CRITICAL METALS IN THE ENERGY TRANSITION: SUPPLY CHAIN CONCENTRATION, GEOPOLITICAL RISK, AND STRATEGIC VULNERABILITIES

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Introduction

The worldwide energy transition has become one of the defining economic and social changes across the globe in the twenty-first century. Motivated by climate mitigation targets, technology advancement and changing regulatory landscapes, governments and corporations around the world are rapidly expanding investment in low-carbon technologies (e.g., electric vehicles (EVs), renewable energy generation, battery storage systems and electricity grid infrastructure). The energy transition – although usually considered as a change of the sources of energy – is also an evolution in commodity demand, which develops, now necessarily and increasingly, a new focus on an ensemble of minerals commonly known as critical metals.

Critical metals such as lithium, cobalt, nickel, and copper play an indispensable role in enabling energy transition technologies. Lithium, cobalt and nickel are critical materials for lithium-ion batteries that power EVs and ESSs, while copper is a basic ingredient in electrification, grid expansion, renewable energy installations and electric mobility. With these technologies increasingly being rolled, demand for critical metals has surged in recent years and changed commodity markets with wider strategic implications for market participants as well policy makers near and far.

Unlike traditional fossil energy products, critical metals have concentrated supply chains, long lead times for investment, and high political and environmental risks. Mining and milling–refining operations also tend to be highly concentrated in a few countries, leading the global supply chain to greater political risk, trade disruptions, and regulatory uncertainty. And, meanwhile, the processing and refining of several key metals are heavily concentrated amongst a small number of players, further compounding vulnerabilities a cross these supply chains. These structures give cause for asking important questions about the capacity of global markets to serve growing demand in a secure and sustainable way.

Rising volumes of energy transition technologies have resulted in a structural shift in demand for essential metals yet supply in these markets is characterised by long development cycles, high geographical concentration and regulatory complications. A core issue is the gap between increasing demand signals and a supply chain’s ability to effectively fulfill them. Although governmental policies, e.g., electric vehicle subsidies, renewable power targets and industrial plans for clean technologies have increased the growth of demand, mining and refining capabilities on critical metals cannot easily be expanded technically or environmentally nor socially. This generates the continuing danger of bottlenecks in supply which could be expressed through price volatility, trade disruption and strategic confrontation between consuming regions.

Moreover, the concentration of these production and refining centres in a few nations creates systemic weaknesses. In fact, for a number of critical metals, mining is controlled by a handful of producers and refining capacity is frequently more concentrated still. This calls into question both supply security, especially in a time of geopolitical rivalries and trade decoupling. In spite of the increasing awareness being raised on these problems, prior research studies often lay emphasis on price transmission, structure of supply chains and policy measures as separate analytical dimensions. This piecemeal strategy restricts the ability to monitor how energy transition developments are reflected in price performance and strategic vulnerabilities of critical metal supply chains.

The main aim of the article is to investigate how critical metals fit into the landscape of the global energy transition, with a special emphasis on dynamic price dynamics and strategic supply chain structure interplay. With the rise of low-carbon technologies, critical metals are now playing more prominent roles in industrial policy, geopolitics and commodity markets. The goal of this research is to provide insight into these phenomena by combining qualitative supply chain analysis with quantitative market-based evidence.

Methodology

This article applies a mixed-method methodology in order to examine the strategic vulnerabilities of critical metal supply chains in the context of the global energy transition. The study combines qualitative comparative case study analysis with descriptive quantitative tools, allowing to assess both structural features of supply chains and selected indicators of concentration. The use of mixed methods is intended to complement qualitative discussion about supply chains and policy with quantitative analysis of concentration calculation. Rather than aiming for a complex methodology, the study seeks for clarity and transparency to keep alignment with the purpose of the research.

The key qualitative method is a comparative case study analysis centered on four critical metals: lithium, cobalt, nickel and copper. These metals were selected because they play a fundamental role in energy transition technologies and display distinct supply chain patterns. Lithium, cobalt and nickel are more directly linked to battery manufacturing and electric mobility, while copper has a broader systemic role in electrification and electricity infrastructure. By comparing these cases, the analysis identifies both common trends and metal-specific patterns in supply concentration, processing structures and exposure to strategic risk. In addition to the case study approach, the article incorporates policy analysis in order to explain how government interventions shape critical metal supply chains.

