Mismeasured raw-material criticality, misdirected policy: a cross-country review of methods and impacts

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Mismeasured raw-material criticality, misdirected policy: a cross-country review of methods and impacts

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Abstract

Governments worldwide rely on "critical" raw materials lists to direct industrial policy, fiscal incentives, and trade strategy. However, the methodological soundness of these instruments remains underscrutinized. We assemble the first global database of critical, strategic or priority raw material lists and their policy uses, combining a large language model-based discovery pipeline across 206 jurisdictions with manual validation. Our analysis reveals a fragmented landscape, ranging from opaque qualitative judgments to indicator-based indices that lack empirical validation. Because these methodologies often rely on uncalibrated proxies rather than causal models, the resulting lists are diffuse, encompassing the majority of the periodic table rather than identifying genuine high-risk bottlenecks. This may lead to misallocation of public resources and strategic blindness to actual supply threats. We conclude that effective raw material governance requires explicitly defining optimization objectives and adopting empirically validated methods, such as probabilistic loss approaches, to identify relevant policies.

1 Introduction

Raw material criticality assessments emerged to help public authorities and firms prioritise attention and resources amid tightening mineral supply–demand balances, geopolitical frictions, and technology shifts associated with the energy transition. In practice, most frameworks distinguish between the likelihood of supply restriction and the consequences for a focal system, operationalised through indicators at the level of products, sectors, firms, or national economies (Graedel, Barr, et al., 2012; Schrijvers et al., 2020). The appeal of criticality is its decision orientation: it screens many materials quickly, flags bottlenecks, and signals where mitigation through substitution, recycling, stockpiles, diversification or domestic processing might matter most. Comparative reviews emphasise that criticality is not an intrinsic property of a material but perspective dependent, time varying, and sensitive to scoping, data and aggregation choices (Dewulf et al., 2016; Graedel and Reck, 2016; Schicho and L. Tercero Espinoza, 2024; Ioannidou et al., 2019; Christmann and Lefebvre, 2022).

Because perspectives differ, so do policy uses. National strategies diverge significantly based on economic structure: import-dependent economies primarily seek to de-risk supply chains, whereas resource-rich exporters prioritize value capture and domestic industrialization. Labels vary ("critical," "strategic," "priority," "transition"), yet the lists attached to them now steer tangible instruments, including subsidies and tax credits, permitting fast-tracks, procurement rules, stockpiles, trade and investment screening, and circularity targets (Dewulf et al., 2016; Hotchkiss, Urdaneta, and Bazilian, 2024; L. A. Tercero Espinoza, 2021). Related approaches at firm and product level translate supply-risk thinking into design and sourcing choices, albeit with different levers and power asymmetries along value chains (Cimprich et al., 2019; Lapko, Trucco, and Nuur, 2016; Lapko and Trucco, 2018; Roelich et al., 2014). In short, criticality exercises have become gatekeepers for policy attention and public capital.

This policy prominence triggered methodological scrutiny. Literature reviews reveal significant heterogeneity in indicator selection for both the likelihood of disruption (e.g., concentration, governance) and the vulnerability to disruption (e.g., substitutability), often without empirical validation of data quality or causal mechanisms (Achzet and Helbig, 2013; Helbig, Bruckler, et al., 2021; Helbig, Wietschel, et al., 2016; Brown, 2018; Schrijvers et al., 2020). Furthermore, static indices frequently fail to capture temporal dynamics and technology foresight (Ioannidou et al., 2019; Christmann and Lefebvre, 2022), while the inclusion of recycling metrics can conflate supply risk with circularity goals, obscuring the specific nature of the vulnerability (L. A. Tercero Espinoza, 2021; Bradley et al., 2024). Finally, the classification process itself involves social and political construction, influencing securitisation narratives beyond purely technical assessments (Machacek, 2017).

A fundamental methodological critique concerns the alignment of criticality assessments with quantitative risk theory. Glöser et al. (2015) demonstrate that the standard criticality matrix is a specific instance of a risk matrix, where risk is defined as the product of disruption probability and consequence. This relationship mandates multiplicative aggregation, resulting in convex iso-risk contours. Conversely, additive scoring, Euclidean distances, and rectangular thresholds distort risk prioritisation by implying that high risk can exist even when one dimension is negligible. Frenzel et al. (2017) advance this framework by recasting criticality within a decision-analytic context. They define the relevant metric as the expected value loss, calculated by integrating probability and impact over a distribution of varying disruption severities and durations. They conclude that conventional assessments are fundamentally flawed because they typically assume a binary disruption state rather than a spectrum of magnitudes, and rely on indicators that lack empirical validation against historical supply interruptions.

Our recent systematic review of 36 criticality studies (2017–2024) examined whether the field has since then adopted these risk-theory principles (Andrieu et al., 2025). The analysis reveals that the methodological deficiencies identified a decade ago persist. The majority of recent studies continue to employ unjustified aggregation methods, such as additive indices or arbitrary thresholds, which violate the multiplicative logic of risk. Furthermore, most assessments fail to account for the duration or varying severity of potential disruptions. Empirical validation remains rare, with assessments frequently relying on indicators that lack demonstrated causal links to supply security. For instance, while national governance scores, such as World Governance Indicators, and concentration metrics, such as the Herfindahl–Hirschman Index, are standard proxies for supply risk, empirical analyses suggest these correlate weakly or negligibly with actual disruption frequency or severity (Kühnel et al., 2023; Bucciarelli, Hache, and Mignon, 2025). Finally, the review identified widespread superficial citation practices. Studies frequently cite Glöser et al. (2015) or Frenzel et al. (2017) without rebuttal, while simultaneously applying the specific methodologies, such as rectangular thresholding, that those authors refuted.

The consequences of mismeasurement extend beyond academic debates. As Cox (2009) warned, some aggregation methods that are inconsistent with risk theory can yield results that are not only uninformative but “worse than useless”, meaning that a random ordering of raw materials would be better than the result of some studies. For policy, the implications are serious. If criticality is mismeasured, scarce fiscal and political resources get misallocated: subsidies may target the wrong materials, stockpiles may be built for the wrong commodities, and trade or industrial policies may be justified on a flawed basis. This risk of systematic misallocation makes the methodological soundness of criticality assessments not a purely technical issue but a pressing concern for economic strategy and governance.

