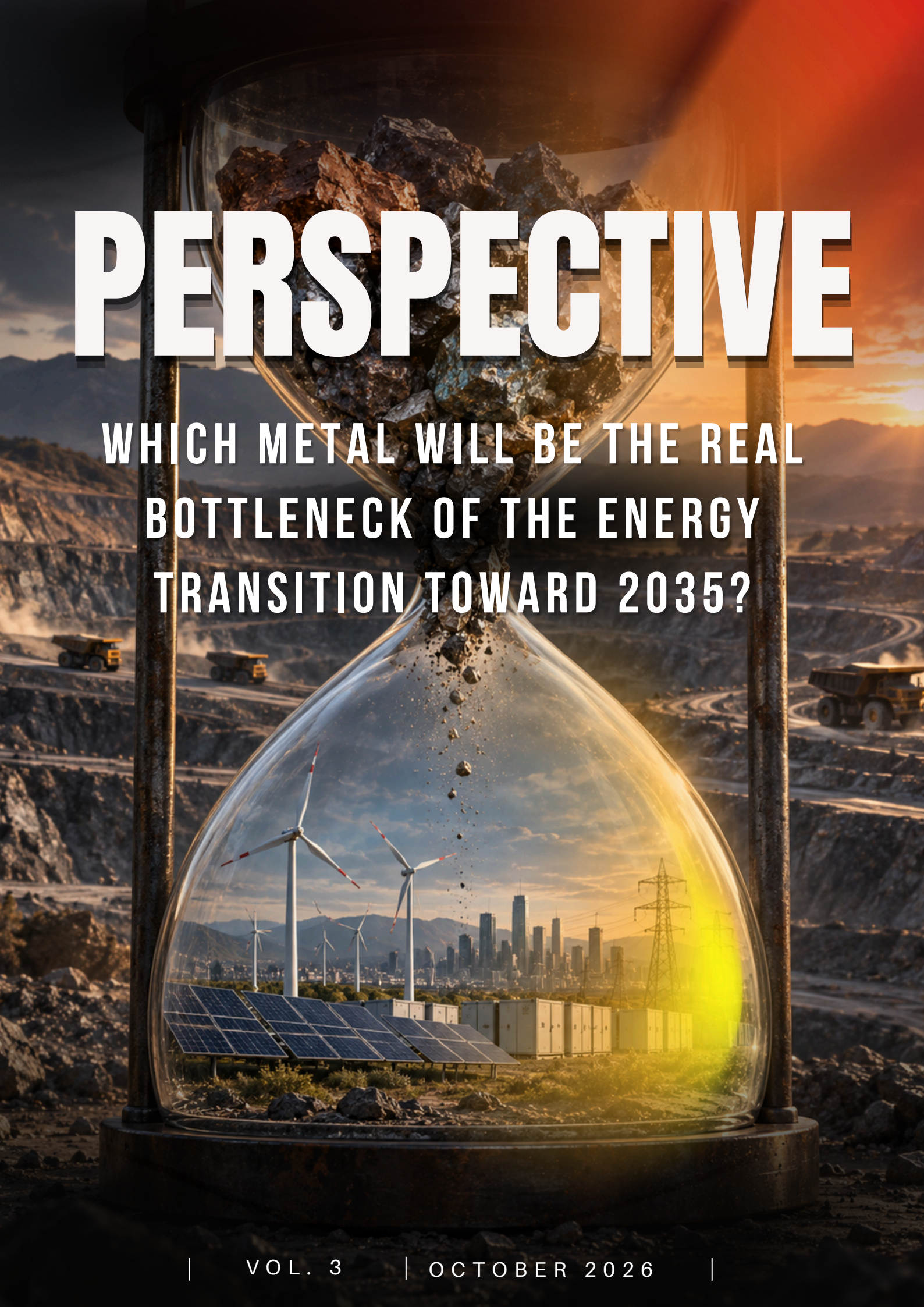


PERSPECTIVE

An hourglass is the central visual element. The top bulb is filled with dark, jagged rocks, representing fossil fuels. The bottom bulb contains a scene of sustainable energy: solar panels in the foreground, several wind turbines, and a city skyline in the background. The background of the entire image is a mining landscape with large yellow dump trucks on roads, set against a sunset sky with orange and red hues. The hourglass is made of dark metal with a glass bulb.

WHICH METAL WILL BE THE REAL
BOTTLENECK OF THE ENERGY
TRANSITION TOWARD 2035?



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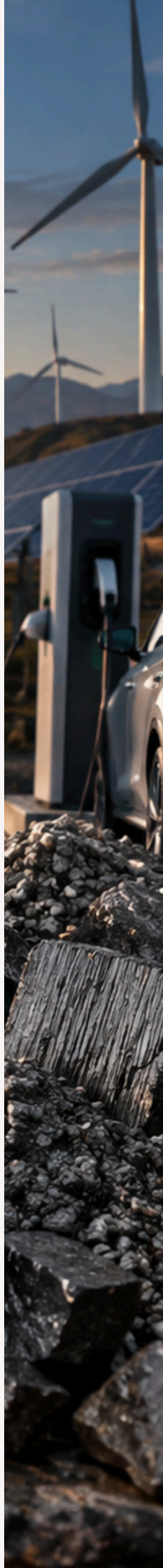
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ABOUT GEM

GEM Mining Consulting is a specialized consulting firm serving the mining industry, integrating technical expertise, economics, strategy, and advanced analytics to support complex decision-making.

With more than 16 years of experience and over 500 projects delivered globally, we work alongside mining companies, investors, and industry organizations in areas such as planning, project evaluation, mining economics, sustainability, and social impact.

We transform data, uncertainty, and technical expertise into actionable decisions for the mining industry.



EDITORIAL

BY PATRICIO FAÚNDEZ
SENIOR SPECIALIST ENGINEER

In mineral economics, discussing scarcity and criticality requires much more than simply observing a gap between supply and demand. A physical shortfall may certainly be significant, but its relevance also depends on how long it takes to close that gap, how many end uses depend on the mineral, and how vulnerable the value chain is in transforming a mineral resource into supply that is effectively available to the market.

This edition of Perspective starts from that premise. The study compares copper, lithium, nickel, cobalt, graphite, and magnetic rare earths, using the International Energy Agency's 2035 balances as a reference and an analytical framework developed by GEM Mining Consulting. Based on this approach, the Systemic Bottleneck Index (SBI) seeks to bring together four dimensions that are typically analyzed separately: volume pressure, technological breadth, mitigation rigidity, and supply-chain fragility.

The results show that there is no single way to measure criticality. Lithium, for example, presents the largest relative supply gap in the base case. Graphite and magnetic rare earths concentrate significant risks in processing and transformation, while cobalt combines supply deficits with a high degree of geographic concentration. Copper, by contrast, stands out when the question shifts from which mineral faces the greatest individual strain to which mineral has the greatest potential to transmit that strain across the energy transition as a whole.

The reason is closely related to the structure of the market. Copper combines a significant supply gap with a scale that is difficult to compare with most of the other minerals analyzed. It is present across power grids, renewable generation, mobility, buildings, industry, and data centers. At the same time, increasing copper supply requires capital-intensive projects, infrastructure, permitting, and, above all, time. Higher prices may strengthen investment incentives, but they do not necessarily shorten the years separating a discovery—or even an advanced-stage project—from commercial production.



This matters because not all constraints propagate in the same way. A severe disruption in a small, highly concentrated market may critically affect a specific technology. A constraint affecting a widely used input, by contrast, can spread across several systems simultaneously. In lithium, the risk is concentrated primarily in electric mobility and energy storage, although there is a relatively broad pipeline of projects available to respond to demand growth that is unprecedented in the history of the mineral. In graphite and rare earths, much of the challenge lies beyond the mine itself: in the capacity to process, transform, and manufacture products to the required specifications outside the centers that currently dominate these stages of the value chain.

For this reason, it is also of limited value to speak of “critical minerals for the energy transition” as though they all posed the same challenge. The required responses are different. For copper, the priority is to accelerate supply that can realistically be brought into production and strengthen the capacity to execute large-scale projects. For lithium, the priority is to expand and diversify the supply base. For graphite and rare earths, the challenge is to develop industrial capabilities that are currently concentrated in the intermediate stages of the value chain.

At GEM Mining Consulting, we hope this work helps bring greater structure and clarity to this discussion. The energy transition will not depend solely on whether sufficient resources exist underground. It will also depend on the ability to convert those resources into available supply, in the required specifications and within the timeframes demanded by the transition.

Viewed from this perspective—in terms of scale, breadth of applications, and the time required to close the physical supply gap—copper emerges as the strongest candidate to become the main systemic bottleneck toward 2035.

