

Article

Critical-Material Recovery from U.S. Industrial Byproducts: A Scenario-Based Supply-Risk Analysis

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Abstract

Recovery of critical materials from industrial byproducts is often presented as a near-term United States (U.S.) supply-security strategy, yet contained inventories, pilot output, announced capacity, and commercial production are not equivalent. This study evaluates eight U.S. pathways for gallium, germanium, tellurium, lithium, magnesium, and cobalt, classified as operational, demonstration/pilot, announced target-year, or technical upper-bound cases. Facility- and stream-specific quantities were converted to qualifying domestic output and incorporated into same-stage material balances under explicit assumptions for utilization, eligibility, demand, and import displacement. Supply risk was calculated from the net import dependence and governance-adjusted production and trade concentration using a geometric index, with arithmetic formulations as robustness checks. The operational U.S. copper-refining tellurium pathway yielded the largest central reduction (49.29%). Announced 2030 Clarksville capacity reduced modeled risk by 13.87% for gallium and 8.75% for germanium, conditional on project completion, feed attribution, product qualification, utilization, and demand. All other central cases produced reductions of 4.63% or less; the current lithium demonstration, Stillwater cobalt, and aluminum-residue magnesium cases had negligible national effects. Policy support should therefore be differentiated by qualifying output, market scale, project maturity, and evidence quality rather than by contained material or nameplate capacity alone.

Keywords: critical materials; industrial byproducts; byproduct recovery; supply risk; net import dependence; metallurgical residues; technology maturity; material security

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1. Introduction

Critical materials are essential to energy, digital, transportation, aerospace, medical, and defense technologies. Gallium (Ga) and germanium (Ge) are used in semiconductor, optoelectronic, infrared, and fiber-optic applications; tellurium (Te) is used in cadmium-telluride photovoltaics and thermoelectric devices; lithium (Li) and cobalt (Co) are important battery materials; and magnesium (Mg) is used in lightweight alloys and metallurgical applications. These materials have been identified as critical in U.S. energy, defense, or mineral supply assessments because their technological importance is accompanied by exposure to supply disruption [1–3]. This exposure reflects not only geological availability, but also geographic concentration of extraction and processing, dependence on host-metal production, limited substitution in important applications, trade restrictions, and insufficient domestic separation and refining capacity.

Reducing these vulnerabilities has become an important objective of U.S. industrial, energy, and national security policy. The Inflation Reduction Act, federal supply-chain reviews, and the U.S. Department of Energy's supply-chain strategy support domestic extraction, expanded processing, recycling, diversified international sourcing, and technological innovation [4–6]. New mines and greenfield processing facilities remain important, but they commonly require substantial investment, permitting, infrastructure, process development, and product qualification. Recovery from streams already generated at mines, smelters, refineries, and other industrial facilities may therefore provide a complementary source of domestic material. However, the presence of a critical element in an industrial stream does not establish that it can be recovered continuously, purified to a qualifying product, or supplied at a scale sufficient to affect national vulnerability.

Material criticality assessment provides a framework for connecting these technical questions to economic and policy decisions. The National Research Council conceptualized criticality as the combination of the likelihood and consequences of supply restriction [7]. Subsequent approaches include the multidimensional Yale methodology [8]; the European Union's economic importance and supply-risk assessments [9,10]; and U.S. frameworks incorporating import reliance, production concentration, governance, trade exposure, and downstream economic vulnerability [11–13]. Kannan et al. compared supply risk and manufacturing sector economic importance across China, the European Union, Japan, and the United States [14]. These frameworks differ in scope, normalization, weighting, and treatment of disruption consequences; their scores should therefore be interpreted as decision support indicators rather than intrinsic material properties. The present study applies an established criticality framework and does not propose a new criticality metric. Its contribution is an application-level integration of facility- and stream-specific recovery evidence with status-differentiated U.S. supply-risk scenarios.

This integration is particularly important for byproduct and companion metals. Gallium, germanium, tellurium, and a substantial share of cobalt production are associated with the extraction or processing of host materials such as aluminum, zinc, copper, nickel, and platinum-group metals. Their output may respond weakly to changes in their own prices because production is governed principally by the economics and operating rate of the host-metal system [15]. Consequently, substantial geological or process stream inventories may coexist with low recovery and constrained supply.

Recent research has shown that U.S. metal mines process appreciable quantities of critical minerals that are not recovered as products and that increased byproduct recovery could reduce import reliance for selected materials [16]. Resource occurrence alone, however, does not determine annual supply. Industrial residues and intermediate streams differ from primary ores in mineralogy, chemical speciation, liberation, impurity content, and variability. Recovery may require collection, pretreatment, leaching, separation, purification, and product finishing, with losses or changes in product form at each stage [17–19]. A calculation based only on stream mass and elemental concentration therefore represents contained material or a technical ceiling, not necessarily qualifying annual output.

Project maturity creates a related distinction. Output from an operating commercial circuit is not equivalent to pilot production, the nameplate capacity of an announced project, or a quantity extrapolated from laboratory tests or national residue estimates. Combining these categories can overstate present domestic availability and obscure the technical and commercial steps required before production occurs. This study therefore distinguishes operational output, demonstration or pilot output, announced target-year capacity, and technical upper bounds.

Metallurgical and criticality studies have generally addressed different analytical scales. Metallurgical research commonly evaluates individual feeds and processes, including composition, extraction efficiency, impurity behavior, and product recovery.

Criticality studies generally assess national or global exposure to production concentration, trade dependence, governance risk, and economic disruption. A gap remains between identifying a material in an industrial stream and establishing the quantity, product form, maturity, and evidence needed to credit that stream as domestic supply. Limited work has connected documented U.S. recovery pathways to national supply-risk indicators while simultaneously controlling for product stage, project maturity, reference year, and evidence quality.

This study addresses that gap by evaluating eight publicly documented U.S. pathways for six materials: Ga and Ge associated with zinc-processing residues and planned integrated-smelter feeds; Te associated with copper-refining intermediates; Li recovered from historical waste rock; Ga and Mg associated with aluminum-processing residues; and Co contained in a nickel-bearing stream generated during platinum-group-metal processing. The unit of analysis is the material–facility–stream pathway, because one facility may generate several streams with different compositions and recovery requirements, and the same material may occur in forms requiring different process routes.

For each pathway, the analysis identifies the material-bearing stream, product basis, supported quantity, recovery evidence, project status, and principal uncertainty. The quantities are incorporated into U.S. material balances in which the baseline and recovery cases use the same material, processing stage, product form, unit, and reference year. Where official production or apparent consumption statistics are withheld, source-constrained central assumptions and bounded sensitivity cases are used rather than unsupported point estimates. Supply-risk effects are calculated from raw index values rather than ordinal ranks. Economic importance is retained as a baseline indicator of potential disruption consequences but is held constant because the recovery scenarios change supply availability rather than downstream sectoral allocation.

The analysis addresses four research questions:

1. What quantities of qualifying domestic Ga, Ge, Te, Li, Mg, and Co output are supported by available evidence at different levels of technology and project maturity?
2. How would these quantities affect U.S. net import dependence and supply risk under same-stage material-balance comparisons?
3. How sensitive are the results to utilization, eligible output, import displacement, future demand, uncertain material-balance statistics, and the method used to aggregate supply-risk indicators?
4. Which pathways combine sufficient national impact, maturity, and evidentiary confidence to justify near-term policy support?

The study contributes a screening framework that connects process- and facility-level recovery evidence to national supply-risk effects without treating contained inventories, pilot output, announced capacities, and commercial production as equivalent. It is not a project-level techno-economic analysis or life-cycle assessment. Rather, it distinguishes pathways appropriate for operational optimization, milestone-based project support, continued demonstration, targeted metallurgical research, or monitoring.

2. Scope, Case Selection, and Evidence for Critical-Material Recovery

2.1. Study Scope and Case Selection Procedure

This study evaluates eight selected U.S. material–facility–stream pathways with the potential to provide Ga, Ge, Te, Li, Mg, or Co. The evidence and project status review covers information available through 30 June 2026. The pathways comprise proposed Ga and Ge recovery from Clarksville zinc-processing residues and other integrated-smelter feeds; Te-bearing intermediates from U.S. copper refining, represented by the publicly documented Kennecott circuit; Li recovery from historical waste rock in Boron, California;

Ga and Mg associated with aluminum-processing residues; and Co contained in a nickel-sulfate stream produced during platinum-group-metal processing in Montana.

The unit of analysis is the material–facility–stream pathway. This unit is more precise than the material or facility alone because one facility may generate multiple residues, solutions, or intermediates with different compositions and recovery requirements. Conversely, the same material may occur in different chemical or physical forms across facilities. Contained Te in copper telluride, for example, is not equivalent to domestically refined Te metal, and Co incorporated in a nickel-sulfate product is not equivalent to separately recovered cobalt sulfate or cobalt metal.