Many governments maintain official lists that guide real instruments and may not be grounded in published criticality assessments. Yet, there has never been any systematic assessment of the lists and methods used by governments across the globe. This creates an evidence gap between academic debates and the policy machinery that allocates resources. In this article, we therefore pursue the following objectives: (i) identify which countries maintain lists of critical, strategic, or priority raw materials; (ii) document the methods used to construct these lists, whether formal assessments, expert judgment, or hybrid approaches; (iii) assess the consistency of these methods with risk-assessment principles; (iv) trace how lists have influenced concrete policies, including subsidies, permitting, procurement, stockpiling, and trade measures; and (v) evaluate the potential impact of methodological flaws on policy efficiency, including the risk of systematic misallocation.

2 Identifying criticality lists and methods around the globe

Criticality definitions vary significantly by jurisdiction, reflecting diverse policy aims that range from national defense security to job security. Consequently, lists appear under various labels, such as strategic, priority, or critical raw materials, and originate from a wide array of institutions including ministries, geological surveys, central banks, and subnational authorities. This institutional fragmentation scatters relevant data across legal gazettes, agency microsites, budget documents, and press releases, often in formats ranging from HTML tables to scanned PDFs. Coupled with inconsistent terminology and the need to navigate dozens of official languages, these factors render a manual global census practically unfeasible without automated assistance.

2.1 Model Selection and Economic Optimization

To address these challenges, we designed a hybrid data collection pipeline combining AI-driven retrieval with rigorous human verification. We began by benchmarking retrieval methods using Large Language Model (LLM) Application Programming Interfaces (APIs). In our context, an API serves as a computational gateway that allows software to interact directly with an AI model. Costs are determined by usage volume, measured in tokens, which represent fragments of words. Crucially, this pricing applies not only to the text the model generates but also to the text it reads. For a model to analyze a foreign mining act, it must ingest the full text of that webpage, treating every word as billable input data.

We specifically tested reasoning models. Unlike standard LLMs, which generate text sequentially based on immediate statistical probability, reasoning models employ a deliberative process. They generate hidden, intermediate chains of thought to plan their search strategy, critique their own findings, and refine their logic before producing a final output. This capability mimics critical thinking, allowing the model to determine which web searches to perform next, how to parse complex search results, and how to verify the reliability of a source. This is essential for complex tasks requiring multi-step investigation in regulatory environments.

Our pilot testing revealed a prohibitive trade-off between cost and retrieval depth when using APIs. Thorough regulatory research requires the model to ingest high volumes of text from multiple web sources. When we capped search budgets to approximately $2.00 per jurisdiction, the models lacked sufficient context to make accurate determinations because they could not read enough documents. Conversely, allowing the model sufficient reading budget to yield high-quality results raised the cost per jurisdiction to unsustainable levels.

To resolve this, we utilized the web-based interface of the GPT-5.1 Thinking model. This approach offered a cost-efficiency arbitrage, as the web subscription model offers a fixed price for access to the model's maximum capabilities. Through this interface, the model could deliberate for extended periods and access the live internet to search, read, and cross-reference multiple primary sources without the per-page metering of the API. While this necessitated manual entry of prompts (the details of which are given in the next section), the finite number of jurisdictions made this labor trade-off operationally efficient, securing the highest possible depth of analysis for a fixed cost.

2.2 Prompt questions

For each jurisdiction, we issued a single, highly structured query to the model. The prompt was designed to function as a strict algorithm, enforcing specific behaviors regarding source hierarchy, search language, and output format. The model was instructed to conduct internet searches in both English and the official languages of the jurisdiction. To ensure the dataset reflected binding policy rather than informal intent, the prompt enforced a strict evidentiary hierarchy. It prioritized primary official sources in the following order: first, legislative acts, regulations, and official gazettes; second, decrees and ministerial decisions; third, official strategies and white papers; and finally, press releases or government FAQs. Secondary sources were explicitly disallowed unless no primary source existed, in which case they were flagged. The exact prompt is given in the supplementary information.

To ensure consistency across countries, the model was required to return data in a single JavaScript Object Notation (JSON) object. JSON is a standardized, machine-readable file format that organizes data into key-value pairs. The schema required the model to make three specific determinations for each jurisdiction. First, it assessed whether an official list of critical, strategic, or priority raw materials exists

(Q1). Second, it determined whether an official methodology describes how these items were selected (Q2). Third, it identified whether adopted or proposed policy instruments, such as subsidies or stockpiling, explicitly reference this list (Q3). For each of the three questions, the model assigned a tri-state status of true, false, or unclear. For every positive or unclear finding, the model was required to provide three distinct URLs to primary sources and a brief description of the document.

The use of a reasoning model was critical during this phase. When the model encountered a query regarding a specific jurisdiction, it did not simply predict an answer based on training data. Instead, it used its internet access to perform iterative investigation. This involved planning search terms in the local language, parsing search results, identifying a potential list in a press release, critiquing that finding by searching for the underlying statute, and finally synthesizing the confirmed data into the required JSON format.

2.3 Verification and Validation

We treated the model's output as a set of high-probability leads rather than final data. Our validation protocol was designed to leverage the asymmetric discovery capabilities of the AI compared to human researchers. The reasoning model, possessing the ability to query local-language government portals and synthesize information across diverse institutional domains, is highly efficient at establishing the absence of documents. If such a model, after an exhaustive search, returns a definitive negative result, it is highly improbable that a human researcher lacking specific institutional knowledge of that jurisdiction would succeed in locating the document. Therefore, we accepted the model's negative findings as final and prioritized our manual resources on validating the affirmative and unclear cases.

For jurisdictions where the model identified positive or ambiguous evidence regarding the existence of a list (Q1) or a methodology (Q2), we manually accessed every URL provided. We verified the institutional provenance of the websites and read the relevant legal or technical passages to confirm the interpretation (using machine translation). This human review served as a strict filter; if the cited documents did not contain the alleged list or explicit selection mechanics, we re-qualified the status as false. Conversely, where the documents confirmed the existence of both an official list and a formal selection methodology, the jurisdiction was selected for inclusion in our final curated inventory.