INTRODUCTION

Governments, multilateral organizations, companies, and the media have included copper, lithium, nickel, cobalt, graphite, rare earths, and other materials on lists of critical minerals. However, “critical” can mean different things depending on the context: physical supply deficits, geographic concentration, technological dependence, lack of substitutes, or economic impact. This multidimensional interpretation is consistent with criticality frameworks in the literature that consider material importance, supply risk, and the potential for substitution or adaptation (Graedel et al., 2012; Watari et al., 2020; U.S. Department of Energy, 2023).

The energy transition, meanwhile, requires the simultaneous deployment of power grids, renewable generation, electric vehicles, energy storage, electrified infrastructure, industrial motors, and data centers, including those associated with artificial intelligence. All of these systems depend on minerals whose supply must materialize in a timely manner: projects must be discovered and financed, obtain permits, be constructed, and enter operation; the mineral must then be processed to the required specifications and reach the market when needed. For this reason, having sufficient geological resources is a necessary but not sufficient condition. The challenge lies in converting those resources into available and usable supply before 2035.

Against this backdrop, among all these critical minerals, it is worth asking which one or which ones could become the true bottleneck for the energy transition. To enable a consistent comparison across minerals, this Perspective report takes as its starting point the 2035 balances presented in the International Energy Agency’s (IEA) Global Critical Minerals Outlook 2026, which provides a baseline supply outlook and estimates of primary requirements under a defined set of assumptions (STEPS scenario[1]).

This starting point is complemented by a proprietary framework developed by GEM Mining Consulting, incorporating supply-chain fragility, technological breadth, and mitigation rigidity.

[1] STEPS (Stated Policies Scenario) is the IEA demand scenario that reflects policies and measures currently in place or announced with sufficient detail; it does not represent a net-zero emissions pathway.

[2] The N-1 test, used by the IEA to assess supply vulnerability, removes the largest supplier from the supply chain and compares the remaining supply with the demand that also remains outside that supplier.



METHODOLOGY

Before addressing how to answer the question that motivates this edition of Perspective, it is necessary to define several key concepts, which are listed in **Table 1**.

TABLE 1. CONCEPTS THAT ARE OFTEN CONFUSED IN PUBLIC DEBATE

CONCEPT	OPERATIONAL DEFINITION	MITIGATION LEVER
01 Physical gap	Difference between the primary requirements of the IEA (2026) STEPS scenario and the 2035 base supply.	Accelerate projects, expansions, recycling and material efficiency.
02 Supply chain fragility	Dependence on a few countries or plants, N-1 ² weakness, complex conversion or commercial risk.	Diversify refining, routes, qualification, contracts and <i>stocks</i> .
03 Systemic bottleneck	A constraint that combines the physical gap, cross-cutting propagation across energy-transition uses and little capacity to relieve the gap before 2035.	Prioritize capacity that prevents delays or simultaneous supply failures across several systems.
04 Materializable supply	Expected production in the IEA base case versus primary requirements; not equivalent to the entire mining project <i>pipeline</i> .	Distinguish probable supply from possible, early-stage or speculative projects.

Table 1. Source: GEM. Own elaboration based on IEA (2026), IRENA (2023), and Graedel et al. (2012).

Along these lines, a bottleneck is not simply the metal with the highest demand growth or the lowest level of demand coverage. Rather, it is a mineral whose constraints can propagate across a broad portion of the system namely, the different applications required by the energy transition and whose supply response cannot scale rapidly enough within the timeframe analyzed (i.e., by 2035).

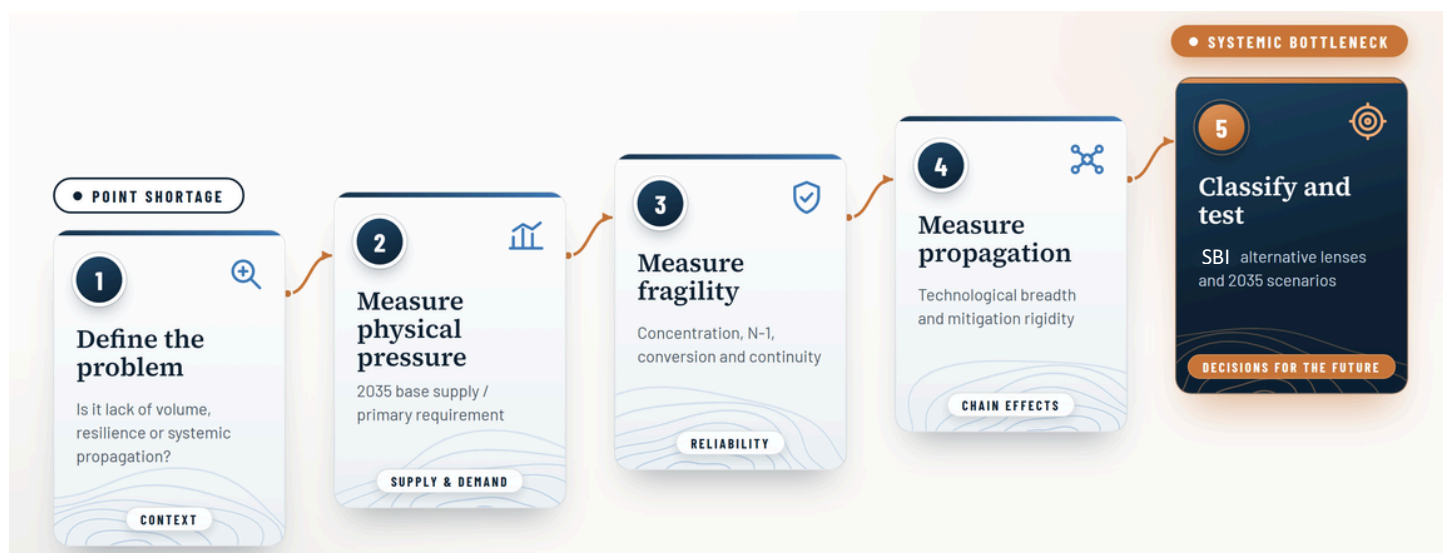
With these definitions in mind, the next steps are to establish both the comparison methodology and the minerals to be included in the analysis. The comparable universe is deliberately limited to six minerals: copper, lithium, nickel, cobalt, graphite, and magnetic rare earths.

The selection does not rely on a single source, as these six materials appear consistently in criticality and energy-transition frameworks developed by organizations such as the IEA, the International Renewable Energy Agency (IRENA), and the World Bank, as well as in media coverage. Other inputs, such as aluminum, silver, steel, or silicon, are incorporated where relevant as contextual factors or potential substitutes (IEA, 2026; IRENA, 2023; World Bank, 2020).

Using this comparison base—the six selected minerals a set of variables is defined, as shown in Figure 1 (steps 2 to 4 of the figure). These variables are intended to assign a score to each mineral in the comparison and thereby generate a criticality ranking.

The variables considered are: (1) volume pressure, measured by comparing baseline supply coverage against primary requirements toward 2035; (2) supply-chain fragility, which combines concentration, the N-1 test, conversion and qualification complexity, trade exposure, supply response, and infrastructure; (3) technological breadth, which measures demand for each mineral across seven key energy-transition applications; and (4) mitigation rigidity, which assesses substitution, the speed of new supply, recycling, and qualification by 2035.

FIGURE 1. ANALYTICAL FRAMEWORK: FROM LOCALIZED SCARCITY TO SYSTEMIC BOTTLENECK



Source: GEM, own elaboration. Each stage addresses a different question and avoids reducing criticality to a single variable

To generate a score for each element, these variables are weighted in the Systemic Bottleneck Index (SBI) equation. This index was developed by GEM Mining Consulting to compare, on a scale from 0 to 100, the potential of each mineral to become a systemic bottleneck for the energy transition toward 2035. A higher score indicates a greater potential for constraints affecting a given mineral to simultaneously impact multiple systems within the energy transition. The index is expressed in the following equation:

$$\text{SBI} = 0.40 \times \text{Volume Pressure} + 0.35 \times \text{Technological Breadth} + 0.15 \times \text{Mitigation Rigidity} + 0.10 \times \text{Supply-Chain Fragility}$$

The baseline-case weights reflect the specific question addressed by this study: which metal has the greatest potential to constrain the energy transition across multiple systems. Accordingly, volume pressure (40%) and technological breadth (35%) together account for 75% of the index, capturing, respectively, the potential shortage of material and the ability of that constraint to propagate across different systems.

Mitigation rigidity (15%) acts as a persistence factor, while supply-chain fragility (10%) serves as a vulnerability factor. These latter two dimensions receive lower weights in order to limit overlap across components. The robustness of this weighting approach is subsequently tested through alternative analytical lenses, including one in which supply-chain fragility accounts for 50% of the index.