A pathway was included when five conditions were satisfied: the facility or stream was located in the United States; the target material was documented in an identifiable residue, intermediate, waste, or planned product; a quantitative basis was available for estimating contained material, capacity, or annual output; the technical literature identified a plausible recovery route; and the pathway could be assigned a project status and evidence grade.

Cases supported only by geological occurrence, without an identifiable industrial stream or quantitative recovery basis, were excluded. The resulting inventory is purposive rather than exhaustive. Absence from the analysis does not imply that another U.S. facility or stream has no recovery potential.

The facility boundary is distinguished from the product-stage boundary. Where a U.S. facility produces a critical-material-bearing intermediate that is subsequently refined abroad, output is credited only at the stage and in the form actually produced domestically. It is not counted automatically as U.S.-refined material.

2.2. Recovery Quantities, Project Status, and Evidence Quality

Four quantities are distinguished. Contained material is the mass of the target element physically present in a stream:

$$Q_{i,f}^{\text{contained}} = M_f G_{i,f} \quad (1)$$

where M_f is the annual mass of stream f , and $G_{i,f}$ is the concentration of material i in that stream.

Technically extractable material is the portion transferable into a target-bearing product through a defined recovery process. Qualifying output is the portion satisfying the product-stage, purity, domestic location, and market availability requirements of the corresponding material balance. Actual annual production is the measured qualifying output produced during a specified period. These quantities are not interchangeable.

Where sufficient information is available, qualifying output may be expressed as:

$$Q_{i,f}^{\text{qualifying}} = M_f G_{i,f} \eta_{\text{col},i,f} \eta_{\text{pre},i,f} \eta_{\text{ext},i,f} \eta_{\text{pur},i,f} U_f \lambda_{i,f} \quad (2)$$

where $\eta_{\text{col},i,f}$, $\eta_{\text{pre},i,f}$, $\eta_{\text{ext},i,f}$, and $\eta_{\text{pur},i,f}$ denote collection, pretreatment, extraction, and purification efficiencies, respectively; U_f is the operating or capacity utilization factor; and $\lambda_{i,f}$ is an eligible output factor. The last accounts for feed attribution, product form, downstream processing location, product qualification, and availability to the relevant U.S. market.

A laboratory extraction percentage is not equivalent to overall plant recovery unless upstream collection and downstream purification are included. Similarly, nameplate capacity is not equivalent to annual production unless utilization and product eligibility are established. Where these data are unavailable, the quantity is treated as a technical upper bound rather than expected output.

Five project status categories are used:

- S0—Baseline: supply without the incremental recovery pathway;

- S1—Operational: an operating commercial circuit or authoritative estimate of current qualifying output;
- S2—Demonstration/pilot: limited-scale demonstrated production without established commercial-scale operation;
- S3—Announced target-year: a formally announced project evaluated in its intended operating year; and
- S4—Technical upper bound: laboratory-, inventory-, engineering-, or feasibility-derived potential that has not been demonstrated as sustained commercial production.

Status is reported separately from evidence quality. Grade A indicates publicly documented annual qualifying output and product specification. Grade B indicates an authoritative statistical estimate, installed capacity, or official engineering basis, but incomplete facility-level production or product disposition information. Grade C indicates laboratory, pilot, or demonstration evidence with uncertain representativeness or commercial scale-up. Grade D indicates an extrapolated quantity, incomplete engineering basis, or reliance on unpublished process information.

An operational pathway may therefore receive Grade B when its output is proprietary, while an announced project may have a strong engineering basis but remain uncertain with respect to construction, feed allocation, utilization, and product qualification.

2.3. Gallium and Germanium from Zinc-Processing Residues

The Clarksville zinc-processing complex in Tennessee is the principal U.S. case evaluated for prospective Ga and Ge production. Korea Zinc completed its acquisition of the Clarksville smelter and associated U.S. mining assets in April 2026 [20]. The site is included in Korea Zinc's proposed U.S. integrated smelter project, Project Crucible, which targets trial operations in 2029 and operation at design utilization during the first quarter of 2030 [21]. Project documentation identifies planned capacities of 54 t/y Ga and 44 t/y Ge beginning in 2030 [21].

These quantities are announced capacities rather than current production. Project documentation identifies Clarksville pond cake as containing Ga, Ge, Zn, Pb, and other metals, but the proposed operation may also process mine-derived material, recycled feeds, and third-party inputs [21]. The fraction of future Ga and Ge output attributable specifically to accumulated pond cake or continuing Clarksville residues is not publicly disclosed.

Gallium and germanium in zinc-processing residues may occur in iron-bearing phases, silica, oxides, sulfides, and other complex matrices. Their recoverability therefore cannot be inferred from total elemental concentration alone. Fayram and Anderson described industrial development of Ga and Ge recovery from zinc smelter wastes [22]. Liu et al. demonstrated sequential removal of Zn and Cu, oxalic-acid leaching of Ga and Ge, and selective iron removal [23]. Rao et al. demonstrated staged acid and alkaline leaching, with recovery strongly influenced by feed composition, pH, temperature, and the association of Ge with silica [24].

These studies establish technical plausibility but do not demonstrate that results from another refinery residue transfer directly to Clarksville pond cake. Facility-specific characterization, continuous pilot testing, impurity control, product specification, and feed accounting remain necessary.

The Clarksville pathways are therefore classified as S3—announced target-year. Announced project capacity receives Grade B support, while attribution to the identified Clarksville byproduct stream receives Grade C support. The model applies utilization, eligible output, demand, and import displacement scenarios rather than treating full nameplate capacity as realized supply.

2.4. Tellurium from Copper-Refining Intermediates

Tellurium commonly reports to anode slimes and related intermediates during copper electrorefining. These streams may contain Cu, Se, Te, Ag, Au, Ni, and platinum-group elements in elemental, oxide, and telluride phases. Recovery requires selective transfer of Te from this multi-element matrix into a product suitable for subsequent purification.

Rio Tinto began operating a Te-recovery circuit in, Kennecott, Utah, in 2022 [25]. The circuit treats copper-refining material and produces a copper-telluride filter cake using copper chips, heat, and agitation [26]. Rio Tinto reports a design capacity of approximately 20 t/y of contained Te [26].

The product-stage boundary is important. USGS reports that two U.S. electrolytic copper refineries produced copper telluride from Te-bearing anode slimes in 2024, but that Te was not refined domestically, and the intermediates were exported for further processing [27]. Facility-level output is withheld. The British Geological Survey independently estimates total U.S. Te production at approximately 20 t in 2024 [28].

The operational scenario therefore uses 20 t as a national same-stage estimate of contained-Te output from U.S. copper refining. Kennecott represents the publicly documented operating pathway, but the model does not attribute the entire national estimate to that facility or describe it as U.S.-refined Te metal.

Downstream conversion introduces further recovery losses. Xu et al. reported more than 95% Te dissolution from copper telluride under pressure-oxidizing alkaline conditions, followed by precipitation as TeO₂; overall Te recovery was approximately 91% after the sequential operations [29]. These results demonstrate technical feasibility but are not assumed to represent U.S. commercial performance.

The pathway is classified as S1—operational, with Evidence Grade B. The grade reflects the operating recovery circuit and authoritative national estimate while recognizing uncertainty in the facility allocation and final refined-product disposition.

2.5. Lithium from Historical Waste Rock at Boron

Rio Tinto's Boron operation in California recovers Li from historical waste rock generated during decades of borate mining and processing. Small-scale roasting and leaching trials were followed by a demonstration plant that produced battery-grade lithium carbonate [30].

The demonstration plant has a design capacity of approximately 10 t/y of lithium carbonate, equivalent to 1.879 t/y of contained Li [30]. This pathway is classified as S2—demonstration/pilot, with Evidence Grade C. Design capacity is not treated as measured annual production; utilization is applied in the scenario model.

Rio Tinto also described a potential 5000 t/y lithium-carbonate production-scale concept to be evaluated through a feasibility assessment [30]. This quantity is equivalent to 939.5 t/y of contained Li but does not represent constructed or commissioned commercial capacity. It is therefore classified as S4—future technical upper bound, with Evidence Grade C/D.

The demonstration and scale-up quantities are evaluated separately and are not combined or presented as equivalent forms of current supply.

2.6. Gallium and Magnesium from Aluminum-Processing Residues

Aluminum-processing residues include primary and secondary dross, salt cake, spent potlining, and downstream remelting residues. Their compositions vary with feed-stock, alloy chemistry, furnace practice, oxidation conditions, flux use, and residue management. They may contain metallic Al, alumina, nitrides, salts, carbides, spinel phases, and trace elements in highly variable proportions [31,32].

This heterogeneity limits extrapolation from individual samples to national recovery. Representative stream mass, grade distribution, collection efficiency, process recovery, and product specification are required before a quantity can be treated as expected output.