For this subset of verified cases, we extracted detailed attributes to construct the comparative dataset presented in this article. Beyond the list of materials itself, we coded the specific regulatory label used (e.g., critical vs. strategic), the responsible institution (e.g., ministry vs. geological survey), and the year of the most recent update. We analysed the methodology text to classify the assessment framework into typologies, such as qualitative expert judgement, quantitative index scoring, or threshold based matrices, and evaluated its alignment with the risk theory principles discussed in the introduction. The analysis of policy instruments (Q3) followed a distinct approach. Instead of constructing a structured database of every individual policy instrument, we qualitatively screened the model's findings across the entire dataset to identify recurring functional archetypes of state intervention. We adopted this qualitative procedure because policy instruments are both more numerous and more heterogeneous than assessment methodologies, and forcing them into a single quantitative scheme would require normative judgements that lie beyond the scope of this study. These archetypes inform the policy discussion later in this article.

3 Results and Discussion

3.1 Global mapping of criticality assessments

Our automated discovery pipeline scanned 206 jurisdictions to identify the global landscape of raw material criticality. The initial AI-driven screening returned positive identifications for official lists (Q1) in 86 jurisdictions, accompanying methodologies (Q2) in 48, and policy instruments referencing such materials (Q3) in 120. The discrepancy between the high prevalence of policy instruments and the lower number of defined lists suggests that "critical raw materials" has become a pervasive term frequently employed to direct state action even in the absence of a formal definition or technical assessment. The full raw output of the model for all jurisdictions is provided in the Supplementary Information.

Figure 1 visualizes these results geographically. In the maps, all European Union (EU) member states are marked as positive (green) across all three questions. This reflects the political reality that the EU Critical Raw Materials Act applies across the single market, meaning a list and associated policies are legally active in all 27 member states even if individual members have not drafted independent national documents.

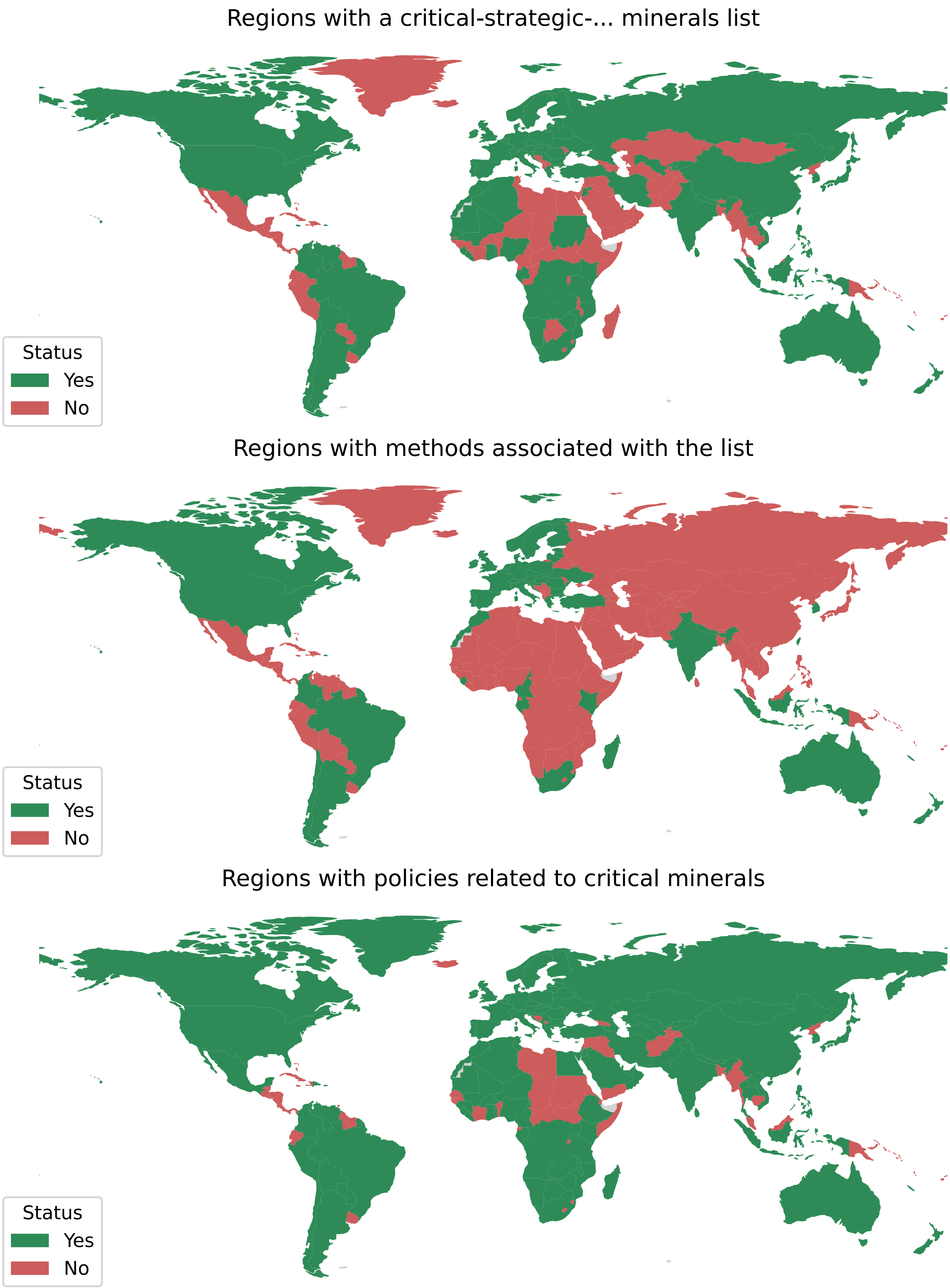

Figure 1: Results from the automatic AI screening. Top: Jurisdictions with an official critical, strategic, or priority list. Middle: Jurisdictions with a publicly available methodology associated with that list. Bottom: Jurisdictions with active policies targeting critical minerals. EU member states are marked positive by default as EU regulation applies.

3.2 Summary of methods used

To move from this broad census to a rigorous methodological analysis, we applied the manual verification protocol described in the Methods. Negative findings from the automated search were accepted as final, while all positive identifications underwent human review. This process yielded 20 jurisdictions with official lists informed by publicly verifiable methodologies. Several maintain multiple lists to serve different policy aims (e.g., Australia's "Critical" and "Strategic" minerals; Korea's "Core" and "Strategic Core" minerals), resulting in 27 distinct assessment frameworks. Table 1 summarises the methods used.

