# A Critical Minerals Enabled Energy Future

A Report by the International Energy Forum

December 2025


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INTERNATIONAL ENERGY FORUM

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## About the International Energy Forum

The International Energy Forum (IEF), the global home of energy dialogue, is the trusted and neutral intergovernmental platform for energy dialogue among member states, industry leaders, and experts. Its Ministers represent producing, consuming, and transit countries in every region, at every stage of economic development, and across both established and emerging energy-system supply chains. The IEF advances global energy security through open and inclusive dialogue spanning all fuels, technologies and systems.

## Acknowledgement

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## Executive Summary and Key Messages

- **Critical minerals, advanced energy technologies, and global energy markets are deeply intertwined.** Critical minerals underpin the technological innovations that drive economic growth, energy security, supply-chain resilience, and the competitiveness of emerging clean-energy industries. Meeting rising demand therefore requires forward-looking policy frameworks that ensure the material foundations of energy transitions remain as robust as their technological ambitions.

- **Access to knowledge and human resources are as critical to mineral supply chains as access to resources and markets themselves.** Expanding production and alleviating shortages will depend not only on access to reserves and markets, but also on access to data and the transfer of expertise in mining and refining. Today, these resources and capabilities are concentrated in a limited number of countries, and the skilled workforce with the technical knowledge required to process these minerals for use in advanced manufacturing remains scarce. Building global capacity therefore depends as much on developing people and knowledge, through skills transfer, cross-technology learning, and continually improving practices as it does on securing physical deposits and market access.

- **Criticality in critical minerals is not inherent to the minerals themselves** but reflects national industrial structures and supply-chain dependencies. Countries define critical minerals differently based on their policy and industry priorities, supply risks, and technological needs. Comparative advantages across countries can create opportunities to diversify suppliers and help countries position themselves more strategically within global value chains.

- **Copper demand from electric vehicles rises from around 0.2 Mt in 2020 to approximately 3.4 Mt by 2035 and benefits from a well-diversified market.** Between 2025 and 2035, electric vehicles drive copper demand growth of roughly 14% per year. Copper remains the largest contributor to future mineral demand, driven by grid expansion, widespread electrification, and accelerating Electric Vehicle (EV) deployment. However, despite its central role in energy transitions, copper has relatively low trade concentration across both mining and refining, indicating a diversified global supply structure.

- **More than 60% of global critical mineral demand is met through international trade**, creating deep interdependence between producing and consuming regions. As demand accelerates with the energy transition, this high level of trade integration makes supply-chain resilience essential. Disruptions may quickly cascade and have wide-ranging impacts across clean energy, transportation, advanced manufacturing, and other resource-intensive sectors competing for the same inputs, especially where supply is concentrated, and substitution options are limited.

- **Producer–consumer dialogue is essential to the reliable functioning of critical mineral markets.** The IEF's experience shows that structured, sustained dialogue anchored in trusted data and transparency helps reduce uncertainty, strengthen predictability, and supports more stable markets. Applying this model to emerging critical mineral markets helps align expectations on supply, demand and investment, easing pressure points as demand accelerates.

- **Post-2020 critical mineral policies almost double in volume over the previous two decades**, signaling a sharp acceleration in government engagement. While strategic planning remains the dominant focus, policy priorities are expanding, with international trade and export controls increasingly prominent and, in some cases, now surpassing environmental and sustainability measures. Streamlined licensing and enhanced processing within coherent policy frameworks reduce supply-chain vulnerabilities, while sustained dialogue and robust data improve access to resources, refining, and offtake markets and mitigate volatility in thinly traded segments.

- **Artificial intelligence (AI) is transforming mineral exploration by dramatically improving discovery efficiency and precision.** AI has reshaped exploration by integrating large geospatial, geophysical, and historical datasets to detect and map mineral reserves with far greater precision than conventional methods. Recent applications demonstrate AI's growing role in strengthening domestic supply and supporting critical mineral market security.

- **Well-functioning markets alone cannot resolve all challenges of critical mineral supply and demand fundamentals but remain the pre-condition for their resolution.** Sustained consumer–producer dialogue and international cooperation are essential to ensure critical mineral market security and resilience. Such collaboration can reduce trade hurdles, boost investor confidence, and facilitate technology transfer and knowledge sharing, creating more transparent, efficient and interoperable governance frameworks to meet critical minerals demand growth globally.

- **Market resilience, strengthened through producer–consumer dialogue and effective risk-management strategies, remains essential for critical-mineral market security.** Concentration in critical minerals mining and refining heightens vulnerability and makes dialogue, data sharing, market diversification and other risk management solutions of vital importance. Broadening dialogue on critical minerals supply and demand, including processing and storage capacity can reduce the risk of disruption and help secure the steady flow of minerals necessary for a critical mineral enabled energy future.

## Introduction

Critical Minerals (CMs) are emerging as the backbone of high-tech industries, renewable energy, transportation, and many other sectors. The rapid expansion of Artificial Intelligence (AI) and digitalization sharply increases demand for specific minerals essential to manufacturing advanced technologies[1]. Demand for Rare Earth Elements (REEs) in the European Union - essential for clean-energy technologies and many other applications - rises five-to-six-fold by 2030. At the same time, national commitments under the Paris Agreement to cut emissions and accelerate the shift toward a green economy further amplify demand, placing critical minerals at the center of both technological progress and climate strategy. The continued growth of Electric Vehicle (EV) sales, and their projected increase over the next decade, will intensify demand for key battery minerals, including lithium, cobalt, nickel, manganese, and graphite[2].

These macro-level drivers translate into substantial and material-intensive deployment requirements at the project level. The scale of material demand is already striking, with the installation of just one gigawatt of offshore wind capacity requiring nearly 15,500 tonnes of critical minerals, in addition to large-volume structural materials such as steel and aluminum[3].

As deployment scales, material intensity increasingly becomes a system-level constraint rather than a marginal consideration. If left unresolved, resource limitations could slow the energy transition, escalate costs, and undermine public trust. Mitigating these risks requires diversifying supply, scaling circular economy practices, and advancing substitutes for vulnerable materials[4]. These efforts require international cooperation, systematic knowledge exchange, and sustained long-term dialogue and collaboration[5]. This remains a demanding task given the geoeconomic sensitivities surrounding mineral extraction and refining, the concentration of resources and expertise in a limited number of countries, and ongoing considerations around equitable market access between advanced-consuming countries and developing-producing nations. Strengthening producer–consumer dialogue on critical minerals is therefore essential for enhancing market stability, affordability, and access. The IEF's neutral global energy dialogue shows that well-structured, sustained engagement between producers and consumers can boost market confidence, stimulate trade and investment, support affordability, and enhance market stability through improved transparency that helps markets function more effectively, offering a relevant framework for emerging critical mineral markets.

Managing these pressures requires not only supply-and demand side responses but also reliable data and analytical frameworks to support producer–consumer decision-making. This report contributes to the IEF's ongoing work in this area, building on the 2023 comparative assessment of critical-minerals outlooks[6] and last year's analysis of copper[7], which examines producer–consumer issues across the renewable-energy technology value chain.

## Why Critical Minerals are Critical

Critical minerals (CMs) refer to a group of elements essential for the production of advanced technologies and industrial applications. The term "*critical minerals*" is widely used by

[1] https://ec.europa.eu/commission/presscorner/api/files/attachment/874736/Factsheet_GD_European%20Critical%20Raw%20Materials%20Act%20.pdf
[2] https://www.energy.gov/sites/default/files/2023-07/doe-critical-material-assessment_07312023.pdf
[3] IEA (2021). The Role of Critical Minerals in Clean Energy Transitions, International Energy Forum.
[4] European Commission (2023). Critical Raw Materials Act.
[5] Bazilian, M. (2023). *Critical minerals and the energy transition: toward global governance*. Nature Energy, 8:193–201.
[6] IEF (2023). Critical Minerals Outlooks Comparison, International Energy Forum.
[7] IEF (2024). Copper Mining and Vehicle Electrification, International Energy Forum.

policymakers and the media; however, its definition varies across countries. Each government identifies its own set of minerals as "critical" based on their strategic importance to national industries and supply security. The United States, for example, designates 60 minerals as critical[8], while China lists 40[9], Türkiye 53[10], Japan 35[11] (or 55 if the combined categories such as rare earths are disaggregated) and Australia 31[12] (or 51 if the combined categories such as rare earths are disaggregated). These variations underscore how national strategies are shaped by differing economic structures, resource endowments, and policy objectives, illustrating that "criticality" is not a fixed concept but a function of geoeconomic context and supply chain vulnerabilities.

