# GEOECONOMIC AND TECHNOLOGICAL IMPLICATIONS OF CRITICAL, STRATEGIC, AND RARE EARTH MINERALS FOR SUSTAINABLE POWER GENERATION

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***Abstract***
*The transition to low-carbon electricity systems is increasing demand for critical, strategic, and rare-earth element minerals used in power generation, storage, hydrogen technologies, and electricity networks. This research accounts for the importance of these minerals for future power-system development by connecting to scenario-based mineral demand with concentration in the supply chain. Demand was calculated for solar PV, wind power, grid battery storage, electricity networks and hydrogen for Stated Policies Scenario (STEPS), Announced Pledges Scenario (APS) and Net Zero Emissions by 2050 Scenario (NZE scenarios), using the International Energy Agency Critical Minerals Dataset. The assessment of supply exposure was conducted by examining the top three supplier concentration at the mining and refining, lithium chemicals and battery-grade graphite stages. The results indicate that the most significant mineral demand under NZE is for electricity networks, totaling 8,853 kt in 2050, and copper is the most significant mineral demand at its lowest level, at 13,936.3 kt in 2050. Grid battery storage, solar PV, and wind form the next major demand cluster. REEs, especially neodymium, praseodymium, dysprosium, and terbium, remain strategically significant despite lower mass demand because of their role in permanent-magnet wind technologies and concentrated supply chains. The study concludes that mineral security must be integrated into power-sector planning through supply diversification, responsible sourcing, recycling, and material efficiency.*

***Keywords:*** *Critical minerals; Strategic minerals; Rare-earth elements; Power generation; Supply-chain concentration.*

## 1. Introduction

The global transition toward low-carbon electricity systems is reshaping the material foundations of power generation. Renewable power technologies, electricity networks, battery storage, and hydrogen-related systems require a wide range of minerals that were previously less central to conventional fossil-fuel-based power systems. As a result, energy security is increasingly linked not only to fuel availability, but also to the reliable supply of critical minerals used in power-system expansion and decarbonisation. Future electricity infrastructure is expected to generate substantial material requirements across generation, transmission, and storage technologies, making mineral availability an important condition for achieving long-term energy-transition pathways (Deetman et al., 2021).

Critical minerals are important because they support technologies that are central to the clean energy transition. Solar PV requires minerals such as silicon, copper, silver, gallium, and tellurium; wind power depends on copper, zinc, nickel, manganese, and rare-earth elements; electricity networks require large quantities of conductive materials; and battery storage depends on graphite, lithium, nickel, manganese, cobalt, and vanadium. These material requirements show that power generation is becoming increasingly mineral-intensive. Sustainability challenges are also associated with the production of wind, solar, and storage technologies, as mineral extraction, processing, and technology manufacturing can create environmental and social pressures if not managed responsibly (Huber & Steininger, 2022).

Rare earth elements are unique in this transition. While they may not be in demand as greatly as bulk minerals like copper, graphite or zinc, they have a very specific technological demand. Applications of rare-earths are found in high-performance magnets, electronics, catalysts and clean energy technologies, and they are strategically important because of their relatively small physical quantities (Balaram, 2019). Neodymium, praseodymium, dysprosium and terbium are also significant for wind power, due to the application of permanent-magnet technologies. This poses a methodological challenge because the assessment of the minerals can only be based on the total volume of demand, and some of these minerals are critical due to technological dependence and concentration of supply.

This study aims to address the central issue of discussing mineral demand in the power-generation sector in a generic way rather than distinguishing between critical minerals, strategic minerals and rare-earth element minerals for specific power system technologies. Previous studies have focused on material losses and availability concerns for solar and wind technologies, which reveal that losses throughout the life cycle can impact the long-term availability of critical raw materials (CRMs) (Cristóbal et al., 2020). A focused assessment is still required, however, which focuses on a comparative evaluation of mineral demand by power generation, storage and electricity network technologies, and then identifies those minerals which are becoming strategically important due to concentration in the supply chain. The difference is significant because the mineral could be strategically significant either because it is needed in very large amounts or because it is concentrated in specific areas.

This is also linked to environmental, social and governance considerations. The expansion of critical mineral extraction can be aligned with energy transition goals, but it can also result in land use issues, water stress, labour issues, governance issues and impacts on the communities. There is a critical need for proper governance and policy oversight of the energy transition's critical mineral supply chains, which are both opportunities for development and ESG risks (Carr-Wilson et al., 2024). So, the shift to renewable energy cannot be examined on just installed capacity or emissions metrics, but must also include mineral systems that enable clean energy technologies.