Table 2 presents the rationale behind the weighting assigned to each of the dimensions that make up the SBI.

TABLE 2. RATIONALE FOR THE BASE-CASE WEIGHTS

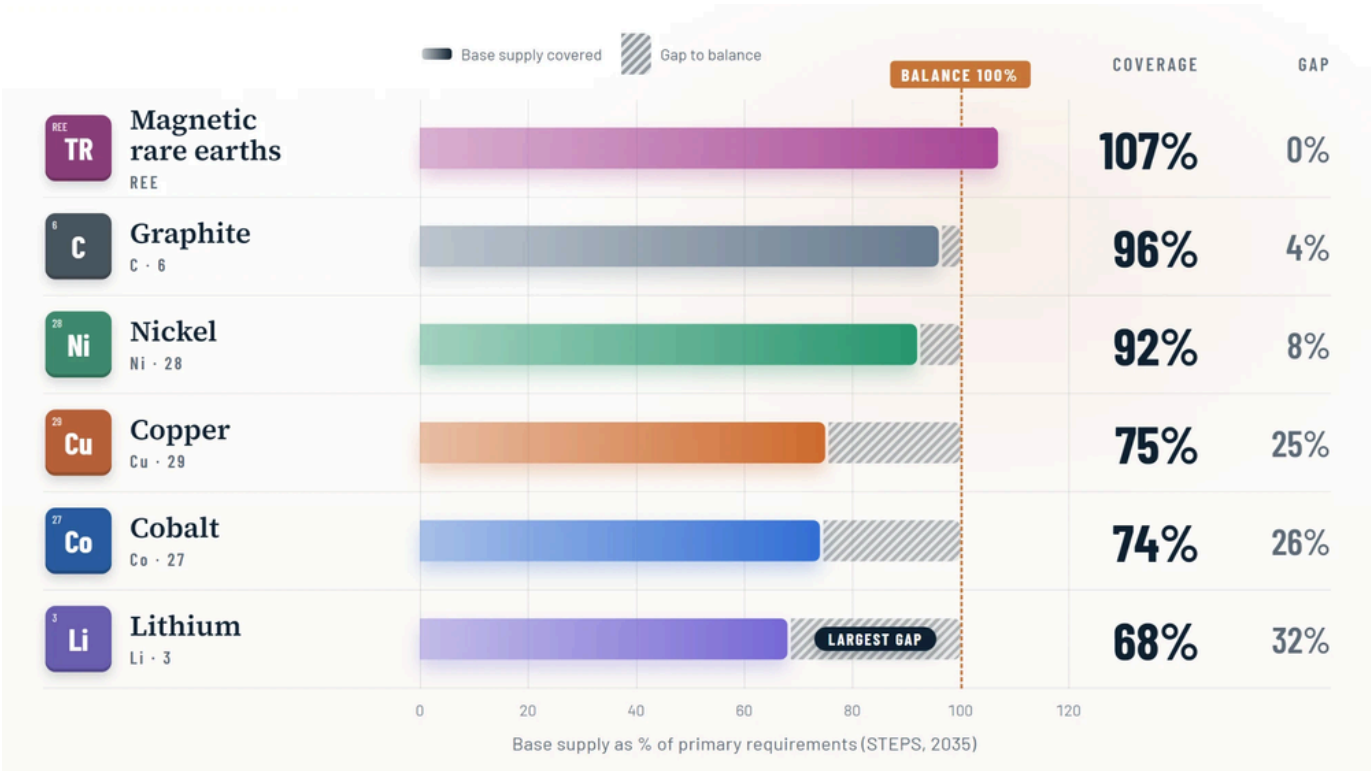
DIMENSION	WEIGHT	RATIONALE
01 Volume pressure	40%	It is the necessary physical condition and the dimension with the most comparable data across metals.
02 Technological breadth	35%	The question is systemic: it almost equals volume in order to capture propagation to multiple systems.
03 Mitigation rigidity	15%	It distinguishes a transitory gap from a persistent one. For example, a gap that can be closed before 2035 with short-cycle projects, substitution or recycling receives lower rigidity than an equivalent gap in copper, where new mines take longer and substitution is partial.
04 Supply chain fragility	10%	It captures concentration and intermediate bottlenecks; a fragile chain does not always have an aggregate impact if the market is small.

Source / note: GEM, own elaboration. The weights correspond to analytical assumptions within the SBI methodology and reflect the relative importance assigned to each dimension in assessing systemic bottleneck potential.

The Starting Point: Physical Supply Gaps in 2035

In this study, “baseline supply” reproduces the coverage of the IEA’s (2026) base case: expected production from existing operations and committed projects. It does not correspond to the full industry project pipeline, since the Base Case excludes uncommitted projects—that is, potential or tentative projects. Accordingly, the Base Case gap should be interpreted as a gap relative to committed or secured supply, rather than as a geological or engineering limit, or as an assertion that no additional projects could come online before 2035. This caveat is particularly relevant for lithium, whose pipeline of new projects is broader than that of copper. For this reason, the SBI calculation incorporates an additional variable mitigation rigidity specifically intended to capture the presence or absence of this capacity to respond to growing demand. The comparison between baseline supply and primary requirements under the STEPS scenario is shown in **Figure 2**.

FIGURE 2. 2035 BASELINE SUPPLY COVERAGE RELATIVE TO PRIMARY REQUIREMENTS



Source: GEM, based on IEA (2026), Global Critical Minerals Outlook 2026. Primary requirement = total demand net of secondary material and refining losses.

Figure 2 shows that lithium has the largest relative gap, with baseline supply covering 68% of primary requirements. It is followed by cobalt at 74% and copper at 75%. Nickel reaches 92% coverage and graphite 96%, while magnetic rare earths show 107% coverage at the mining stage.

BASE-CASE SCORECARD

Table 3 starts from the 2035 coverage reported by the IEA baseline supply divided by primary requirements and shows the gap relative to full (100%) coverage. To compare this gap across minerals, the Volumetric Scarcity Index (VSI)[3] is calculated, normalizing the gap on a scale from 0 to 100, where a gap of 40% or more is equivalent to 100 points.

Fragility, Technological Breadth, and Mitigation Rigidity are also expressed on a scale from 0 to 100 and correspond to GEM analytical scores developed from commodity-specific public evidence. The SBI integrates all four dimensions; detailed criteria, sources, and formulas are presented in the methodological appendix.

[1] $VSI = 100 \times \min[1; \text{Gap} / 40\%]$

TABLE 3. BASE-CASE SCORECARD

METAL	COVERAGE / (GAP)	VSI	FRAG.	BREADTH	RIGIDITY	SBI	INTERPRETATION
 Cu Copper	75% / (25%)	62.5	36.0	93.3	77.0	72.8	Mass, cross-cutting market. The gap spreads to grids, mobility, buildings, industry and data.
 Li Lithium	68% / (32%)	80.0	52.0	38.3	68.0	60.8	Largest relative deficit, concentrated in batteries. Although relative potential supply is broader than in copper.
 Co Cobalt	74% / (26%)	65.0	78.0	25.0	48.8	49.9	Significant gap and heavy dependence on the DR Congo for mining and on China for refining. The expansion of LFP and the lower cobalt intensity per battery moderate demand and its systemic spread.
 C Graphite	96% / (4%)	10.0	89.1	35.0	66.2	35.1	Aggregate coverage close to balance, but high fragility in purification, spheroidization and coating ⁴ .
 Ni Nickel	92% / (8%)	20.0	66.1	36.7	47.0	34.5	Lower physical pressure; risk concentrated in geography, routes and battery specification.
 REE Magnetic rare earths	107% / (0%)	0.0	94.8	33.3	71.2	31.8	Aggregate mining slack, but separation, metallization and magnets are highly concentrated.

Source / note: GEM Mining Consulting. Coverage is based on IEA data; the gap and VSI are GEM calculations; Fragility, Breadth, and Rigidity are GEM analytical indices; and the ICBS results from their weighted integration.

How the scores are supported. The Fragility and Mitigation Rigidity indices do not correspond to directly observed data; rather, they are scores constructed from a range of risk factors. To support these scores, each factor was assessed against publicly available evidence, and the resulting relative ranking across minerals was then reviewed for consistency with external indicators such as concentration, N-1 vulnerability, substitution capacity, and the speed of supply response.

