Concentration of critical mining assets and the geoeconomic fragmentation

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Abstract:

The geographical concentration of mines supplying critical minerals has recently been studied, but much less attention has been given to the concentration of ownership of mining assets. This research investigates market concentration in critical minerals production by incorporating geographical location, direct, and financial ownership structures of mining assets. Using data from Standard and Poor's, the study reveals that while production of critical minerals is geographically concentrated in groups of countries that vary with each mineral, direct and especially equity ownership are mainly controlled by large multinational mining companies and financial institutions concentrated in leading economies. The findings emphasize the geopolitical risks posed by these concentrated ownership structures, which could affect the effectiveness of policies aimed at securing mineral supply chains for green technologies.

Introduction

The success of the energy transition will largely depend on a stable supply of the critical minerals which are essential to the construction of green infrastructures (Ali et al., 2017). The International Energy Agency estimates that, on average, the production of these critical minerals would have to be multiplied by 6 by 2040 to meet net-zero targets in 2050 (IEA, 2021). In this context, concerns are growing about the reliability of the supply of these minerals in the mid-transition period (Miller et al., 2023; Espagne et al., 2023). While such a rapid growth in demand is challenging to meet under any circumstances, it is exacerbated by price volatility, supply chain disruptions, and escalating geopolitical tensions, all of which could potentially hinder the progress of the energy transition (De La Torre De Palacios & Espí Rodríguez, 2024 ; IEA, 2024).

The recent trend in geoeconomic fragmentation creates new security concerns for the stable supply of critical minerals for the transition. The global economic structures have until recently been characterized by an unprecedented interconnectedness through complex trade networks, cross-border financial flows, and internationalized supply chains (Aiyar et al., 2023). However, the Covid-19 crisis starting in 2020 and later Russia's invasion of Ukraine in 2022 seemed to destabilize this model, leading the IMF to warn about a possible geo-economic fragmentation of commodity trade, that could notably affect the supply of critical minerals (Aiyar et al., 2023). These geopolitical tensions create an environment that favors for a small group of producers to take a dominant position on the market (De La Torre De Palacios & Espí Rodríguez, 2024). In recent years, there has notably been little advancement in the diversification of supply sources of critical minerals. The concentration has even increased for some minerals (IEA, 2024).

A new geopolitics of mineral supply chains is emerging, whereby protectionist policies are attempting to secure the supply chains for green technologies, particularly critical minerals (Müller, 2023). The Inflation Reduction Act (IRA) in the USA and the Raw Materials Act (RMA) in the European Union are notably designed to reduce dependency on geopolitical competitors (Müller, 2023). These policies establish national ownership criteria for suppliers of green technologies to prioritize domestic production and encourage national companies to invest abroad. This policy approach explicitly aims at kick-starting a friendshoring process in the mining sector, characterized by increased partnerships between geopolitically aligned nations, as seen in initiatives like the Minerals Security Partnership or the Belt and Road Initiative.

Understanding the level of concentration in critical mineral production and identifying key producing countries becomes an essential pre-requisite for a more effective and multilateral coordination of low-carbon transition policies. Recent literature has focused primarily on the geographic location of mines to determine production control (see Bucciarelli et al., 2024). However, the mining sector's complex ownership structures—comprising various investors like governments and tech companies—complicate the identification of the entities that truly control mineral production and, by extension, the supply chain. Current criticality assessments methods often overlook these higher levels of ownership, even though they, too, have the potential to be concentrated – risking distorted competition, higher mineral prices, and missed opportunities for mining countries to fully benefit from their resources (Leruth et al., 2022).

In this article, we re-examine market concentration in critical minerals production by considering not only the geographical location of mines but also the Direct and financial ownership structures (Equity ownership) of the producing companies. To achieve this, we exploit the mining assets data provided by Standard and Poor's, which gives us access to the complete ownership structure of mining assets exploiting critical minerals. First, we analyze the market concentration of critical minerals producers according to three definitions of control. The first is **Geographical control**, determined by mine's physical location. The second is **Direct ownership**, defined by the location of the headquarters of companies holding direct stakes in the mine. Lastly, the third is **Equity ownership**, where we trace the financial stakeholders of the mining companies up to their countries of origin. These three definitions of control allow us to obtain a complete picture of the different potential risks associated with company ownership. Secondly, we propose to put these new measures of concentration in the production of critical minerals into perspective by comparing them with measures of the average geopolitical distance separating the main producers based on their relative geopolitical position in the global landscape.

The results of this study shed light on the geopolitical risks linked to the ownership structures of critical minerals mining assets. While the production of critical minerals is typically concentrated in different groups of countries depending on the mineral, ownership—whether direct or through financial investors—remains concentrated in a few countries that do not vary across different minerals. Major international mining companies, headquartered in a handful of countries, control most of the production through investments in significant mineral deposits. These companies are predominantly owned by investors from major economies. Most notably, attributing control to the highest levels of ownership structure tends to increase the average geopolitical distance between the countries overseeing mineral production from the rest of the world.