Seven minerals - Cerium, Cobalt, Dysprosium, Lanthanum, Neodymium, Nickel, and Terbium - are consistently identified as "*Globally Supply-Critical*" across national criticality assessments[13] (Figure 1). The combined evaluations span more than 40 countries (see Appendix 1 for the list of countries included) representing over 90% of global consumption of these minerals. These seven minerals underpin core components of modern technologies, powering electric vehicles, energy storage systems, and advanced aerospace applications. Their unique properties make them essential and difficult to substitute. At the same time, production and refining remain highly concentrated, exposing global supply chains to significant disruption risks ranging from operational outages and transport bottlenecks to policy shifts. Cobalt illustrates this concentration risk: the Democratic Republic of the Congo accounts for more than 70% of global cobalt production[14], concentrating exposure to shocks in a single jurisdiction. Beyond these seven minerals, similar concentration patterns are widespread, nearly 30 countries share a common set of at least 20 minerals that are classified as "*Strategically Indispensable*" to their economies.

[8] https://www.usgs.gov/news/science-snippet/interior-department-releases-final-2025-list-critical-minerals
[9] National Mineral Resources Planning - National Development and Reform Commission
[10] Türkiye | Critical Minerals Initiative Turkiye
[11] Japan's new international resource strategy to secure rare metals / Special Contents -Energy Japan- / Agency for Natural Resources and Energy
[12] Critical minerals in Australia – Parliament of Australia
[13] Despite their importance, limited data makes some of these elements difficult to track in a consistent manner. This report therefore focuses on five minerals: copper, nickel, cobalt, lithium and rare earth elements, whose demand continues to grow across clean energy technologies and diverse industrial sectors.
[14] United States Geological Survey (2025), Mineral Commodity Summaries: Cobalt.

## Global Patterns in the Strategic Importance of Critical Minerals

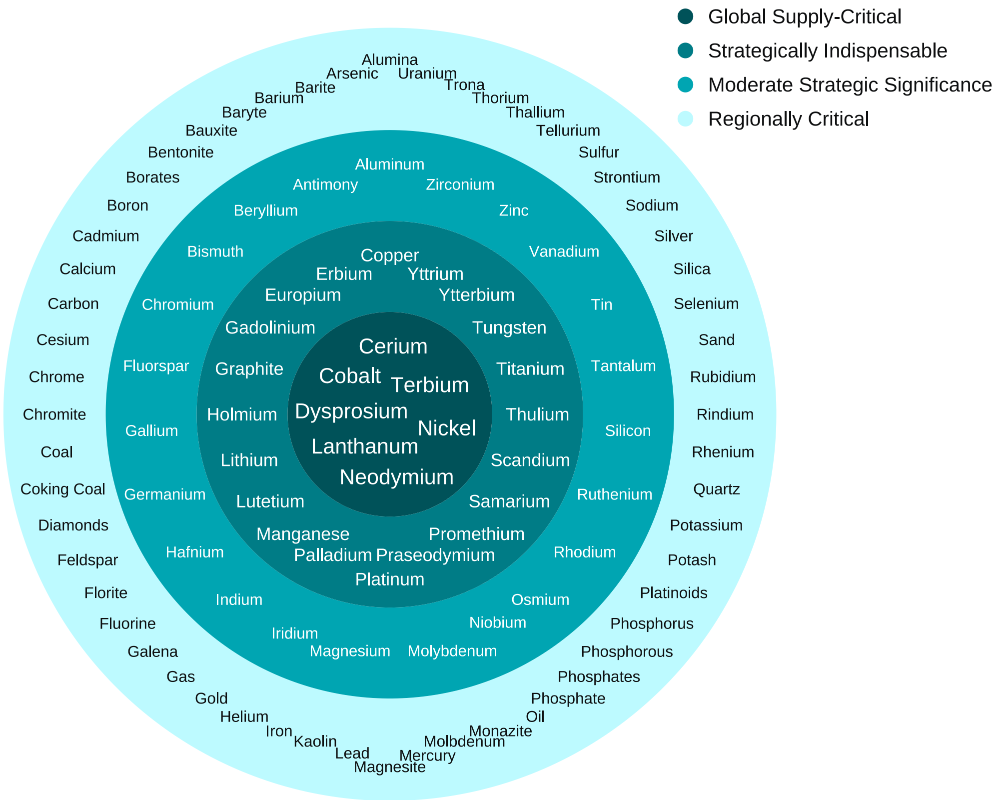


**Figure 1:** Sources: IEF and national Critical Mineral lists. Note: The minerals are grouped into four categories based on how frequently they appear across national CM lists.

Criticality assessments reflect domestic industrial structures rather than technology deployment alone. A country that installs large volumes of renewable energy systems but relies heavily on imported equipment and technologies, may place less emphasis on minerals embedded in those supply chains (such as *Lithium* in batteries). By contrast, a nation with significant electronics manufacturing is far more likely to identify *Tungsten* as supply critical given its role in hard metals and high-performance components.

Differences in national critical mineral lists can create strategic opportunities when comparative advantages are systematically mapped. Such heterogeneity allows countries to identify prospective suppliers, anticipate demand before constraints emerge, and position themselves advantageously within global value chains. Lists may also serve as policy signals to help shape investment expectations and partnership priorities in resource-rich nations while guiding processing and manufacturing ambitions in emerging countries.

## Role of Critical Minerals in Energy Transition

Mitigating the escalating impacts of climate change demands deep reductions in greenhouse gas emissions and a structural shift toward a low-carbon economy. Achieving this transition will depend on the large-scale deployment of innovative energy technologies, that currently range from wind turbines and solar grids to electric vehicles and nuclear power, through to CCUS and as-yet undiscovered breakthrough technologies, energy sources, and carriers. However, the rapid expansion of these technologies ultimately depends on securing reliable, ongoing and equitable access to the critical materials and intermediate resources required for their production, as well as processing, refining and use across energy technologies and other critical-material-enabled industries.

Understanding how these materials are produced and traded is therefore essential to assessing the feasibility and resilience of the clean-energy transition. Global trade concentration varies between minerals and between mining and processing (Figure 2). Values approaching zero indicate widely diversified production (less trade concentration), whereas values nearing one reflect extreme dependence on a single supplying country (more trade concentration). A comparison of two transport-critical materials - oil and lithium - shows broadly similar levels of mining concentration, yet a clear divergence downstream. Refined petroleum products are far more widely available and accessible across countries than lithium-based products, by roughly a factor of six. In contrast, despite its central role in the energy transition, copper shows relatively low trade concentration across both mining and refining, indicating a diversified global supply structure.