A first pattern is the prevalence of qualitative, policy driven approaches. Qualitative screening underpins Australia's critical and strategic minerals lists, Brazil's, Colombia's, Morocco's and the Democratic Republic of Congo's strategic lists, Canada's and Indonesia's critical minerals lists, and Kenya's legislated strategic minerals designation (Department of Industry, Science and Resources, 2024a; Ministry of Mines and Energy, 2021; Natural Resources Canada, 2024; Agencia Nacional de Minería, 2023; Ministry of Energy and Mineral Resources of the Republic of Indonesia, 2023; Republic of Kenya, Ministry of Mining, 2017; Conseil économique, social et environnemental, 2023; Premier ministre de la République démocratique du Congo, 2018). In these cases, materials are assessed against narrative criteria related to priority technologies, defence or national security, importance for green and digital transitions, domestic geological potential, existing production capacity and exposure to possible international disruptions. Screening draws on internal geological and trade analysis and consultations with sectoral ministries, industry and subnational actors, yet none of these jurisdictions publishes reproducible indicators, weights or thresholds. In the DRC and Kenya, "strategic" status is codified in legislation and conferred by the executive, anchoring list formation in legal procedure rather than quantitative assessment (Premier ministre de la République démocratique du Congo, 2018; Republic of Kenya, Ministry of Mining, 2017).

A second group uses indicator based matrices modelled on, or adapted from, the European Commission's framework. Belgium and Poland apply the EU indicator structure to national data, scoring materials on the likelihood of disruption and on economic importance or vulnerability (Christis, Van den Abeele, and Deckers, 2024; Galos et al., 2021). National adaptations include domestic sectoral value added, import dependence, consumption trends, modified thresholds and corrections for re exports. The European Union applies the same basic template for its critical list and then adds a forward looking assessment of strategic importance, demand growth and difficulty of scaling supply (European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2023).

A third set of indicator based approaches departs more markedly from the EU template. Denmark combines EU derived disruption scores with Denmark specific measures of economic importance and classifies materials using domestic value added percentiles (Clausen et al., 2023). New Zealand constructs a weighted "supply risk" index based on six metrics spanning import dependence, market balance, reserves, concentration and country risk, applied after an initial essentiality screen, although the resulting score is not a probabilistic risk measure (Ministry of Business, Innovation and Employment, 2025). South Africa, Turkey, the Republic of Korea and Taiwan develop multi indicator scoring systems combining aspects of disruption likelihood, economic exposure and, in some cases, recycling, industrial importance and price volatility (Mineral Resources and Energy, 2025; T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2025; Ministry of Trade, Industry and Energy, 2023; Environmental Protection Administration, 2017). South Africa's framework explicitly integrates export potential, domestic industrial linkages, employment and market demand (Mineral Resources and Energy, 2025). Turkey aggregates disruption related indicators with import and export data for ores, intermediates and finished products (T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2025). Korea scores minerals on economic impact and disruption indicators, then qualitatively prioritises those essential for electric vehicles, batteries and semiconductors (Ministry of Trade, Industry and Energy, 2023). Taiwan adopts a Yale style three pillar structure quantifying supply risk, vulnerability to supply restriction and environmental implications (Environmental Protection Administration, 2017).

Only one framework implements a fully probabilistic risk model. The United States Geological Survey simulates numerous trade disruption scenarios, estimates associated GDP losses and combines these with scenario probabilities to derive an expected GDP loss for each commodity (Nassar, Pineault, et al., 2025). This expected loss determines inclusion in the critical minerals list, with qualitative adjustments for data poor cases. The United Kingdom adopts a geometric mean of disruption likelihood and economic vulnerability, which yields convex iso critical contours, but does not calibrate either dimension against observed disruption probabilities or impacts (Mudd et al., 2024).

Overall, import dependent advanced economies such as the European Union, the United Kingdom, Denmark, Belgium, New Zealand, Korea and Taiwan emphasise the likelihood of disruption in external supply and downstream economic vulnerability, with indicator rich methods centred on import reliance, producer concentration, governance in supplier countries and domestic manufacturing structure (European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2023; Clausen et al., 2023; Christis, Van den Abeele, and Deckers, 2024; Ministry of Business, Innovation and Employment, 2025; Ministry of Trade, Industry and Energy, 2023; Environmental Protection Administration, 2017; Mudd et al., 2024). Resource rich exporters such as South Africa, Brazil, Morocco, the DRC, Kenya and, to a degree, Turkey use their lists to support industrial policy and value capture (Ministry of Mines and Energy, 2021; Conseil économique, social et environnemental, 2023; Mineral Resources and Energy, 2025; T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2025; Premier ministre de la République démocratique du Congo, 2018; Republic of Kenya, Ministry of Mining, 2017). Their criteria emphasise export revenues, employment, downstream processing and state control over strategic deposits. South Africa's focus on jobs, export diversification and industrial development is thus consistent with its role as a major producer of several metals (Mineral Resources and Energy, 2025), while Brazil and Morocco align their lists with long term industrial and energy strategies shaped by domestic geological potential (Ministry of Mines and Energy, 2021; Conseil économique, social et environnemental, 2023).

Finally, the typology in Table 1 highlights wide variation in transparency and reproducibility. Indicator based matrices appear more technical but often combine heterogeneous metrics into composite indices without calibration to disruption outcomes, and many apply arbitrary thresholds in the two dimensional space of disruption likelihood and economic importance or vulnerability. Qualitative frameworks embed contextual industrial policy reasoning but concentrate discretion in ministries or cabinets and rarely define update procedures as markets evolve.

Table 1: Summary of methods used to define critical, strategic or core minerals across jurisdictions.