Fragility. The score combines concentration (25%), the N-1 test (20%), conversion/qualification (20%), policy/trade exposure (15%), supply response (10%), and infrastructure/continuity (10%). The resulting ranking is: (1) magnetic rare earths, 94.8; (2) graphite, 89.1; (3) cobalt, 78.0; (4) nickel, 66.1; (5) lithium, 52.0; and (6) copper, 36.0. Under the IEA's N-1 test, supply outside the largest supplier almost fully covers residual demand in copper;

it covers around 65% in lithium and cobalt, less than 55% in nickel, and only 35–40% in graphite and rare earths. These differences are compounded by several additional factors: (1) China accounts for more than 90% of graphite and rare earth refining; (2) cobalt combines high mining concentration in the Democratic Republic of the Congo with concentrated refining capacity and export quotas; (3) nickel is becoming increasingly concentrated in Indonesia and China; (4) lithium retains a concentrated refining base but has a more diversifiable mining supply; and (5) copper has the comparatively most diversified supply chain.

For this reason, the ranking does not depend on a single indicator, but rather on a combination of GEM observations based on IEA (2025, 2026), IRENA (2023), and USGS (2026).

[3] VSI = $100 \times \min[1; \text{Gap}/40\%]$.

[4] For anode materials, spheroidization transforms purified graphite into more rounded particles to improve density and electrochemical performance; coating refers to the surface coating—typically carbon-based—applied before its use as an active battery material.

Mitigation Rigidity. The score combines substitution barriers (35%), new-supply response time (35%), the lag in relief provided by recycling (20%), and qualification/standards (10%).

Copper ranks first, with a score of 77.0, because substitution at scale remains only partial, mining projects have long development cycles, and recycling alone cannot close a gap of several million tonnes. In this regard, GEM's Perspective No. 4 estimates that substitution and thrifting could reduce refined copper demand by approximately 2–5% by 2035.

Rare earths (71.2), lithium (68.0), and graphite (66.2) form a second group. For rare earths, the key constraint lies in the difficulty of replicating separation, metallization, magnet manufacturing, and qualification capabilities outside China. In lithium, the metal's role in dominant battery chemistries maintains a degree of rigidity, although a broader project pipeline and supply routes such as hard-rock mining, new brine projects, and direct lithium extraction (DLE) improve the potential supply response. In graphite, alternatives exist between natural and synthetic material, but both must meet anode-grade specifications and undergo qualification.

Cobalt (48.8) and nickel (47.0) rank lower in terms of mitigation rigidity, as LFP batteries eliminate both metals from the cathode across a growing share of the market. In addition, for nickel, Indonesia's recent expansion demonstrates a comparatively faster supply response.

By contrast, cobalt remains slightly higher due to its status as a by-product and its exposure to sovereign decisions. This relative position is consistent with the available evidence reviewed by GEM based on IEA (2026), IRENA (2023), and GEM Mining Consulting (2024, 2025).

When all variables are considered together, the comparative analysis shows that copper leads in technological breadth and mitigation rigidity; lithium in relative supply gap; cobalt in the combination of deficit and concentration; and graphite and rare earths in processing fragility.

Two dimensions help explain why copper and lithium represent different forms of criticality. The VSI measures the intensity of physical supply pressure toward 2035, while Technological Breadth measures how many energy-transition systems are exposed to a constraint affecting a given mineral. Lithium leads in volumetric pressure, with a VSI of 80.0, while copper leads by a wide margin in technological breadth, with a score of 93.3. The systemic result emerges from combining these two dimensions with Mitigation Rigidity and Supply-Chain Fragility.



COPPER AND LITHIUM: TWO DISTINCT FORMS OF CRITICALITY

COPPER SPANS NEARLY THE ENTIRE ENERGY TRANSITION
FIGURE 3 SHOWS THE LEVEL OF TECHNOLOGICAL BREADTH BY MINERAL, UNDERSTOOD AS THE PRESENCE OF EACH MINERAL ACROSS THE DIFFERENT APPLICATIONS OF THE ENERGY TRANSITION.

FIGURE 3. COMPARATIVE TECHNOLOGICAL BREADTH OF THE SIX MINERALS



Source: GEM. The technological classification is based on IEA (2021, 2026), World Bank (2020), and the Energy Transitions Commission (2023). Scale by system: 0 = no relevant exposure; 1 = secondary; 2 = important; 3 = essential.

The breadth calculation is explicit: $A_i = (100/3) \times \sum(w_s \times exposure_{i,s})$, where each metal's exposure to each system is scored from 0 to 3. The w_s values are GEM analytical assumptions informed by the scale and enabling role of each system toward 2035: power grids 25%, electric vehicles 20%, renewables 15%, energy storage 15%, data centers and AI 10%, industrial electrification 10%, and hydrogen and other applications 5%. In this framework, power grids and mobility receive greater weight due to their scale, while hydrogen receives a lower weight given the uncertainty surrounding its deployment. When the analysis is stress-tested using equal weights across all seven systems (applications), copper continues to rank first in technological breadth, indicating that the result is robust across different weighting combinations.

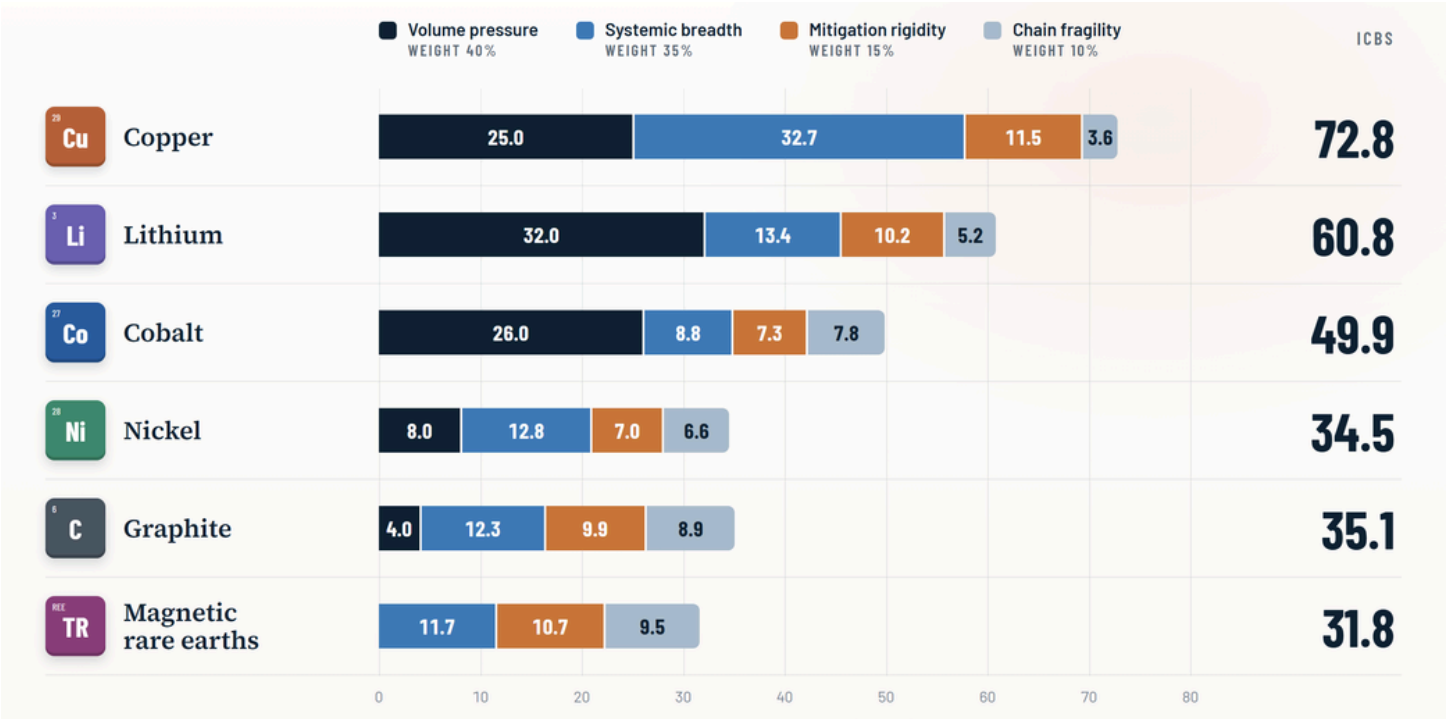
The matrix highlights the difference between technological concentration and systemic propagation. Lithium, graphite, nickel, and cobalt are essential for certain battery technologies, but their exposure declines outside mobility and energy storage. Magnetic rare earths are critical for high-performance motors and certain wind turbines. Copper, by contrast, plays a major role across power grids, renewable generation, vehicles, data centers, buildings, and industry.