This study is restricted to the minerals employed in the production of power energy and related power-system technologies. Solar PV, wind power, grid battery storage, electricity networks and hydrogen technologies are the focus of the analysis. Electric vehicles are not included since the scope is to assess the power generation and supporting power infrastructure, and not transport electrification. The research relies on secondary quantitative data, and thus does not directly measure impacts on the environment at the mine, mineral prices, recycling rates, country-level electricity generation, or local supply risks at the mine. Technological, economic and collection system constraints determine the role of recycling and secondary supply for long-term mineral security, especially in the case of rare earths (Gaustad et al., 2021).

The relevance of the study is regarding the future mineral demand and the strategic exposure in the mineral supply chain. Rare earths are well known for their critical role in the energy transition, given their close connection with high-performance clean energy technologies and concentrated supply chains (Gielen & Lyons, 2022). More recent studies highlight two sides to the rare-earths challenge: the lack of substitution and processing concentration, as well as geopolitical sensitivity (Depraiter & Goutte, 2023). This study is also a first in its specific interest in minerals used in power generation and power-system technologies, in order to better understand by mass the dominating minerals, which are strategically exposed and how rare-earth elements might be incorporated to the decarbonisation of the electricity sector.

The study is guided by the following research objectives:

- To quantify future mineral demand across selected power-generation and power-system technologies under STEPS, APS, and NZE scenarios.
- To identify the major critical, strategic, and rare-earth element minerals required for power-system decarbonisation by 2050.
- To assess strategic exposure by linking projected mineral demand with supply-chain concentration indicators.

## 2. Literature Review

The mineral base of low carbon power systems has become a topic of increasing academic and policy interest as a result of the energy transition. Unlike conventional fossil-fuel electricity systems, renewable energy and electrification pathways require substantial quantities of minerals for generation technologies, electricity networks, storage systems, and associated infrastructure. Early assessments of the total material requirement for the global energy transition showed that electricity and transport decarbonisation could significantly increase demand for metals and minerals by 2050, making material availability a central issue in long-term energy planning (Watari et al., 2019). This shift has encouraged researchers to move beyond fuel-centred energy security and examine the mineral inputs needed to support renewable power expansion.

A major contribution to this debate is the recognition that minerals are essential for climate action. The World Bank's analysis of minerals for climate action emphasised that the deployment of clean energy technologies will require large increases in minerals such as graphite, lithium, cobalt, nickel, copper, and rare earth elements (Hund et al., 2020). Similarly, IRENA's work on critical minerals for the energy transition highlighted that supply security, processing capacity, and international cooperation are becoming increasingly important as low-carbon technologies expand (Gielen, 2021). These studies establish that critical minerals are not peripheral inputs but structural requirements for renewable energy systems.

In recent literature, there has been an interest in the size of the future material demand under different climate scenarios as well. Kalt et al. (2022) estimated the material needs for pathways to electricity sector decarbonisation in the global scale for 2050 and revealed that a pathway to electricity sector decarbonisation with greater material demand for renewables generation and storage can be achieved, but is also associated with wider emissions reduction benefits. Wang et al. (2023) also found that the demand for electricity-generation materials is highly scenario dependent, highlighting the strong role of technology selection and pathway in defining mineral demand. The results of this study are relevant for scenario-based analyses: the demand for minerals is not given, but depends on the rate and the nature of the transformation of the power system.

A number of studies have discussed critical minerals specifically in the context of the NET ZERO transition. The IEA Net Zero Emissions by 2050 scenario would result in a substantial rise in the demand for critical materials, particularly for batteries, renewable generation and electricity infrastructure, according to Liang et al. (2023). This aligns with the findings that net zero pathways can only be achieved through not only the rapid deployment of technology but with increased mineral supply chains. A systematic review of the minerals–energy interface by Srivastava and Kumar (2022) also suggested that minerals have emerged as a significant limiting factor and enabler in the pathways of energy transition. They have found that the availability of minerals, their concentration in the supply, recycling and substitution need to be part of the planning of energy transitions.

Rare-earth elements are a special subset of these materials, as they are typically more strategically important than mass demand materials. Li et al. (2020) demonstrated that wind energy targets around the world may be at risk of being outcompeted by the availability of key rare-earth elements, most notably those in permanent magnets. This is particularly the case for neodymium, praseodymium, dysprosium and terbium, which are used in high-performance wind turbine technologies. Thus, rare-earth elements must be specifically analyzed and addressed, and not just as part of the analysis of aggregate mineral demand.