Wang et al. demonstrated laboratory Ga recovery from a specific aluminum-smelting slag using combined bioleaching and chemical treatment [33]. The study establishes technical mobilization of Ga from that feed, but not its representativeness of U.S. residues or its ability to yield a qualifying commercial product.

Magnesium may occur as metallic inclusions, MgO, spinel-type phases, or other stable compounds. Recovery requirements depend on the phase and intended product. Contained Mg cannot be equated with magnesium-metal production without a defined separation, reduction, purification, and finishing route.

Screening quantities of no more than approximately 5 t/y of contained Ga and 2.5 t/y of contained Mg are therefore retained only as technical upper bounds based on laboratory evidence and national residue assumptions [31–33]. They are not assigned to individual aluminum producers and are not interpreted as expected output.

Both pathways are classified as S4—technical upper bounds, with Evidence Grade D. They enter only bounded sensitivity cases designed to determine whether favorable technical quantities would be nationally material.

2.7. Cobalt from a PGM-Related Nickel-Bearing Stream

The Columbus Metallurgical Complex in Montana treats concentrates from the Stillwater and East Boulder platinum-group-metal operations and produces platinum-group-metal intermediates and byproduct base-metal streams. Available documentation indicates that minor Co reports with a crystalline nickel-sulfate product rather than being recovered as a separate cobalt product [34,35].

Facility information supplied through private communication indicates that a nickel-crystallization stream may contain approximately 100 g/L Ni and 1.4 g/L Co [36]. A preliminary process-based estimate suggests up to approximately 12 t/y of contained Co [37]. Publicly available information does not provide a complete annual stream balance, concentration variability, separation yield, purification recovery, or product specification. The quantity therefore cannot be interpreted as 12 t/y of qualifying cobalt production.

Selective separation of Co from a Ni-rich sulfate stream is technically feasible but generally requires solvent extraction, scrubbing, stripping, precipitation, or related purification. Kursunoglu et al. demonstrated bench-scale Ni–Co separation using sequential solvent-extraction circuits [38]. That study establishes technical plausibility but not facility-specific recovery or product performance at Stillwater.

The pathway is classified as S4—technical upper bound, with Evidence Grade D. No incremental qualifying Co is assigned in the principal case unless a dedicated separation circuit and verified product are documented. The contained-Co estimate enters only bounded eligibility and import displacement scenarios.

2.8. Summary of Recovery Pathways

Table 1 summarizes the supported quantities, maturity classifications, evidence grades, and principal qualifications. Quantities refer to different product forms and years and are not directly additive.

Table 1. Recovery pathways and evidence.

Pathway	Supported Quantity and Status	Evidence	Principal Qualification and Model Treatment
Ga-Clarksville	54 t/y announced capacity from 2030; S3	B/C	Not current production; the residue-derived share and qualifying product are not disclosed. Evaluated

			using demand, utilization, eligibility, and import displacement scenarios [21].
Ge-Clarksville	44 t/y announced capacity from 2030; S3	B/C	Construction, feed allocation, product form, and utilization remain uncertain. Evaluated as a 2030 announced project scenario [21].
Te-U.S. copper refining	Approximately 20 t contained Te in 2024; S1	B	National intermediate-stage estimate; facility allocation is withheld, and further refining occurs outside the United States. Output sensitivity: 17.25–20 t [26–28].
Li-Boron demonstration	10 t/y lithium carbonate, equivalent to 1.879 t/y Li; S2	C	Demonstration design capacity, not measured annual output. Utilization-adjusted in the model [30].
Li-Boron scale-up	5000 t/y lithium carbonate, equivalent to 939.5 t/y Li; S4	C/D	Feasibility-scale concept with no documented commercial construction, commissioning, or sustained production [30].
Ga-aluminum residues	No more than approximately 5 t/y contained Ga; S4	D	Laboratory-to-national extrapolation; representative grades, collection, purification, and product qualification are unverified [31–33].
Mg-aluminum residues	No more than approximately 2.5 t/y contained Mg; S4	D	No demonstrated commercial separation route or qualifying product. Evaluated only as a technical sensitivity [31,32].
Co-Stillwater	No more than approximately 12 t/y contained Co; S4	D	No separate qualifying Co product; annual stream balance, separation yield, purity, and product qualification are unverified [35–38].

Notes: S1 = operational; S2 = demonstration/pilot; S3 = announced target-year; S4 = technical or feasibility-scale upper bound. Grade B indicates an authoritative statistical or engineering basis with incomplete facility-level output or product disposition information; Grade C indicates laboratory, pilot, or demonstration evidence with uncertain commercial scale-up; and Grade D indicates extrapolated or incomplete engineering evidence. B/C indicates Grade B support for the announced project capacity and Grade C support for attribution to the identified byproduct stream.

These classifications define the pathway-specific quantities and uncertainty ranges used in the scenario analysis.

3. Materials and Methods

3.1. Analytical Design and System Boundary

This study combines facility- and stream-specific recovery evidence with national material-balance and supply-risk assessment. The analytical unit is a material–facility–stream pathway under a defined project status scenario, identified by material *i*, pathway *f*, scenario *s*, and reference year *t*.

The current-period analysis uses 2024 as the reference year. Announced and future-scale projects are evaluated separately for 2030. Project information published after 2024 is used to define prospective status and capacity but is not inserted retrospectively into the 2024 baseline.

For every pathway, the baseline and recovery cases use the same material, product stage, unit, and reference year; only the recovery assumption changes. Extraction-stage and processing-stage observations are therefore not interpreted as before-and-after recovery cases. Where a U.S. facility produces an intermediate that is subsequently refined abroad, the quantity is credited only at the domestic intermediate stage and is not treated as U.S.-refined metal.

The S0–S4 classifications defined in Section 2 remain separate throughout the analysis. Operational output, demonstration capacity, announced capacity, and technical

potential are not aggregated into a single post-recovery scenario because they have different evidentiary and policy meanings.

3.2. Data Sources and Product-Form Harmonization

U.S. production, imports, exports, apparent consumption, net import reliance, and import source shares were obtained principally from the applicable chapters of the U.S. Geological Survey's Mineral Commodity Summaries 2026 [39]. Country-level production for 2024 and the statistical estimate of U.S. Te output were obtained from the British Geological Survey's World Mineral Production 2020–2024 [28]. Governance inputs were taken from the World Bank Worldwide Governance Indicators [40]. Economic importance context follows Kannan et al. [14] and U.S. industry value-added concepts reported by the Bureau of Economic Analysis [41].

Where multiple values were available, priority was given to official national statistics, followed by international statistical compilations, peer-reviewed studies, official company documentation, and engineering estimates or private communications. Supplementary Material S1 records the source, year, unit, product basis, evidence grade, and principal qualification for each input.

Material-balance quantities are expressed as metric tonnes of contained element unless another basis is explicitly stated. Lithium carbonate was converted to contained *Li* as:

$$1 \text{ t } Li_2 CO_3 = \frac{2M_{Li}}{M_{Li_2 CO_3}} = 0.1879 \text{ t } Li. \quad (3)$$

Thus, a capacity of 10 t/y lithium carbonate corresponds to 1.879 t/y contained *Li*.

Tellurium in copper telluride is expressed as contained Te at the intermediate product stage and is not equated with refined Te metal. Similarly, Co contained in a nickel-sulfate stream is not credited as separately qualifying Co output unless separation, purification, and product qualification are included.

Where a foreign production series does not exactly match the U.S. product stage, it is treated as a fixed foreign supply exposure proxy. Recovery-induced changes are isolated through the U.S. material balance rather than interpreted as changes in the complete global production system.

Scenario calculations are provided as formula-driven worksheets in Supplementary Material S1. Figures 1–3 were generated in Python 3.13.5 using Matplotlib 3.10.8.

3.3. Baseline Material Balances and Net Import Dependence

For material *i* and reference year *t*, apparent U.S. consumption is:

$$C_{i,t} = P_{i,t} + I_{i,t} - E_{i,t} \quad (4)$$

where $P_{i,t}$ is domestic production, $I_{i,t}$ is imports, $E_{i,t}$ is exports, and $C_{i,t}$ is apparent consumption.

Net imports are:

$$NI_{i,t} = \max(I_{i,t} - E_{i,t}, 0) \quad (5)$$

and net import dependence is:

$$NID_{i,t} = \frac{NI_{i,t}}{C_{i,t}} \quad (6)$$

A value outside [0, 1] is treated as evidence of an inconsistency in unit, product form, year, stock treatment, or processing stage and is investigated before use.