Country or region	**List type**	**Method typology**	**Method summary**
Australia (Department of Industry, Science and Resources, 2024a)	critical	Qualitative multi-criteria policy screen	Materials are assessed qualitatively against essentiality, Australian geological potential, partner demand and supply risk. Evidence from trade and geology informs decisions, but there is no numerical scoring or aggregation rule.
Australia (Department of Industry, Science and Resources, 2024a)	strategic	Qualitative multi-criteria policy screen	Strategic materials meet importance and geological criteria but not the high supply-risk threshold. They are prioritised for monitoring and industrial development through qualitative policy judgement.
Belgium (Flemish Region) (Christis, Van den Abeele, and Deckers, 2024)	critical	Hybrid EU-style index with expert adjustment	Belgium recalculates the EU economic-importance and supply-risk indicators using Belgian data and adjusts for imports routed through EU intermediaries. Final inclusion combines numerical results with expert judgement on regional industrial relevance.
Brazil (Ministry of Mines and Energy, 2021)	strategic	Qualitative criteria, expert judgement	Brazil groups minerals by import dependence, high-technology use and domestic economic importance using policy and expert judgement. No quantitative model or scoring system is published.
Canada (Natural Resources Canada, 2024)	critical	Qualitative strategic screening	Minerals must show supply-chain vulnerability and potential Canadian production, and meet one of three strategic criteria. Selection relies on departmental analysis and consultation rather than a quantitative index.

Country / region	List type	Method typology	Method summary (2 sentences)
Colombia (Agencia Nacional de Minería, 2023)	strategic	Multi-step qualitative screening	Colombia combines policy priorities, geological potential, trade deficits and global demand scenarios to screen minerals qualitatively. No explicit scoring or thresholding is used.
Democratic Republic of Congo (Premier ministre de la République démocratique du Congo, 2018)	strategic	Legal designation process	Strategic minerals are designated directly by prime ministerial decree based on technological relevance and market conditions. No indicators or quantitative criteria are defined.
Denmark (Clausen et al., 2023)	critical	EU-style supply-risk–economic-importance index	Denmark estimates economic importance from raw-material-equivalent value added and adopts EU supply-risk scores. Minerals above both thresholds in a two-dimensional matrix are classified as critical.
India (Ministry of Mines, Government of India, 2023)	critical	Hybrid qualitative and quantitative	India combines international comparison, ministerial consultation and results from a modified EU-style criticality assessment. Final selection is qualitative because numerical thresholds were judged unsuitable for bulk minerals.
Indonesia (Ministry of Energy and Mineral Resources of the Republic of Indonesia, 2023)	critical	Qualitative criteria, expert judgement	Indonesia applies four qualitative criteria relating to strategic use, national importance, supply disruption and lack of substitutes. No quantitative scoring or weighting is published.
Kenya (Republic of Kenya, Ministry of Mining, 2017)	strategic	Legal designation process	Strategic status is granted through a formal procedure in which agencies propose minerals and Cabinet approval is required. Regulations define information requirements but no quantitative indicators or thresholds.
Korea (Republic of) (Ministry of Trade, Industry and Energy, 2023)	core	Quantitative multi-indicator index	Korea evaluates 33 minerals across eight indicators for economic impact and supply risk. Weights and thresholds are not disclosed, so final classification blends quantitative results with expert judgement.
Korea (Republic of) (Ministry of Trade, Industry and Energy, 2023)	strategic core	Qualitative prioritisation within index	Ten minerals essential for EV, battery and semiconductor chains are prioritised from within the core list. Selection emphasises technological indispensability and supply vulnerability.

Country / region	List type	Method typology	Method summary (2 sentences)
Morocco (Conseil économique, social et environnemental, 2023)	strategic	Qualitative industrial policy screening	Morocco maps minerals to national development priorities, geological potential and partner critical lists and refines selections through stakeholder consultation. No explicit numerical index is used.
Morocco (Conseil économique, social et environnemental, 2023)	critical	Quantitative supply-risk index	Morocco applies a supply-risk index based on import dependence, politically weighted producer concentration and export restrictions. Minerals with high composite scores form the critical subset.
New Zealand (Ministry of Business, Innovation and Employment, 2025)	critical	Quantitative supply-risk index	A consultant study identifies essential minerals and computes a weighted six-metric “supply risk” index. Minerals above a threshold are classed as critical, with a few additions based on strategic export considerations.
Poland (Galos et al., 2021)	key	Quantitative consumption–import analysis	Key minerals are selected using domestic consumption value, its trend and net import reliance. Minerals with high economic importance and import dependence are retained.
Poland (Galos et al., 2021)	strategic	Hybrid sector screening and import analysis	Minerals indispensable to priority sectors are identified qualitatively, then filtered using import-reliance and consumption data. The final list reflects both sectoral importance and exposure.
Poland (Galos et al., 2021)	critical	Adapted EU supply-risk index	All key and strategic minerals are treated as economically important and assessed only on supply-risk scores. A slightly lower threshold than in the EU method produces Poland’s critical list.
South Africa (Mineral Resources and Energy, 2025)	critical	Quantitative multi-indicator index	South Africa uses eight indicators covering supply risk, export potential, domestic significance and partner-list alignment, each scored 1–10. Aggregated scores classify minerals into criticality tiers.
Taiwan (Environmental Protection Administration, 2017)	critical	Yale three-dimensional criticality index	Taiwan applies the Yale framework with indicators for supply risk, vulnerability to supply restriction and environmental implications. Normalised indicator scores produce dimension scores used to identify key materials.
Turkey (T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2025)	critical	Quantitative multi-indicator risk–trade index	Turkey evaluates minerals using 12 indicators across five weighted risk categories plus import and export scores. A weighted aggregation produces final classifications into high, important and potential critical.
Turkey (T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2025)	strategic	Qualitative defence-focused screening	Strategic minerals are those indispensable for defence and high-technology systems, selected with the Defence Industry Presidency. The process is qualitative and not based on the risk score.

Country / region	List type	Method typology	Method summary (2 sentences)
United Kingdom (Mudd et al., 2024)	critical	Quantitative EI–SR index with geometric mean	The UK computes global supply risk and national vulnerability using weighted geometric means, then combines them multiplicatively into a criticality score. A threshold of 4.0 defines the critical materials.
United States (Nassar, Pineault, et al., 2025)	critical	Scenario-based expected-GDP-loss metric	USGS simulates more than 1,200 disruption scenarios and computes probability-weighted expected GDP loss for each mineral. Minerals reaching moderate risk or exhibiting single-point failures are included.
European Union (European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2023)	strategic	Forward-looking three-dimension strategic index	The EU scores materials on strategic importance, demand growth and difficulty of scaling production. Top-ranking materials form the strategic list and are automatically included in the CRM list.
European Union (European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2023)	critical	Quantitative EI–SR index	The EU computes supply risk at the bottleneck stage and economic importance from sectoral value added and material-input shares. Materials above defined thresholds in both dimensions are classified as critical.