### Trade Risk Exposure in Mined and Refined Minerals (2024)

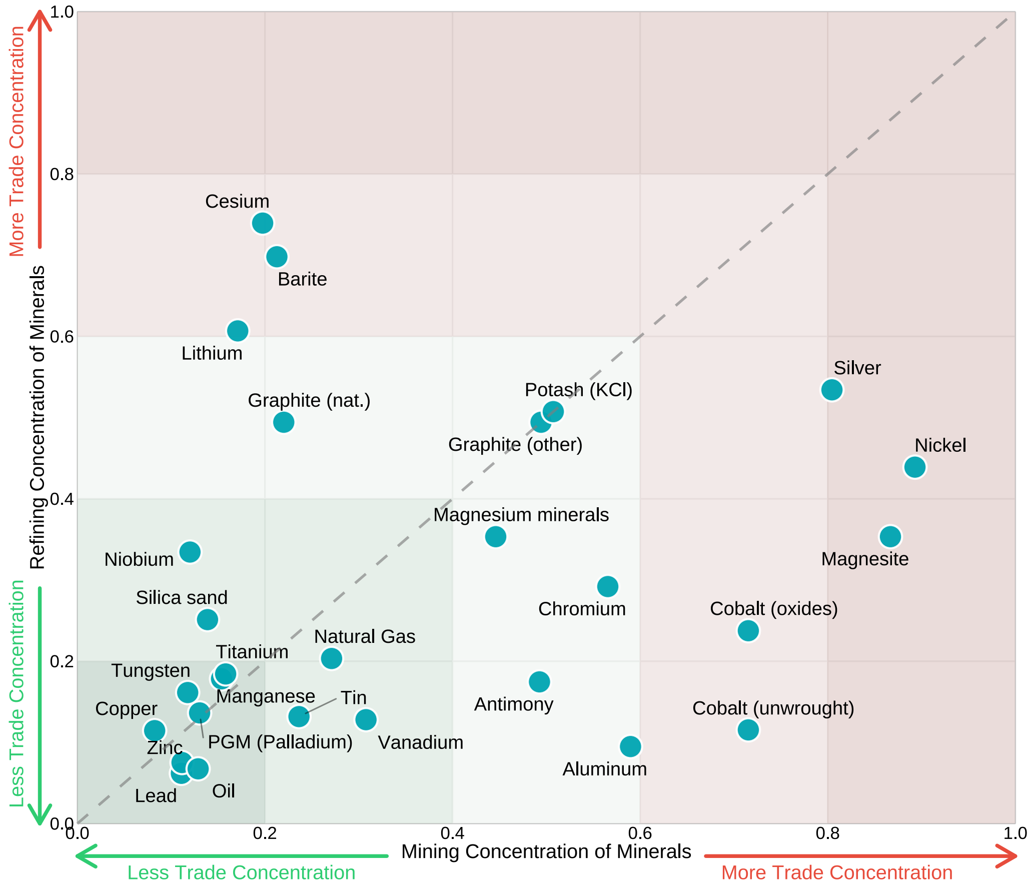


**Figure 2:** Source: IEF and UN Comtrade.

Understanding how these materials are produced and traded is essential to assessing the feasibility and resilience of the clean energy transition. The analysis therefore focuses on energy-relevant minerals for which global production and trade data are sufficiently robust. On this basis, the report examines five minerals, copper, cobalt, nickel, lithium, and rare earth elements, that are foundational to the energy transition. As shown in Figure 3, more than 900 copper mines, smelters and refineries are currently in operation worldwide, spanning a wide range of production confidence levels, from *low* associated with early stage, informal or poorly documented operations to *high* reflecting long established and fully operational facilities. Approximately one third of these mines are in the Americas.

### Geographic patterns in mining and mineral infrastructure

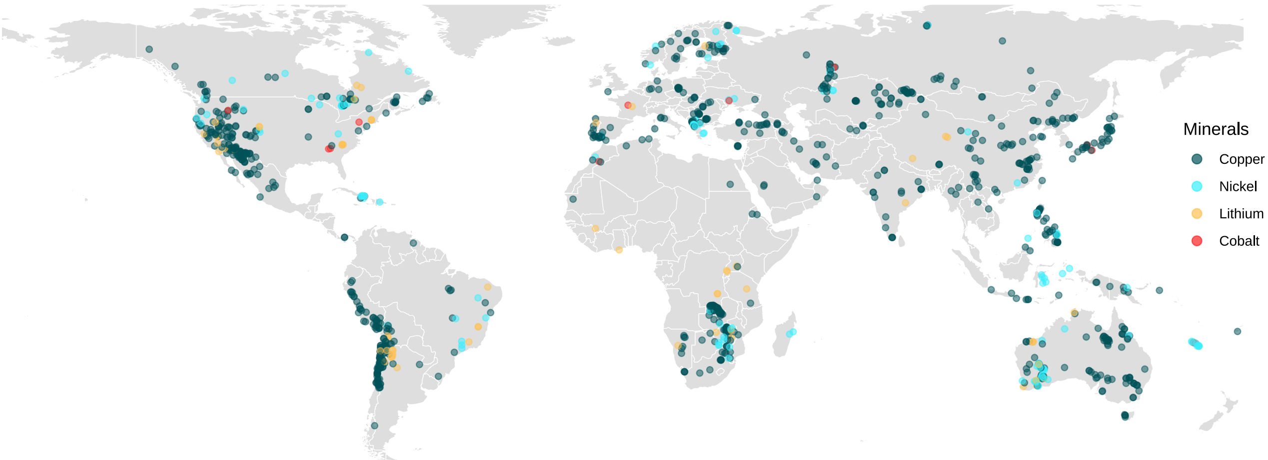


**Figure 3:** Source: IEF and ICMM Global Mining Dataset, September 2025 (V1) release. Data is not available for REEs. The data represents mining, smelters and refineries. Note: Data for rare earth elements (REEs) are not available. The dataset covers mining, smelting, and refining activities. Mines shown may produce secondary or co-products in addition to the primary commodities presented on the map. For example, in the Democratic Republic of Congo, several copper mines also extract cobalt as a secondary product.

Demand for these minerals continues to rise, driven by the material requirements of global energy system transformations (Figure 4). Total global demand increases from roughly 28 mega tonnes (Mt) in 2021 to nearly 41 Mt by 2040, highlighting the growing dependence of clean energy technologies on mineral-intensive supply chains. Within clean energy applications, copper remains the dominant component, more than doubling to exceed 12 Mt, while Lithium and Nickel record the fastest growth, expanding more than tenfold as their roles in electric vehicle batteries and energy storage systems deepen. In contrast, REEs and cobalt show steady but moderate increases, reflecting their indispensable use in high-efficiency motors, electronics, and advanced manufacturing.

## Projected Demand Growth for Key Energy Transition Minerals (2021–2040)

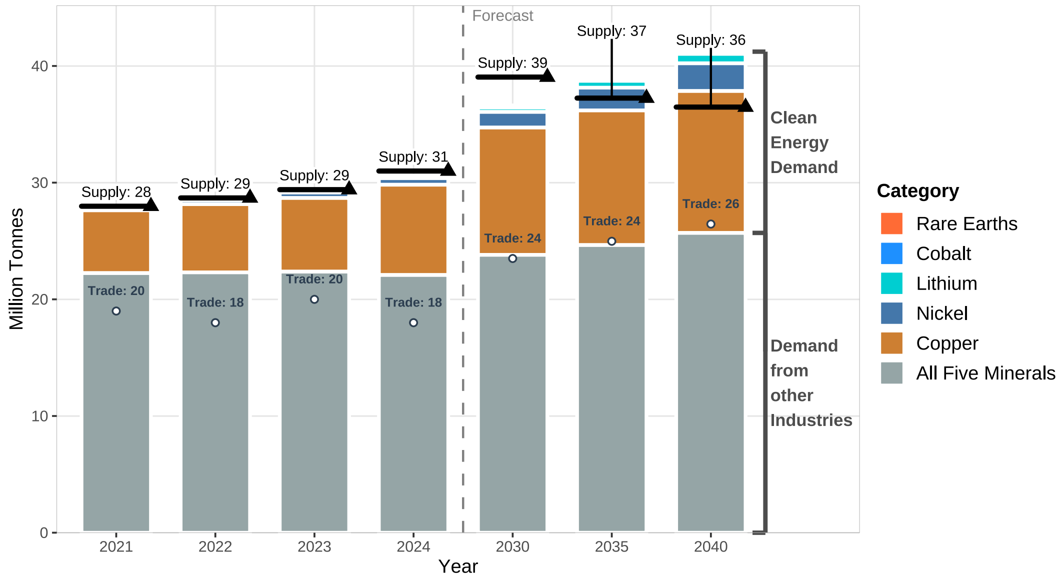


**Figure 4:** Source: IEF estimations, IEA, UN Comtrade and US Geological Survey. Cobalt and REEs constitute a very small proportion of the five minerals analyzed, which explains their limited visual prominence in the figure.

