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Midstream concentration and geopolitical risk in critical mineral supply chains: A scenario-based assessment of refining chokepoints in the energy transition

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ABSTRACT

The global energy transition is increasing demand for critical minerals essential to low-carbon technologies, raising concerns regarding supply-chain concentration and long-term energy security. Using International Energy Agency (IEA) datasets covering 2024–2050, this study examines projected demand growth, mining and refining concentration, and potential chokepoint risks across three transition pathways: the Net Zero Emissions (NZE), Announced Pledges (APS), and Stated Policies (STEPS) scenarios. The analysis focuses on six strategically significant minerals—lithium, cobalt, nickel, graphite, rare earth elements (REEs), and copper—and evaluates concentration patterns using Top-3 Concentration Ratios (CR_3) and selected Herfindahl–Hirschman Index (HHI) estimates.

The findings indicate that refining concentration remains substantially higher and more persistent than mining concentration across most minerals and scenarios. Graphite, cobalt, lithium, and rare earth refining exhibit particularly elevated concentration levels, with several systems dominated by a limited number of actors. Accelerated decarbonization pathways substantially increase mineral demand without necessarily producing equivalent geographic diversification in refining capacity. The results further suggest that chokepoint risk depends not only on concentration itself, but also on asymmetry within refining systems, technological substitutability, and the pace of industrial diversification.

Rather than treating these vulnerabilities as deterministic outcomes, the study emphasizes the role of industrial policy, recycling, technological adaptation, and international supply-chain coordination in shaping future concentration dynamics. More broadly, the findings suggest that the clean-energy transition may redistribute rather than eliminate certain forms of strategic dependency, particularly where refining capacity remains highly concentrated.

1. Introduction

The global energy transition is expected to substantially increase demand for a range of critical minerals essential to low-carbon technologies, including lithium, cobalt, nickel, graphite, copper, and rare earth elements (REEs). Renewable energy systems, grid battery storage, electric vehicles (EVs), hydrogen technologies, and electricity networks require substantially greater mineral inputs than conventional fossil-fuel-based energy systems, intensifying concerns regarding material availability, supply security, and industrial dependency within critical mineral supply chains. Recent assessments by the International Energy Agency (IEA) indicate that demand for several transition minerals could increase multiple times over current levels under ambitious decarbonization pathways, placing growing pressure on global mining and refining systems (IEA, 2023; IEA, 2025a).

These developments have broadened energy security debates beyond traditional concerns surrounding hydrocarbons, transportation chokepoints, and price volatility toward the material foundations of clean-energy technologies (Ang et al., 2015). Traditional understandings of energy security focused primarily on physical supply reliability and affordability, shaped largely by the oil crises of the 1970s and subsequent geopolitical disruptions (Burgherr et al., 2023; Borovsky, 2024). More recent scholarship increasingly conceptualizes energy security as a multidimensional and dynamic framework encompassing environmental, technological, governance, and resilience dimensions within increasingly interconnected global energy systems (Paravantis & Kontoulis, 2018; Koulouri and Mouraviev, 2019). Existing scholarship further emphasizes that energy transitions may generate new forms of industrial and technological interdependence centered on critical mineral supply chains (Hafner and Tagliapietra, 2020; Vakulchuk et al., 2020; Boute, 2023).

A growing body of literature examines mineral criticality, supply-chain resilience, strategic competition, resource nationalism, and the geopolitical implications of concentrated mineral production and processing (Kalantzakos, 2023; Hache et al., 2023; Zhou and Månberger, 2024). Recent studies also highlight the strategic role of refining and downstream processing capacity, particularly China's dominant position across several clean-energy mineral value chains (Jetin, 2023; Müller et al., 2025). At the same time, existing research presents differing interpretations regarding the severity and persistence of these

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vulnerabilities. Some studies emphasize the potential for technological innovation, recycling, substitution, diversification strategies, and international cooperation to mitigate concentration risks over time (Nygaard, 2022; Valero et al., 2018; Park and Melendez, 2024). Others argue that concentrated supply chains, industrial policy competition, uneven refining capacity, and geopolitical rivalries may reinforce concentration asymmetries within the emerging low-carbon economy (Golden, 2023; Hira, 2025). These debates reflect broader uncertainty regarding whether the energy transition will reduce supply-chain dependencies or reorganize them around new material and industrial chokepoints.

Recent policy initiatives—including the EU Critical Raw Materials Act (European Commission, 2026), the Minerals Security Partnership (U.S. Department of State, 2025), and industrial-policy frameworks adopted in the United States, European Union, Japan, South Korea, and Australia—reflect growing concern regarding concentrated refining systems and long-term supply resilience among G7 and partner economies (Government of Canada, 2025a, 2025b). These developments increasingly frame refining capacity and strategic mineral processing as industrial and energy-security priorities rather than purely commercial activities. The United States Geological Survey (USGS, 2024) reports that the United States remains heavily import-reliant for numerous critical minerals, while the European Union continues to depend substantially on Chinese rare earth imports (European ParliamentEuropean Parliamentary Research Service, 2025).

Despite the rapid expansion of the literature, several analytical challenges remain. First, existing research often discusses critical mineral dependency in broad terms without consistently distinguishing between (upstream) mining concentration and (midstream) refining concentration through comparative concentration metrics. This distinction is analytically important because mining concentration is shaped partly by geological endowments, whereas refining concentration depends more heavily on industrial and technological capacity. As a result, refining systems are often slower to diversify and adapt than mining production.

Second, while existing studies extensively examine mineral dependency and geopolitical risk, fewer provide comparative cross-mineral assessments distinguishing mining and refining concentration using standardized concentration metrics. Much of the literature focuses on individual minerals, regional case studies, or specific supply-chain segments rather than comparative assessments across multiple mineral systems. In addition, renewable energy technologies are often treated as relatively homogeneous categories despite important differences in mineral intensity, substitutability, and refining dependence across technologies such as EV batteries, wind turbines, solar photovoltaics, and hydrogen systems (Vakulchuk et al., 2020).

Third, less attention has been devoted to examining whether concentration structures remain persistent across alternative long-term energy-transition pathways. Although decarbonization scenarios are widely used to estimate future mineral demand, less research has explored whether accelerated transition scenarios materially alter the geography of mining and refining concentration or reduce chokepoint vulnerability over time.

This paper contributes to these debates by comparatively analyzing concentration dynamics across key critical minerals used in clean-energy technologies under multiple energy-transition scenarios. The study distinguishes between mining and refining concentration structures and evaluates how these evolve across Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS), and Net Zero Emissions by 2050 Scenario (NZE) using International Energy Agency datasets. Concentration is assessed primarily through the Top-3 Concentration Ratio (CR_3), supplemented by approximate Herfindahl–Hirschman Index (HHI) estimates to illustrate asymmetry within highly concentrated refining systems.

The analysis highlights three main findings. First, refining concentration appears generally more acute and persistent than mining concentration across most critical minerals examined. Second, accelerated energy-transition scenarios substantially increase mineral demand without necessarily producing equivalent diversification in refining capacity. Third, while all six minerals exhibit varying degrees of concentration risk, graphite, cobalt, lithium, and rare earth elements display particularly severe chokepoint exposure due to highly concentrated refining systems and limited short-term substitutability.

Rather than treating critical mineral vulnerabilities as deterministic outcomes, the analysis emphasizes that concentration risks are shaped by technological change, industrial policy, recycling capacity, market coordination, and geopolitical strategy. The study therefore does not assume that existing concentration patterns are immutable and recognizes that industrial upgrading, technological substitution, and policy coordination may alter supply-chain structures over time. Instead, it evaluates the extent to which current mining and refining systems may constrain diversification under projected transition pathways.