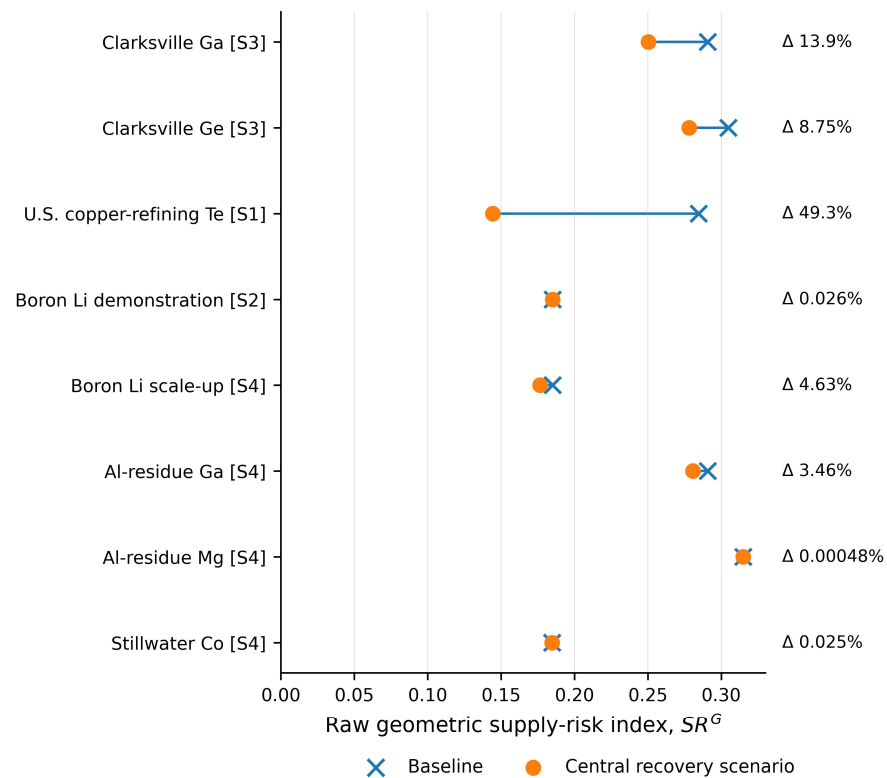


Figure 1. Raw geometric supply-risk indices under the same-stage baseline and central recovery scenarios for all eight evaluated pathways. Crosses denote baseline scores, circles denote central scenario scores, and horizontal connectors show the modeled change. Status codes identify operational (S1), demonstration/pilot (S2), announced target-year (S3), and technical upper-bound (S4) pathways. Values are raw geometric supply-risk scores; no rank transformation is applied.

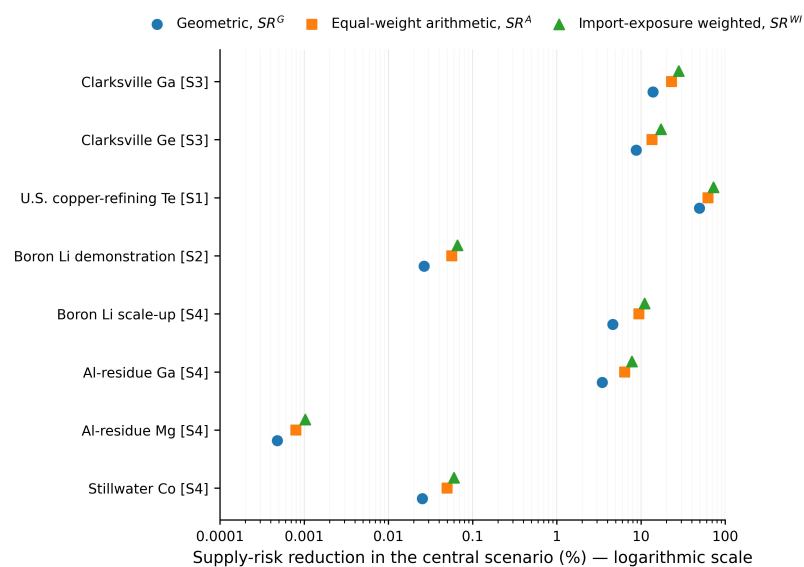


Figure 2. Sensitivity of central scenario supply-risk reductions to the aggregation method for all eight evaluated pathways. Circles show the geometric formulation, squares show the equal-weight arithmetic formulation, and triangles show the import-exposure-weighted formulation. The horizontal axis is logarithmic because the modeled effects span several orders of magnitude. Percentage reductions are calculated from raw same-stage indices.

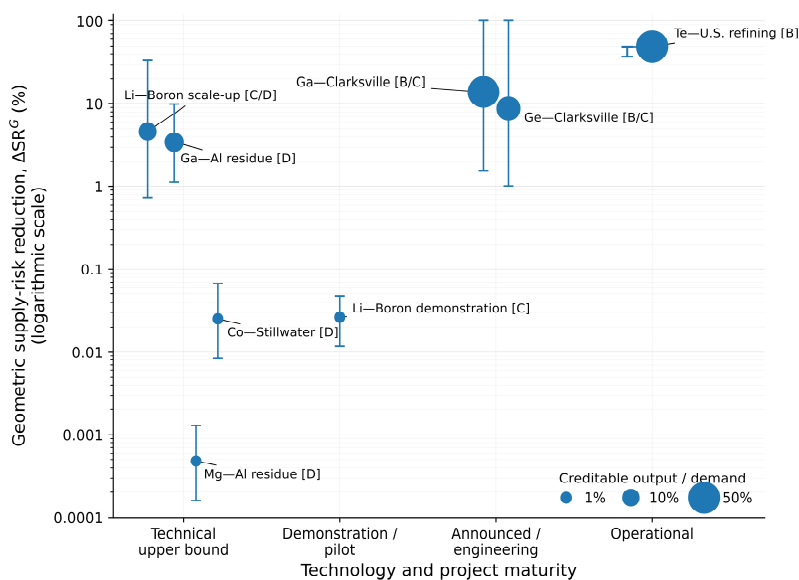


Figure 3. Geometric supply-risk reduction and technology/project maturity of the eight evaluated recovery pathways. Points show the central scenario, vertical whiskers show the lower-to-upper deterministic scenario envelope, and marker area represents creditable output as a share of modeled demand. Bracketed labels report evidence grade. Where the central scenario coincides with an envelope bound, the whisker is one-sided; the U.S. copper-refining Te interval is offset slightly from its marker for legibility. The vertical axis is logarithmic, and the scenario envelope is not a statistical confidence interval.

Table 2 reports the central material-balance inputs. These values are model inputs rather than recovery results.

Table 2. Central baseline material balances and concentration inputs.

Material or Balance	Apparent Consumption, t Element	Net Imports/NID	aHHI/aHHI _p	Principal Qualification
Ga	18.7	18.7/1.000000	0.047079/0.521971	Official consumption and 100% net import reliance.
Ge	30.0	22.908/0.763600	0.070977/0.522475	The 30 t denominator is a source-constrained central value, not reported 2024 consumption.
Te—S0 counterfactual	23.0	23.0/1.000000	0.071329/0.323402	Same-stage balance without estimated domestic output.
Te—S1 operational	23.0	3.0/0.130435	0.071329/0.323402	Based on 20 t estimated domestic output, 6 t imports, and 3 t exports.
Li—central case	2216.7	1330.0/0.600000	0.186989/0.056597	Central NID assumption; sensitivity range 0.51–0.75.
Mg	91,000	65,000/0.714286	0.089810/0.486607	Apparent-consumption approximation using net imports and old-scrap recovery.
Co	7960	5920/0.743719	0.022878/0.370797	Official refined-stage 2024 balance.

Notes: NID denotes net import dependence. $aHHI_i$ and $aHHI_p$ denote governance-adjusted import trade concentration and foreign production concentration, respectively. Table values are model inputs rather than recovery results.

For Ga, USGS reports 18.7 t consumption and 100% net import reliance; net imports were therefore set equal to consumption. Metal imports alone were not used because the consumption total covers multiple Ga product forms.

For Ge, 2024 net imports were calculated as:

$$NI_{Ge} = 21 + 11 - 9 - 0.092 = 22.908 \text{ t} \quad (7)$$

where the first two terms are contained Ge in metal and GeO_2 imports, and the final terms are corresponding exports. Because 2024 apparent consumption is not reported, 30 t is used as a source-constrained central denominator and tested through demand sensitivity.

For Te, estimated 2024 domestic output of 20 t [28], imports of 6 t, and exports of 3 t [27] imply:

$$C_{Te} = 20 + 6 - 3 = 23 \text{ t} \quad (8)$$

The S0 counterfactual removes the 20 t domestic quantity and replaces it with imports while holding consumption at 23 t. The S1 balance therefore compares $NI = 23$ t without recovery with $NI = 3$ t under the operational estimate.

For Li:

$$NI_{Li} = 3020 - 1690 = 1330 \text{ t} \quad (9)$$

Because domestic production and apparent consumption are withheld and reported net import reliance exceeds 50%, three NID cases were evaluated:

$$NID_{Li} \in \{0.51, 0.60, 0.75\} \quad (10)$$

For each case, the corresponding consumption denominator is:

$$C_{Li} = \frac{1330}{NID_{Li}} \quad (11)$$

The central value $NID = 0.60$ implies $C = 2216.7$ t Li. These are bounded scenarios consistent with the reported import reliance information, not estimates of withheld proprietary statistics.