The literature also highlights the environmental, social and governance issues related to mineral supply chains. Lèbre et al. (2020) emphasized the social and environmental complexities of energy transition metals extraction, demonstrating that expansion of energy transition metals mining can overlap with land use, water, ecosystems and communities. If the production of renewable energy involves mining in sensitive habitat, it could increase the threats to biodiversity caused by mining, as suggested by Sonter et al., (2020). The results show that there are no impacts with clean energy technologies, but sustainability also involves the governance of mineral extraction and processing.

Social justice and land-related issues are also a key part of the critical minerals debate. Owen et al. (2023) demonstrated that energy transition minerals often overlap with land based peoples, resulting in issues of consent, rights and distributional justice. A lack of sustainability in mineral and metal supply chains would also be key to achieving a low-carbon future, as suggested by Sovacool et al. (2020) who also highlighted responsible sourcing, recycling, and social considerations within mineral and metal supply chains. The pieces of this puzzle reveal that the security of minerals cannot be divorced from ethics and environment.

Other recent policy-based documents also highlight the strategic and macroeconomic importance of critical minerals. Stinson and Cam (2025) explored how the world's energy transition is transforming demand for critical minerals and impacting trade flows, investment, and supply chain risks. The literature shows that mineral demand for power generation cannot be considered independently from three closely related perspectives: predicted growth in demand; concentration in power generation value chains; and risk of sustainability. In this study, the focus is specifically on critical materials, strategic materials and rare earth element minerals for power-generation and power-system technologies.

## 3. Methodology

### 3.1 Research design

This study uses a quantitative, scenario-based design to examine the role of critical, strategic, and rare-earth element minerals in power generation and related power-system technologies. The analysis looks at future mineral demand for key low-carbon power technologies and correlates demand outcomes with concentration indicators for the supply chain to assess strategic exposure. This method takes into account the criticality of minerals both based on the amount of demand as well as the technological dependence and geographic concentration of mineral extraction or processing. Secondary data from the Critical Minerals Data Explorer is used for the study. Demand analysis is performed for 2024 as baseline year and 2030, 2035, 2040, 2045, and 2050 for all scenarios (STEPS, APS and NZE). The supply projection horizon has been used for supply-side analysis for the years 2024, 2030, 2035, and 2040.

### 3.2 Data source and analytical scope

The empirical focus of the study is limited to technologies relevant to the power generation and power-system transformation. This final analytical coverage contains solar PV, wind, grid battery storage, electricity networks, hydrogen technologies and other low emission power-system categories. Electric vehicles were also omitted from the main analysis as the scope of the study is to examine mineral needs in power generation and supporting power infrastructure, as opposed to the electrification of transport.

The study uses the Critical Minerals Dataset: 2024 edition published by the International Energy Agency (IEA), last updated in May 2025. The demand data includes mineral requirements by technology, scenario and year in kilotonnes. The data supplied includes country/region-level data for mining, refining, lithium chemicals, battery-grade graphite, total supply, rest-of-world values and for the top three suppliers. This facilitates the assessment from both the demand side and the supply side and takes the study beyond the simple ranking of minerals based on mass to a more strategic understanding of mineral dependence, as noted by the International Energy Agency (IEA) (2025).

### 3.3 Data preparation and harmonisation

The original data were restructured into a consistent long-format analytical dataset because technologies, minerals, scenarios, years, and case types were distributed across multiple technology-specific and aggregate data blocks. Scenario labels were standardised as Baseline, STEPS, APS, and NZE, with 2024 treated as the baseline year and 2030–2050 as projection years. Each demand observation was assigned a technology, mineral, scenario, year, case type, unit, and demand value to enable consistent aggregation. To avoid double counting, the main empirical analysis used the technology-specific base-case dataset, which provided the most detailed mineral coverage for the selected power-system technologies. Duplicate checks at the technology–mineral–scenario–year level confirmed that each analytical observation was unique before aggregation.

### 3.4 Mineral classification

This study uses an overlapping mineral classification system. Energy-transition technologies are related to all minerals included in the final power system dataset, and are thus considered critical minerals. Strategic minerals include minerals that have functional relevance for power generation and electricity networks, battery storage, hydrogen technologies, solar PV and wind power. REEs are recognized as a subcategory of C&SMs.

The rare-earth elements include neodymium, praseodymium, dysprosium, terbium and yttrium. In the supply-side analysis these individual rare-earth elements are grouped with the other rare-earth elements in the broader category of 'magnet rare earth elements', as the supply data includes mining and refining concentration at the aggregate level for magnet-REEs. Minerals can also be categorised according to their functional use, such as battery minerals, grid and power-infrastructure, solar PV minerals, wind related minerals, hydrogen related minerals and rare earth elements.