To understand the challenge posed by copper’s relevance to the energy transition, it is important to note that GEM Mining Consulting’s Perspective No. 4 (2025), which examines substitution threats to copper, estimates refined copper demand of 31–35 Mt by 2035 and firm supply of 25.5–26.1 Mt. The resulting gap would therefore range from 5.6 to 8.9 Mt. Potential mitigating factors are relatively limited: substitution and thrifting[5] could reduce demand by only 2% to 5%, but would not be sufficient on their own to close the imbalance. Looking more closely at substitution in the case of copper, aluminum is the substitute with the greatest potential scale, particularly in overhead transmission, busbars, and

applications where weight or cost justify the use of a larger cross-sectional area. However, aluminum is not an equivalent substitute in compact wiring, motors, transformers, underground grids, or high-current-density applications. Other materials—such as graphene, carbon nanotubes, superconductors, or advanced interconnects—remain concentrated in niche applications and, in many cases, complement copper rather than replace it.

FIGURE 4. COMPOSITION OF THE SYSTEMIC BOTTLENECK INDEX (SBI) BY MINERAL

Figure 4 illustrates the contribution of the different components of the SBI developed by GEM Mining Consulting to the final score of each mineral.



Source: GEM Mining Consulting

[5] Thrifting refers to reducing the amount of copper required per unit of equipment or service through design optimization, smaller conductor cross-sections, integration, or improved material efficiency, without fully substituting copper with another material.

Copper scores 72.8 points, the highest SBI in the sample, and emerges as the strongest candidate for a systemic bottleneck in the base case. It does not lead in supply-chain fragility graphite and rare earths are far more concentrated nor in relative supply gap, where lithium faces a larger deficit. Rather, copper leads because it combines three conditions that rarely occur simultaneously: a material supply deficit, the broadest market in the sample, and a cross-cutting presence across nearly all of the infrastructure underpinning the energy transition.

A constraint on copper can propagate widely because the metal is not tied to a single technology. It is used in transmission lines and cables, substations, transformers, generators, inverters, vehicles and charging infrastructure, buildings, industrial infrastructure, pumps, motors, automation systems, cooling systems, artificial intelligence data centers, and also in recent advances in robotics.

Across these applications, copper primarily performs an electrical conductivity function that is difficult to replace without redesigning systems, oversizing components, or accepting additional efficiency losses. Under these conditions, copper emerges as the metal with the greatest potential to transmit a supply constraint across the energy transition as a whole.

Copper use is not only broad, but also massive in scale. Its refined market is measured in tens of millions of tonnes per year. A percentage gap similar to that of a niche metal therefore implies a much greater requirement for projects, capital, infrastructure, and permitting.

Copper supply also responds slowly. Copper ore grades have declined as higher-grade deposits have been progressively depleted, the capital intensity required to develop new projects has increased, and significant new discoveries have become increasingly scarce. In this context, the time from discovery to production can span several decades for many assets. As a result, a higher price signal may stimulate exploration and project development, but it does not guarantee that additional tonnes will reach the market within the 2035 horizon.

Lithium: a bottleneck for mobility and storage, but not for the entire system

Lithium is the main volumetric bottleneck in the base case and could represent a critical constraint for electric mobility and energy storage. However, its direct impact is concentrated primarily in battery-based systems. When the energy transition is assessed as a whole, copper retains a significantly greater capacity to propagate constraints across multiple systems.

Lithium requires a differentiated interpretation. Its 68% coverage is the lowest in the sample, and its demand is rising rapidly alongside electric mobility and energy storage. Under an analytical lens that assigns 60% of the weight to volume pressure, lithium ranks above copper. It is therefore the main volumetric bottleneck and a material risk for the battery supply chain.

However, its exposure is much more concentrated. Both LFP and NMC[6] chemistries use lithium, meaning that switching between them does not eliminate the need for the metal. Yet a lithium constraint does not directly affect the construction of power grids, transformers, buildings, industrial motors, or data centers in the same way as a copper constraint. The scope of the shock is therefore more focused.

A Geological and Technological Base Still Expanding[7]

Large-scale economic interest in lithium is relatively recent compared with copper. Accelerated exploration over the past two decades has expanded reserves, resources, and the number of producing countries. Global production grew at an annual rate of nearly 9% between 1996 and 2023, while hard-rock projects emerged in Africa and Europe, alongside oil- and gas-associated brines, direct lithium extraction processes, and a developing recycling industry.

This potential supply should not be confused with secured production: each pathway faces constraints related to costs, water, energy, ore grades, permitting, conversion, and qualification. However, the range of available options is broader, and supply response cycles have generally been faster than in copper. This difference reduces lithium's structural rigidity, although it does not eliminate the risk of a market gap before 2035.

The conclusion, however, is not that lithium is "not critical." It is the metal with the largest relative deficit in the base case. The key distinction is that this deficit is concentrated in battery-related applications and coexists with a supply frontier that is younger, more diversifiable, and technologically dynamic.

[6] LFP (lithium iron phosphate) does not use nickel or cobalt in the cathode. NMC (nickel-manganese-cobalt) uses both, in varying proportions. Both chemistries require lithium and typically graphite in the anode.

[7] Context source: GEM Mining Consulting (2024), *Emerging Lithium Markets and Chile's Role in Global Supply*.

DEFICIT, CONCENTRATION, AND SUBSTITUTION DO NOT MOVE IN TANDEM

COBALT: A SIGNIFICANT SUPPLY GAP, HIGH FRAGILITY, AND LIMITED TECHNOLOGICAL BREADTH

Cobalt combines two distinct constraints. First, mining supply is extraordinarily concentrated: the Democratic Republic of the Congo accounted for around 73% of global production in 2025, while China remained the leading producer of refined cobalt (USGS, 2026). This concentration means that a sovereign decision can alter the global balance rapidly. The IEA (2026) attributes a significant share of the projected 2035 gap to export quotas introduced by the Democratic Republic of the Congo.

Second, a large share of cobalt is produced as a by-product of copper or nickel operations. As a result, an increase in the cobalt price does not automatically trigger new capacity: production decisions also depend on the economics, timing, and output of the primary metal. This is what is meant by a less independent supply response.

The adoption of LFP batteries reduces cobalt demand because this battery chemistry uses iron and phosphate in the cathode, with neither cobalt nor nickel. In addition, NMC formulations have reduced the amount of cobalt required per unit of energy. The result is a dual risk: a physical supply gap and a fragile supply chain, but a lower capacity to propagate constraints across the system as a whole.

Nickel: a more comfortable aggregate balance, but rising concentration

Nickel has 92% baseline supply coverage, meaning that physical supply pressure is lower.

However, production and processing have become increasingly concentrated in Indonesia and China, while battery-grade nickel requires specific processing routes. This illustrates how an apparently comfortable global balance can coexist with high geographic and technological dependence.

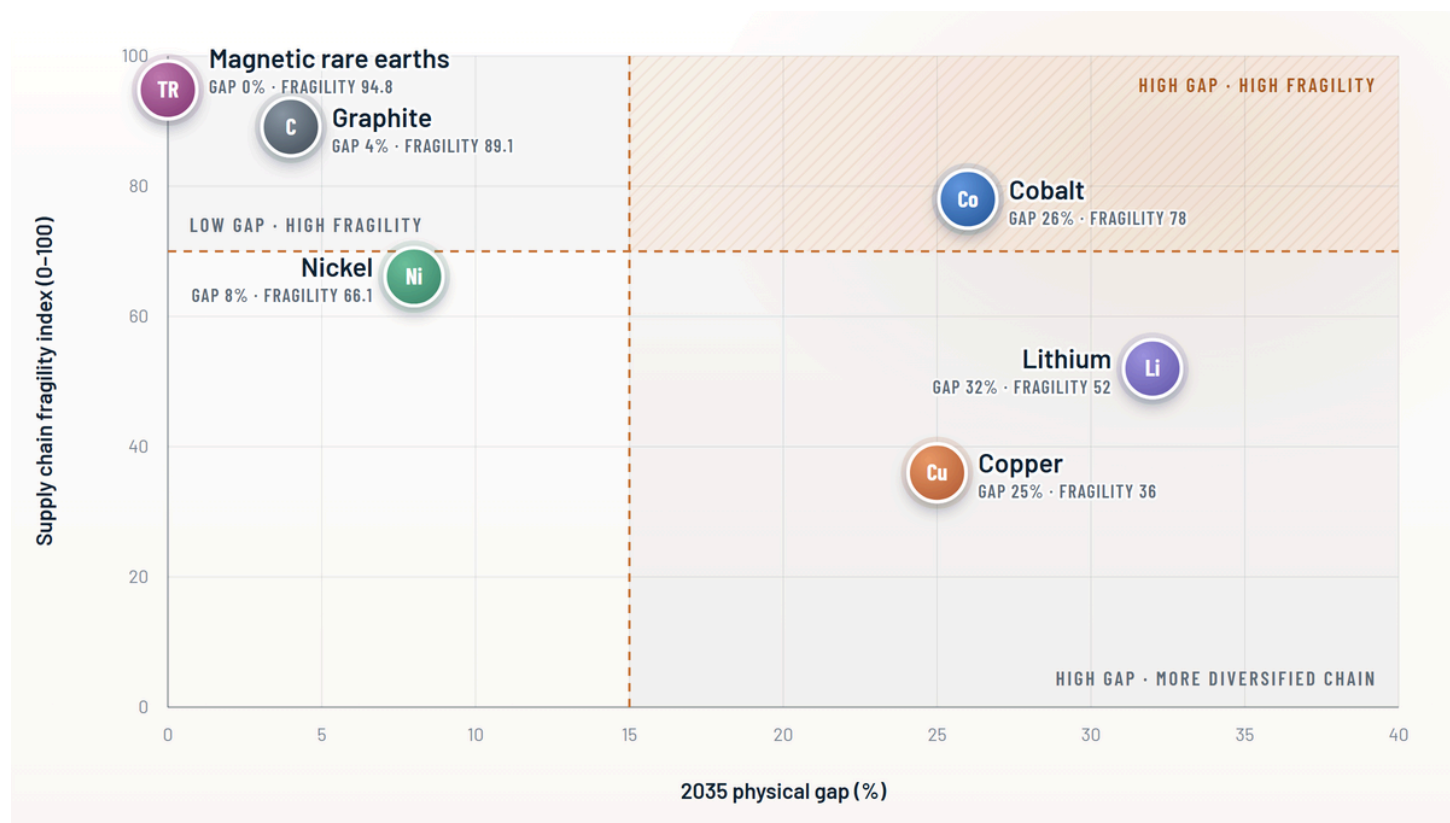
Here again, LFP acts as a mitigating factor: because it does not use nickel, it reduces exposure in lower-cost batteries and certain vehicle segments. This does not eliminate nickel's role in high-energy-density cathodes, stainless steel, alloys, or industrial applications, but it limits its relative technological breadth compared with copper.