The findings contribute to the literature on critical minerals and energy security by comparatively assessing concentration persistence across mining and refining stages. More broadly, the study highlights how the industrial geography of mineral processing may shape supply-chain resilience, industrial strategy, and the political economy of the energy transition.

The remainder of the paper is organized as follows. Section 2 presents the data sources, scenario framework, and analytical methodology. Section 3 examines technology–mineral dependencies, demand trajectories, and chokepoint sensitivity across clean-energy technologies. Section 4 analyzes concentration patterns in mining and refining together with their geopolitical implications. Section 5 evaluates the persistence of midstream chokepoints across alternative energy-transition scenarios. Section 6 discusses the broader implications for energy security, industrial strategy, and supply-chain governance in the context of accelerating decarbonization.

2. Methodology

2.1. Data sources and scope

This study draws on the International Energy Agency's (IEA) Critical Minerals Dataset (IEA, 2025b), which provides comprehensive scenario-based projections of mineral demand, supply, and technology-specific demand patterns for the period 2024–2050. The analysis integrates four core components: (1) total mineral demand by year and scenario—Net Zero Emissions by 2050 Scenario (NZE), Announced Pledges Scenario (APS), and Stated Policies Scenario (STEPS); (2) base-case supply projections for mining and refining capacities by country; (3) technology-specific mineral demand across major clean-energy sectors, including electric vehicles (EVs), wind, solar photovoltaics (PV), electricity networks, grid battery storage, and hydrogen technologies; and (4) clean-energy mineral demand by scenario and year.

The analysis focuses on six strategically significant minerals—lithium, cobalt, nickel, graphite, rare earth elements, and copper—selected due to their importance for clean-energy technologies, concentration risks, and cross-sectoral industrial relevance. The temporal scope spans 2024–2050, with particular attention to 2030, 2040, and 2050 as key transition benchmarks.

2.2. Scenario framework

The analytical foundation of this study is based on three IEA climate-policy scenarios reflecting different levels of policy ambition and technological deployment. The Net Zero Emissions by 2050 Scenario (NZE) represents the most ambitious pathway, aligned with limiting global warming to 1.5°C through accelerated electrification, rapid renewable-energy deployment, energy-efficiency improvements, and large-scale expansion of low-carbon infrastructure. The Announced Pledges

Scenario (APS) incorporates all climate commitments and net-zero targets formally announced by governments as of 2024, assuming full and timely implementation. The Stated Policies Scenario (STEPS) reflects currently enacted or legislated policies and therefore represents the most conservative transition trajectory among the three scenarios.

Mineral demand is projected annually from 2024 through 2050 across these scenarios, enabling comparative analysis of how varying levels of climate-policy ambition influence the scale and composition of critical mineral demand over time. Supply-side projections are provided in five-year increments through 2040 and include both mining and refining capacities by country. These projections are based on the IEA's base-case assessment of operating and announced projects, taking into account financing status, permitting progress, project maturity, and technical feasibility. By comparing concentration metrics across scenarios, the analysis identifies supply-chain structures that may remain significant under different decarbonization pathways.

2.3. Analytical framework: concentration metrics

This study employs a comparative analytical framework to evaluate how different levels of climate-policy ambition influence critical mineral demand and associated supply-chain concentration risks. The analysis integrates both demand-side and supply-side dimensions to assess vulnerabilities across minerals, technologies, and stages of the supply chain.

On the demand side, the framework examines the three IEA climate scenarios—STEPS, APS, and NZE—to evaluate projected growth trajectories for lithium, cobalt, nickel, graphite, REEs, and copper across the period 2024–2050. Growth multipliers are calculated across three temporal intervals (2024–2030, 2030–2040, and 2040–2050) to identify how varying levels of decarbonization ambition affect mineral demand expansion over time.

To further assess sectoral exposure, the framework calculates the clean-energy share of total mineral demand, defined as the proportion of total demand attributable to low-carbon technologies. This approach distinguishes minerals driven primarily by clean-energy deployment from those with broader industrial demand structures. The analysis also differentiates demand across major clean-energy technologies, including EV batteries, wind turbines, solar PV systems, electricity networks, hydrogen technologies, and grid battery storage, in order to assess technology-specific mineral dependencies and chokepoint sensitivity.

On the supply side, concentration risk is evaluated using country-level mining and refining projections derived from the IEA dataset. The principal concentration metric employed is the Top-3 Concentration Ratio (CR_3), which quantifies the combined market share held by the three largest mining or refining countries. CR_3 is calculated as:

$$CR_3 = \frac{\left(\sum_{i=1}^{3} Q_i\right)}{Q_{global}} \times 100$$

where Q_i denotes production of the top three countries by output and Q_{global} the total global output.

For analytical purposes, chokepoint severity is classified into three tiers: severe ($CR_3 \geq 75\%$), moderate ($50\% \leq CR_3 < 75\%$), mild ($CR_3 < 50\%$). Concentration metrics (CR_3) are applied separately to (upstream) mining and (midstream) refining stages. While mining concentration is influenced partly by geological endowments and extraction capacity, refining concentration reflects broader industrial and technological capabilities. Refining systems are often slower to diversify and expand than mining capacity due to capital intensity, technical specialization, and permitting constraints. As a result, refining concentration may remain comparatively persistent under rapidly growing demand conditions.

To complement CR_3 and capture asymmetry within highly concentrated supply chains, the study also employs the Herfindahl–Hirschman Index (HHI), calculated as:

$$HHI = \sum_{i=1}^{n} s_i^2$$

where s_i represents the market share of producer i, and n is the total number of producing countries. Whereas CR_3 measures aggregate concentration among leading producers, HHI[1] provides additional insight into whether concentration is distributed across several major producers or dominated primarily by a single actor (U.S. Department of Justice and Federal Trade Commission, 2010). For example, a CR_3 of 80% could reflect three firms with shares of 27%, 27%, and 26% (HHI ≈2187) or one firm with 70% and two with 5% each (HHI ≈ 4950). The latter reflects a substantially more asymmetric market structure. By integrating both CR_3 and HHI, the analysis provides a more thorough assessment of concentration dynamics in critical mineral refining.

By integrating demand projections, technology-specific dependencies, CR_3 metrics, and HHI estimates, the framework operationalizes chokepoint risk through measurable indicators and enables comparative assessment of systemic constraints across minerals, technologies, and transition scenarios.

2.4. Limitations and replicability

Several limitations merit acknowledgment. First, the analysis relies on IEA datasets and projections, which are inherently uncertain given future changes in technology, policy implementation, industrial strategy, and geopolitical conditions. Second, the study focuses on six strategically significant minerals and does not capture the full spectrum of materials relevant to the energy transition, such as platinum-group metals, silver, or silicon.

Third, while the framework identifies concentration risks and chokepoints, it does not model disruption probabilities or estimate the economic costs associated with supply interruptions. Fourth, the analysis does not quantitatively incorporate demand-side adjustments such as material substitution, recycling expansion, circular-economy dynamics, or technological breakthroughs, although these factors are discussed qualitatively in the discussion section. Fifth, the dataset excludes informal and artisanal mining activities, which remain especially relevant for cobalt and graphite supply chains.