### 3.5 Demand-side analytical procedure

Demand analysis was done in three levels. Total mineral demand was first aggregated by technology, scenario and year to determine the technologies in the power system that have the highest mineral demand by 2050. Second, this was done by combining the mineral level demand of all the technologies included and led to ranking the minerals according to the total demand under STEPS, APS and NZE. Third, the demand for REEs was analysed separately, since the REEs demand, although small in quantity of minerals by mass, is strategically important.

Growth between 2024 and 2050 was determined by multiplying each technology's 2024 baseline demand by the demand for the technology as identified in the scenario. Absolute growth, percentage growth and compound annual growth rate were calculated. However, absolute demand and strategic relevance were emphasized more than percentage growth, as the latter can be deceptive for technologies with a small absolute value.

### 3.6 Supply concentration and strategic exposure assessment

Concentrations were determined by the top three percentage share of suppliers for each mineral and each stage of the supply chain from which the minerals were supplied, with the concentrations being categorized as low, moderate, high, and very high. The analysis separates out the three different products of mining, refining, lithium chemicals, and battery-grade graphite, as strategic vulnerability may be seen at different stages of the supply chain. Demand-side importance was then correlated to supply-side vulnerability by comparing the 2040 top-three supplier concentration indicators, where they exist, with 2050 NZE mineral demand, using the same categories of minerals. The direct matches were made between copper, nickel, lithium, cobalt and battery-grade graphite, and between neodymium, praseodymium, dysprosium and terbium and the larger group of magnet rare earth elements. Minerals were determined to have high strategic exposure if they had a high projected demand but also a high concentration. The very large projected demand for copper, and the combined role of REEs in wind technologies and concentrated magnet-REE supply chains, were the rationale for considering copper as demand-driven strategic exposure and REEs as REE strategic exposure.

## 4. Results

### 4.1 Analytical dataset and empirical coverage

The final analytical dataset provides a structured basis for examining mineral demand in power-generation and power-system technologies. After cleaning and harmonising the original data, the broader power-relevant dataset contained 2,384 observations after excluding aggregate mineral totals. For the main empirical results, the technology-specific base-case dataset was used to avoid double counting across aggregate and technology-level records. This dataset contained 672 observations covering solar PV, wind, grid battery storage, electricity networks, and hydrogen. As shown in Table 1, the analysis covers 2024 as the baseline year and projection years from 2030 to 2050 under STEPS, APS, and NZE scenarios.

**Table 1.** Analytical dataset scope and coverage

| Indicator | Value |
|---|---|
| Parsed demand observations | 3,952 |
| Power-relevant observations after filtering | 2,512 |
| Final analytical observations excluding aggregate totals | 2,384 |
| Main technology-specific base-case observations | 672 |
| Main technologies analysed | 5 |
| Unique minerals in main base-case demand analysis | 30 |
| Demand scenarios | Baseline, STEPS, APS, NZE |
| Baseline year | 2024 |
| Projection years | 2030, 2035, 2040, 2045, 2050 |
| Demand unit | kt |

### 4.2 Mineral demand by power-system technology

The technology-level results indicate that future mineral demand is concentrated in electricity networks, grid battery storage, solar PV, and wind power. Figure 1 shows that electricity networks generate the largest mineral demand by 2050 in all three projection scenarios. Under NZE, electricity networks require 8,853 kt of minerals, compared with 7,479 kt under APS and 5,641 kt under STEPS. This reflects the material intensity of grid expansion and reinforcement required to support power-system decarbonisation.

Grid battery storage is the second-largest technology category under NZE, with 4,558 kt of mineral demand by 2050. Solar PV records 4,322 kt under NZE, while wind reaches 3,762 kt. Hydrogen remains much smaller in absolute mass terms, reaching only 86 kt under NZE. The scenario-wise comparison of total mineral demand by technology is presented in Table 2.

**Table 2.** Total mineral demand by technology in 2050

| Technology | STEPS (kt) | APS (kt) | NZE (kt) |
|---|---|---|---|
| Electricity networks | 5,641 | 7,479 | 8,853 |
| Grid battery storage | 2,969 | 3,784 | 4,558 |
| Solar PV | 3,804 | 4,420 | 4,322 |
| Wind | 2,325 | 3,538 | 3,762 |
| Hydrogen | 6 | 73 | 86 |

The values show that mineral demand is not distributed evenly across the power-system technologies. Electricity networks account for the largest material requirement, reflecting the mineral intensity of grid expansion and reinforcement under deeper electrification. The next significant demand is combined grid battery storage, solar PV, and wind, which makes both mineral generation and flexibility technologies significant demand sectors. In general, the higher the transition ambition, the more demand it creates, especially for networks and storage and wind. The situation is slightly different with solar PV, where APS is slightly higher than NZE in 2050, indicating that the deployment pathways vary by technology. The pattern demonstrates that there are mineral pressures for each infrastructural, storage and generation technology in the power-system decarbonisation process.