Demand from other industries is already substantial and is expected to remain high over the coming decade. This reflects growing use of these minerals in advanced technologies, the expansion of data centers and AI systems, and increased telecommunications and satellite activity (further detail on copper use, for example, is provided later in the report). Consequently, substitution options remain limited and overall mineral use is unlikely to decline. The findings also show that by the mid-2030s, global copper and nickel market imbalances may deepen, highlighting the urgent need for large-scale capital deployment, technological innovation, and strengthened international dialogue to sustain investment and trade in critical minerals at scale.

These emerging imbalances further underscore the central role of international trade in meeting global mineral requirements. Global trade in Critical Minerals (CMs) remains substantial and continues to expand as demand for energy technologies accelerates. More than 60% of global demand for these materials is traded across borders, highlighting the deep interdependence of producing and consuming regions. This high level of trade integration makes supply chain resilience a critical factor in sustaining technological progress. It also places greater weight on the policy and regulatory frameworks that shape how these markets operate.

## Global Patterns and Trends in Critical-Minerals Policy Activity

Considering this growing interdependence and the heightened importance of regulatory oversight, governments around the world are intensifying policy activity aimed at strengthening the resilience of critical-mineral supply chains. Policy actions on CMs shows strong geographic concentration and thematic diversity. Drawing on more than 600 policies examined in this report, Organization for Economic Co-operation and Development (OECD) countries such as the United States, Australia, Canada, Italy, and others demonstrate the range and scale of these initiatives (Figure 5A), reflecting mature institutional frameworks that integrate strategic planning, investment, and innovation. Several countries prioritize long-term strategic planning and resource exploration, while others emphasize trade and export control.  Key producers, including Indonesia, Chile, and Peru, focus their policies predominantly on exploration and mining, underscoring their roles as upstream suppliers within global value chains though focus on building critical minerals-derived added value through in-country critical minerals-enabled industries is also growing.

At the same time, policy activity intensifies sharply over time and has become more concentrated in recent years. The policies introduced during 2020–2025 are nearly double the cumulative total of those adopted across the previous two decades (Figure 5B). While the thematic distribution remains broadly consistent, covering exploration, recycling, sustainability, and finance, strategic planning continues to dominate, underscoring its central role in shaping long-term critical mineral security frameworks. At the same time, new policy themes are gaining prominence, particularly those related to international trade and export controls, and in some cases, these now outpace policies focused on environmental performance.

### Evolution of Critical Mineral Policy Initiatives

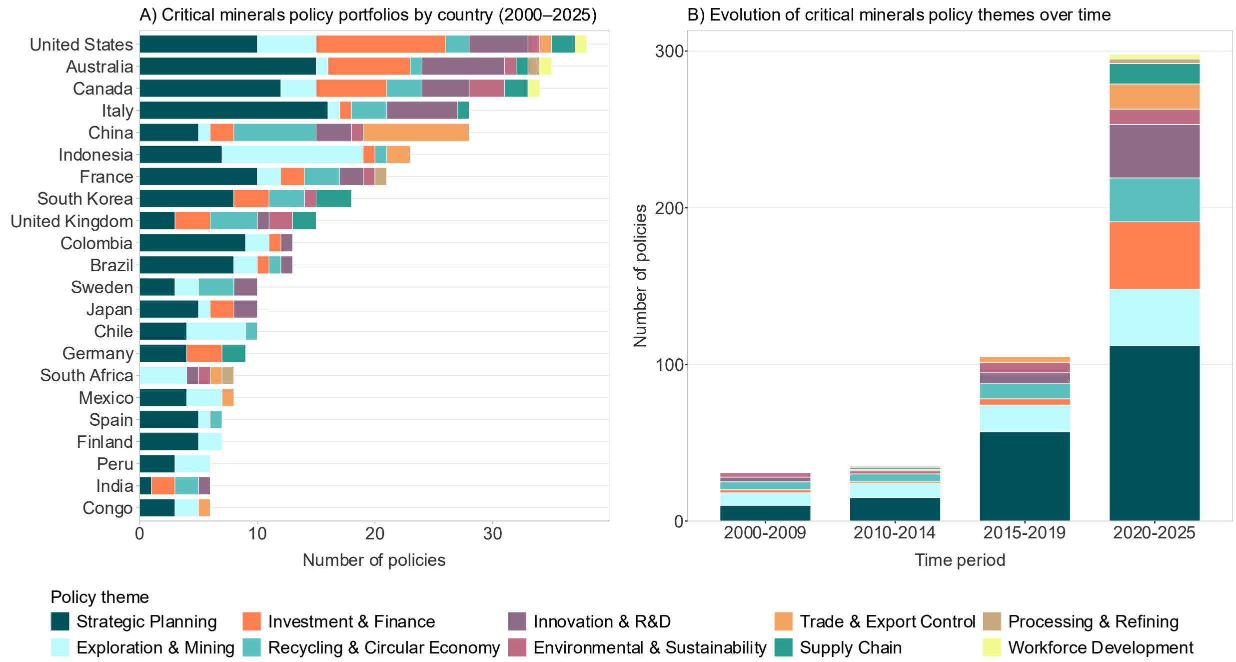


**Figure 5:** Source: IEF, IEA and national sources. Note: Policies are clustered into ten themes based on their stated objectives and official announcements by the respective countries.

## Overview of Key Minerals

Demand for the key minerals examined in this report is driven not only by renewable energy technologies but also by a wide range of industrial, transportation, and digital applications. This creates both intra-sector competition (across clean-energy technologies) and inter-sector competition (between energy, industry and technologies), widening the potential demand drivers that must be accounted for. Together, these uses reflect the expanding material base required to support electrification, digitalization, and advanced manufacturing.

### Copper

Copper is among the most widely used critical minerals, underpinning renewable energy technologies and a broad spectrum of industries from electricity networks and construction to transport and digital infrastructure. Figure 6 using the US as an example shows that copper is directly used by more than one hundred industries across the US economy, and this number might roughly double once indirect upstream and downstream linkages are considered[15]. Electrical equipment accounts for about 26% of total intermediate copper inputs[16], while motor-vehicle electrical systems make up more than 12%. The structure shown reflects the composition of the US economy, but the underlying industrial organization and production infrastructure are broadly consistent across major manufacturing systems worldwide. As economies advance in their electrification pathways, demand for copper continues to rise, underscoring its central role as the primary material for transmitting and distributing electricity.