3.3 Lists intercomparison

To compare the outputs of governmental assessments, we aggregated all commodities appearing on the 27 validated critical, strategic or core lists described above. For each commodity, we counted the number of frameworks in which it is designated as critical, strategic, core or equivalent. The resulting matrix, reported in the Supplementary Information, reveals convergence on a subset of metals associated with the energy transition, together with surprisingly broad coverage of the commodity space once all jurisdictions are considered jointly. Cobalt is the most frequently designated commodity, appearing in 20 frameworks, followed by natural graphite and nickel with 19 occurrences each. Aluminium and manganese appear on 18 lists, and lithium, magnesium, rare earth elements as a group, silicon and titanium each appear on 17 lists. Copper, niobium, tungsten, phosphate and germanium form a second tier of widely listed materials, while other base and speciality metals, including chromium, vanadium, zinc, molybdenum and tantalum, are flagged in more than ten frameworks.

These patterns are broadly consistent with the policy aims and method typologies summarised in Table 1. Import dependent advanced economies concentrate on metals that are central to batteries, permanent magnets, power electronics and low carbon infrastructure, such as cobalt, lithium, nickel, manganese, high purity graphite and rare earth elements. Several jurisdictions also designate fertiliser related materials, including phosphate and potash, and a few treat fossil fuels such as coal, crude oil and natural gas as strategic. Resource rich exporters add minerals that underpin their current export baskets or targeted industrialisation strategies, for example platinum group metals and manganese for South Africa or phosphates for Morocco.

For cross framework comparability, we harmonised commodity names and mapped them to their constituent chemical elements. Simple commodities such as cobalt, nickel or tin were matched one to one. Multi element minerals and industrial groupings were decomposed into their dominant elemental constituents. For instance, feldspar and kaolin contribute to aluminium and silicon, bentonite contributes to aluminium and magnesium, gypsum and limestone contribute to calcium, and ferroalloys contribute to iron. Phosphate fertilisers were mapped to phosphorus and potash to potassium. Group labels such as "rare earth elements", "light rare earth elements" and "heavy rare earth elements" were expanded to the corresponding subsets of the lanthanide series plus yttrium and scandium. In this way, a framework that lists "rare earth elements" increases the count of all members of that group. Fossil energy vectors (coal, crude oil and natural gas) were omitted from the periodic table representation. For each element, we then computed a criticality count equal to the number of distinct frameworks in which that element appears explicitly or via a mapped compound.

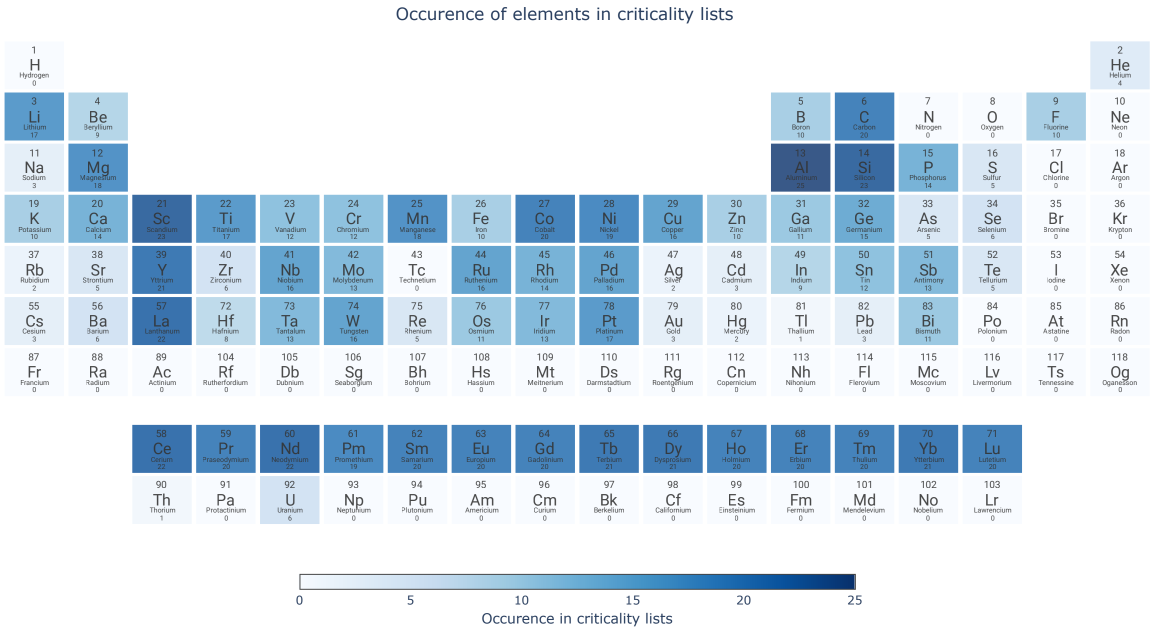

Figure 2: Occurrence of elements in governmental criticality lists. Colours indicate, for each element, the number of validated frameworks in which it appears as part of a critical, strategic, core or equivalent list, either explicitly or via mapped compounds or mineral groups. Elements with no occurrences are shown in the lightest shade.

At the scale of the periodic table presented in Fig. 2, three features stand out. First, coverage is remarkably broad. Out of 118 elements, 74 appear at least once across the 27 frameworks, and 51 appear in ten or more lists. In other words, most elements that are mined at any scale are treated as critical, strategic or core by at least one jurisdiction. Second, the largest criticality counts concentrate in a set of light and transition metals central to structural, energy and high technology applications together with the rare earth series. Aluminium is the single most frequently listed element, appearing in 25 frameworks (including in aluminium bearing minerals such as feldspar, clays and corundum), followed by silicon and scandium with 23 each. Carbon (including natural graphite) and cobalt have counts of 20, magnesium and manganese 18, and titanium and platinum 17. Many lanthanides, including lanthanum, cerium, neodymium and several heavy rare earths, show counts around 20 or higher. This near uniformity reflects group based listing practices, which treat rare earth elements as a single category and thereby elevate all members irrespective of differences in their market scale or application diversity. Third, a small set of elements remains largely untouched by current governmental criticality narratives. Apart from helium, noble gases, halogens such as chlorine and iodine, and synthetic transuranic elements do not appear in any list, which is unsurprising given that they are not mined as primary commodities or have limited large-scale uses. A few mined elements, including thallium and thorium, appear only once, while sodium, lead and gold are listed in three frameworks each. Overall, Figure 2 shows that, when viewed in aggregate, governmental criticality lists do not act as a narrow filter on a small subset of elements. Instead, they cover a large fraction of the periodic table.