To complement the qualitative analysis, the article applies supply concentration metrics to assess structural vulnerabilities in critical metal supply chains. Concentration measures provide a numerical representation of how dependent global supply is on a limited number of producing or processing countries and therefore help identify potential exposure to geopolitical risk, regulatory shocks and supply disruptions. The analysis focuses on two key stages of the supply chain: mining production and refining or processing capacity. These stages are selected because they represent the most critical bottlenecks for metals used in energy transition technologies.

$$HHI = \sum s_i^2$$

Supply concentration is measured using the Herfindahl–Hirschman Index (HHI), calculated as the sum of squared country shares in global production or refining capacity. Higher HHI values indicate greater concentration and lower diversification. For each metal, HHI values are calculated separately for mining and refining, using data for the top producing and processing countries only. Specifically, the analysis includes the five largest countries at each stage, which together account for the substantial majority of global output. The interpretation of HHI values follows commonly used thresholds from industrial organization literature, where values below approximately 1,500 indicate relatively low concentration, values between 1,500 and 2,500 indicate moderate concentration, and values above 2,500 indicate high concentration. In this article, these thresholds are used as indicative benchmarks rather than strict classifications. High concentration is interpreted as a signal of structural vulnerability, particularly when dominance is concentrated in countries facing political, regulatory or environmental constraints.

The data used in the analysis are drawn from publicly available international sources. Production data are mainly taken from the U.S. Geological Survey, refining and processing data are based on publications of the United Nations Conference on Trade and Development, complemented with industry reports where applicable. The HHI metrics are descriptive and are not included in econometric models. Their purpose is to supplement the qualitative analysis by measuring supply chain features discussed descriptively and by identifying where strategic vulnerabilities are most likely to emerge.

Literature review

The world's ongoing energy transition – the transition from fossil-based energy systems to low-carbon alternatives – has brought a materials dimension to decarbonisation strategies. After the initial focus on energy sources and emissions, policy and academic debates have increasingly been devoted to the physical inputs needed to scale up clean energy technologies. Renewable electricity, EVs, battery storage and power grids are all far more mineral- and metal-intensive than traditional fossil-fuelled technologies. Consequently, the success of the energy transition is increasingly reliant on the accessibility, affordability and security of supply of a group of materials generally known as critical metals [International Energy Agency (IEA), 2021; World Bank, 2023].

The concept of critical metals is not related to a specific, fixed, or generally accepted list of elements. Rather, criticality is commonly described in terms of two primary dimensions: economic importance and supply risk. Economic importance refers to the contribution that a material makes to important industries and strategic technologies, and supply risk indicates the potential for disruption as a result of production concentration in certain geographies, governance issues, environmental constraints or lack of substitutability. Based on this framework, institutions such as the European Commission and the U.S. Department of Energy periodically update lists of critical raw materials to reflect changes in technology, markets, and geopolitical conditions [European Commission, 2023; U.S. Department of Energy, 2023].

In the energy transition, lithium, cobalt, nickel and copper have garnered significance as they are critical for deployments of electrification and energy storage solutions. Lithium is a key ingredient in lithium-ion batteries, which dominate EV and stationary storage markets. Cobalt and nickel are ingredients in several battery chemistries that boost energy density and performance, so they are critical inputs for long-range electric vehicles. Copper, while not directly related to battery chemistry, is a substance of utmost necessity for electrification more generally due to its wide application in power grids, renewable energy deployments, transformers, electric motors and EV charging infrastructure [IEA, 2021; IEA, 2024].

One reason critical metals matter for the energy transition is the mineral intensity of clean energy technologies. According to the International Energy Agency, EVs need more minerals per unit of capacity than internal combustion engine vehicles, and renewable power technologies and electricity networks also need large amounts of metals for their construction and installation. This means that decarbonisation pathways which are consistent with climate targets will entail significantly higher cumulative demand for many metals, even if material efficiency and recycling is improved [IEA, 2021]. Further supporting such a perspective, the World Bank calculates that, in order to reach global climate goals, production may need to multiply by dozens of times for certain minerals [World Bank, 2023].

Rising demand for strategic metals has added to market instability. The IEA's Global Critical Minerals Outlook has highlighted episodes of rapid price escalation followed by a course correction in battery materials, captured by a combination of rising demand, supply shortages, speculative behaviour and evolving policy expectations [IEA, 2024]. This contrasts with historical commodity cycles, where the growth of demand was more closely tied to macroeconomic shifts than to policy-driven structural trends. Accordingly, price signals may not elicit timely supply responses, especially given the long start-up periods for developing new mining and smelting capacity.