## Overview of Copper Use Across US Industrial Sectors

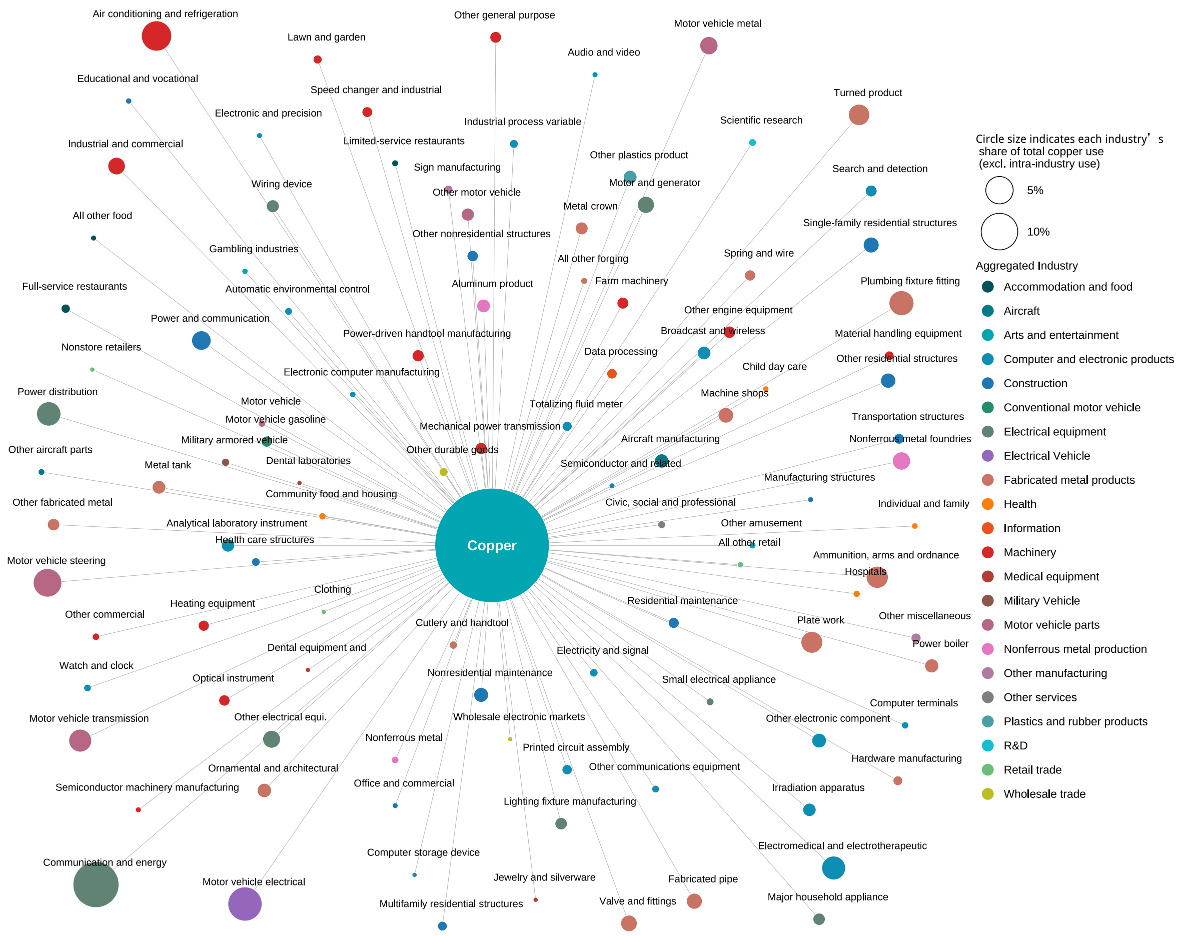


**Figure 6:** Source: IEF estimates derived from the US detailed sectoral production–consumption input–output accounts. Note: The most recent detailed benchmark table (2017; released 2022) is produced on a five-year cycle; while individual sectoral shares might have evolved, the broader production–consumption structure is expected to show moderate variation. These estimates are based on monetary valuations rather than physical quantities.

This rising demand is especially evident in the transport sector. Electric vehicles contain, on average, nearly four times more copper than conventional cars. Although efforts are underway to substitute some copper with aluminum[17], such a shift raises environmental concerns. Aluminum

[15] See an example of the indirect value estimates at this link https://www.wto.org/english/res_e/statis_e/miwi_e/all_Profiles_e.pdf
[16] Inter-industry copper-to-copper transactions are excluded; the estimates capture only manufactured copper products (rolling, drawing, extruding, and alloying) and do not include copper-ore inputs.
[17] https://source.benchmarkminerals.com/article/ev-copper-demand-to-grow-despite-efficiency-driven-content-reductions

production has higher environmental impacts than copper on a per-unit basis[18] [19] and requires substantially more energy, with primary aluminum needing about 70 GJ per tonne[20] compared with roughly 24 GJ per tonne[21] for copper.

Copper demand from Electric Vehicles rises from ~0.2 million tonnes in 2020 to ~2.5 million tonnes in 2030 and ~3.4 million tonnes in 2035 (Figure 7). This represents less than 0.01% of global supply in 2020 but expands to 7% by 2030 and 11% by 2035[22]. Between 2025 and 2035, copper demand from EVs is expected to increase at an average annual growth rate of 14%. Such an expansion adds significant pressure to global copper requirements, alongside growing demand from other energy technologies and non-energy sectors.

### Growth in Copper Demand from Electric Vehicles

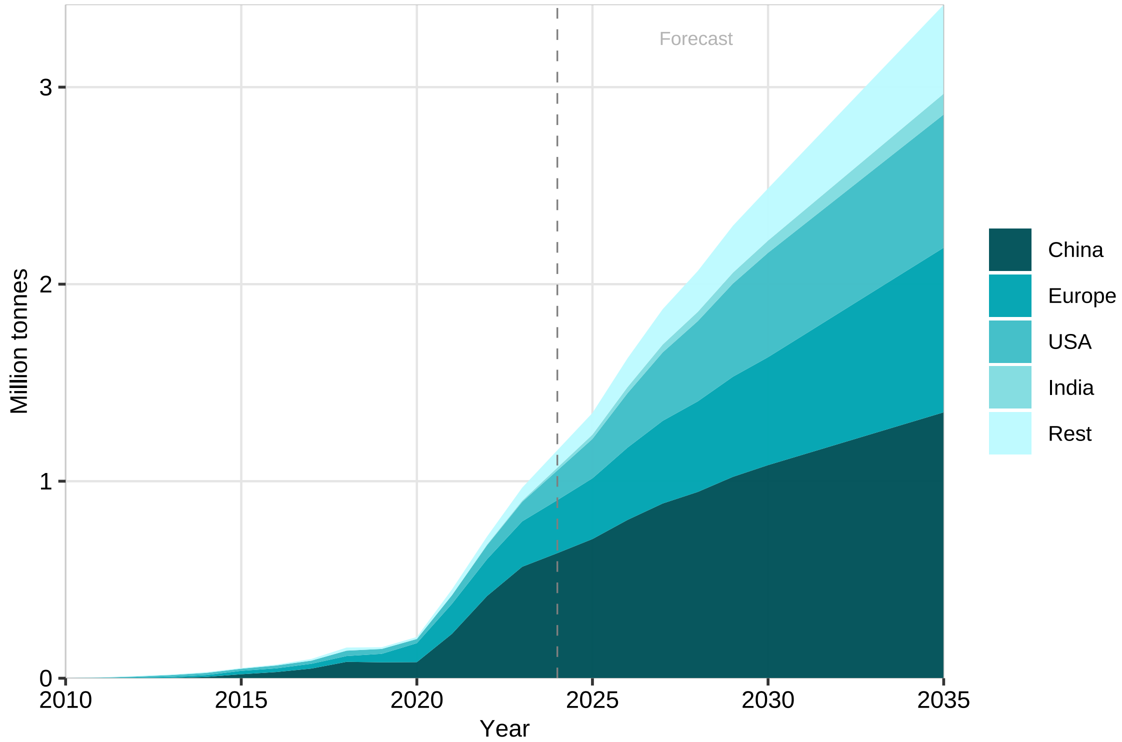


**Figure 7:** Source: IEF, IEA and Benchmark Minerals Intelligence. Note: estimates incorporate the expected reduction in copper usage from efficiency gains.

## Cobalt

Cobalt stands as a cornerstone of the clean-energy transition, underpinning technologies from electric-vehicle batteries to renewable-power storage systems.

Cobalt production has shifted from a relatively diversified supply base in the mid-1990s to one dominated by the Democratic Republic of the Congo (DRC), even as global output expanded substantially (Figure 8). In 1995, global mine production amounted to roughly 24 kt, with the DRC contributing about 15% and several other producers including, Canada, Russia, Australia, Cuba,

[18] https://international-aluminium.org/global-aluminium-industry-greenhouse-gas-emissions-intensity-reduction-continues-with-total-emissions-below-2020-peak/
[19] https://internationalcopper.org/wp-content/uploads/2023/05/ICA-LCI-GlobalSummary-202305-F.pdf
[20] https://publications.jrc.ec.europa.eu/repository/bitstream/JRC136525/JRC136525_01.pdf
[21] https://www.ceecthefuture.org/component/cck/?file=publication_file&id=3701&task=download
[22] This estimate incorporates data from the British Geological Survey (https://www.bgs.ac.uk/mineralsuk/).