Finally, concentration metrics such as CR_3 and HHI provide indicators of concentration but cannot fully capture dynamic factors such as vertical integration, export restrictions, strategic stockpiling, or firm-level market coordination. All calculations are based on fixed values within the IEA scenario framework to ensure internal consistency and comparability across scenarios. Metrics, formulas, and calculation procedures are provided in the **Appendix.**

3. Demand for critical minerals

The global energy transition is reshaping patterns of industrial dependency and strategic resource competition, increasing the importance of critical minerals within the global energy system. Whereas twentieth-century energy security was shaped largely by hydrocarbons, contemporary energy transitions increasingly involve mineral-intensive industrial dependencies. This transformation is driven by a dual dynamic: the rapid diversification of demand as clean-energy technologies scale, and the persistent geographic concentration of critical mineral supply.

In the NZE scenario, clean-energy technologies emerge as the dominant consumers of several key minerals. By 2050, over 90% of global lithium demand is projected to originate from low-emission

[1] HHI values presented in this study are approximate estimates calculated using reported country-level refining shares and a residual category representing all remaining producers.

technologies, alongside around 60% of cobalt and nickel, and between 40% and 60% of graphite and rare earth elements (Table 1). Once peripheral to the energy system, these minerals now underpin core components of clean-energy infrastructure: electric vehicle batteries, wind turbines, power grids, and hydrogen electrolysers. These materials increasingly function as strategically important industrial inputs.

The pace and scale of this transformation are historically significant. In the NZE pathway, total mineral demand for clean-energy technologies is projected to grow from 12.3 million tonnes in 2024 to approximately 43 million tonnes by 2050. Even under less ambitious pathways—APS and STEPS—demand still reaches approximately 37 million and 28 million tonnes respectively. This surge is concentrated in six highly central minerals: lithium, nickel, graphite, cobalt, rare earth elements, and copper.

Across all scenarios, mineral demand growth remains concentrated within a relatively small group of strategically important minerals. In the NZE pathway, the six minerals examined account for nearly 80% of clean-energy mineral demand in 2024 and continue to represent approximately 75% by 2050. This concentration increases the potential for supply disruptions within individual minerals to affect multiple clean-energy sectors simultaneously, including electric mobility, electricity networks, and hydrogen deployment. Table 2 summarizes projected demand growth and refining concentration across the principal transition minerals.

Among the minerals examined, lithium exhibits the most rapid projected growth, increasing more than thirteenfold by 2050 under the NZE scenario to approximately 1.68 million tonnes. Nickel demand increases eightfold, graphite fivefold, and cobalt more than fourfold. Copper grows more modestly but remains strategically indispensable because of its foundational role in electrification and electricity networks.

These overlapping dependencies create a structurally exposed system in which substitution possibilities remain uneven. Some technological adaptation is occurring—for example, lithium iron phosphate (LFP) batteries reduce cobalt intensity—but such shifts often reconfigure material dependencies, increasing exposure to lithium and graphite refining instead. Consequently, disruptions in graphite refining could simultaneously affect battery manufacturing, stationary storage systems, and segments of hydrogen infrastructure.

These vulnerabilities are compounded by temporal mismatches between accelerating demand and slower supply-side expansion. In the NZE pathway, lithium supply is projected to meet only approximately 37% of demand by 2030. Even under APS and STEPS pathways, supply adequacy remains constrained. Given that major mining and refining projects often require 7–15 years to become operational, rapid short-term adjustment remains difficult without accelerated permitting, investment, and processing expansion.

Refining capacity for several critical minerals remains highly concentrated, particularly in China, reflecting long-term industrial policy support, infrastructure investment, and accumulated processing expertise. However, concentration alone does not automatically translate into geopolitical leverage. The strategic significance of refining concentration depends on factors such as substitutability, technological adaptation, industrial coordination, and the availability of alternative processing ecosystems.

In this study, chokepoints are understood not simply as statistical concentrations, but as supply-chain vulnerabilities capable of affecting multiple clean-energy sectors. Chokepoints emerge where supply is concentrated within a narrow set of countries and where disruption or strategic restriction can cascade across multiple clean-energy technologies. Accordingly, chokepoint analysis requires both concentration metrics (CR_3 and HHI) and attention to geopolitical agency, industrial lock-in, and supply-chain rigidity.

Table 1
Clean-energy shares of total mineral demand, NZE scenario (%).

Mineral/Category	2024	2030	2040	2050	Strategic role
Lithium	62	88	92	92	Battery core mineral
Cobalt	32	60	57	58	Battery co-input – declining share due to chemistry shift
Nickel	17	45	58	59	Dual role: batteries and hydrogen electrolysers
Battery-grade Graphite	32	64	64	49	Primary anode material; supply chain bottleneck
Rare Earth Elements (Nd, Dy, Pr, Tb)	21	43	41	40	Magnet inputs – essential for EVs and wind turbines
Copper[a]	29	44	50	48	Grid and network backbone metal

Note: Author's calculations based on IEA Net Zero by 2050 Scenario datasets. Values are rounded multi-year averages.

[a] By 2050, copper's role within the energy system deepens in both relative and absolute terms: its clean-energy share of total demand rises from about 29% to nearly 50%, while total clean-energy copper demand expands roughly 2.4 × under the NZE scenario (as shown in Table 2).

3.1. *Technology–mineral dependencies, substitutability, and chokepoint sensitivity*

Different clean-energy technologies exhibit varying dependencies on critical minerals, with differing levels of substitutability, refining dependence, and chokepoint sensitivity. Table 3 provides a comparative qualitative assessment of substitutability, refining dependence, and chokepoint sensitivity across major clean-energy technologies.

EV batteries exhibit the highest chokepoint sensitivity as they rely simultaneously on lithium, graphite, nickel, and cobalt—minerals characterized by high refining concentration. While chemistry shifts such as LFP batteries reduce cobalt intensity, they often reinforce dependence on lithium and graphite refining.

Wind turbines using permanent magnet generators depend heavily on rare earth elements such as neodymium, praseodymium, and dysprosium. Although induction-generator alternatives exist, they may involve efficiency trade-offs, especially in offshore applications. Solar PV systems exhibit comparatively lower chokepoint sensitivity as silicon is geologically abundant, although processing capacity remains concentrated. Silver and thin-film materials such as tellurium and indium introduce additional supply-chain dependencies.

Electricity networks depend heavily on copper and, increasingly, aluminum under large-scale electrification pathways. Although these materials are comparatively more geographically diversified than several battery minerals, rapidly expanding grid infrastructure may still generate important refining and processing bottlenecks under accelerated transition scenarios.

Hydrogen technologies—including electrolysers and fuel cells—depend on nickel and platinum-group metals. Although substitution research continues, refining concentration and industrial bottlenecks remain important sources of concentration risk in the near to medium term. Grid battery storage systems exhibit mineral dependencies broadly similar to EV batteries, particularly for lithium, graphite, and nickel. Although stationary storage applications may permit somewhat greater flexibility in battery chemistry selection, refining concentration and large-scale deployment requirements continue to generate moderate-to-high chokepoint sensitivity.

These technology–mineral profiles demonstrate that concentration exposure and chokepoint sensitivity vary substantially across clean-energy technologies. Taken together, these technology-specific differences suggest that concentration risk within critical mineral supply chains is not uniform across the energy transition, but instead varies according to mineral intensity, substitutability, refining dependence, and infrastructure-scaling requirements.

Table 2
Top-growth minerals by clean-energy demand (by 2050) and refining concentration.