Criticality is not a fixed property of an element. It changes with the dominant chemistry, material intensity, acceptable sources of supply, carbon footprint, and trade restrictions. As a result, the same aggregate supply coverage can imply very different risks for manufacturers and regions.

Graphite and Rare Earths: The Bottleneck May Lie in Processing

Figure 5 compares the estimated physical supply gap toward 2035 with the Supply-Chain Fragility Index.

FIGURE 5. VOLUME PRESSURE AND SUPPLY CHAIN FRAGILITY ARE DISTINCT CHALLENGES



Source: GEM. Fragility is a comparative index, not a probability of disruption.

Graphite shows aggregate coverage of 96%, considering natural flake graphite and synthetic graphite together, while magnetic rare earths reach 107% coverage at the upstream stage. An interpretation based solely on these aggregate balances might suggest that the problem has been resolved. However, the high concentration of downstream processing stages means that apparently sufficient supply coverage can coexist with a high degree of dependence on the parts of the value chain that convert the material into a usable product.

For graphite, the bottleneck may emerge in purification, spheronization, and coating of anode active material. For magnetic rare earths, it may lie in separation, metallization, alloy production, and magnet manufacturing. The IEA (2026) projects that, outside the leading refiner, committed projects toward 2035 could provide around 50 kt of rare earth mining capacity, but less than 40 kt of separation capacity and approximately 18 kt of capacity in metals, alloys, and magnets.

In both cases, therefore, having sufficient supply at the early stages of the value chain does not guarantee the availability of battery-grade material or qualified magnets.

For graphite, aggregate coverage of 96% including both natural flake and synthetic graphite coexists with a high concentration of processing stages and battery-grade material production in China.

For magnetic rare earths, 107% upstream coverage does not eliminate the bottleneck either: outside the leading refiner, projected capacity declines from mining to separation and falls again at the stages of metals, alloys, and magnet manufacturing. The central point is that the risk does not necessarily lie in the initial availability of the material, but in the capacity to convert it into a specified, qualified, and commercially available product outside the dominant processing hub.

Magnetic Rare Earths: Criticality Beyond the Energy Transition

Magnetic rare earths have strategic relevance that extends beyond the energy transition. Rare-earth permanent magnets are important inputs for the defense industrial base and are used, among other applications, in guidance and control systems and other advanced components. The U.S. Department of Defense includes rare earth oxides and permanent magnets among the strategic and critical material supply chains whose availability must be secured to sustain defense capabilities (U.S. Department of Defense, 2022).

This dual-use role across civilian and defense applications increases their strategic importance: a bottleneck in separation, metallization, or magnet manufacturing could simultaneously affect electrification technologies and industrial capabilities linked to national security.

It is important to clarify that the SBI was designed specifically to measure the potential of each metal to become a bottleneck for the energy transition toward 2035, considering its exposure to power grids, renewables, electric mobility, energy storage, digitalization, industrial electrification, and hydrogen. Accordingly, the index does not explicitly incorporate defense-related demand, nor is it intended to measure the full geopolitical criticality of each mineral.

In the case of magnetic rare earths, their strategic importance could therefore be significantly greater than that reflected in their SBI if defense and national security requirements were also included.

Opening a Mine Alone Does Not Solve a Midstream Bottleneck

The response required for graphite and rare earths is not the same as for copper. In copper, the priority is to accelerate mine supply and the associated processing capacity. In the midstream stages of the value chain, by contrast, the challenge is to build a complete industrial ecosystem outside China: plants, reagents, equipment, know-how, intellectual property, laboratories, quality-control systems, contracts, and customers willing to qualify a new supply route.

The challenge is also economic. The IEA (2026) estimates that new refining projects outside the dominant supplier may face capital costs ranging from 20% to more than 150% higher, as well as operating costs that are around 50% higher on average. This makes plants outside China vulnerable to periods of low prices or to increases in supply from the incumbent producer.

Long-term offtake agreements can help reduce this risk by securing demand and providing greater revenue visibility during the ramp-up phase. A 10-year agreement, for example, can establish minimum purchase volumes, incorporate price floors or cost-recovery mechanisms, and facilitate project financing. As a reference, MP Materials Corp. (2025) disclosed a 10-year magnet purchase commitment together with an NdPr price-protection mechanism extending for approximately 10 years.

The objective is not to permanently shield the plant from market forces, but rather to allow it to reach sufficient scale and withstand price and supply shocks without losing the strategic capacity that diversification efforts are intended to create.

Table 4 presents mitigation mechanisms for addressing excessive supply-chain concentration.

TABLE 4. SPECIFIC LEVERS TO REDUCE CRITICALITY IN MIDSTREAM SUPPLY CHAINS

LEVER	WHAT MUST BE BUILT
01 Industrial capacity	Purification, separation, metallization, <i>coating</i> and magnets outside the dominant <i>hub</i> .
02 Knowledge and equipment	Technology transfer, specialized suppliers, process engineering and intellectual property.
03 Customer qualification	Samples, pilot batches, audits, approval and long-term contracts.
04 Diversification economics	Long-term <i>offtakes</i> (e.g., 10 years), guarantees, price floors, insurance and financing that reduce risk during <i>ramp-up</i> and low-price cycles.
05 Continuity	Energy, water, reagents, logistics, inventories and redundancy.

The key is sequencing. A new mine without local conversion capacity may simply increase dependence on the same dominant processor. A processing plant without qualified customers or sufficiently long-term offtake agreements may operate below capacity and remain vulnerable to closure during periods of low prices. A customer without long-term contracts, in turn, may fail to provide the anchor demand needed to support project financing. Diversification therefore requires coordination across the entire value chain, rather than the addition of isolated assets.

Copper primarily requires more supply that can realistically be brought into production, together with stronger project execution. Graphite and rare earths, by contrast, also require the rebuilding of processing and manufacturing stages where expertise, learning effects, and commercial relationships are highly concentrated.

Robustness Tests and Sensitivity Analysis

To test robustness, no new variables are introduced. Instead, the same four dimensions presented in **Table 3** are recalculated using four different weighting vectors that is, the results are tested under different analytical lenses.

(1) Systemic: 40% volume pressure, 35% technological breadth, 15% mitigation rigidity, and 10% supply-chain fragility.