Zambia, and New Caledonia, accounting for similar shares. By 2023, total output had risen to around 202 kt, a seven- to eight-fold increase, yet nearly 70% of this volume originated from the DRC. In other words, most of the absolute growth in cobalt supply over the past three decades is explained by the expansion of production in a single country.  Only a limited number of mines globally produce cobalt as a primary commodity at relatively high production rates; in most other regions, cobalt is recovered as a by-product of copper or nickel mining, where production volumes are geologically constrained.

Cobalt production over time

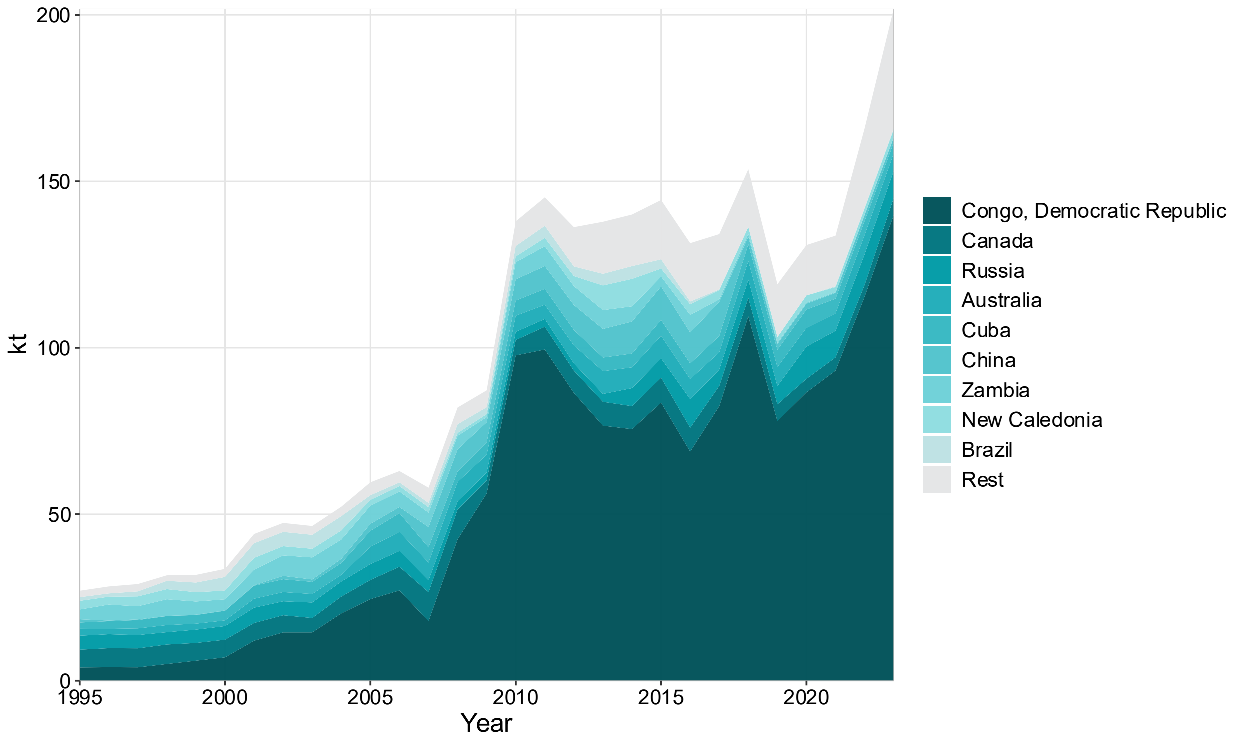


**Figure 8:** Source: IEF and Minerals British Survey.

### Rare Earth Elements (REEs)

Rare earth elements have become among the most critical and debated resources in recent years, reflecting their indispensable role across modern industries. REEs encompass 17 elements, including the 15 Lanthanides (from Lanthanum to Lutetium) along with Scandium and Yttrium, which are typically found in the same geological formations and processed using similar techniques. These elements are essential in technologies such as electric vehicles, which require approximately 1.3 to 3.6 kilograms of REEs per unit [23]. In the clean energy sector, their importance continues to grow, with the share of rare earth minerals used in renewable energy equipment expected to rise considerably.

Rare earth mining remains highly concentrated in a small number of countries, with China, Myanmar, and Australia together accounting for more than 80 percent of global supply and projected to maintain over two-thirds of global production by 2050. The refining and processing stages are even more geographically concentrated, as China alone controls more than 90 percent of global refining capacity for these critical elements.

[23] UK Energy Research Centre (2013). Materials Availability: Potential constraints to the future low-carbon economy.  Working Paper II: Batteries, Magnets and Materials.

Countries show substantial variation in their upstream extraction and downstream processing imports across the Rare Earth Elements (REE) value chain (Figure 9). High concentration risk in this context indicates reliance on a single or very limited set of partners, while lower concentration risk reflects a more diversified network of suppliers. Resource-oriented producers such as Canada and South Africa hold strong positions in REE mining, yet their refining activities draw on a broader set of partners. In contrast, countries such as Japan and Malaysia maintain highly concentrated REE refining systems based largely on imported compounds and metals. Some nations, including Russia, Kazakhstan, and Chile, show high concentration in both extraction and refining, suggesting emerging forms of vertical integration along the value chain. Most European economies fall into an intermediate position, engaging with multiple partners across both segments, although several display notably concentrated refining networks. The United States maintains a diversified base of REE mining suppliers, while refined compounds and metals are sourced from a comparatively narrower group of partners. More recently, US federal policy now places greater emphasis on recovering critical minerals from mine waste, coal refuse, and abandoned uranium sites, advancing a re-mining strategy that mobilizes legacy assets as a faster and less contentious alternative to new project permitting[24].