Mineral	Demand growth × (STEPS)	Demand growth × (APS)	Demand growth × (NZE)	Key drivers	Top refining (2024 Base-Case, %)
Lithium	8.0×	10.9×	13.1×	EV and stationary batteries	China 70% Chile 20% Argentina 5%
Nickel	5.0×	7.2×	8.0×	High-Ni cathodes, hydrogen electrolysers	Indonesia 43% China 31% Russia 4%
Battery-grade Graphite	2.9×	3.9×	5.0×	EV anodes	China 96% Japan 2% United States 0.05%
Cobalt	2.4×	3.4×	4.1×	Li-ion stabilizer	China 78% Finland 8% Japan 2%
Rare Earth Elements (Nd, Dy, Pr, Tb)	3.0×	4.1×	4.2×	Magnets for wind and EVs	China 91% Malaysia 5% United States 1%
Copper	1.8×	2.1×	2.4×	Grid networks and electrification	China 44% Chile 7% Japan 6%

Note: Author's calculations based on IEA datasets.

Table 3
Technology–mineral dependencies, substitutability, and chokepoint sensitivity.

Technology	Key Minerals	Substitutability	Refining Dependence	Chokepoint Sensitivity
EV Batteries	Lithium, cobalt, nickel, graphite	Low–Moderate	High	High
Wind Technologies	Rare earth elements	Low	High	High
Solar PV Systems	Silicon, silver, tellurium, indium	Moderate	Moderate	Medium
Hydrogen Technologies	Nickel, platinum-group metals	Moderate	Moderate–High	Medium–High
Electricity Networks	Copper, aluminum	Moderate	Moderate	Medium
Grid Battery Storage	Lithium, graphite, nickel	Moderate	High	Medium–High

Note: Substitutability refers to the availability of alternative materials or technological pathways. Refining dependence reflects reliance on geographically concentrated processing capacity. Classifications are qualitative assessments based on CR_3/HHI concentration metrics based on the IEA Critical Minerals Dataset.

4. Supply-side concentration in mining and refining, and geopolitical implications

4.1. *Supply-side concentration in mining and refining*

Critical mineral supply chains exhibit significant geographic concentration across both mining and refining activities. However, refining represents one of the most structurally persistent sources of concentration risk within critical mineral supply chains. To assess these bottlenecks systematically, this study employs the Top-3 Concentration Ratio (CR3)— the combined market share of the three largest producing or refining countries. In addition, selected Herfindahl–Hirschman Index (HHI) calculations are used to supplement CR3 analysis by capturing asymmetry within concentration structures.

Drawing on IEA base-case projections for 2024, 2030–2035 averages, and 2040, these indicators provide a basis for evaluating supply-chain dependencies and concentration asymmetries within the political economy of decarbonization. Table 4 illustrates CR_3 patterns across six key minerals—copper, cobalt, lithium, nickel, graphite, and rare earth elements—illustrating concentration patterns across mining and refining stages.

The results demonstrate that both mining and refining are highly concentrated, with refining consistently more centralized. For copper, for instance, the three largest mining countries—Chile, the Democratic Republic of Congo (DRC), and Peru—account for nearly half of global extraction, yet China alone refines almost 47% of refined output. Similarly, the DRC dominates cobalt extraction (62%), while more than three-quarters of cobalt refining occurs in China. Lithium exhibits moderate upstream concentration (67%) but significantly higher midstream concentration (85%), with China responsible for more than 60% of global refining capacity. Nickel presents a distinctive dual-core configuration in which Indonesia and China dominate both extraction

Table 4
Concentration of mining and refining for key minerals (2030 Base case, %).

Mineral	Mining CR_3	Leading mining countries	Refining CR_3	Leading refining countries
Copper	47	Chile 22.7% DR Congo 14.7% Peru 10.0%	57	China 46.6% Chile 5.5% Japan 4.8%
Cobalt	83	DR Congo 62.0% Indonesia 18.1% Russia 2.5%	87	China 77.5% Finland 6.2% Indonesia 3.3%
Lithium	67	China 28.5% Australia 26.3% Chile 12.3%	85	China 61.6% Chile 12.9% Argentina 10.9%
Nickel	79	Indonesia 67.7% Philippines 6.0% Russia 5.0%	81	Indonesia 45.2% China 32.9% Russia 3.2%
Graphite	86	(natural) China 63.3% Madagascar 12.0% Mozambique 10.5%	91	(battery-grade) China 87% Japan 3.6% United States 0.7%
Rare earths (Nd, Dy, Pr, Tb)	75	China 51.0% Australia 13.0% Myanmar 11.0%	88	China 75.7% Malaysia 9.3% United States 7.8%

Note: Author's calculations based on IEA datasets. Table 4 is based on the IEA's 2030 base-case dataset (operating and announced projects). Tables 5 and 6 use a smoothed average of 2030 and 2035 to represent mid-term concentration trends.

and refining. For graphite and rare earth elements, China maintains highly concentrated positions across both stages.

Consequently, the top three refining countries account for a majority—and in several cases, a supermajority—of global supply. This concentration is further illustrated in Table 5, which tracks CR_3 trends from 2024 through 2040.

The persistence of concentration across multiple time horizons suggests that the energy transition may generate new forms of mineral-centered dependence alongside the gradual decline of hydrocarbon dependence. Importantly, these concentration structures remain relatively persistent across alternative transition pathways, even as demand trajectories differ substantially.

Although mining is also constrained by geological location, permitting cycles, and capital-intensive development, midstream refining exhibits particularly strong path dependencies. Refining systems depend on technologically specialized metallurgical and chemical infrastructure that is difficult to relocate or replicate at scale. Expansion is further constrained by high capital requirements, technical specialization, permitting delays, and long project-development timelines. Co-location advantages and integration with downstream industries such as battery manufacturing and EV production further reinforce existing concentration patterns. As a result, even substantial increases in global demand may not rapidly alter the geography of refining concentration.

The gap between mining and refining concentration shown in Table 6 varies across minerals but is especially pronounced in lithium, rare earth elements, and copper. While nickel displays apparent parity between mining and refining concentration, this equilibrium masks a dual-core configuration in which Indonesia and China jointly dominate both extraction and processing. In cobalt and graphite, high concentration persists at both stages of the value chain, creating compound vulnerability.

To supplement CR_3 analysis, selected HHI calculations indicate that concentration is not merely oligopolistic but frequently highly asymmetric, especially in refining systems dominated by a single actor. Graphite and rare earth refining exhibit markedly elevated HHI values because one country—China—accounts for the overwhelming majority of global processing capacity. These findings suggest that chokepoint risk depends not only on market concentration itself, but also on how refining capacity is distributed among dominant actors.

The HHI estimates in Table 7 reinforce the broader concentration patterns identified through CR_3 analysis while providing additional insight into the internal structure of refining dominance. Graphite refining exhibits particularly elevated concentration due to China's dominant market share, while cobalt and rare earth refining also display extremely asymmetric concentration patterns in which one actor controls a dominant proportion of global processing capacity. Lithium refining remains highly asymmetric, but comparatively more distributed among several producing states, whereas nickel refining reflects a highly concentrated dual-core structure centered on Indonesia and China.

Table 5
Concentration trends by mineral and stage (CR_3, 2024–2040).

Mineral	Segment	2024	2030-35 Avg.	2040	Trend
Copper	Mining	48	47.5	50	↔
Copper	Refining	57	58	60	↑
Cobalt	Mining	81	83	82	↔
Cobalt	Refining	89	86	86	↓
Lithium	Mining	77	67.5	69	↓
Lithium	Refining	96	85	85	↓
Nickel	Mining	78	81	84	↑
Nickel	Refining	78	83	83	↑
Graphite	Mining	93	86	86	↓
Graphite	Refining	98	90	90	↓
Rare Earths	Mining	86	75	76	↓
Rare Earths	Refining	97	92	92	↓

Note: Author's calculations based on IEA datasets. 2030–35 values represent mid-term averages from IEA projections.

Table 6
Refining dominance over mining (Δ%, 2030–2035 Average).

