U, U, U
- All U because complementarity potential depends on feedstock chemistry, modular facility design, and flowsheet flexibility that cannot be assessed from generic stage structure alone.

Stage 6 — Chemical Conversion / Hydromet Processing

- Answers: U, U, U, U
- All U because the degree to which conversion steps can be modularized or shared across actors depends heavily on mineral-specific process integration and cannot be inferred structurally.

Stage 7 — Purification & Refining

- Answers: U, U, U, U
- All U because refining's complementarity potential varies widely with purity pathways and flowsheet coupling, and generic structural rules do not indicate clear modularity or interoperable outputs.

Stage 8 — Specialty Oxide / Metal / Salt Production

- Answers: U, U, U, U
- All U since the modularity of specialty-material production cannot be determined generically without knowing the stability, tradability, or integration requirements of intermediates.

Stage 9 — Alloying & Powder / Material Preparation

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because alloying/powder preparation is structurally modular, requires diverse competencies, and produces standardizable intermediates transferable across producers; Q4 is U due to uncertain co-processing flexibility.

Stage 10 — Active Material Synthesis

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes given strong inherent modularity, distributed capability requirements, and high interoperability of synthesized intermediates; Q4 is U where co-processing flexibility cannot be fully confirmed.

Stage 11 — Component Fabrication — Structural & Functional

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because component fabrication is structurally divisible, benefits from distributed competencies, and generates standardized parts that integrate cleanly across systems; Q4 is U due to uncertain separability from adjacent stages.

Stage 12 — Component Fabrication — Magnetic & Alloy Components

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes as magnetic/alloy components are highly modular, competency-diverse, and interoperable in downstream systems; Q4 is U because co-processing flexibility varies by design type.

Stage 13 — Substrate & Wafer Processing

- Answers: Y, Y, Y, Y
- Q1–Q4 are Yes because wafer/substrate production is structurally modular, competence-diverse, produces globally standardizable intermediates, and can be separated from upstream/downstream steps without structural constraints.

Stage 14 — Electrode / Submodule Fabrication

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes due to inherent modularity, distributed capability requirements, and standardizable submodules; Q4 is U because dependence on sequential co-processing varies across archetypes.

Stage 15 — Device / Cell Manufacturing

- Answers: Y, Y, Y, Y
- Q1–Q4 are Yes because cell manufacturing is modular, requires diverse competencies, yields interoperable units, and is structurally divisible across production and testing streams.

Stage 16 — Module / Pack / Magnet Assembly

- Answers: Y, Y, Y, Y
- Q1–Q4 are Yes since assembly is inherently modular, requires varied mechanical/electrical integration capabilities, produces standardized outputs, and can structurally separate or co-locate sub-stages.

Stage 17 — System Integration

- Answers: Y, Y, Y, U
- Q1–Q3 are Yes because integration can be distributed across multiple centers, requires diverse competencies, and produces interoperable systems; Q4 is U as co-processing flexibility is not universally obvious.

Stage 18 — Final Testing & Certification

- Answers: Y, N, Y, U
- Q1 is Yes because testing processes can be modularized; Q2 is No since technical capability requirements are not structurally diverse; Q3 is Yes as outputs are standardized and interoperable; Q4 is U because placement relative to adjacent stages is not inherently flexible.

**Note: Factor 8 addresses all Stage Archetypes, 1-18*