To examine whether these designations align with basic physical or economic scarcity, we assembled a second dataset linking element level criticality counts to rock to metal ratios and approximate market prices. Rock to metal ratio (RMR) is defined as the mass of ore and waste rock that must be mined per unit mass of contained metal. It captures the combined effect of ore grade, by product status and co extraction on the material intensity of production. For a subset of 47 elements represented in our lists, we collated published global RMR estimates and matched them to the same commodities used in the list comparison (Nassar, Lederer, Brainard, et al., 2022; Nassar, Lederer, Padilla, et al., 2023; Wang et al., 2024). For these elements, we also compiled indicative prices in US dollars per kilogram, standardised to metal content. The scatter plot in Figure 3 shows no meaningful relationship between the frequency with which an element is designated critical or strategic and either its RMR or its price. The coefficient of determination for criticality count versus log RMR is approximately $R^2 \approx 0.03$, and for criticality count versus log price it is approximately $R^2 \approx 0.02$. Cheap and relatively abundant elements such as aluminium and silicon exhibit some of the highest criticality counts, while several of the most expensive or geologically demanding elements, including gold, silver and ruthenium, are rarely listed.

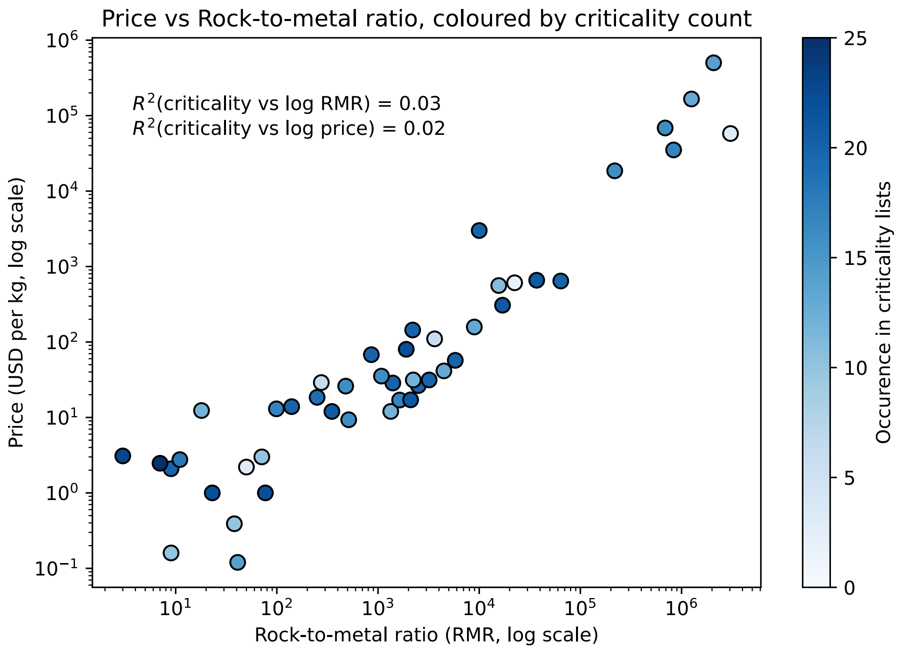

Figure 3: Joint distribution of criticality counts, rock to metal ratios (RMR) and prices for 47 elements. Each point represents one element, positioned by its RMR and price on logarithmic axes and coloured by the number of governmental frameworks in which it appears as critical, strategic, core or equivalent. The annotation reports the coefficient of determination for linear regressions of criticality counts on log RMR and log price.

Taken together, the periodic table visualisation and the RMR–price show that very diverse elements are included in criticality lists.

3.4 How governments use criticality lists in practice

Criticality lists have evolved into central mechanisms of industrial policy. Across jurisdictions, they are used in three main ways: to guide capital allocation through fiscal instruments, to support state control over trade flows and ownership of mineral resources, and to shape regulatory procedures for permitting and land access.

In import-dependent economies, list inclusion primarily serves to internalise supply security externalities and to direct fiscal support toward markets that private capital considers too volatile. This pattern is characterised by a close coupling between lists, tax expenditures and public finance. Australia limits eligibility for its refundable Critical Minerals Production Tax Incentive specifically to listed minerals (Department of Industry, Science and Resources, 2024b), a structure mirrored by Canada's restriction of the Critical Mineral Exploration Tax Credit and manufacturing incentives to its federal list (Government of Canada, 2025). In the United States, statutory definitions govern the boundary for consumer tax credits under the Inflation Reduction Act (Internal Revenue Service, 2024). The same logic extends to state backed guarantees and grants, with the United Kingdom (UK Export Finance, 2024), France (Ministère de l'Économie, des Finances et de la Souveraineté industrielle et numérique, 2025), and Germany (Bundesministerium für Wirtschaft und Klimaschutz (BMWK), 2024) all conditioning access to strategic funds on list adherence.

In resource rich jurisdictions, the "strategic" or "critical" designation serves more as an instrument of value capture and sovereignty. Here, lists justify state intervention in trade flows and asset ownership. The Democratic Republic of Congo leverages its "strategic substance" classification to impose export bans and market oversight (Ministère des Mines, République Démocratique du Congo, 2025), while Indonesia mandates that its list guides domestic prioritisation and downstreaming obligations (Kementerian Energi dan Sumber Daya Mineral (ESDM), 2023). This pattern often involves the assertion of state property rights. Kenya codifies pre-emption rights over strategic minerals (Republic of Kenya, 2016), Gabon establishes participation measures for "sovereign substances" (République Gabonaise, n.d.), and Timor-Leste dictates rules for the commercialisation of minerals in its strategic category (República Democrática de Timor-Leste, 2024).