Mineral	Mining CR_3	Refining CR_3	Refining dominance (Δ%)
Lithium	67.5	85	+18
Rare Earths	75	88	+13
Copper	47.5	58	+11
Graphite	86	90	+4
Cobalt	83	86	+3
Nickel	83	83	=

Note: Author's calculations based on IEA datasets.

Table 7
Approximate HHI values for refining concentration (2030 base-case).

Mineral	Top 3 Refining Countries (Shares)	HHI	Concentration Classification
Lithium	China (61.6%), Chile (12.9%), Argentina (10.9%)	≈4290	Highly asymmetric
Cobalt	China (77.5%), Finland (6.2%), Indonesia (3.3%)	≈6225	Extremely asymmetric
Nickel	Indonesia (45.2%), China (32.9%), Russia (3.2%)	≈3490	Highly concentrated
Graphite	China (87%), Japan (3.6%), United States (0.7%)	≈7660	Extremely concentrated and asymmetric
Rare Earth Elements	China (75.7%), Malaysia (9.3%), United States (7.8%)	≈5930	Extremely concentrated and asymmetric

Note: Author's calculations based on IEA datasets. HHI values are approximate estimates calculated using reported country-level refining shares and a residual category representing all remaining producers. The metric is employed here to supplement CR3 analysis by illustrating asymmetry within concentrated refining systems rather than as a comprehensive market-structure model.

Copper behaves differently from the other minerals because refining capacity is more geographically diversified and distributed across a larger number of producers. Although China remains the largest refining actor, the residual market share is fragmented among numerous countries rather than concentrated within a narrow group of dominant producers. As a result, HHI estimates for copper can artificially overstate concentration when residual producers are aggregated into a single category. For this reason, copper is excluded from the selected HHI illustration despite its strategic importance for electrification and electricity networks.

The HHI analysis also highlights an important distinction between concentration and asymmetry. Although lithium and cobalt exhibit similarly high CR_3 values, cobalt's substantially higher HHI reflects the far greater dominance of a single refining actor. Similarly, graphite's exceptionally high HHI underscores the combined effects of extreme concentration and asymmetry within its refining structure. These findings suggest that chokepoint severity depends not only on concentration itself, but also on how market shares are distributed among leading actors.

In this study, chokepoints refer to concentration patterns capable of generating broader supply-chain vulnerability across multiple clean-energy sectors. However, concentration alone does not automatically translate into strategic leverage, which also depends on factors such as substitutability, technological adaptation, industrial coordination, and alternative processing capacity.

4.2. Geopolitical implications

As critical minerals become increasingly central to energy, defense, and digital systems, dominance in refining capacity and supply-chain coordination may provide important geopolitical advantages. Countries that dominate refining—most notably China—occupy structurally advantageous positions within clean-energy supply chains because influence increasingly derives from the ability to transform raw materials into value-added industrial outputs.

The conversion of technological capacity into geopolitical leverage operates through several reinforcing dimensions. These illustrate how control over refining infrastructure and industrial technologies allows states to translate technical dominance into systemic influence (Table 8).

Together, these mechanisms illustrate how midstream concentration functions not only as an economic bottleneck, but also as a source of geopolitical influence. Countries possessing extensive refining capacity, metallurgical expertise, and integrated industrial ecosystems are increasingly able to shape market dynamics, influence supply-chain governance, and coordinate strategic industrial policy.

At the same time, mineral-rich but industrially underdeveloped countries—including the Democratic Republic of Congo, Peru, Madagascar, Mozambique, and Myanmar—often remain primarily concentrated in extraction-oriented roles with limited downstream value capture. In the absence of significant midstream investment, these countries risk remaining dependent on external refining ecosystems.

China has strategically consolidated midstream leverage through expansive investments in overseas mining and refining projects. Between 2000 and 2021, it disbursed approximately USD 57 billion in aid and concessional loans to nineteen Belt and Road Initiative (BRI) countries to develop extractive infrastructure (Jamasmie, 2025). In 2023 alone, its overseas metals and mining investments totaled USD 19.4 billion (Zhou and Månberger, 2024), with state-owned enterprises leading most projects. In 2024, 18% of all BRI-linked investment—approximately USD 21.4 billion—was allocated to mining activities (IEA, 2025c).

This capacity is reinforced by the integration of refined materials into downstream sectors including battery manufacturing, electric vehicles, grid battery storage, and advanced industrial technologies. Firms such as CATL and BYD exemplify how refining capacity, industrial policy, and manufacturing scale can reinforce strategic positioning within global supply chains.

Emerging AI-driven digital infrastructure may intensify these dynamics further. Expanding datacenters, semiconductors, electricity-network upgrades, and computational infrastructure are likely to increase demand for copper, rare earth elements, electricity systems, and associated mineral inputs, potentially amplifying existing midstream concentration pressures.

As the energy transition accelerates, refining capacity and export governance are likely to become increasingly important arenas of international competition. However, the future evolution of these systems will also depend on technological substitution, recycling, diversification strategies, strategic coordination among importing states, and the extent to which alternative refining ecosystems emerge over time.

Table 8
How midstream technological capacity may translate into geopolitical influence.

Dimension	Geopolitical mechanism	Technological expression
Asymmetric interdependence	Resource-rich states remain dependent on refining hubs, limiting their ability to capture value or influence supply.	Concentration of refining technologies and metallurgical expertise centralizes value creation.
Weaponization potential	Dominant actors can impose export restrictions or selective supply, converting market power into strategic leverage.	Ownership of refining, separation, and purification technologies enables targeted trade coercion.
Alliance formation	Shared vulnerabilities foster coordinated supply-chain diplomacy and industrial partnerships.	Joint R&D, technology-transfer agreements, and cooperative refining ventures.
Technology competition	Leadership in refining standards and intellectual property locks downstream manufacturers into dependent supply chains.	Control over technical standards, patents, and industrial scaling.
Environmental arbitrage	Concentration in weaker-regulated jurisdictions externalizes costs and sustains cost advantages.	Technological and regulatory asymmetries shape production geography and competitiveness.

5. Results: spatial persistence of midstream chokepoints across transition scenarios

A defining feature of the clean-energy transition is the persistence of concentration across several critical mineral supply chains under different decarbonization pathways. Across the STEPS, APS, and NZE scenarios, strategically important segments of these supply chains—particularly refining—remain highly concentrated. These patterns suggest that while clean-energy technologies may alter the material foundations of energy systems, they do not necessarily eliminate structural dependencies associated with mining and refining capacity.

Integrating demand projections with supply-side concentration metrics reveals the severity and persistence of these chokepoints across minerals and scenarios. Table 9 summarizes chokepoint severity across six key minerals at both the mining and refining stages based on the IEA's 2030 base-case projections (visualized in Fig. 1).

Several findings emerge when Table 9 is considered alongside Table 2. First, refining concentration remains severe ($CR_3 > 75\%$) for five of the six minerals across all scenarios and time periods. Lithium, cobalt, graphite, nickel, and rare earth refining remain notably concentrated through 2050, even under slower-transition pathways. Second, concentration remains persistently high over time, especially in refining systems where industrial expansion proceeds more rapidly than geographic diversification.

Accelerated transition pathways may intensify some midstream pressures by increasing mineral demand more rapidly than refining capacity can expand geographically. However, the implications of concentration vary across minerals and technologies depending on factors such as substitutability, recycling potential, technological flexibility, and the availability of alternative refining capacity. The persistence of these chokepoints reflects the interaction between rapidly expanding

Table 9
Chokepoints by mineral and stage (2030 base-case, %).