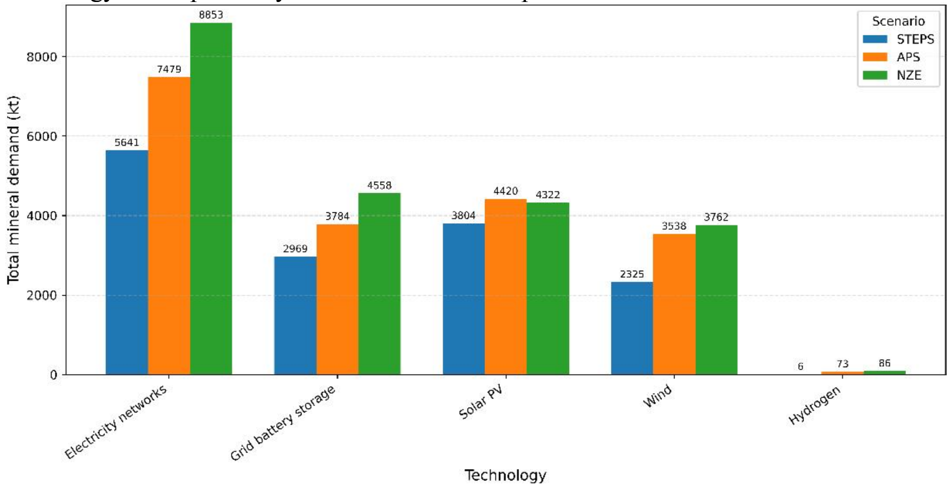


**Figure 1.** 2050 mineral demand by power-system technology and scenario.

**4.3 Mineral-level demand ranking under NZE**

The mineral-level ranking is indicative of the very uneven nature of total demand across minerals. Under NZE, copper becomes the major mineral by 2050 at 13,936.3 kt as illustrated in figure 2. This is significantly above the rest of the minerals and reflects copper's vital position in the electricity network, renewable generation and power-system growth. The second place is taken by zinc at 1,817.1 kt with silicon at 1,554.4 kt and battery-grade graphite at 1,206.7 kt.

Other elements such as manganese, vanadium and nickel are primarily linked with battery storage, wind and general power system technologies. While graphite, manganese, vanadium, and nickel are more abundant on an absolute mass basis, lithium still has strategic value due to its use in battery storage technologies as well as its supply-chain concentration. Neodymium has also been included in the rankings, due to its lower mass demand, but high importance in the field of permanent-magnet wind technologies. Table 3 shows the complete ranking of the top 15 minerals under NZE scenario.

**Table 3.** Top 15 minerals by 2050 demand under NZE

| Rank | Mineral | NZE demand in 2050 (kt) |
|---|---|---|
| 1 | Copper | 13,936.3 |
| 2 | Zinc | 1,817.1 |
| 3 | Silicon | 1,554.4 |
| 4 | Battery-grade graphite | 1,206.7 |
| 5 | Manganese | 1,053.6 |
| 6 | Vanadium | 836.1 |
| 7 | Nickel | 764.9 |
| 8 | Chromium | 164.2 |
| 9 | Lithium | 136.6 |
| 10 | Molybdenum | 34.7 |

| | | |
|---|---|---|
| 11 | Neodymium | 18.6 |
| 12 | Arsenic | 18.2 |
| 13 | Zirconium | 10.3 |
| 14 | Gallium | 7.3 |
| 15 | Tin | 5.0 |

The distribution of mineral demand demonstrates a strong concentration in a small number of materials. The most significant material pressure in transition to a power system is the expansion of the grid and electrification; copper stands out significantly from all other minerals. The second tier of demand includes primarily zinc, silicon, battery-grade graphite, manganese, vanadium and nickel, which are shaped by the integrated impact of electricity networks and solar PV and battery storage. By contrast, lithium and rare-earth elements have a lower apparent mass, but it is not possible to evaluate their strategic value based on volume. They are important because of the functions they serve in technology, and because of the clustering of supply chains. This separation of high volume minerals and strategically sensitive minerals is key in understanding the demand ranking.