The structure of the supply chain is a key determinant of how critical these metals are. It is not only the upstream mining stage that matters, but also the midstream processing and refining stages. Refining capacity, in many cases, is even more geographically concentrated than mining, providing potential chokepoints that could disrupt global supply even when raw material supplies are adequate. These structural features give rise to concerns that supply chains could become stumbling blocks rather than enablers for the energy transition, particularly amid escalating geopolitical risks and trade splintering [IEA, 2024; IRENA, 2023].

To address this risk, governments are moving to direct both industrial and trade policies toward securing access to key metals. A more active industrial policy in raw materials is reflected in the European Union's Critical Raw Materials Act, which seeks to alleviate strategic dependencies while securing supply sources and bolstering domestic processing capabilities [European Commission, 2023]. The United States has similarly identified key materials as a strategic priority for the energy sector and has pursued initiatives to support domestic and allied supply chains [U.S. Department of Energy, 2023]. Such policy responses demonstrate that critical metals are increasingly thought of in strategic and geopolitical terms rather than merely as commodities transacted on world markets.

Critical metals in the energy transition exhibit highly concentrated global supplies as a defining feature. In contrast with many conventional commodities, for which production and processing are more widely distributed, key steps in the extraction, processing and refining of critical metals take place in a few countries. This concentration presents geopolitical and strategic risks that may exacerbate market volatility and erode supply reliability, especially at times of political tension or policy interference. The refining capacity for a number of battery metals is much more geographically concentrated than mining output, providing chokepoints that have the potential to destabilize global supply even when raw material production is in place [Bridge & Faigen, 2022].

Recent research also emphasizes the increasing importance of geo-economic competition in critical metal supply chains. With energy transition technologies emerging as strategic products, critical metals are more likely to be viewed as tools of economic statecraft than neutral resources that trade on market fundamentals alone. Farrell and Newman describe this as "weaponized interdependence," in which control over critical nodes within global economic networks provides states with levers for coercion [Farrell & Newman, 2019]. In tightly packed critical metal supply chains, these dynamics leave import-dependent regions doubly exposed. Governance and institutional quality in producing areas also matter, since regime instability, regulatory uncertainty and social unrest can affect supply reliability and investor confidence [EITI, 2023].

Critical metals markets are increasingly shaped by government policy and industrial strategy in the wake of the energy transition. Policies such as electric vehicle subsidies, renewable energy targets, carbon pricing and requirements for grid expansion all drive demand for metals used in batteries, electrification and clean power systems. At the same time, governments intervene on the supply side through industrial policies focused on mining, refining and processing capacity, especially in regions concerned about dependence on foreign suppliers [Aghion et al., 2016; Dechezleprêtre & Sato, 2017; Evenett & Fritz, 2022]. Trade and investment policies such as export restrictions, local content requirements and investment screening mechanisms can influence where and how critical metals are produced and processed, while also increasing price volatility and uncertainty in concentrated markets [Bown, 2021; Evenett & Fritz, 2022].

The acceleration of the energy transition has also significantly altered corporate behavior across critical metal value chains. Firms face a market environment characterized by long-term growth expectations, heightened price volatility, supply chain concentration and policy uncertainty. In response, corporate strategies have evolved beyond traditional short-term optimization toward approaches focused on securing supply, managing risk and positioning for structural market change. Among the leading corporate responses has been vertical integration, with mining companies moving downstream into processing and refining, while battery and automotive manufacturers move upstream to secure raw materials [Williamson, 1985; Bridge, 2008]. Long-term offtake agreements, geographic diversification and stronger risk management have also emerged as core strategic tools [Humphreys, 2020; Gibbon & Ponte, 2005]. Commodity trading companies play an essential role in bridging geographically separated suppliers and buyers, managing logistics and financing, and acting increasingly as risk intermediaries in politically sensitive critical metal markets [Trafigura, 2018].

Despite the growing literature, several gaps remain. First, research often concentrates either on supply-side risks or on demand projections based on energy transition scenarios, while offering fewer explicit connections between these structural features and observed price dynamics. Second, despite extensive qualitative evaluations of supply chain risks, there is limited systematic empirical evidence on how prices react to policy changes. Third, critical metals are often treated as a homogeneous group even though their market structures, applications and trading characteristics differ significantly. Finally, there is still insufficient integration of qualitative supply chain analysis with quantitative market evidence. This is the gap the present study addresses by combining case-study analysis of critical metal supply chains with evidence on prices, policy events and concentration measures in order to provide a more integrated and market-responsive view of the strategic role of critical metals in the energy transition [Pindyck, 2001].