Mineral	Mining CR_3	Refining CR_3	Mining Risk	Refining Risk	Chokepoint Severity
Copper	47%	57%	Mild	Moderate	Relatively diversified mining; refining more vulnerable (China 46.6%)
Cobalt	83%	87%	Severe	Severe	DRC dominates mining (62%); China leads refining (77.5%)
Lithium	67%	85%	Moderate	Severe	China controls 61.6% of refining; midstream is the critical bottleneck
Nickel	79%	81%	Severe	Severe	Indonesia dominates both stages; refining also concentrated in China
Graphite	86%	91%	Severe	Severe	Extremely high concentration centered on China
Rare Earths	75%	88%	Severe	Severe	China dominates both stages; long-standing strategic concern

Note: Author's calculations based on IEA Critical Minerals Dataset (2024). Chokepoint severity is classified into three tiers: **severe (≥75%), moderate (50–75%), mild (<50%)** based on the Top-3 Concentration Ratio (CR_3).

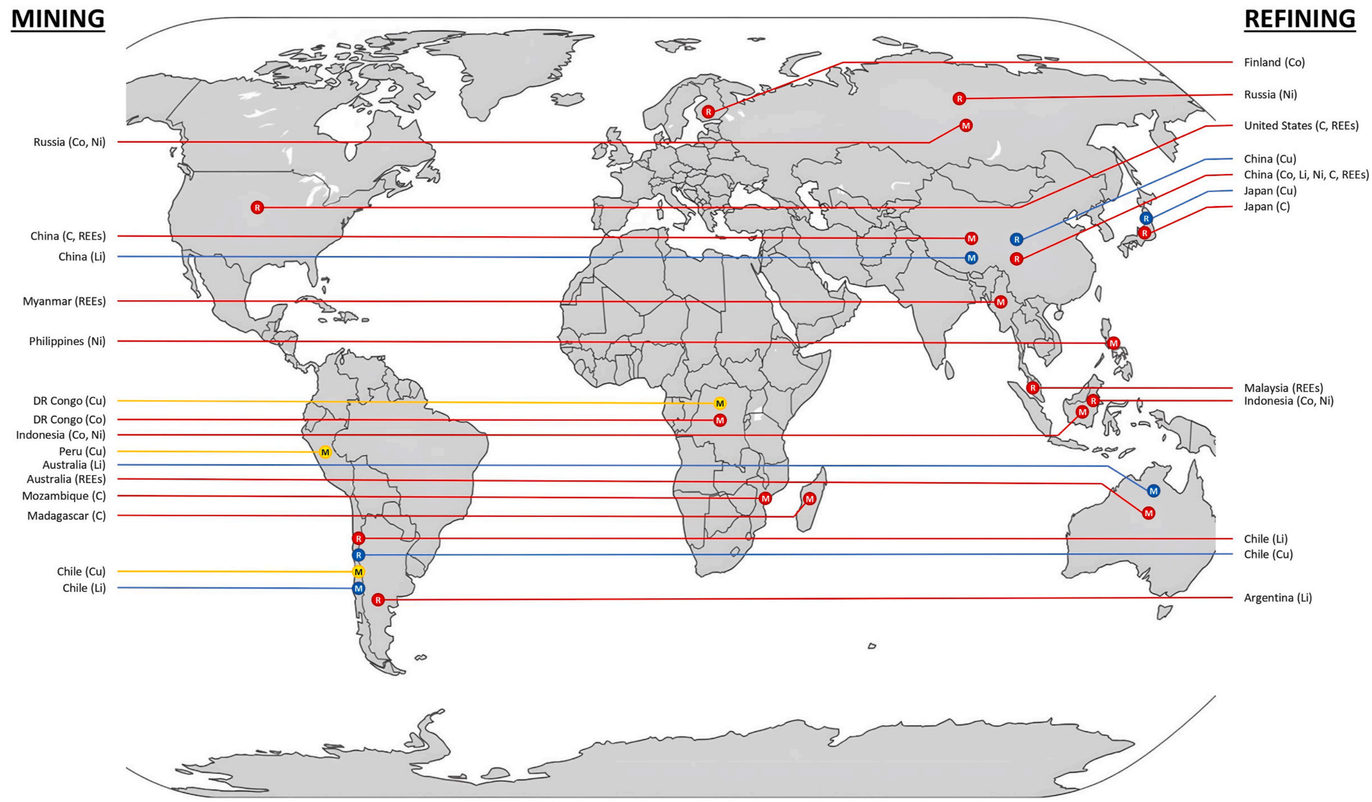

Fig. 1. Chokepoint Geography by Top-3 Concentration Ratio (CR_3), (2030 Base Case)
Notes: Countries inherit mineral chokepoint severity based on their CR_3 status in mining or refining. Chokepoint severity is classified into three tiers: **severe (≥75%)** (Red), **moderate (50–75%)** (Blue), **mild (<50%)** (Yellow). Six minerals are considered: Lithium (Li), Cobalt (Co), Nickel (Ni), Graphite (C), Rare Earth Elements (REEs), Copper (Cu). Map lines delineate study areas and do not necessarily depict accepted national boundaries.

demand and comparatively slow rates of industrial-capacity expansion. Although demand trajectories differ substantially across scenarios, refining systems diversify more gradually than clean-energy deployment, limiting the pace of geographic diversification within critical mineral supply chains.

The comparative findings presented in Tables 6 and 7 also reveal variation within highly concentrated refining systems. Although lithium and cobalt exhibit similarly high CR_3 values, cobalt's substantially higher HHI indicates a more uneven distribution of refining capacity centered on a single dominant actor. Lithium refining, while still highly concentrated, remains comparatively more distributed across several producers. Graphite displays both extremely high concentration and strong asymmetry, reflecting the dominance of a single refining hub. These differences indicate that similarly concentrated mineral systems may exhibit distinct internal market structures.

Lithium and rare earth elements also exhibit particularly large disparities between mining and refining concentration, with refining remaining substantially more concentrated than extraction. Copper behaves differently from the other minerals examined in this study because mining activity remains comparatively diversified geographically, while refining concentration is moderate rather than severe. This suggests that copper vulnerability derives less from severe concentration itself and more from the scale of future electrification demand and copper's central role in electricity networks, transmission infrastructure, and digital systems.

While nickel displays near parity between mining and refining concentration, this apparent symmetry reflects a dual-core structure in which Indonesia and a limited number of refining actors jointly dominate both extraction and processing. In cobalt and graphite, high concentration persists simultaneously at both stages of the value chain, creating compound exposure across mining and refining systems.

The countries embedded within these chokepoints occupy different positions within the emerging clean-energy political economy. Inclusion within a CR_3 grouping, however, does not imply equal influence across mineral systems. Some actors possess greater technological capacity, institutional coordination, industrial integration, and export-governance capability than others. In several refining systems—including graphite, cobalt, and rare earth elements—market concentration is also associated with substantial asymmetry in processing capacity and downstream industrial integration.

The potential for strategic leverage has already been demonstrated in practice. China's export restrictions on gallium and germanium in 2023 illustrated how midstream technological and refining dominance can be operationalized within broader geopolitical competition (U.S. International Trade Commission et al., 2024). Although these measures involved minerals outside the core set examined here, they nevertheless demonstrate how concentrated refining capacity can become strategically consequential under conditions of geopolitical rivalry.

Fig. 1 visualizes the spatial distribution of chokepoint concentration across both mining and refining stages. Several refining hubs emerge as central nodes within highly concentrated supply-chain configurations, while countries including the Democratic Republic of Congo, Indonesia, Chile, Australia, Madagascar, and Myanmar occupy important upstream positions within mineral supply chains.