For Mg, apparent consumption was approximated using 65,000 t of net imports and 26,000 t of old-scrap recovery. Co uses the official refined-stage 2024 balance. The conclusions for both materials are insensitive to small denominator changes because their candidate recovery quantities are very small relative to consumption.

3.4. Incorporation of Recovery into the Material Balance

Output is credited to domestic supply only when it can be expressed on the selected material-balance basis, represents qualifying rather than merely contained material, is produced domestically, is available to the relevant U.S. market, and is not already included in baseline production.

For pathway f and scenario s , creditable output is:

$$R_{i,f,s} = K_{i,f} u_{i,f,s} \lambda_{i,f,s} \quad (12)$$

where $K_{i,f}$ is reported nameplate capacity or contained-element potential, $u_{i,f,s}$ is the capacity utilization factor, and $\lambda_{i,f,s}$ is the eligible output factor.

The eligible output factor accounts for feed attribution, collection and process losses not already included in K , conversion to the selected product stage, product qualification, downstream processing location, and availability to the U.S. market.

The quantity of net imports displaced is:

$$DNI_{i,f,s} = \min(NI_{i,0}, d_{i,f,s} R_{i,f,s}) \quad (13)$$

where $d_{i,f,s}$ is the import displacement factor.

Scenario net imports are:

$$NI_{i,f,s} = \max(NI_{i,0} - d_{i,f,s} R_{i,f,s}, 0) \quad (14)$$

and scenario net import dependence is:

$$NID_{i,f,s} = \frac{NI_{i,f,s}}{C_{i,s}} \quad (15)$$

Once net imports reach zero, additional output does not produce a negative *NID*. Surplus capacity could result in exports, inventories, unused capacity, or supply for future demand, but these outcomes are not modeled as further reductions in import dependence.

For 2030 pathways, baseline consumption and net imports are scaled by the demand multiplier $D_{i,h}$:

$$C_{i,2030,h} = D_{i,h} C_{i,2024}, \quad (16)$$

$$NI_{i,2030,h} = D_{i,h} NI_{i,2024} \quad (17)$$

This preserves baseline *NID* before the recovery project while allowing the effect of a fixed project capacity to vary with demand. Demand multipliers of 1.0, 1.5, and 2.0 are evaluated.

3.5. Governance-Adjusted Production and Trade Concentration

Supply concentration is represented by governance-adjusted Herfindahl–Hirschman indices following the structure adopted by Kannan et al. [14]. Foreign production concentration and U.S. import trade concentration are calculated separately.

For material i , the foreign production share of country j is:

$$s_{i,j}^p = \frac{P_{i,j}}{\sum_{k \neq US} P_{i,k}} \quad (18)$$

where U.S. output is excluded from the denominator.

The U.S. import share supplied by country j is:

$$s_{i,j}^t = \frac{I_{i,j}^{US}}{\sum_k I_{i,k}^{US}} \quad (19)$$

Production shares use 2024 country output [28], while import shares use combined 2021–2024 USGS source distributions [39]. For an unspecified “other” import category, the governance factor is the import-share-weighted mean risk of the identified suppliers.

Governance exposure uses the six 2021 Worldwide Governance Indicators: Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law, and Control of Corruption [40]. For governance dimension r , the country value is inverted and normalized as:

$$g_{j,r} = \frac{x_{r,max} - x_{j,r}}{x_{r,max} - x_{r,min}} \quad (20)$$

where a higher value denotes weaker governance and greater potential supply exposure. The composite country governance risk factor is:

$$G_j = \frac{1}{6} \sum_{r=1}^6 g_{j,r} \quad (21)$$

The governance-adjusted foreign production concentration is:

$$aHHI_{p,i} = \sum_j (s_{i,j}^p)^2 G_j \quad (22)$$

and the governance-adjusted U.S. import trade concentration is:

$$aHHI_{t,i} = \sum_j (s_{i,j}^t)^2 G_j \quad (23)$$

Both indicators lie between 0 and 1 under the stated normalization. Higher values indicate that supply is concentrated among a small number of countries with comparatively high governance risk factors.

The Ge production index is interpreted as a conservative documented-output estimate. Quantified production is available for the dominant producers, but additional countries are identified as producing Ge without publicly reported output quantities.

3.6. Supply-Risk Aggregation

3.6.1. Geometric Specification

The principal supply-risk score is:

$$SR_{i,f,s}^G = (NID_{i,f,s} aHHI_{p,i} aHHI_{t,i})^{\frac{1}{3}} \quad (24)$$

The geometric specification is retained for comparability with Kannan et al. [14]. It treats proportional changes in NID, production concentration, and trade concentration symmetrically. The elasticity of SR^G with respect to each component is one-third:

$$\frac{\partial \ln SR^G}{\partial \ln NID} = \frac{\partial \ln SR^G}{\partial \ln aHHI_p} = \frac{\partial \ln SR^G}{\partial \ln aHHI_t} = \frac{1}{3} \quad (25)$$

The multiplicative structure limits compensation among components but has a zero-collapse property: if one component equals zero, the composite equals zero even when the remaining components are positive. Arithmetic formulations are therefore reported as robustness checks.

3.6.2. Arithmetic Specification

The equal-weight arithmetic score is:

$$SR_{i,f,s}^A = \frac{NID_{i,f,s} + aHHI_{p,i} + aHHI_{t,i}}{3} \quad (26)$$

An import-exposure-weighted score is also calculated:

$$SR_{i,f,s}^{WI} = 0.50NID_{i,f,s} + 0.25aHHI_{p,i} + 0.25aHHI_{t,i} \quad (27)$$

The weighted formulation tests the effect of assigning greater policy importance to direct U.S. import dependence while retaining the two concentration dimensions. These weights are a sensitivity specification rather than an estimate of the probability of disruption. Variation in indicator selection, normalization, and aggregation can materially affect criticality results, making explicit cross-method comparison important [42].

3.6.3. Scenario Effects

For aggregation method q , where $q \in \{G, A, WI\}$, the percentage reduction is:

$$\Delta SR_{i,f,s}^q = 100 \frac{SR_{i,0}^q - SR_{i,f,s}^q}{SR_{i,0}^q} \quad (28)$$

All reductions are calculated from raw index values. No rank or percentile transformation is applied to the primary results. If an index is displayed on a 0–100 scale, it is linearly rescaled as $100SR^q$, not replaced by the observation's rank within a comparison set.

The principal partial-equilibrium specification holds $aHHI_p$ and $aHHI_t$ fixed and allows the recovery pathway to change NID. This isolates the direct national material-balance effect without assuming changes in foreign production or supplier country structure.

Under fixed concentration, the following identity must hold:

$$\frac{SR_{i,f,s}^G}{SR_{i,0}^G} = \left(\frac{NID_{i,f,s}}{NID_{i,0}} \right)^{\frac{1}{3}} \quad (29)$$

Equation (29) is used as an automated validation test for every scenario.

3.7. Economic-Importance Indicator and Model Treatment

Economic importance represents the potential downstream economic exposure associated with a material supply disruption. Consistent with Kannan et al. [14], it can be expressed as:

$$EI_i = R_i \sum_z A_{i,z} VA_z \quad (30)$$

where VA_z is the value added of manufacturing sector z , $A_{i,z}$ is the fraction of material i allocated to that sector, and R_i is the relative market value factor. Industry value added follows the U.S. Bureau of Economic Analysis definition of an industry's contribution to gross domestic product [41].

EI is treated as a baseline contextual attribute rather than a recovery-dependent outcome. The recovery scenarios change the origin and availability of supply but do not directly change sectoral material allocation, relative material value, or downstream value added. EI is therefore held constant across scenarios and is not used to calculate the percentage reductions reported for the recovery pathways.

3.8. Sensitivity and Scenario Interpretation

Uncertainty is evaluated through deterministic scenarios because statistically defensible probability distributions are unavailable for several project and metallurgical variables. The scenario grid varies utilization, eligible output, import displacement, future demand, and selected baseline assumptions. Pathway-appropriate cases include utilization of 25–100%, import displacement of 50–100%, 2030 demand multipliers of 1.0–2.0, Li NID values of 0.51–0.75, U.S. copper-refining Te output of 17.25–20 t, and alternative SR aggregation methods. Complete combinations are provided in Supplementary Material S1.

The Te lower case of 17.25 t is the minimum domestic output consistent with apparent consumption of 23 t and reported net import reliance below 25%. Central and upper cases use the 20 t national estimate.