A further set of uses treats criticality lists as regulatory filters that delineate a fast-track institutional environment for selected projects. This role is codified in the European Union's Critical Raw Materials Act, where list membership triggers streamlined permitting and the establishment of single points of contact in member states such as Spain (Ministerio para la Transición Ecológica y el Reto Demográfico (MITECO), 2024), Finland (Ympäristöministeriö (Ministry of the Environment), 2024), and Croatia (Narodne Novine, 2025). In India, this gatekeeping role allows projects extracting critical minerals to bypass standard public hearing requirements for environmental impact assessments (Ministry of Environment, Forest and Climate Change, 2025). In Türkiye, the designation can also validate the use of state expropriation powers to secure access to land (Türkiye Büyük Millet Meclisi (TBMM), 2024).

3.5 Policy implications of misidentifying "critical" materials

In jurisdictions prioritising value capture and industrial policy, such as Australia, Canada and Brazil, assessment methods rely on narrative criteria and expert judgement rather than reproducible quantitative models. For example, Australia assesses minerals against a qualitative four-part test based on essentiality, geological potential and international partnership requirements, but publishes no quantitative scoring formula, weights or explicit thresholds (Department of Industry, Science and Resources, 2024a). Consequently, the final composition of these lists is often determined by ministerial decision or decree rather than a transparent technical mechanism (Premier ministre de la République démocratique du Congo, 2018; Republic of Kenya, Ministry of Mining, 2017). While these assessments serve to direct state intervention, the absence of a formalised model renders the specific quantity being optimised opaque. Narrative criteria frequently conflate disparate objectives, such as geological prospectivity, export potential and domestic economic developmen, without establishing a rigorous functional relationship between these indicators and the intended outcome, or defining how trade-offs between conflicting goals are resolved.

In import-dependent jurisdictions seeking to secure supply, such as the European Union and South Korea, frameworks adopt the structural aesthetics of classical risk assessment (matrices and indices) but fail to define the specific physical quantity they aim to measure. Unlike the USGS, which explicitly models expected GDP loss (Nassar, Pineault, et al., 2025), these frameworks populate their models with indicators such as the Herfindahl-Hirschman Index or World Governance Indicators. These proxies have no empirically demonstrated causal link to the actual probability of supply chain disruptions. Furthermore, the aggregation of these indicators often contradicts risk theory. Frameworks in South Korea and Turkey employ weighted aggregation to combine diverse metrics into a final classification (Ministry of Trade, Industry and Energy, 2023; T.C. Enerji ve Tabii Kaynaklar Bakanlığı, 2025). This arithmetic implies that a high score in one category, such as economic importance, can compensate for a low score in supply risk, violating the axiom that risk is the product of likelihood and consequence. Similarly, the European Union and its national adaptors define criticality using rectangular thresholds in a two-dimensional matrix (European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, 2023; Clausen et al., 2023). This topology creates non-convex risk contours that exclude materials with extreme vulnerability but moderate supply risk, while including those that marginally cross both thresholds. Finally, these assessments typically rely on static, backward-looking data snapshots, failing to account for market dynamics or the spectrum of potential disruption severities.

The methodological fragility of government lists becomes a matter of economic consequence when these lists are coupled directly to powerful policy instruments. When tax credits, subsidies and permitting fast-tracks are conditioned on binary list membership, measurement errors in the underlying assessment translate directly into policy failure. We identify three specific mechanisms through which these divergent methodologies distort economic strategy.

Allocative inefficiency and dilution The primary economic function of a criticality list is to focus limited administrative and fiscal capacity on the most severe vulnerabilities. However, because lists have expanded to cover nearly two-thirds of the periodic table based on arbitrary methodologies (Fig. 2), public funds risk being misused. There is a high risk that subsidies and tax credits are prioritised for materials selected by opaque or flawed methods rather than targeted at genuine supply chain bottlenecks. When lists constructed on this basis determine eligibility for tax credits, as in Australia (Department of Industry, Science and Resources, 2024b) and Canada (Government of Canada, 2025), the state may subsidise minerals that are economically significant but do not face meaningful disruption risk. The fiscal transfer yields little improvement in supply security.

Regulatory cliff-edges The use of binary thresholds in indicator-based matrices creates regulatory cliff-edges. In jurisdictions where list inclusion triggers permitting fast-tracks or fiscal benefits, a minor update in underlying data can flip a material's status from non-critical to critical. This sensitivity means that small statistical changes trigger immediate, large-scale differences in legal treatment. The conversion of continuous scores into binary lists introduces discontinuities where a project may be exempt from Environmental Impact Assessment hearings in India (Ministry of Environment, Forest and Climate Change, 2025) purely due to small numerical shifts in the scoring process. Similarly, a minor change in an index can move a project from streamlined permitting (Ministerio para la Transición Ecológica y el Reto Demográfico (MITECO), 2024) to standard procedures, or trigger expropriation rights in Türkiye (Türkiye Büyük Millet Meclisi (TBMM), 2024).

Strategic blindness and false security The presentation of complex indicator methods provides an appearance of scientific precision that masks the underlying lack of rigorous calibration. This veneer of robustness can lead policymakers to underestimate the actual fragility of supply chains, operating under the assumption that risks are managed simply because they have been indexed.

4 Conclusion

This global review demonstrates that the designation of critical raw materials has become a ubiquitous instrument of statecraft, yet the methodological foundations of these lists remain remarkably fragile. Our analysis of 206 jurisdictions reveals a fragmented landscape ranging from opaque qualitative judgements to indicator-based indices that frequently lack empirical grounding. As these diverse methodologies often rely on uncalibrated proxies rather than causal models, the aggregate result is not a targeted identification of strategic bottlenecks but a diffuse categorization encompassing the majority of the periodic table.

We do not advocate for a single universal methodology, as sovereign nations legitimately pursue divergent policy objectives, ranging from securing imports to maximising domestic value addition. However, the current lack of alignment between stated goals and assessment mechanics undermines effective governance. Governments must explicitly define the objective function they seek to optimise, whether it is minimizing economic loss, securing defence capabilities, or expanding industrial employment. Once this objective is defined, the assessment framework must be constructed using indicators that are empirically validated to predict that specific outcome, combined through mathematical formulas that reflect logical causal relationships rather than arbitrary aggregation.

For import-dependent economies, the move toward probabilistic loss-modelling, as recently demonstrated by the United States Geological Survey, represents a rigorous starting point. Future research should expand such frameworks to account for a broader spectrum of disruption mechanisms beyond trade restrictions. In the absence of clear goals and rigorous measurement, these strategies risk misallocating public capital rather than securing essential supply chains.

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