Concentration alone, however, does not automatically translate into geopolitical dominance. The significance of chokepoints depends on several intervening factors, including substitutability, technological adaptation, vertical integration, institutional capacity for export governance, strategic coordination among importing states, and the development of alternative refining ecosystems. Battery chemistry shifts, recycling, and supply-chain diversification efforts may gradually reduce dependence on some concentrated systems, although these adjustments are likely to unfold unevenly and over extended time horizons.

Additional vulnerabilities also emerge from conditions surrounding upstream extraction. Several mineral-producing countries face institutional fragility, infrastructural limitations, or political instability, creating further uncertainty within global supply chains. Yet the implications of these upstream risks depend largely on how they interact with the more technologically intensive and geographically concentrated refining systems located elsewhere.

Taken together, these findings suggest that the energy transition may reconfigure strategic dependencies around mineral-intensive industrial systems. While renewable energy technologies may decentralize electricity generation at the point of use, the supply chains underpinning them remain highly concentrated, particularly within midstream refining capacity.

6. Discussion

6.1. Decarbonization and persistent refining concentration

The findings indicate that decarbonization does not necessarily reduce concentration within the material systems underpinning the energy transition. Although renewable electricity generation can become more geographically distributed, critical mineral refining remains concentrated within a limited number of industrial hubs. Across several minerals examined in this study, refining CR_3 values remain above 85%, while HHI estimates indicate substantial asymmetry within these systems.

At the same time, concentration should not be interpreted as synonymous with automatic geopolitical leverage. The strategic implications of refining concentration depend on technological substitution, industrial coordination, recycling capacity, diversification efforts, and policy responses among importing economies. The findings therefore point less toward deterministic dependency than toward concentration-related risks under conditions of rapid demand growth.

These dynamics suggest that long-term energy resilience increasingly depends not only on decarbonization itself, but also on diversification strategies, alternative refining ecosystems, and circular-economy capacity.

6.2. Technology-specific vulnerabilities and chokepoint sensitivity

The analysis demonstrates that critical mineral vulnerabilities differ substantially across clean-energy technologies. This distinction is important because the energy transition is often discussed as a relatively uniform process despite major variation in mineral intensity, substitutability, and refining dependence across technologies.

EV batteries exhibit particularly high chokepoint sensitivity because they depend simultaneously on lithium, graphite, nickel, and cobalt refining systems, several of which remain highly concentrated geographically. Although battery chemistries continue to evolve, including shifts toward lower-cobalt configurations such as lithium iron phosphate (LFP) batteries, these transitions may reduce dependence on some minerals while reinforcing dependence on others, particularly lithium and graphite supply chains.

Wind turbines relying on permanent magnet systems remain heavily dependent on REE refining capacity, especially for neodymium, praseodymium, and dysprosium. Although technological alternatives exist, they may involve trade-offs in efficiency, scale, or deployment and operational costs, especially in offshore applications where permanent magnet systems remain advantageous.

Solar PV systems exhibit comparatively lower chokepoint sensitivity because silicon is geologically abundant and production is more geographically dispersed than several battery minerals. Nevertheless, dependencies remain significant in areas such as polysilicon processing and certain thin-film materials, including tellurium and indium.

Taken together, these findings suggest that chokepoint risk cannot be evaluated solely through aggregate mineral demand projections. The severity of vulnerability depends not only on concentration levels, but also on technological substitutability, downstream manufacturing structures, industrial adaptability, and the pace at which alternative supply chains can emerge.

6.3. Industrial policy, diversification, and capacity constraints

The persistence of refining concentration suggests that market mechanisms alone may be insufficient to diversify critical mineral supply chains at the pace implied by global decarbonization targets. Recent initiatives—including the U.S. Inflation Reduction Act, the EU Critical Raw Materials Act, and the Minerals Security Partnership—reflect growing recognition that refining capacity constitutes a strategic industrial capability rather than merely a commercial activity.

However, diversification faces substantial structural barriers, including high capital requirements, technical specialization, permitting constraints, and long project-development timelines. These constraints help explain why refining systems diversify more slowly than global mineral demand expands.

Diversification strategies also involve trade-offs between resilience, affordability, efficiency, and environmental sustainability. More geographically distributed refining systems may reduce strategic dependency but can also increase production costs and weaken economies of scale. Similar constraints apply to recycling systems. Although recycling may mitigate long-term vulnerabilities, large-scale deployment still requires substantial technological development, infrastructure investment, and industrial coordination.

At the same time, vertical integration and long-term procurement arrangements may partially reduce exposure to supply disruptions. Major automakers and battery manufacturers are increasingly investing in mining partnerships, refining capacity, and long-term supply agreements to strengthen supply-chain resilience, even where geographic concentration persists.

6.4. China's position in global refining supply chains

China occupies a dominant position across multiple critical mineral refining supply chains, yet it is important to distinguish dominance from monopoly. Although China controls exceptionally large shares of refining capacity for several minerals examined in this study, alternative refining capacity exists in countries including Indonesia, Chile, Finland, Malaysia, Japan, South Korea, and the United States.

China's position reflects decades of industrial policy, vertical integration, infrastructure development, technological accumulation, and downstream manufacturing integration rather than short-term market fluctuations alone. The integration of refining systems with battery manufacturing, EV production, magnet industries, and broader industrial ecosystems further reinforces these advantages.

Importantly, the findings suggest that vulnerability arises not solely from dependence on a single country, but from the broader structural concentration of refining capacity within a limited number of actors and industrial hubs. Concentration therefore represents a broader supply-chain coordination challenge rather than simply a bilateral dependency relationship.

At the same time, current concentration patterns should not be interpreted as permanent or uncontested. Attempts to weaponize supply chains may accelerate diversification efforts, stimulate substitution, intensify industrial policy responses, and encourage strategic coordination among importing economies. The long-term evolution of refining systems therefore remains dynamic and contingent rather than predetermined.

Accordingly, the analysis does not imply that existing concentration structures are immutable. Rather, it identifies conditions under which refining concentration may generate heightened vulnerability, particularly under accelerated transition scenarios characterized by rapidly expanding mineral demand.

6.5. Rethinking energy security in the mineral age

The transition from fossil-fuel systems toward mineral-intensive energy systems requires a broader conception of energy security. Traditional frameworks focused primarily on fuel availability, transportation chokepoints, and price stability, whereas the clean-energy transition increasingly introduces vulnerabilities linked to refining capacity, industrial ecosystems, technological specialization, and long-term supply-chain resilience.

These vulnerabilities extend beyond the energy sector itself. Critical minerals increasingly underpin advanced manufacturing, semiconductors, electricity networks, defense systems, and AI-driven digital infrastructure. The rapid expansion of AI infrastructure and hyperscale datacenters may further intensify demand for copper, rare earth elements (REEs), nickel, graphite, and other strategic minerals required for semiconductors, electricity networks, power electronics, and cooling systems. In this sense, decarbonization and digitalization are becoming increasingly interconnected industrial transformations.

The findings therefore suggest that critical mineral chokepoints represent systemic constraints associated with the industrial organization of the energy transition itself. These vulnerabilities become particularly significant where refining capacity, technological capabilities, and industrial coordination remain highly concentrated.

6.6. Limitations and future research

Several limitations should be acknowledged. First, the analysis relies on IEA scenarios, which remain sensitive to future policy implementation, technological change, industrial strategy, and geopolitical developments. Alternative transition pathways may therefore produce different concentration trajectories over time.

Second, the study focuses on six strategically significant minerals and does not capture the full range of materials relevant to clean-energy technologies, advanced manufacturing and digital infrastructure. Future research could expand the scope to include additional minerals and industrial supply chains. Third, CR_3 and HHI provide structural indicators of concentration but cannot fully capture dynamic dimensions of leverage such as export restrictions, ownership structures, vertical integration, strategic stockpiling, or long-term contractual arrangements.