Reported lower-to-upper ranges are deterministic scenario envelopes, not statistical confidence intervals. An upper-bound result indicates that the specified assumptions are sufficient to produce that result; it does not establish that the outcome is expected or probable. Operational, demonstration, announced, and technical upper-bound pathways remain distinct throughout the analysis.

3.9. Reproducibility and Validation

Supplementary Material S1 provides the data inputs, product-stage conversions, governance factors, production and import shares, baseline balances, pathway assumptions, formulas, source register, and 677 scenario combinations. The Scenario_Summary worksheet identifies the lower, central, and upper cases used in the manuscript tables and figures.

Formula-based checks verify that production and import shares sum to one; concentration and NID values remain within [0, 1]; material balances close; scenario net imports are nonnegative; creditable output does not exceed the applicable capacity or technical quantity; and each scenario has evidence grade and source treatment information. Equation (29) is also checked whenever concentration factors are fixed. All 25 validation checks were satisfied, and manuscript values were taken directly from the scenario summary outputs.

4. Results

Results are reported separately for each material–facility–stream pathway. Operational, demonstration, announced target-year, and technical upper-bound quantities are not combined because they represent different levels of maturity and evidentiary support.

Each central scenario is accompanied by a deterministic lower-to-upper scenario envelope based on the assumptions described in Section 3. These envelopes are not statistical confidence intervals. All percentage changes were calculated from raw supply-risk indices; no rank or percentile transformation was applied.

4.1. Baseline Supply Conditions and Central Scenario Outputs

The baseline material balances indicate substantial U.S. dependence on foreign supply for all six materials. Baseline net import dependence was 1.0000 for Ga, 0.7636 for Ge, 0.6000 in the central Li case, 0.7143 for Mg, and 0.7437 for Co. For Te, the same-stage S0 counterfactual assumes complete import dependence in the absence of domestic copper-refining recovery, whereas the estimated operational balance has an NID of 0.1304.

Creditable output was generally lower than reported nameplate capacity or contained material potential because utilization and eligible output factors were applied before a quantity entered the national balance. The resulting scale relative to modeled demand differed markedly among pathways. U.S. copper-refining Te output represented 86.96% of same-stage demand. Central Clarksville Ga and Ge output represented 48.13% and 24.44% of their respective 2030 demand cases. The Boron Li scale-up and aluminum-residue Ga cases represented 10.60% and 13.37%, respectively. By contrast, the Boron Li demonstration, Stillwater Co, and aluminum-residue Mg cases each represented less than 0.1% of modeled demand.

Figure 1 compares the raw geometric supply-risk indices for the same-stage baseline and central recovery scenarios across all eight pathways, while Table 3 summarizes their central outputs, supply-risk reductions, and deterministic scenario envelopes. Every central scenario reduced the modeled index, but the magnitude ranged from approximately 49% for operational Te to less than 0.001% for aluminum-residue Mg.

Table 3. Central supply-risk results by recovery pathway.

Recovery Pathway	Status/Evidence	Central Creditable Output (% of Modeled Demand)	Central SR ^G Reduction	Scenario Envelope
U.S. copper-refining Te	S1, 2024/B	20.00 t Te (86.96%)	49.29%	37.00–49.29%
Clarksville Ga	S3, 2030/B/C	13.50 t Ga (48.13%)	13.87%	1.53–100%
Clarksville Ge	S3, 2030/B/C	11.00 t Ge (24.44%)	8.75%	1.01–100%
Boron Li scale-up concept	S4, 2030/C/D	352.31 t Li (10.60%)	4.63%	0.74–33.54%
Ga from aluminum residues	S4, 2024/D	2.50 t Ga (13.37%)	3.46%	1.13–9.85%
Boron Li demonstration plant	S2, 2024/C	1.409 t Li (0.0636%)	0.0265%	0.0118–0.0471%
Stillwater Co technical case	S4, 2024/D	6.00 t Co (0.0754%)	0.0253%	0.00845–0.0676%
Mg from aluminum residues	S4, 2024/D	1.25 t Mg (0.00137%)	0.000481%	0.000160–0.001282%

Notes: Outputs are expressed as contained element; Li quantities are converted from lithium carbonate equivalent. S1 = operational; S2 = demonstration/pilot; S3 = announced target-year; and S4 = technical upper bound. The scenario envelope is deterministic and is not a confidence interval. Complete baseline and scenario NID and raw SR^G values are provided in Figure 1 and Supplementary Material S1.

4.2. Operational and Demonstration-Scale Pathways

4.2.1. U.S. Copper-Refining Tellurium

The U.S. copper-refining Te pathway produced the largest supported current effect. The central case uses the statistical estimate of 20 t/y of domestic contained-Te output. With same-stage apparent consumption of 23 t, this output reduces net import dependence from 1.0000 in the without-recovery counterfactual to 0.1304 and reduces geometric supply risk by 49.29%.

The lower case, based on 17.25 t/y of domestic output, reduces SR^G by 37.00%. The central and upper cases both use the 20 t national estimate; therefore, the upper bound coincides with the central result, and the scenario envelope is one-sided.

This result applies to contained Te in a copper-refining intermediate. It should not be interpreted as 20 t/y of domestically refined Te metal or as output attributable entirely to a single refinery. Nevertheless, the pathway materially changes the same-stage national balance because domestic output is large relative to the U.S. market.

4.2.2. Boron Lithium Demonstration Plant

The Boron demonstration plant has a design capacity of 10 t/y lithium carbonate, equivalent to 1.879 t/y contained Li. After applying the central utilization assumption, 1.409 t/y enters the material balance.

This amount represents only 0.0636% of modeled Li demand and reduces the central geometric supply risk by 0.0265%. The scenario envelope is 0.0118–0.0471%.

The result distinguishes process demonstration from national-scale supply significance. The pathway demonstrates production of battery-grade lithium carbonate from historical waste rock, but its current capacity is too small to materially affect U.S. supply risk.

4.3. Announced Gallium and Germanium Capacity

The Clarksville Ga and Ge pathways were evaluated as announced 2030 scenarios rather than current domestic supply. The central cases assume 50% utilization of announced capacity, 50% eligible output, 75% import displacement, and a demand multiplier of 1.5.

Under these assumptions, Clarksville reduces central geometric supply risk by 13.87% for Ga and 8.75% for Ge. The corresponding creditable outputs are 13.5 t/y Ga and 11.0 t/y Ge.

The scenario envelopes are wide—1.53–100% for Ga and 1.01–100% for Ge—because the results depend on future demand, project utilization, feed attribution, product qualification, and import displacement. Nameplate capacity alone therefore does not determine the national effect.

In the upper scenarios, qualifying output is sufficient to reduce modeled NID to zero. Because the geometric formulation is multiplicative, $NID=0$ causes $SR^G = 0$ even though production and trade concentration remain positive. The resulting 100% reductions are mathematical zero-collapse cases, not evidence that project, processing, trade, or broader supply-chain risks disappear.

The central and lower scenarios provide the more relevant interpretation: the project could make a meaningful future contribution, but the result remains conditional on construction, commissioning, utilization, feed allocation, qualifying product output, and market displacement.

4.4. Future and Technical Upper-Bound Pathways

4.4.1. Boron Lithium Scale-Up Concept

The 5000 t/y lithium-carbonate concept is equivalent to 939.5 t/y contained Li at full nameplate capacity. Under the central assumptions, 352.31 t/y enters the national balance, representing 10.60% of modeled demand.

The central geometric supply-risk reduction is 4.63%, with a scenario envelope of 0.74–33.54%. The result indicates that commercial-scale development could provide a more consequential national contribution than the current demonstration plant. However, the 5000 t/y quantity remains a feasibility-scale concept rather than constructed or commissioned commercial capacity. It should therefore be interpreted as conditional technical potential, not expected production.

4.4.2. Gallium from Aluminum Residues

The central aluminum-residue Ga scenario credits 2.5 t/y of qualifying output after applying a 50% eligibility factor to the 5 t/y contained-Ga upper bound. The resulting central reduction in geometric supply risk is 3.46%, with a scenario envelope of 1.13–9.85%.

The potential effect is non-negligible relative to the small U.S. Ga market, but the pathway has Evidence Grade D. The quantity depends on extrapolation from laboratory recovery and national residue assumptions, for which representative grades, collection rates, purification recoveries, and product specifications have not been established. The result is therefore a screening bound rather than a commercial production forecast.

4.4.3. Low-Impact Magnesium and Cobalt Cases

The Mg and Co pathways produced negligible national effects under all evaluated assumptions. Aluminum-residue Mg reduced central geometric supply risk by 0.000481%; even the complete 2.5 t/y upper-bound case produced a reduction of only 0.001282%.

The central Stillwater Co case reduced geometric supply risk by 0.0253%, with an upper result of 0.0676%. The pathway may warrant metallurgical investigation, but it lacks a documented dedicated Co separation circuit, verified annual recovery, and qualifying cobalt product.