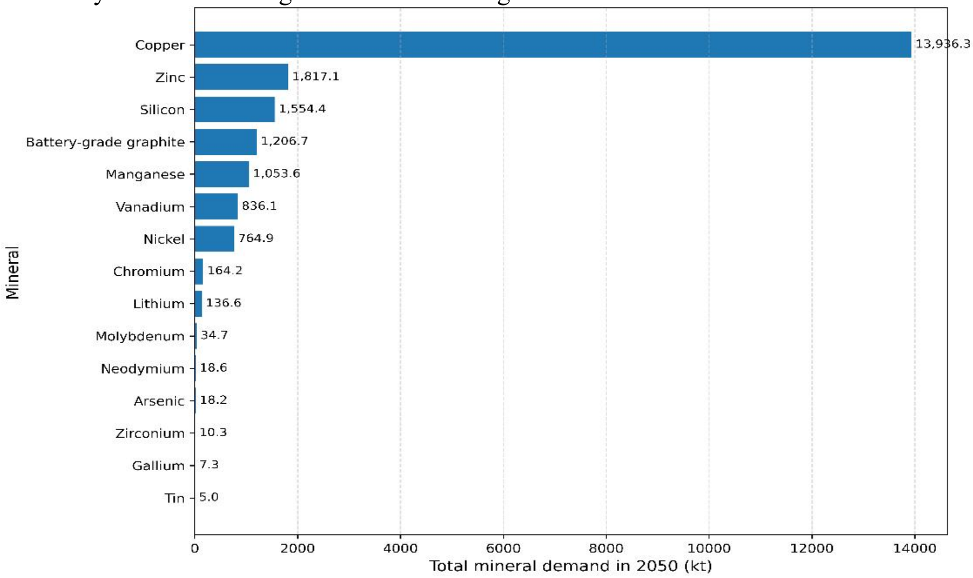


**Figure 2.** Top 15 minerals by 2050 demand under the NZE scenario.

**4.4 Rare-earth element demand in wind power**

Demand for rare-earth elements is far less than demand for bulk minerals on a mass basis, but is significant for technological use. As shown in Figure 3, the selected technologies of power systems are highly dependent on wind power for REE demand. Neodymium is the dominant REE, reaching 12.78 kt under STEPS, 19.54 kt under APS, and 18.56 kt under NZE by 2050. Praseodymium is the second-largest REE, followed by dysprosium and terbium.

The results show that REE demand should not be interpreted only through total mass. Although neodymium, praseodymium, dysprosium, and terbium are much smaller in demand volume than copper, zinc, or graphite, their role in permanent-magnet wind turbines makes them strategically relevant. Dysprosium and terbium are especially important because they are used to improve magnet performance under high-temperature operating conditions. Therefore, the REE results support the argument that strategic mineral importance depends on technological function as well as demand quantity.

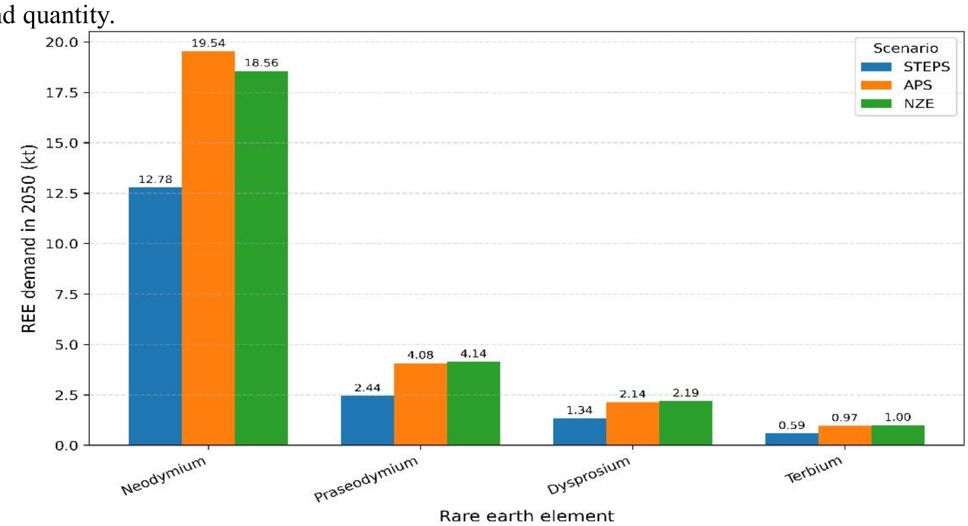


**Figure 3.** 2050 rare-earth element demand in wind power by scenario.

### 4.5 Supply concentration and strategic exposure

The supply-side results reveal substantial concentration across several minerals and supply-chain stages. Figure 4 shows that magnet rare earth element refining has the highest top-three supplier concentration, at 92.1% in 2040. Battery-grade graphite also shows very high concentration, with a top-three supplier share of 90.2%. Natural graphite mining, cobalt refining, lithium chemicals, nickel mining, and nickel refining all exceed 80%, indicating high exposure to concentrated supply structures.