Fourth, while substitution, recycling, and technological adaptation are discussed conceptually, these dynamics are not modeled quantitatively within the present framework. Future research should integrate these factors more systematically into long-term concentration and vulnerability assessments. Finally, this study does not attempt to predict the strategic behavior or intentions of states. Rather, it identifies structural conditions under which refining concentration may become geopolitically consequential under alternative energy-transition pathways.

7. Conclusions and policy implications

This study examined the evolving geography of critical mineral supply chains under three IEA transition pathways—NZE, APS, and STEPS—with particular attention to the distinction between mining and refining concentration. By integrating scenario-based demand projections with CR_3 and selected HHI concentration metrics, the analysis evaluated how mineral demand growth, refining concentration, and chokepoint risks may evolve through 2050.

The findings indicate that refining concentration remains substantially higher and more persistent than mining concentration across most minerals and scenarios examined. Graphite, cobalt, lithium, and REE refining exhibit markedly elevated concentration levels, while HHI estimates further demonstrate that several refining systems are not only concentrated, but also highly asymmetric in their internal structure. Accelerated decarbonization pathways substantially increase mineral demand but do not necessarily produce equivalent geographic diversification in refining capacity. These dynamics suggest that future supply-chain vulnerability depends not only on mineral availability, but also on the industrial organization of refining systems and the pace at which alternative processing capacity can emerge.

More broadly, the analysis suggests that the clean-energy transition may reconfigure strategic dependencies around mineral-intensive industrial systems. While renewable energy technologies can decentralize electricity generation at the point of use, the industrial systems underpinning them remain highly concentrated in several segments of the supply chain, particularly refining and advanced processing capacity.

At the same time, the findings should not be interpreted erministically. Concentration alone does not automatically translate into geopolitical leverage, nor are existing refining structures necessarily permanent. Future trajectories will depend on technological adaptation, recycling expansion, substitution pathways, industrial-policy coordination, vertical integration strategies, and the emergence of diversified refining capacity. The study therefore identifies conditions of heightened vulnerability rather than fixed geopolitical outcomes.

Several policy implications emerge from the analysis. First, energy-security frameworks increasingly need to incorporate midstream industrial resilience alongside traditional concerns related to fossil-fuel supply, pipeline systems, and maritime transport chokepoints. Second, diversification strategies should extend beyond mining expansion alone. Policy efforts increasingly also require geographically diversified refining systems, downstream industrial integration, and long-term investment in metallurgical and chemical processing capacity. Third, recycling and circular-economy systems may gradually reduce some concentration pressures over time, although large-scale deployment will itself require substantial technological and industrial capacity. Finally, international coordination mechanisms—including strategic partnerships, long-term procurement arrangements, joint refining initiatives, and coordinated industrial policies—may become increasingly important under conditions of concentrated refining capacity.

The findings also suggest that the accelerating interaction between decarbonization and digitalization may intensify future pressure on critical mineral systems. Expanding AI infrastructure, datacenters, electricity networks, advanced semiconductors, and digital industrial systems are likely to increase demand for copper, rare earth elements, nickel, graphite, and associated strategic minerals beyond earlier transition assumptions focused primarily on renewable energy and electric mobility.

Overall, the study contributes to the growing literature on critical minerals and energy security by demonstrating that midstream refining capacity constitutes a central dimension of long-term supply-chain resilience within mineral-intensive energy systems. Future research could extend this framework through disruption modeling, trade-network analysis, firm-level ownership structures, recycling scenarios, and technology-substitution pathways in order to evaluate how concentration dynamics evolve under alternative industrial and geopolitical conditions.

Declaration of competing interest

The author declares that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

APPENDIX A. Technical Methodology and Data Validation

A1. Dataset descriptions

This study draws on the International Energy Agency's (IEA) *Critical Minerals Dataset* and integrates five core datasets covering mineral demand, supply projections, and technology-specific applications across the period 2024–2050.

- Dataset 1 – Total demand for key energy-transition minerals (2024–2050) across STEPS, APS, and NZE scenarios.
- Dataset 2 – Base-case supply projections for mining and refining capacity by country, including operating and announced projects.
- Dataset 3 – Mineral demand by clean-energy technology and sector (electric vehicles, wind, solar PV, electricity networks, grid battery storage, and hydrogen technologies).
- Dataset 4 – Aggregate mineral demand for clean-energy technologies by mineral (kt, 2024–2050) for all scenarios.

Tables produced from the datasets.

Table	Description	Main Dataset(s)
Table 1	Clean-energy shares of total mineral demand	*Total demand for key minerals (Dataset 1) + Cleantech demand by mineral (Dataset 4)*
Table 2	Demand growth and refining concentration across scenarios	*Cleantech demand by tech (Dataset 3) + Cleantech demand by mineral (Dataset 4) + Total supply for key minerals (Dataset 2)*
Table 3	Technology–mineral dependencies and chokepoint sensitivity	*Cleantech demand by tech (Dataset 3) + literature synthesis*
Table 4	Mining and refining concentration by mineral	*Total supply for key minerals (Dataset 2)*
Table 5	Concentration trends (2024–2040)	*Total supply for key minerals (Dataset 2)*
Table 6	Refining dominance over mining concentration	*Total supply for key minerals (Dataset 2)*
Table 7	Country-level refining shares used to estimate approximate Herfindahl–Hirschman Index (HHI) values for selected minerals.	*Total supply for key minerals (Dataset 2)*

A2. Formulae for key calculations

- Demand expansion analysis:

Clean-energy mineral demand was aggregated for each scenario (STEPS, APS, NZE) and benchmark year (2024–2050). Growth factors were computed as:

$$G = \frac{D^{2050}}{D^{2024}}$$

where D^{2050} and D^{2024} represent total clean-energy mineral demand (kt) for 2050 and 2024 respectively.

- Clean-energy share estimation:

The proportion of each mineral's total demand attributable to clean-energy technologies was derived as:

$$St = \left(\frac{Ct}{Tt}\right) \times 100$$

where Ct represents clean-energy demand and Tt total demand in year t.

- Supply-side concentration metrics:

The Top-3 Concentration Ratio (CR_3) quantifies the sum of market shares held by the top three mining and refining countries:

$$CR_3 = \frac{\left(\sum_{i=1}^{3} Q_i\right)}{Q_{global}} \times 100$$

where Q_i denotes production of the top three countries by output and Q_{global} the total global output. Chokepoint severity is classified as extreme (>70%), high (50–70%), moderate (30–50%), or low (<30%) based on CR_3 thresholds.

- Herfindahl–Hirschman Index (HHI)

To assess asymmetry within concentrated refining systems, approximate HHI values were calculated as:

$$HHI = \sum_{i=1}^{n} s_i^2$$

where s_i represents the market share of producer i, and n is the total number of producing countries. Higher HHI values indicate greater concentration and stronger dominance by a limited number of actors.

A3. Data availability and replicability

All numerical data used in this study were obtained from publicly accessible datasets accompanying the IEA critical minerals dataset, which include scenario-based projections of mineral demand, supply, and technology-specific applications. All calculations—covering growth multipliers, concentration ratios, and clean-energy demand shares—are reproducible through the formulas detailed in the Appendix, with complete excel datasets available on the IEA website, Critical Minerals Dataset: https://www.iea.org/data-and-statistics/data-product/critical-minerals-dataset.

Data availability

https://www.iea.org/data-and-statistics/data-product/critical-minerals-dataset.

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