These results show that a material may be strategically important while an individual recovery stream remains too small to alter national supply risk materially.

4.5. Sensitivity to the Supply-Risk Aggregation Method

The aggregation method changed the magnitude of the modeled reductions but not their direction or broad ordering. Figure 2 compares the geometric, equal-weight arithmetic, and import-exposure-weighted central results for all eight pathways.

The arithmetic formulations produced larger proportional reductions because changes in NID enter those indices linearly. Under the geometric formulation, when the concentration components are fixed, the elasticity of the composite index with respect to NID is one-third.

The qualitative ordering remained stable. Operational Te produced the largest central effect, followed by Clarksville Ga and Ge, the Boron scale-up concept, and aluminum-residue Ga. The Boron demonstration, Stillwater Co, and aluminum-residue Mg cases remained small under all three formulations.

The arithmetic results also clarify the upper Clarksville scenarios. When NID reaches zero, the geometric index collapses to zero, whereas the arithmetic indices remain positive because production and trade concentration remain in the composite. Reporting all three

formulations therefore prevents the 100% geometric reductions from being interpreted as elimination of every form of supply risk.

4.6. Technology Maturity and Modeled Impact

Figure 3 positions the eight pathways according to technology and project maturity and central geometric supply-risk reduction. Vertical whiskers represent the deterministic lower-to-upper scenario envelopes, while marker area represents creditable output relative to modeled demand.

The pathways form distinct maturity–impact groups. U.S. copper-refining Te combines operational status with the largest supported current reduction. Clarksville Ga and Ge provide meaningful central effects but remain announced projects with wide scenario envelopes. The Boron demonstration has direct process evidence but a negligible national effect at its present scale, whereas the larger Boron concept produces a more material modeled effect but remains a technical future case. Aluminum-residue Ga has modest potential with low evidentiary confidence, while Mg and Stillwater Co remain nationally small even under favorable assumptions.

The pattern demonstrates that national supply-risk impact and project maturity are separate dimensions. A demonstrated pathway may be too small to affect national supply materially, whereas a potentially large pathway may remain conditional on project development, scale-up, or product qualification.

4.7. Supply-Risk Results at Fixed Economic Importance

Economic importance was held constant across recovery scenarios because the analysis changes supply origin and availability rather than downstream material allocation or manufacturing sector value added. The reported results therefore represent changes in the supply-risk dimension at a fixed level of economic importance.

A reduction in supply risk should not be interpreted as a proportional reduction in economic importance or in every dimension of material criticality. This distinction is particularly relevant for Li and Co, which remain economically important even though the individual recovery pathways evaluated here produce only small changes in current national supply risk.

5. Discussion and Policy Implications

5.1. Interpretation of the Main Findings

The results demonstrate that recovery from metallurgical and industrial byproducts cannot be treated as a uniform supply-security strategy. The national contribution of a pathway depends jointly on the quantity of output that qualifies at the relevant product stage, the size of the domestic market, baseline import dependence, project maturity, and evidence quality. Technical feasibility alone does not establish national significance, while a potentially large modeled contribution may remain conditional on construction, scale-up, feed attribution, product qualification, or market displacement.

The U.S. copper-refining Te pathway provides the clearest current example. Its central modeled reduction is large because estimated domestic contained-Te output is substantial relative to the same-stage U.S. market. However, the recovered product is a tellurium-bearing intermediate rather than domestically refined Te metal, and the national production estimate cannot be assigned entirely to one refinery [26–28]. The pathway therefore reduces dependence at the copper-telluride stage while leaving downstream purification as a remaining supply-chain exposure.

The Clarksville Ga and Ge pathways illustrate the difference between prospective capacity and realized supply. Their central effects are potentially meaningful because the

associated U.S. markets are small and highly import-dependent. Nevertheless, the wide scenario envelopes show that the national contribution depends on project completion, utilization, the fraction of output attributable to the identified residue, product form, qualification, future demand, and import displacement [21]. Announced capacity should therefore be interpreted as conditional future potential rather than present domestic supply.

The two Boron Li cases demonstrate that project maturity and national scale are separate considerations. The demonstration plant establishes that battery-grade lithium carbonate can be produced from historical waste rock, but its current capacity has a negligible effect on the national supply risk. The larger scale-up concept produces a more material modeled contribution, but it remains a feasibility-scale case without documented sustained commercial production [30].

The technical upper-bound pathways further reinforce the distinction between contained material and qualifying supply. Aluminum-residue Ga could become relevant because the U.S. Ga market is comparatively small, but the estimate depends on extrapolating laboratory evidence to heterogeneous national residue streams. Aluminum-residue Mg and Stillwater Co remain nationally small under the evaluated quantities, even though further metallurgical work may still be justified for waste management, process efficiency, or product recovery reasons.

Overall, the results support a differentiated policy approach based on the intersection of modeled national effect, project maturity, evidence strength, and the remaining steps required to produce a qualifying market product.

5.2. Policy Priorities

Figure 3 provides the maturity–impact comparison, while Table 4 translates that comparison into policy priorities. The categories are not based on a single numerical threshold; they reflect central supply-risk reduction, scenario uncertainty, project status, product stage, and evidence quality.

Table 4. Policy priorities for the evaluated recovery pathways.

Pathway	Status/Evidence/Central Reduction	Recommended Policy Priority
U.S. copper-refining Te	S1 Operational; B; 49.29%	Deploy and optimize. Improve annual output reporting, assess additional domestic feed streams, and strengthen downstream purification and product qualification.
Clarksville Ga and Ge	S3 Announced; B/C; 13.87% (Ga); 8.75% (Ge)	Milestone-based project support. Link assistance to engineering, permitting, construction, commissioning, feed attribution, utilization, and qualifying product output.
Boron Li demonstration	S2 Demonstration/pilot; C; 0.0265%	Continue demonstration and qualification. Emphasize operating reliability, actual annual output, process learning, and product consistency.
Boron Li scale-up	S4 Future technical case; C/D; 4.63%	Evaluate commercial scale-up. Require continuous-operation evidence, techno-economic and environmental assessment, customer qualification, and a formal investment and commissioning plan.
Ga from aluminum residues	S4 Technical upper bound; D; 3.46%	Targeted metallurgical research. Establish representative residue quantities and grades, complete process recovery, purification performance, and product specification.
Mg from aluminum	S4 Technical upper bounds; D; 0.000481% (Mg); 0.0253% (Co)	Low national supply-security priority. Pursue where process research, waste reduction, environmental benefits, or recovery of additional products provides an independent justification.

**residues and
Stillwater Co**

Notes: Central reduction refers to the geometric supply-risk index. S1 = operational; S2 = demonstration/pilot; S3 = announced target-year; S4 = technical or feasibility-scale upper bound. Evidence grades: B = authoritative statistical or engineering evidence; C = demonstration evidence with scale-up uncertainty; D = screening-level evidence. Detailed pathway assumptions and deterministic scenario envelopes are provided in Supplementary Material S1.

5.2.1. Deploy and Optimize Operational Tellurium Recovery

The immediate priority for the Te pathway is to optimize and integrate the existing recovery chain rather than simply announce additional capacity. More transparent reporting of annual contained-Te output would permit evaluation of utilization, recovery efficiency, and year-to-year variability. Because domestic recovery currently produces an intermediate that is processed further outside the United States, policy should also consider downstream purification, product qualification, and offtake [27,28]. Without such integration, one form of import dependence is reduced while exposure at a later processing stage remains.

Additional Te-bearing streams at U.S. copper refineries may warrant assessment, but any expansion should be supported by measured stream composition, actual process recovery, and qualifying product output rather than contained Te alone.

5.2.2. De-Risk Announced Gallium and Germanium Capacity Through Milestones

Support for Clarksville should be conditional on measurable development milestones. Relevant stages include engineering completion, permitting, financing, construction, commissioning, sustained operation, and demonstrated capacity utilization. Announced nameplate quantities should not be credited as national supply before qualifying production is achieved.

Feed attribution is also essential. The proposed integrated facility may use pond cake, mine-derived feed, recycled materials, and other inputs [21]. The share of Ga and Ge output attributable specifically to the identified Clarksville residue should therefore be reported separately. Product form, purity, customer acceptance, and long-term offtake are equally important because contained Ga or Ge does not automatically satisfy semiconductor, optical, or other high-purity market requirements.

5.2.3. Continue Lithium Demonstration and Scale-Up

The Boron demonstration plant merits continued support as a process learning and qualification platform, but its present scale does not justify a large national supply-security claim. Evaluation should focus on operating reliability, feed variability, actual output, recovery and purification performance, product consistency, reagent and energy use, and residue management.

Before the 5000 t/y lithium-carbonate concept is treated as expected domestic supply, it should be supported by continuous-operation evidence, a project-level techno-economic assessment, a life-cycle or environmental assessment, product qualification, and a formal investment and construction decision. The demonstration and scale-up cases should remain distinct in both policy analysis and public reporting.