Copper has lower concentration than most battery and REE-related supply chains, with 59.7% concentration in refining and 50.5% in mining. However, its very large demand volume makes it strategically important from a demand perspective. This distinction is important because strategic exposure can arise from either high demand scale, high supplier concentration, or the combination of both.

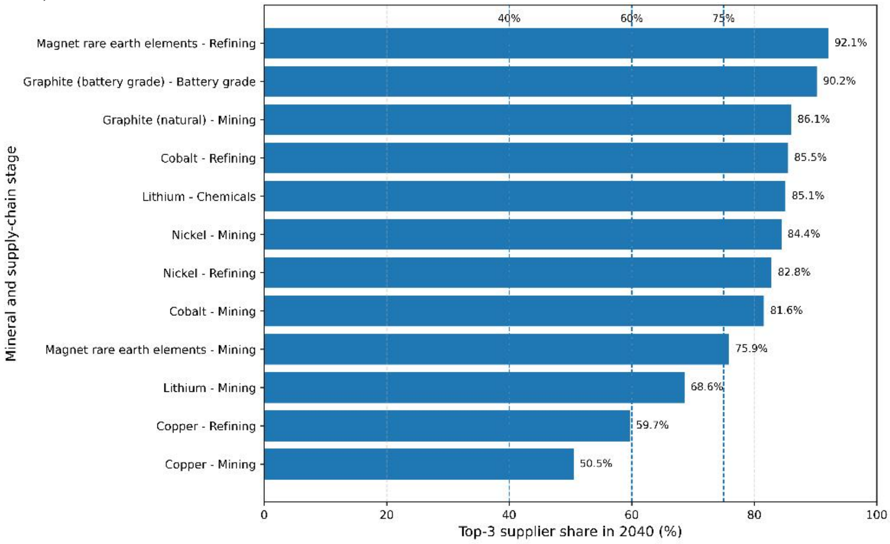


**Figure 4.** Top-three supplier concentration for strategic minerals in 2040.

When demand-side and supply-side indicators are considered together, the results show that strategic exposure is not determined by demand volume alone. Copper represents a demand-driven strategic mineral because it records the highest 2050 demand under NZE, despite only moderate supplier concentration. In contrast, battery-grade graphite, lithium chemicals, nickel mining and refining, and magnet rare earth element refining represent high strategic-exposure areas because they combine strong technological relevance with high supplier concentration. Rare-earth elements are especially important because their demand volume is comparatively small, but their role in permanent-magnet wind technologies and the high concentration of magnet-REE refining create significant supply-chain vulnerability. Overall, the results demonstrate that power-system decarbonisation creates two forms of mineral dependence. The first is high-volume dependence, led by copper, zinc, silicon, graphite, manganese, vanadium, and nickel. The second is strategic dependence, led by rare-earth elements, lithium, graphite, nickel, and cobalt, where supply concentration and technological specificity create vulnerability even when demand volumes are smaller.

## 5. Discussion

The results demonstrate that power-system decarbonisation is not mineral-neutral; rather, it reorganises energy dependence around a smaller group of high-volume and strategically sensitive minerals. The dominance of electricity networks in total 2050 mineral demand indicates that the material requirements of the energy transition extend beyond renewable generation technologies themselves. Under the NZE scenario, electricity networks require 8,853 kt of minerals by 2050, making them the largest technology category in the analysis. Thus, infrastructure development in the form of grid expansion, reinforcement and electrification are identified as key factors in mineral demand going forward, notably for copper. It is significant that when people talk about clean energy minerals they refer to batteries, solar PV or wind turbines – this is because the infrastructure, which enables the generation, transport and storage of electricity, could have the biggest requirement by mass. The second significant demand group consists of grid battery storage, solar PV and wind, demonstrating that both generation capacity and system flexibility are key components to future mineral needs.

The mineral level results also highlight the unique role of copper in power system decarbonisation. The copper demand under NZE is highest among all minerals analysed at 13,936.3 kt in 2050. It is an indication of its wide application in electricity networks, renewable generation and related facilities. The finding is consistent with earlier work that has demonstrated that material needs in electricity generation, transmission and storage for global pathways to 2050 are expected to be quite high (Deetman et al., 2021). The results also indicate, however, that volume of demand is not enough to gauge the importance of a mineral. Technological specificity and concentrated supply chains give strategic significance to minerals, like lithium and rare-earth elements, which are much smaller in mass terms when compared to copper, zinc, silicon and graphite.