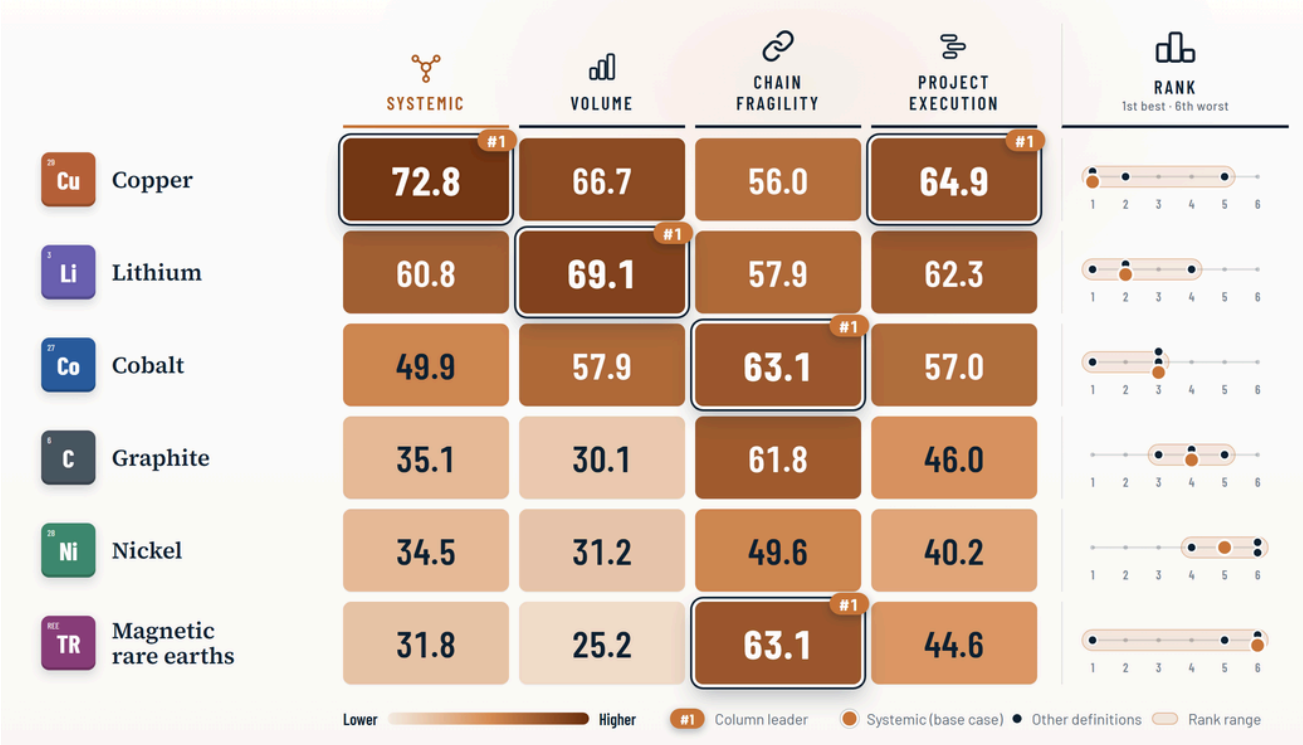
(2) Physical scarcity: 60%, 15%, 15%, and 10%, respectively, to assess which metal faces the greatest physical supply pressure.

(3) Supply-chain resilience: 20%, 15%, 15%, and 50%, respectively, to assess which supply chain is most vulnerable to concentration, loss of the largest supplier, and processing bottlenecks.

(4) Project execution: 35%, 20%, 20%, and 25%, respectively, increasing the combined weight of volume pressure, mitigation rigidity, and supply-chain fragility to test which results are most sensitive to announced capacity failing to materialize on time.

Each column in Figure 6 therefore answers a different question using exactly the same underlying input data.

FIGURE 6. 0–100 INDEX UNDER FOUR ALTERNATIVE DEFINITIONS OF “BOTTLENECK”



Source: GEM. Each block shows the 0–100 index recalculated using the weight vector defined in the previous paragraph; “#1” identifies the leader in each column. The input data remain unchanged.

The “Systemic” column places copper first because it combines physical supply pressure with broad cross-system propagation. The “Volume” column places lithium first because it has the largest relative supply gap. The “Supply-Chain Fragility” column places cobalt and magnetic rare earths at the top, with graphite close behind, because the weight assigned to supply vulnerability increases to 50%. The “Project Execution” column once again places copper first because it combines a material supply gap with high mitigation rigidity and the need for projects at very large scale.

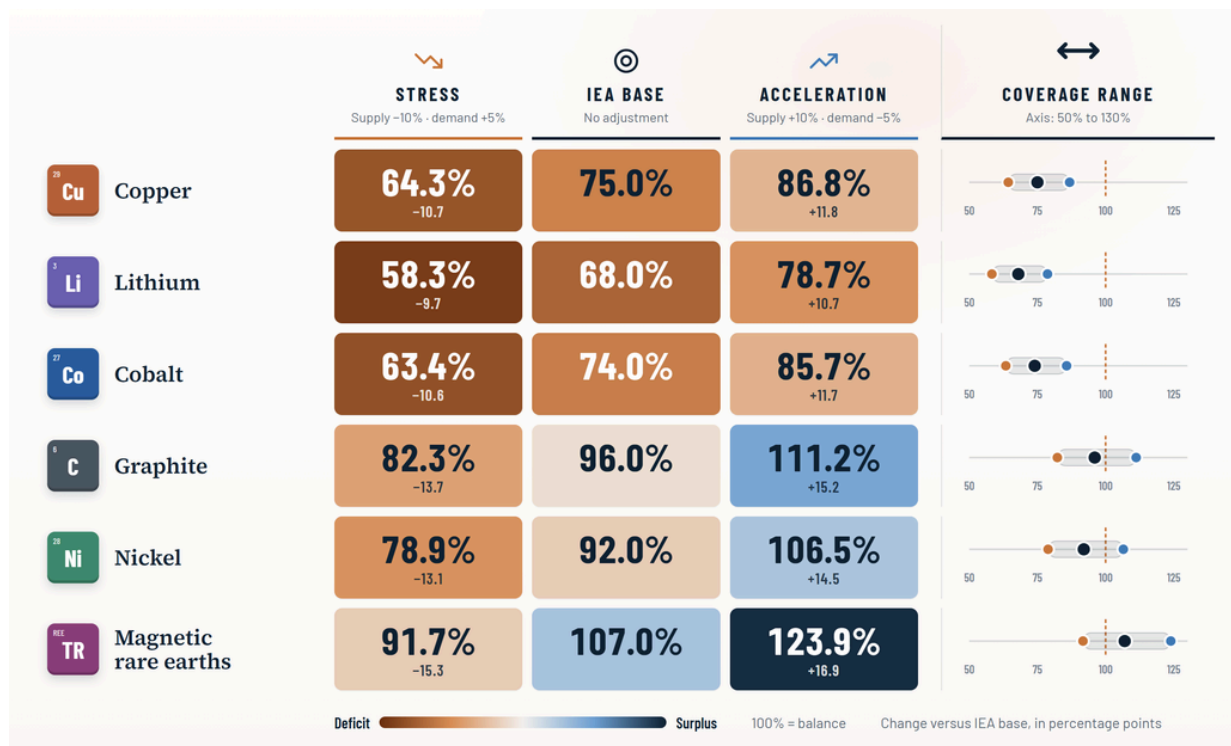
The pattern does not represent a different ranking built from new data; rather, it is a transparent sensitivity analysis of the same SBI under four different questions or decision-making lenses. This helps bring greater clarity to the discussion. Saying that “lithium is the scarcest mineral over the long term when considering only current commitments” and that “rare earths have the most fragile value chains” can both be correct at the same time. What would be incorrect is to conflate those statements and conclude that they require the same policy or market response.

Supply and Requirement Sensitivities Toward 2035

Three sensitivities are defined to deepen the analysis (see Figure 7). (1) “Stress” reduces effective supply by 10% and increases requirements by 5% relative to the base case. (2) “Base” maintains the original balance. (3) “Accelerated Delivery” increases effective supply by 10% and reduces requirements by 5%, representing improved execution, greater material efficiency, and increased recycling.

These are not probabilistic scenarios and are not intended to replace market forecasts.

FIGURE 7. 2035 SUPPLY COVERAGE UNDER STRESS, BASE, AND ACCELERATED DELIVERY SENSITIVITIES



Source: GEM. Each cell shows supply coverage relative to requirements. The sensitivity analysis simultaneously modifies effective supply and demand.

The accelerated delivery scenario significantly improves supply coverage, but it does not eliminate all risks. Copper reaches 86.8% and lithium 78.7%, both still below balance. Graphite, nickel, and rare earths exceed 100% coverage on an aggregate basis, although their concentration and processing risks remain. Under the stress sensitivity, the gaps widen, making it even more important to distinguish between volume pressure and supply-chain fragility.

The top ranking remains stable: copper, lithium, and cobalt occupy the first three positions under stress, the base case, and accelerated delivery. However, the absolute level of criticality does change. Under stress, both copper and lithium exceed 65 points; under accelerated delivery, copper remains in first place, but its SBI falls to 61.0. This shows that the conclusion regarding relative leadership is robust, although the severity of the risk depends materially on the execution of new supply and the growth of requirements.