5.2.4. Target Research Toward Technical Upper-Bound Pathways

For aluminum-residue Ga, the immediate research need is facility-representative characterization. National recovery cannot be inferred reliably from one laboratory slag sample because aluminum residues vary by feedstock, alloy, furnace operation, flux use,

and residue type [31–33]. Research should establish annual stream mass, grade distribution, phase occurrence, collection requirements, complete extraction and purification recovery, and achievable product quality.

The evaluated Mg and Co quantities do not justify major national supply-security programs. Mg research may still be valuable where it contributes to residue stabilization, waste reduction, energy efficiency, or recovery of other constituents. Similarly, the Stillwater Co pathway may warrant process research because selective Ni–Co separation is technically plausible [35,38]. However, a complete stream balance, dedicated separation route, verified recovery, and qualifying product would be required before the pathway could be credited as a material domestic Co source.

5.3. Implications for Criticality and Recovery Assessment

The analysis provides four broader methodological lessons.

First, supply-chain stage and recovery scenario must be treated separately. Extraction-stage and processing-stage scores describe different supply-chain exposures; they do not represent baseline and post-recovery conditions. A valid recovery comparison must hold material basis, product stage, unit, and reference year constant.

Second, changes in ordinal rank should not be interpreted as proportional changes in supply risk. Rank movement depends on the composition and density of the comparison set. Percentage reductions should therefore be calculated from raw index values, as in the present study.

Third, the aggregation method affects the magnitude of the estimated benefit. When recovery changes NID while the concentration indicators remain fixed, the geometric index responds with one-third elasticity, whereas arithmetic formulations transmit the NID change more directly. Although the numerical reductions differ, the broad ordering of the evaluated pathways remains stable across the geometric, equal-weight arithmetic, and import-exposure-weighted formulations [14,42]. This stability supports the qualitative policy ordering.

Fourth, the geometric index has a boundary effect. When NID reaches zero, SR^G becomes zero even though production and trade concentration remain positive. The 100% upper-bound reductions for Clarksville Ga and Ge therefore indicate elimination of modeled net import dependence under the stated assumptions, not elimination of every supply-chain risk. Arithmetic formulations are necessary to make this residual exposure visible.

The same need for analytical precision applies to recovery quantities. A potential pathway progresses through several distinct stages: contained inventory → collected stream → extracted intermediate → purified product → qualified market supply.

Losses, uncertainty, or incompatibility at any stage reduce the quantity entering the national balance. This is especially important for byproduct and companion metals, whose supply is influenced by host-metal production and process conditions [15]. Accordingly, laboratory extraction, contained inventory, design capacity, demonstration output, and commercial production should not be presented as equivalent forms of supply.

5.4. Limitations and Future Research

This study evaluates selected publicly documented U.S. pathways and is not an exhaustive census of every industrial residue or byproduct stream. Additional opportunities may exist where facility-level data are unavailable. Some material-balance statistics are also withheld: the Ge denominator is represented by a source-constrained central value and demand sensitivity; the Li balance uses an NID range consistent with published import reliance information; and the Te case relies on a national output estimate because

facility allocation is proprietary. The Stillwater Co estimate relies partly on private communications and is therefore treated as an Evidence Grade D upper bound [36,37].

The future cases are partial-equilibrium scenarios rather than complete market forecasts. Demand is represented through multipliers, while prices, substitution, inventories, competing projects, changes in supplier structure, export responses, and global production adjustments are not modeled dynamically. Production and import concentration are held fixed within each scenario, and the governance calculation uses the stated 2021 reference year. The Ge production concentration may understate supplier diversity because some producing countries lack quantified output data.

The study also does not establish project profitability or environmental superiority. Capital and operating costs, permitting, financing, energy and water demand, reagent requirements, waste management, product prices, and customer qualification are outside the quantitative model. Recovery from an existing stream may avoid some primary extraction, but it can also require energy-intensive pretreatment, leaching, separation, and purification [17–19]. Environmental benefits should therefore be demonstrated rather than assumed. Economic importance is held constant and does not capture future changes in technology mix, substitution, sectoral allocation, or value added.

Future work should prioritize facility-level stream characterization, complete mass balances, continuous pilot operation, overall recovery and product purity measurements, and documented output variability. These data should then be integrated with project-level techno-economic and life-cycle assessments. Dynamic criticality models could additionally represent demand growth, prices, substitution, project entry, trade changes, stockpiling, and changes in global production concentration. Such work would permit more rigorous evaluation of milestone-based grants, loan support, procurement, offtake mechanisms, and production incentives.

The central policy implication is not that all industrial residues deserve equivalent support. Recovery pathways should be screened jointly for qualifying output, national supply-risk effect, maturity, evidence confidence, project economics, and environmental performance. This approach directs deployment support toward operational or advanced pathways while reserving research funding for cases that remain technically uncertain or nationally small.

6. Conclusions

This study evaluated eight U.S. critical-material recovery pathways for Ga, Ge, Te, Li, Mg, and Co by integrating facility- and stream-specific recovery evidence with national material balances and supply-risk indicators. The analysis distinguished operational, demonstration, announced target-year, and technical upper-bound cases; separated contained material from qualifying domestic output; and compared each recovery scenario with a baseline defined at the same product stage, unit, and reference year. Supply-risk changes were calculated from raw geometric indices and tested using equal-weight arithmetic and import-exposure-weighted formulations.

The results show that the national contribution of byproduct recovery varies substantially among pathways. The operational U.S. copper-refining Te pathway produced the largest central reduction in geometric supply risk, at 49.29%. The announced 2030 Clarksville capacity produced conditional central reductions of 13.87% for Ga and 8.75% for Ge. All other central cases produced reductions of 4.63% or less. In particular, the current Boron Li demonstration, Stillwater Co, and aluminum-residue Mg pathways were too small to materially affect national supply risk. The broad ordering of the pathways remained stable across the geometric and arithmetic aggregation methods, although the magnitude of the estimated reductions differed.

These findings support a differentiated policy strategy. Existing Te recovery should be maintained and optimized while remaining downstream purification and product-stage vulnerabilities are addressed. Support for Clarksville Ga and Ge should be linked to measurable engineering, construction, commissioning, feed attribution, utilization, and product qualification milestones rather than announced nameplate capacity alone. The Boron Li pathway warrants continued demonstration and scale-up assessment, but the 5000 t/y concept should not be treated as expected commercial supply without investment and operating evidence. Aluminum-residue Ga may justify targeted facility-specific research, whereas the evaluated Mg and Co pathways should receive low national supply-security priority unless independent environmental, waste management, or process efficiency benefits justify further development.

This study is a screening assessment rather than a project-level techno-economic analysis, life-cycle assessment, or exhaustive inventory of U.S. industrial residues. Some material-balance statistics were represented through source-constrained assumptions and deterministic sensitivity ranges, and technical upper bounds should not be interpreted as forecasts. Industrial byproduct recovery can strengthen U.S. material security, but its policy value depends on qualifying output, national market scale, project maturity, evidence quality, economic feasibility, and environmental performance—not on contained material or announced capacity alone.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/resources15080104/s1>, Supplementary Material S1: Criticality Calculation Data and Scenario Analysis, an Excel workbook containing the data dictionary; facility and recovery evidence inventory; governance risk inputs; production and import source shares; governance-adjusted concentration calculations; 2024 baseline material balances; pathway assumptions; 677 scenario combinations; lower, central, and upper scenario summaries; source register; assumptions and limitations; and validation checks; Supplementary Material S2: Figure-Generation Code and Data, containing the Python figure-generation script, machine-readable figure data, data dictionary, software requirements, verification report, figure captions, and publication figures in raster and vector formats.

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Abbreviations

The following abbreviations are used in this manuscript:

AMMTO	Advanced Materials and Manufacturing Technologies Office
BGS	British Geological Survey
DNI	Displaced net import
EI	Economic importance
HHI	Herfindahl–Hirschman Index
aHHI	Governance-adjusted Herfindahl–Hirschman Index
aHHIp	Governance-adjusted Herfindahl–Hirschman Index for foreign production

aHHIt	Governance-adjusted Herfindahl–Hirschman Index for U.S. import trade
LCE	Lithium carbonate equivalent
NI	Net import
NID	Net import dependence
PGM	Platinum-group metal
S0	Same-stage baseline without the incremental recovery pathway
S1	Operational recovery scenario
S2	Demonstration or pilot recovery scenario
S3	Announced target-year recovery scenario
S4	Technical or feasibility-scale upper-bound scenario
SR	Supply risk
SR ^A	Equal-weight arithmetic supply-risk index
SR ^G	Geometric supply-risk index
SR ^{WI}	Import-exposure-weighted arithmetic supply-risk index
USGS	U.S. Geological Survey
WGI	Worldwide Governance Indicators

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