### Import Concentration Risk in REE Supply Chains (2024)

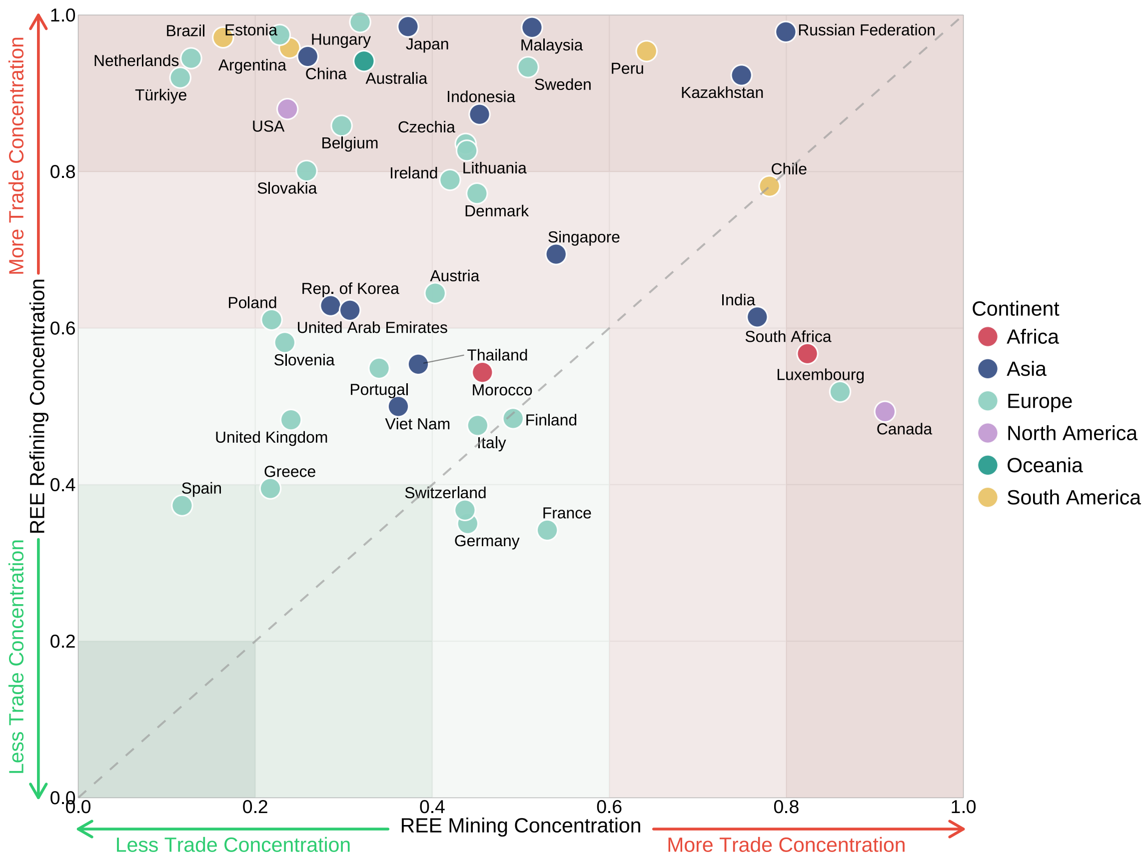


**Figure 9:** Source: IEF and UN Comtrade. Note: Figure includes only countries for which data is available. The results capture concentration in import flows rather than domestic production. The analysis is based on 6-digit customs trade statistics; because some REE elements are identifiable only at more granular levels (e.g., 8- or 10-digit codes), the estimates necessarily include some non-REE elements aggregated within the 6-digit classification.

[24] https://www.doi.gov/pressreleases/department-interior-launches-effort-unlock-critical-minerals-mine-waste

## Lithium

Lithium is a critical mineral for electric-vehicle batteries, and its importance grows with the rapid expansion of artificial intelligence and electronics. Global demand has increased sharply over the past decade and continues to rise in the coming decades. Supply, however, remains highly concentrated, with more than three-quarters of global lithium mining taking place in just three countries - Australia, China, and Chile - in 2022 (Figure 10). By 2040, this share is projected to remain high, with an estimate of around 69 percent. Many countries are developing policies, regulations, and financing mechanisms to expand production or extract minerals from existing fields. For example, a joint venture between Saudi Aramco and the mining company Ma'aden is planned to extract lithium from an oil field in Saudi Arabia[25].

### Concentration in Global Lithium Production (2022)

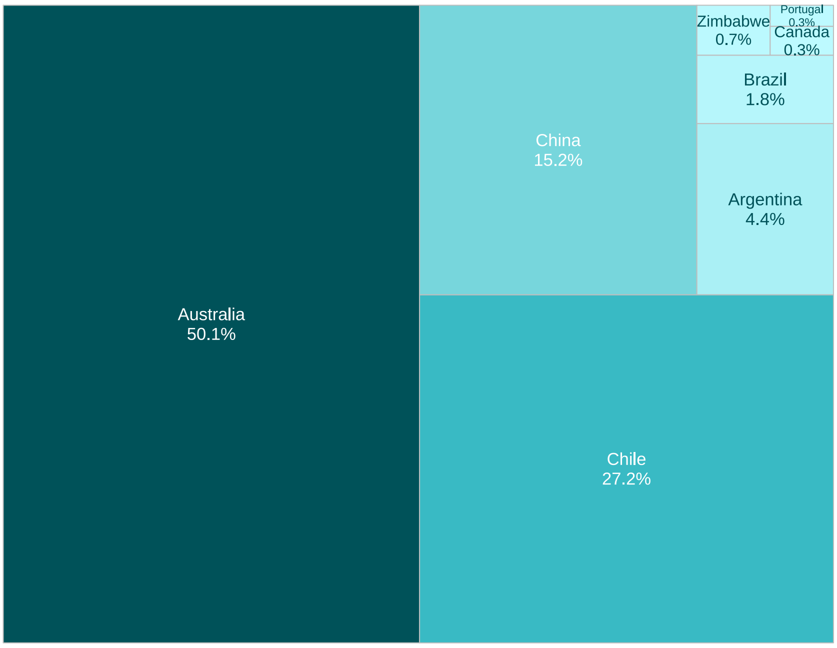


**Figure 10:** Source: IEA and US Geological Survey. Note: Data for the United States is not available.

## Nickel

Indonesia overwhelmingly dominates global nickel mining, accounting for more than half of total output (Figure 11). The Philippines, which contributes around 11% of global supply, represents the second-largest producer, followed by New Caledonia (6%), Russia (5.6%), Canada (4.2%), and Australia (4.0%). This concentration places substantial weight on Indonesia's policy choices, where shifts in export rules, domestic processing mandates, or environmental standards can quickly reshape global market conditions. These dynamics are also influenced by the structure of the value chain itself. At certain stages, production and processing are controlled by large multinational companies whose investment decisions and operational strategies can amplify or moderate the effects of national policy changes[26].

[25] INTERVIEW: Saudi Aramco, Ma'aden planned JV targets commercial-scale lithium production by 2027 | S&P Global

[26] https://www.reuters.com/markets/commodities/chinese-firms-control-around-75-indonesian-nickel-capacity-report-finds-2025-02-05/

### Concentration in Global Nickel Mining Production (2023)

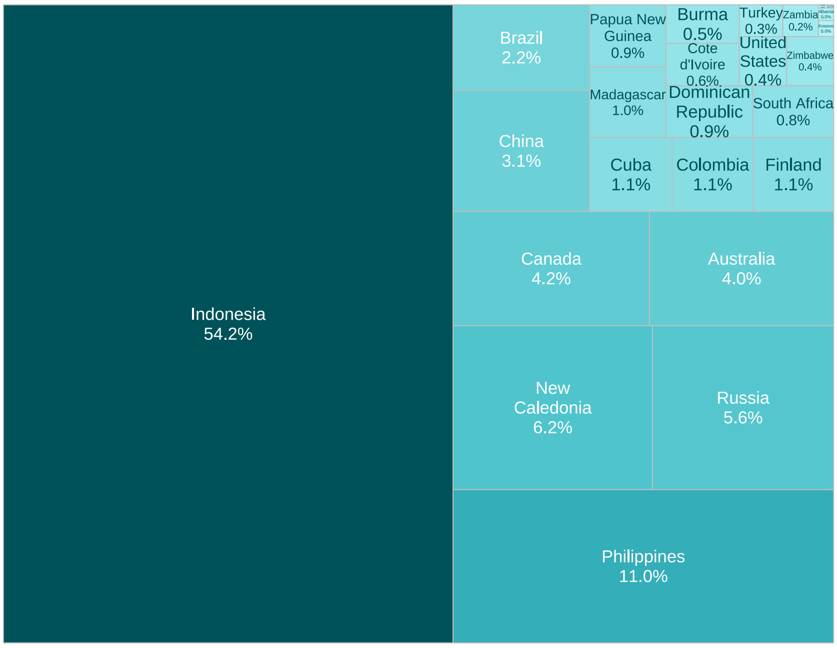


**Figure 11:** Source: IEF and US Geological Survey.

Nickel's share of total global demand allocated to clean energy demand increases from around 17% in 2024 to about 44% by 2050. This growth is driven primarily by electric vehicles and battery storage, and some technologies such as hydrogen production rely on nickel for nearly 90% of their mineral requirements.

## AI and Mineral Exploration

Meeting this rising demand for key minerals will require new approaches to mineral discovery and resource development. Over the past decade, Artificial Intelligence (AI) has reshaped multiple sectors, from medicine and transportation to energy efficiency. In mineral exploration, AI emerges as a transformative force, enabling the detection and mapping of mineral reserves with unprecedented precision. By integrating large geospatial and geophysical datasets, AI systems accelerate discovery processes and significantly reduce costs. These advances have improved exploration success rates, which have historically ranged between 0.1 and 3 percent[27], while optimizing investment efficiency and decision-making across the mining value chain. Recent studies show that AI-based mineral prospectivity models substantially outperform traditional statistical approaches in identifying mineralized targets, with deep-learning frameworks achieving predictive accuracy exceeding 90% in validation tests[28]. While these metrics do not directly represent economic or exploration discovery rates, improved targeting precision is a critical determinant of exploration outcomes and can materially increase the likelihood of success per exploration campaign in a sector where historical success rates have remained below a few percent.