Scientific novelty

The scientific novelty of this article lies in its integrated and metal-specific approach to the study of critical metals in the context of the global energy transition. While existing literature often discusses critical metals as a broad and homogeneous group, this study demonstrates that lithium, cobalt, nickel, and copper differ significantly in their supply chain structures, price behavior, and exposure to policy and geopolitical risk. In this sense, the article moves beyond generalized discussions of critical raw materials and provides a more differentiated interpretation of strategic vulnerabilities across metals.

A second contribution of the article is the combination of qualitative supply chain analysis with quantitative concentration metrics. In particular, the study incorporates Herfindahl–Hirschman Index (HHI) calculations for both mining and refining stages, which makes it possible to identify structural bottlenecks more clearly and to show that refining concentration is often a more serious vulnerability than mining concentration alone. This helps bridge the gap between descriptive supply chain discussions and measurable indicators of concentration risk.

Finally, the article contributes to the literature by presenting a strategic vulnerability framework that links supply concentration, geopolitical exposure, and policy-driven market change within a single analytical perspective. By doing so, it provides a more integrated understanding of how critical metal markets function under the accelerating energy transition and offers conclusions that are relevant not only for academic discussion, but also for policymakers, commodity traders, and industry participants.

Results and analysis

The qualitative case studies and the HHI concentration results together show that critical metal supply chains differ significantly in structure, exposure to risk, and strategic vulnerability. Although lithium, cobalt, nickel, and copper are all essential to the energy transition, they do not face the same types of constraints. The case studies reveal wide variation in upstream mining concentration, downstream refining bottlenecks, and vulnerability to political and regulatory uncertainty. These structural asymmetries help explain why critical metals should not be treated as a homogeneous category and why strategic vulnerability emerges in different ways across markets.

Lithium represents a case where downstream dependence is more severe than upstream scarcity alone would suggest. The qualitative analysis shows that lithium has become indispensable for battery technologies and therefore occupies a central place in the energy transition. At the same time, the lithium supply chain is characterized by a strong concentration of refining and chemical conversion capacity, which creates a structural chokepoint between raw extraction and battery-grade products. This finding is strongly reinforced by the HHI results. Lithium mining shows a highly concentrated structure, with an HHI of 3,034.0, indicating meaningful upstream concentration. However, lithium refining exhibits very high concentration, with an HHI of 5,555.0. This means that even where mining is distributed across several countries, access to processed lithium remains heavily dependent on one dominant refining jurisdiction. The combined evidence therefore suggests that the major strategic vulnerability in lithium lies less in extraction alone and more in downstream processing and refining control.

Cobalt emerges as the most structurally vulnerable of the four metals. The qualitative case study highlights the exceptional concentration of cobalt mining in a single producing country, together with governance concerns, regulatory uncertainty, and geopolitical sensitivity. These factors make cobalt particularly exposed to supply disruption and policy-driven market instability. The HHI results strongly confirm this assessment. Cobalt mining displays extreme concentration, with an HHI of 5,704.3, the highest among all metals analysed. Cobalt refining also shows extreme concentration, with an HHI of 5,426.0. The combination of these two values indicates compounding concentration risk across the value chain, making cobalt uniquely exposed to geopolitical and policy-related disruptions. This is why cobalt is consistently identified as one of the most strategically sensitive metals in the energy transition. The qualitative and quantitative findings therefore point in the same direction: cobalt's vulnerability is rooted both in upstream geographical dependence and in downstream industrial concentration.

Nickel presents an intermediate case. The qualitative evidence suggests that nickel has become increasingly important because of its role in high-nickel battery chemistries and the wider expansion of electric mobility. At the same time, its supply chain is shaped by a mixture of industrial concentration, evolving processing capacity, and policy-related uncertainty. The HHI analysis shows that nickel mining exhibits a high level of concentration, with an HHI of 3,815.3, reflecting the dominant role of a limited number of producers.

Nickel refining also displays a highly concentrated structure, with an HHI of 2,685.0, which exceeds the threshold for high concentration. Compared with cobalt, nickel is less extreme, but the pattern still indicates that both upstream and downstream segments are exposed to structural constraints. The case study therefore supports the view that nickel is strategically important not only because of demand growth from batteries, but also because limited processing diversification can create bottlenecks in battery-grade material supply.