The rare-earth element results are of a very special value. The wind power industry is the largest market for REE, driving demand to 18.56 kt of neodymium and 14.24 kt of dysprosium by 2050, in the NZE scenario, respectively. Although they account for only a small fraction of the total mass of minerals consumed, they are very important for permanent-magnet wind technologies. This is in line with the researchers at Li et al., 2020, who suggested that global wind-power targets might be limited by critical rare-earth elements (REEs) availability. The results thus further underscore the importance of considering REEs separately from the overall mineral demand ranking. The significance of REEs can be underestimated based on their mass, but become more apparent when based on their technological function and concentration in supply chains.
This is strengthened by the results of the supply concentration. Battery-grade graphite has the highest concentration in the top three suppliers (90.2%) and Magnet rare earth element refining has the highest concentration in the top three suppliers (92.1%). Strategic exposure is not only limited to minerals with the highest demand volumes, as natural graphite mining, cobalt refining and lithium chemicals and nickel mining/refining also exhibit high concentration. Rather, vulnerability can occur at the intersection of technological dependency and a clustering of mining, refining or processing power. This result is consistent with that of Liang, et al., (2023) which demonstrated that while net zero development significantly raises demand for critical materials, it also demands that supply chain development be carefully considered. It is particularly significant: copper is strategically relevant primarily due to its huge demand scale, whereas REEs are strategically relevant due to their specialized applications in wind power and REE supply chains for magnets.
The consequences of this impact are great for energy policy, industrial planning, and energy supply-chain governance. Firstly, the grid planning is not just an infrastructure or electricity-market problem, but also a mineral planning problem. Second, the deployment of batteries and storage should take into account the demand for graphite, lithium, nickel, manganese, and vanadium. Third, there is a need to focus on the REE supply chains in the context of the expansion of wind power, particularly in the fields of refining and processing. Fourth, mineral security is a goal that should be achieved not just by the expansion of extraction, but also by recycling, substitution, enhancing material efficiency, diversifying supply and responsible sourcing. These measures are crucial as they can result in environmental, social and governance (ESG) challenges, such as land-use conflicts, water stress, biodiversity pressures and community impacts, when mining operations expand (Carr-Wilson et al., 2024).
The study has several limitations. It is based on secondary information on scenarios and does not estimate effects for the mine level, prices, recycling rates or substitution potential or on country-specific electricity generation pathways. The supply-side analysis is constrained to minerals defined in the dataset and the stages of supply chains included in the dataset, and some minerals relevant to demand were not completely aligned to the supply concentration indicators. The analysis is also based on demand in kilotonnes and could underestimate the significance of the small volume, high criticality minerals. More detailed supply-chain mapping, incorporation of price dynamics, consideration of recycling scenarios, and the regional pathways for power-sector development, along with life-cycle environmental impacts, should be included in future research. Additionally, the impacts of strategically sourced and rare-earth element minerals on power generation under the responsibility sourcing principles and the strategies of circular economy should also be investigated.

## Conclusion

This study examined the role of critical, strategic, and rare-earth element minerals in power generation by linking scenario-based mineral demand with supply-chain concentration. The findings show that power-system decarbonisation creates both high-volume and strategic mineral dependencies. Electricity networks represent the largest technology-level demand category, requiring 8,853 kt under NZE by 2050, while copper dominates mineral demand at 13,936.3 kt. The next largest demand cluster is technology for grid batteries, solar PV, and wind, suggesting a coming need for infrastructure, generation, and flexibility technologies. The conclusions also indicate rare-earth elements, including neodymium, praseodymium, dysprosium, and terbium, whose supply chains are concentrated and whose mass demand is lower are important in terms of their use in permanent-magnet wind technologies. The study also indicates that exposure is highest when these three elements (expected demand, technological dependency and cluster of stages in supply chains) come together, such as for magnet rare earth element refining, battery grade graphite, lithium chemicals, and nickel supply chains. The results suggest that the issue of mineral security needs to be considered as part of the energy transition planning for the power-sector policy. Diversified supply chains, responsible sourcing, recycling, material efficiency and developing processing capacities are required for the grid expansion, the deployment of storage and the development of wind-power. Attention in policy should not only be paid to minerals with the highest demand volumes but also to minerals with smaller volume demand and high technological specificity and vulnerability of supply. Further research is needed that takes into account the impact of mineral prices, the recycling potential, regional electricity pathways, substitution possibilities and environmental and social impacts of mining and processing.

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