TABLE 5. SBI VALUES UNDER SENSITIVITY ANALYSIS

METAL	STRESS	BASE CASE	ACCELERATED DELIVERY	INTERPRETATION
Cu Copper	83.5	72.8	61.0	Holds 1st place in all three scenarios
Li Lithium	68.8	60.8	50.1	Holds 2nd place; under stress it exceeds the threshold of 65
Co Cobalt	60.4	49.9	38.2	Holds 3rd place
C Graphite	48.8	35.1	31.1	Rises materially under stress
Ni Nickel	47.6	34.5	26.5	Risk increases under stress, but does not change the top hierarchy
REE Magnetic rare earths	40.1	31.8	31.8	Risk remains dominated by fragility, not by volume

CONCLUSION

The original question addressed by this study may appear to call for a single answer, but the evidence points to at least three distinct conclusions. The shortage of physical tonnes is most acute in lithium, cobalt, and copper when considering only committed or baseline supply. Processing vulnerability is concentrated in graphite and magnetic rare earths. Finally, the ability to transmit a constraint across multiple technologies is exceptionally high in copper. For this reason, the answer to the question that motivated this edition of Perspective “Which metal will be the true bottleneck of the energy transition toward 2035?” depends on how “bottleneck” is defined.

In this study, a systemic bottleneck is defined as a metal whose constraint combines a significant physical supply gap, exposure across a broad range of energy-transition systems, limited mitigation alternatives before 2035, and a supply chain vulnerable to disruption. To compare these dimensions, GEM developed the Systemic Bottleneck Index (SBI), a 0–100 scale that weights volume pressure, technological breadth, mitigation rigidity, and supply-chain fragility.

Toward 2035, copper is the metal with the greatest potential to constrain the energy-transition system as a whole; lithium faces the largest relative supply gap; and magnetic rare earths and graphite are the supply chains most exposed to bottlenecks in the intermediate stages of processing and transformation.

If one metal had to be identified as the central protagonist of the energy transition from a criticality perspective, copper emerges as the strongest candidate to become its true systemic bottleneck toward 2035. Its position does not depend on having the lowest supply coverage or the most concentrated supply chain. Rather, it arises from the combination of a material supply gap, a market of enormous scale, applications across virtually the entire energy transition, and a supply response that can take many years to materialize.

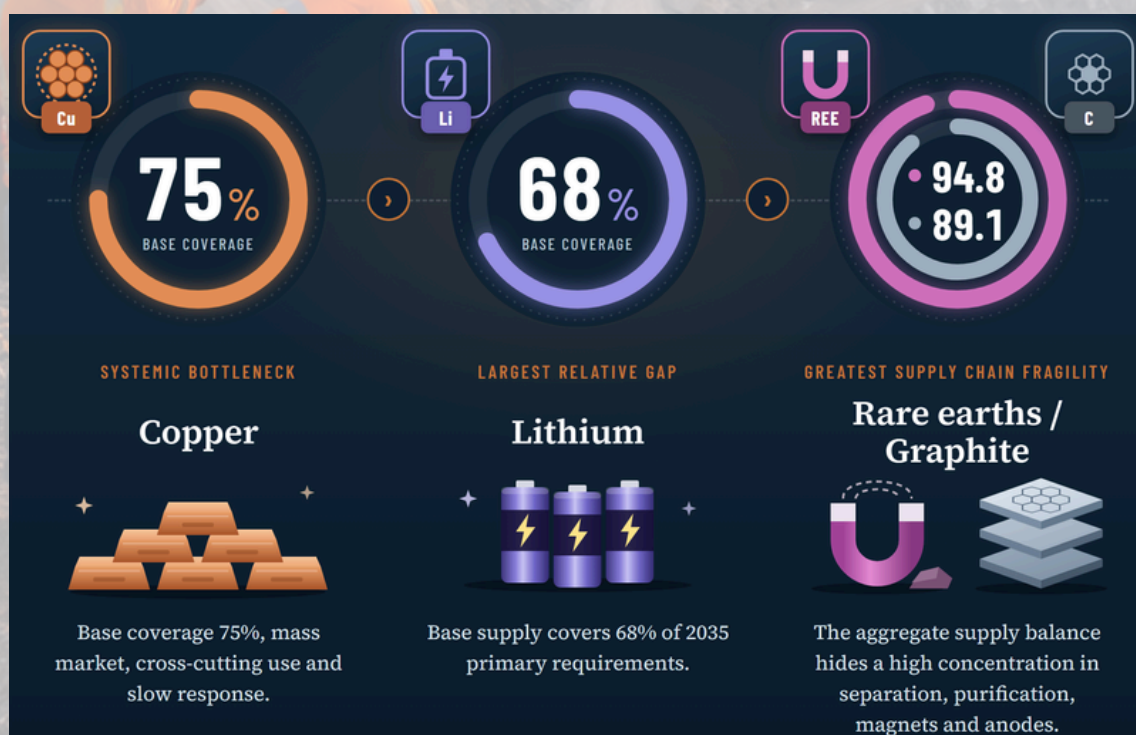
This is why, even though lithium has the largest gap relative to committed supply, copper exhibits greater rigidity in its ability to mitigate that gap. In this respect, large-scale economic interest in lithium is relatively recent, in contrast with copper, which has been explored and mined for millennia.

Accelerated exploration, hard-rock projects, new brine developments, direct lithium extraction (DLE), projects in Africa and Europe, and recycling are materially expanding the potential supply base. This does not eliminate the 2035 gap, but it does reduce the structural rigidity of the problem relative to copper.

With respect to the other elements examined in this report, cobalt, graphite, and magnetic rare earths can generate severe disruptions due to concentration and processing constraints, although their aggregate impact is more focused. Nickel, meanwhile, faces greater challenges related to origin and specification than to a physical supply gap comparable to that of copper.

The main result is robust to reasonable changes in weights and scenarios. Copper records an SBI score of 72.8, followed by lithium at 60.8. Under a sensitivity that gives near-dominant weight to volume pressure, lithium moves into first place. Under a sensitivity that increases the weight assigned to supply-chain fragility that is, vulnerability to disruptions arising from concentration, dependence on the largest supplier, and processing constraints cobalt and magnetic rare earths move to the top. The conclusion therefore changes depending on the question being asked, but not arbitrarily. Copper remains the strongest candidate for a systemic bottleneck. Lithium presents the largest relative volume gap, although that gap appears less structurally difficult to close than copper’s, for example. Graphite and magnetic rare earths, meanwhile, concentrate the greatest processing fragility.

Beyond any reasonable methodological differences, copper is set to be the key material underpinning the energy transition, followed albeit to a lesser extent by the other metals examined in this study. Copper is present across nearly every system, represents the largest volume, and requires the greatest number of projects, as well as the largest commitments of capital and infrastructure. In this sense, the energy transition as a whole can partially adapt to constraints affecting other materials. Without copper, however, the infrastructure required to connect and electrify those technologies cannot be built, because copper remains indispensable.



BIBLIOGRAPHY

Energy Transitions Commission (2023). Material and Resource Requirements for the Energy Transition.

GEM Mining Consulting (2024). Emerging Lithium Markets and Chile's Role in Global Supply. Lithium Seminar, August 21, 2024.

GEM Mining Consulting (2025). Perspective No. 4: Threats of Substitution to Copper.

Graedel, T. E. et al. (2012). "Methodology of Metal Criticality Determination." *Environmental Science & Technology*, 46(2), 1063–1070.

International Energy Agency (2021). The Role of Critical Minerals in Clean Energy Transitions.

International Energy Agency (2025). Global Critical Minerals Outlook 2025.

International Energy Agency (2026). Global Critical Minerals Outlook 2026.

International Renewable Energy Agency (2023). Geopolitics of the Energy Transition: Critical Materials.

MP Materials Corp. (2025). Quarterly Report on Form 10-Q, Quarter Ended September 30, 2025. U.S. Securities and Exchange Commission.

<https://www.sec.gov/Archives/edgar/data/1801368/000180136825000054/mp-20250930.htm>

U.S. Department of Defense (2022). Securing Defense-Critical Supply Chains: An Action Plan Developed in Response to Executive Order 14017. February 2022.

U.S. Department of Energy (2023). Critical Materials Assessment 2023. U.S. Department of Energy.

U.S. Geological Survey (2026). Mineral Commodity Summaries 2026.

Watari, T., Nansai, K., and Nakajima, K. (2020). "Review of Critical Metal Dynamics to 2050 for 48 Elements." *Resources, Conservation and Recycling*, 155, 104669.

World Bank (2020). Minerals for Climate Action: The Mineral Intensity of the Clean Energy Transition.



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