Copper stands apart from the other three metals. The qualitative case study presents copper as the broadest and most systemically important metal in the energy transition because of its role in electrification, grid expansion, renewable power systems, electric motors, and charging infrastructure. Unlike lithium, cobalt, and nickel, copper is not tied to one narrow technological use, but rather to the wider electrification of the economy. The HHI results show that copper mining exhibits the lowest concentration, with an HHI of 968.8, indicating a relatively diversified global mining base. However, copper refining exhibits a high concentration, with an HHI of 3,193.5. This divergence is one of the most important findings of the analysis. It demonstrates that even a metal with diversified upstream production can still face strategic vulnerabilities when downstream processing is more concentrated. Thus, copper appears less vulnerable at the mining stage than the battery metals, but still exposed through refining, industrial policy, and the broader challenge of ensuring sufficient processed supply for accelerating electrification demand.

The comparative interpretation of the HHI results reveals several clear patterns. First, refining concentration is in most cases at least as important as mining concentration, and in some cases more important. Lithium is the clearest example of this asymmetry: although mining is already concentrated, the refining stage represents the more severe chokepoint. Second, cobalt is exceptional because it is extremely concentrated at both stages, which creates a compounded form of structural vulnerability. Third, copper shows that relatively diversified mining does not eliminate strategic risk if refining remains concentrated. Finally, nickel occupies an intermediate position, with substantial but less extreme concentration than cobalt. Taken together, these patterns show that supply chain vulnerabilities in critical metals are driven not only by geological scarcity, but also by institutional and industrial concentration, particularly at the refining stage.

The broader qualitative findings of the thesis reinforce this interpretation. The accelerating global energy transition has elevated lithium, cobalt, nickel, and copper to strategic importance, yet the rapid growth in demand for these materials is unfolding within supply chains marked by long development cycles, pronounced geographical concentration, environmental and governance risks, and deepening geopolitical tensions. These structural features help explain why supply security has become a central concern of industrial policy and why governments increasingly seek to diversify sources of extraction, expand domestic or allied refining capacity, and reduce dependence on dominant processing hubs. The case studies therefore show that critical metals are not only inputs into clean technologies, but also strategic assets within a more contested global economic environment.