[27] Banks, G. J., Olsen, S. D., & Gusak, A. (2020). A method to evaluate REE-HFSE mineralised provinces by value creation potential, and an example of application: Gardar REE-HFSE province, Greenland. Geoscience Frontiers, 11(6), 2141-2156. https://doi.org/10.1016/j.gsf.2020.05.019

[28] He, H., Zhu, H., Yang, X. et al. Mineral prospectivity prediction based on convolutional neural network and ensemble learning. Sci Rep 14, 22654 (2024). https://doi.org/10.1038/s41598-024-73357-0

The use of artificial intelligence extends beyond mineral exploration to applications across the entire value chain. By integrating diverse datasets, including geological maps, geophysical surveys, remote sensing imagery, and historical records, AI enables a more comprehensive understanding of resource distribution, extraction efficiency, and supply chain optimization. In the United States, for instance, the application of AI lead to the discovery of one of the largest REE deposits found in nearly seventy years at the Brook Mine in northeastern Wyoming[29]. This discovery substantially enhances domestic supply and supports the growing demand for these strategically important minerals. Other studies observe that increasing investment in AI for mining research and development shortens project timelines and reduces the level of required capital investment, thereby minimizing potential operational and financial risks[30]. These advances highlight how technological innovation can help alleviate some upstream pressures, yet broader system-level vulnerabilities persist.

## Resiliency and Risk Management in Critical Mineral Markets

By the late twentieth century, Western countries began establishing strategic petroleum reserves to safeguard against supply disruptions and strengthen energy security. These reserves, in combination with improved producer-consumer relationships, and greater market transparency have proven highly effective in stabilizing markets and maintaining reliable oil supplies during periods of shortage. Today, as renewable energy technologies expand and trade hurdles and supply chain disruption risks increase, securing equitable access to critical minerals, as well as to processing, refining, and utilization across energy and other critical material enabled industries, becomes increasingly urgent. Strengthening producer-consumer dialogue and data transparency in critical mineral markets, including public private engagement on critical mineral market security, supports the rational and sustainable use of resources, equitable participation, and transparent price discovery. Together with collective risk management strategies, including storage, diversification, and related strategies, these efforts contribute to building more resilient and sustainable critical-mineral markets. Japan provides an early example: in 1983 its national rare-metal stockpiling program was established. Implemented through the Japan Organization for Metals and Energy Security (JOGMEC) in cooperation with private industry, the program was launched to ensure stable supplies of 34 critical metals[31] [32]. More recently, the International Energy Agency has also underscored rising supply-chain vulnerabilities and urged member countries to consider coordinated strategies to strengthen critical mineral security.

These efforts address an important dimension of market resilience. However, ensuring sustainable access to critical minerals also requires addressing significant environmental and social challenges associated with extraction.

## Environmental and Social Considerations

Rising demand for critical minerals in the coming decades will intensify pressure on an extraction sector already constrained by slow rates of capacity expansion. The environmental and social impacts of mining are substantial, and the development of new reserves typically requires 13 to 23 years to progress from discovery to production[33]. Beyond these timelines, additional considerations, including securing a community social license to operate and maintaining stable

[29] https://www.wsj.com/business/energy-oil/the-2-million-coal-mine-that-might-hold-a-37-billion-treasure-181dbdcf
[30] Vespignani J, Smyth R. Artificial intelligence investments reduce risks to critical mineral supply. Nat Commun. 2024 Aug 24;15(1):7304. doi: 10.1038/s41467-024-51661-7. PMID: 39181882; PMCID: PMC11344786.
[31] https://www.jogmec.go.jp/english/stockpiling/stockpiling_10_000001.html
[32] https://www.enecho.meti.go.jp/en/category/special/article/detail_158.html
[33] Ali et al. (2017). *Mineral supply for sustainable development requires resource governance.* Nature, 543:367–372.

governance and economic conditions, are essential for sustainable and just functioning of global critical mineral markets.

Lithium, for example, is concentrated in a limited number of countries that face significant water scarcity, including Chile, Bolivia, and Argentina[34]. Evidence shows that large-scale mining activities that overlook environmental and sustainability considerations pose serious risks to biodiversity, particularly in parts of Africa[35]. In several regions, mineral extraction is also linked to water stress and human rights concerns, highlighting the urgent need for responsible and transparent resource management[36].

## Conclusion

The accelerating global demand for critical minerals defines a new frontier in the geoeconomics of energy markets, producer–consumer relations, and energy-system transformations. As renewable-energy technologies, digital infrastructure, transportation, and other strategic sectors increasingly converge around mineral-intensive supply chains, competition for these materials will increase.

Trade is an important factor for critical minerals with more than 60 percent of global demand being traded globally. Ensuring resilience therefore requires coordinated international action that integrates environmental stewardship, social inclusion, and technological cooperation. Policies that expand supply diversity, strengthen recycling systems, promote transparency across value chains, and support responsible investment can transform mineral dependence from structural vulnerability into a foundation for sustainable growth globally.

Technological innovation also has a central role. AI-enabled exploration, advances in processing efficiency, and the development of material substitutes can help alleviate pressure on primary supply. Yet these measures must be accompanied by strong environmental safeguards, meaningful community engagement, and governance structures that sustain public trust and ensure that new projects proceed in a socially responsible manner.

This report underscores that producer–consumer dialogue on critical minerals is essential to improving market transparency and predictability in markets where mining, refining, and processing capacity is geographically concentrated, and trade hurdles are rising. As export controls and other policy interventions become more prominent in critical mineral strategies, sustained cooperation can help reduce friction, strengthen investor confidence, and support more resilient supply chains. Well-functioning, rule-based, and transparent markets, rather than excessively restrictive investment and trade controls or fragmented environmental and governance standards, are essential to a fair and inclusive critical mineral enabled energy future.

The IEF will continue to support producer–consumer engagement by providing member countries and partners with deeper analysis on critical minerals and strengthening dialogue on market functioning, enhancing transparency. Upholding non-discriminatory treatment of

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[34] Kirshen, A.B., Moran, B.J., Munk, L.A. et al. Freshwater inflows to closed basins of the Andean plateau in Chile, Argentina, and Bolivia. Commun Earth Environ 6, 177 (2025). https://doi.org/10.1038/s43247-025-02130-6
[35] Junker J, Quoss L, Valdez J, Arandjelovic M, Barrie A, Campbell G, Heinicke S, Humle T, Kouakou CY, Kühl HS, Ordaz-Németh I, Pereira HM, Rainer H, Refisch J, Sonter L, Sop T. Threat of mining to African great apes. Sci Adv. 2024 Apr 5;10(14):eadl0335. doi: 10.1126/sciadv.adl0335. Epub 2024 Apr 3. PMID: 38569032; PMCID: PMC10990274.
[36] Sovacool et al. (2020). "Sustainable minerals and metals for a low-carbon future." Science, 367(6473):30–33.

investors and fostering equitable trade practices and reciprocity among stakeholders will be essential to avoiding new barriers and reducing risks, thereby ensuring that critical-mineral markets evolve in a manner that supports global energy security and sustainable energy transition pathways.

## Abbreviations

| | |
|---|---|
| AI | Artificial Intelligence |
| CMs | Critical Minerals |
| EV | Electric Vehicle |
| kt | kilotonne |
| Mt | Megatonne |
| R&D | Research and Development |
| REEs | Rare Earth Elements |

**Appendix 1 :** List of Countries Included in Figure 1.

| | | | |
|---|---|---|---|
| Argentina | Denmark | Japan | Slovakia |
| Australia | Estonia | Latvia | Slovenia |
| Austria | Finland | Lithuania | South Africa |
| Belgium | France | Luxembourg | South Korea |
| Brazil | Germany | Malta | Spain |
| Bulgaria | Greece | Netherlands | Sweden |
| Canada | Hungary | New Zealand | Türkiye |
| China | India | Poland | United Kingdom |
| Croatia | Indonesia | Portugal | United States |
| Cyprus | Ireland | Romania | Vietnam |
| Czechia | Italy | Russia | |

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