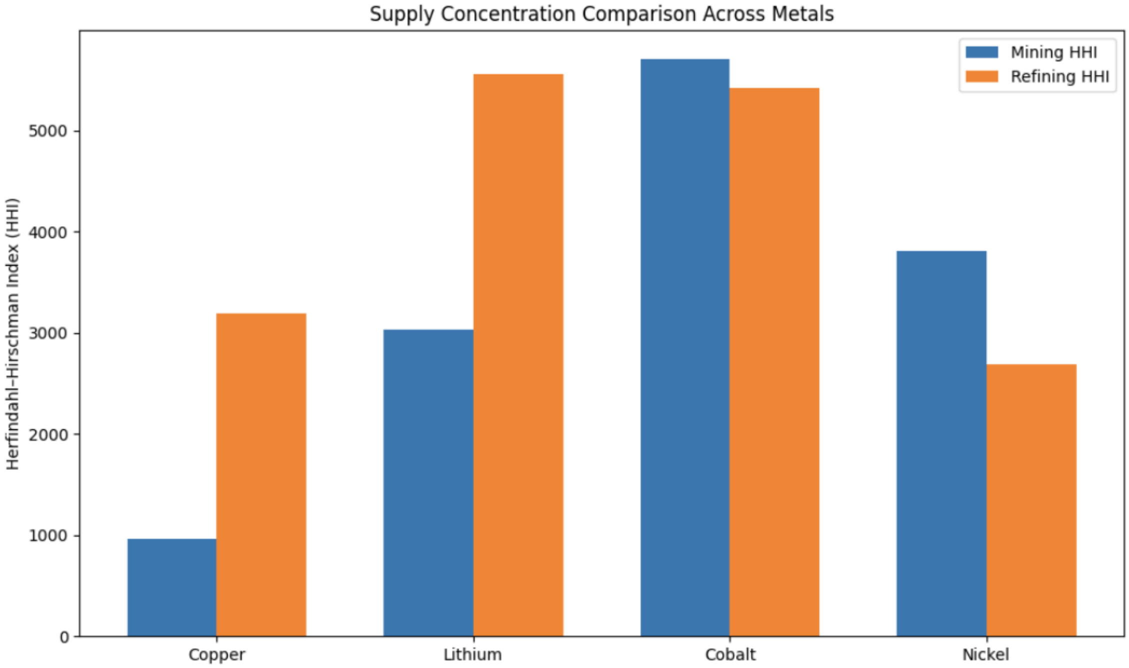

Figure 1. Supply concentration across metals

Taken together, the qualitative case studies and HHI analysis support the central argument of the article: the energy transition is creating not only new demand for critical metals, but also new forms of strategic vulnerability rooted in concentrated and unevenly distributed supply chains. The results indicate that these markets cannot be understood through traditional commodity frameworks alone. Instead, they increasingly reflect a policy-driven and strategically contested environment in which supply chain resilience, geopolitical alignment, and downstream industrial capacity play central roles. In this sense, the analysis shows that the most important bottlenecks in critical metal markets are often not simply where the resource is mined, but where it is refined, processed, and controlled.

Policy advice

The findings of this study suggest that policy responses to critical metal vulnerability should move beyond a narrow focus on raw material access and instead address the full supply chain. Securing mining output alone is not sufficient if refining and processing remain heavily concentrated in a limited number of jurisdictions. The HHI results and qualitative case studies show that downstream concentration often represents the more serious strategic bottleneck, particularly for lithium and cobalt. For this reason, policymakers should place greater emphasis on diversifying refining and processing capacity, not only extraction. This requires support for domestic and allied-country investment in midstream capacity, as well as stronger long-term industrial strategies aimed at reducing dependence on dominant processing hubs.

At the same time, governments should strengthen cooperation with a number of reliable producing and processing partners and promote greater transparency, resilience, and coordination across supply chains. Policies aimed at accelerating the deployment of clean energy technologies should be accompanied by policies that secure the material basis of that transition. Environmental, social, and governance standards should also remain central, because long-term supply security depends not only on increasing volumes, but also on the resilience, legitimacy, and sustainability of supply chains. In this sense, critical metals policy should be designed not only as a resource-access strategy, but also as an industrial, geopolitical, and strategic resilience policy.

Conclusions

This article has shown that the energy transition is creating not only a structural increase in demand for critical metals, but also new forms of strategic vulnerability rooted in concentrated and unevenly distributed supply chains. The comparative case studies of lithium, cobalt, nickel, and copper, together with the HHI results for mining and refining, demonstrate that these metals differ significantly in their concentration levels, supply chain structures, and forms of strategic exposure. Cobalt emerges as the most structurally vulnerable metal due to extreme concentration at both mining and refining stages, lithium shows especially high dependence at the refining stage, nickel remains exposed through concentrated upstream and downstream structures, and copper, although more diversified in mining, still faces downstream concentration risks.

Overall, the results confirm that critical metals should not be treated as a homogeneous group and that their markets cannot be understood only through traditional commodity frameworks. Instead, they increasingly reflect a policy-driven and strategically contested environment in which supply chain resilience, downstream industrial capacity, and geopolitical alignment play central roles. By combining qualitative case study analysis with HHI-based concentration measures, the study provides a more integrated understanding of how strategic vulnerabilities emerge across critical metal markets. The central conclusion is that refining and processing capacity are often the key sources of structural dependence and that future responses to critical metal insecurity must address these downstream bottlenecks if supply security is to keep pace with the accelerating global energy transition.

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Critical Metals in the Energy Transition: Supply Chain Concentration, Geopolitical Risk, and Strategic Vulnerabilities

Key words: critical metals, energy transition, supply chain concentration, strategic vulnerability, Herfindahl–Hirschman Index, lithium, cobalt, nickel, copper

This article examines the strategic role of critical metals in the global energy transition, with a focus on lithium, cobalt, nickel, and copper. The study applies a mixed-method approach combining qualitative comparative case study analysis with Herfindahl–Hirschman Index (HHI) calculations for mining and refining concentration. The findings show that critical metal supply chains are characterized by uneven and highly concentrated structures, with refining often representing a more serious bottleneck than mining. Cobalt appears as the most structurally vulnerable metal due to extreme concentration at both stages, while lithium shows especially high dependence on refining capacity. Nickel also displays significant concentration risks, whereas copper, despite a more diversified mining base, remains exposed through downstream concentration. The results suggest that critical metals should not be treated as a homogeneous group and that their markets are increasingly shaped by geopolitical risk, industrial policy, and strategic competition. The article concludes that supply security in the energy transition depends not only on access to raw materials, but also on the diversification and resilience of downstream processing and refining capacity.