This paper is structured as follows. Section 2 presents a review of the recent literature on the market concentration of critical minerals. Section 3 introduces data - including the S&P database – and the main methodology to assess the ownership control. Section 4 presents the main results for market concentration by critical minerals. Finally, we discuss in the last section the potential implications of those results for the low-carbon transition.

Literature review

The criticality of minerals can be broadly defined as a measure of their importance to an economy, industry, or for a specific application, as well as the measure of the associated supply and demand risks (Schrijvers et al., 2020). The study of mineral criticality is not new; it dates to at least the Cold War era, when the strategic importance of minerals for national economies—especially in the defense sector—prompted governments to closely monitor their supply. This concept has seen a notable resurgence with the double transition, energy and digital, driven by life-cycle analysis efforts that aim to pinpoint vulnerabilities in the value chains of products, such as renewable energy technologies, which are increasingly reliant on a diverse range of minerals (Hayes & McCullough, 2018; IEA, 2021).

Although there are a growing number of studies on critical minerals, there is no consensus on how to estimate this criticality. The methods surrounding the evaluation of the criticality of minerals for the low-carbon transition do not rely on any purely scientific assessment but rather aim at guiding public action (Prina Cerai, 2024). The methods and objectives of criticality assessment studies often vary depending on the institutions conducting them (Schrijvers et al., 2020). However, in recent years, these assessments have increasingly emphasized the geopolitical dimension associated with mineral supply. This focus has gained significance in the context of green industrialization and the increasing dependence of many countries on imported minerals, particularly when these resources are sourced from geopolitically distant countries. Thus, the concentration of producers is truly problematic when we consider the geopolitical dimension of international relations. Indeed, the less diversity there is between producers, the higher the risk of market disruption if one of them unilaterally decides to adopt measures restricting exports (quotas, taxes, etc.).

Control over production has thus become a central focus in current analyses of the criticality of minerals vital to the ongoing "double transition"—the shift toward both energy and digital economies. The ability of private entities or governmental bodies to control mining production is a complex issue, shaped by the intricacies of global mining operations (Hodge et al., 2022). This topic has only recently gained attention, largely due to the availability of new data sources. By examining different perspectives on control over mining production, researchers have identified three generations of studies that assess the criticality of mining operations through measures of market concentration:

- **The first generation of studies considers the production site, *i.e.* the geographical location of the mine, as the main criterion for determining control of this production.** The country hosting the mine is therefore considered to have ultimate control over the production and export of the minerals. This method is particularly useful for capturing supply risk dependent on national factors, whether political (e.g. export restrictions) or natural (mining accident, natural disaster). This approach prevails in most current classifications of critical minerals, notably those produced by the International Energy Agency (IEA, 2021), the World Bank (Hund et al., 2020), the Joint Research Center of the European Commission[1] or the U.S. Department of Energy[2] (DOE). However, this approach does not adequately integrate the complexity of the mineral resources sector,

[1] https://rmis.jrc.ec.europa.eu/eu-critical-raw-materials
[2] https://www.federalregister.gov/documents/2023/08/04/2023-16611/notice-of-final-determination-on-2023-doe-critical-materials-list

characterized by a large number of intra- and inter-company exchanges (Hodge et al., 2022). It does not take into account the influence of mine owners, whether national, international or state-owned. Thus, the risks associated with the various off-take contracts and other agreements between mining companies and the host state are not taken into account in this first generation of criticality analysis. This is particularly important in the case of small states, which can be crucial for the supply of certain minerals, and where the presence of multinational mining companies can significantly influence them.

- **A second generation of studies on critical minerals considers mine production control to be determined by the nationality of the mine's shareholders.** This approach highlights the Direct of mine owners, often foreign, capturing the extraterritorial transfer of rights and the impact of technological and investment capacities. Ericsson et al., (2020) analyzed Chinese influence in African mining, finding it weaker than expected and noting the continued dominance of Anglo-Saxon transnational companies. Recently, Leruth et al., (2022) suggested however that China's control over global value chains involving critical minerals and rare earths is more significant than expected. Finally, Sun et al., (2024) compared market concentration from both a geographical perspective and the origin of the equity ownership. Their analysis confirmed that transnational investments are significantly involved in the value chains of cobalt, lithium, nickel, and platinum. They suggested that by controlling the production of critical minerals abroad, countries with high demand manage to compensate for their insufficient domestic production of these minerals.
- **A third generation of studies attributes the control of mining production to the institutional shareholders of mining companies exploiting critical minerals.** The so-called equity ownership of critical mining production looks into financial linkages rather than direct mining production. Although this area is still underexplored, it has started to appear in deep supply chain analyses, revealing close connections between mining companies, investors, and end clients. As Prina Cerai (2024) noted, complex relationships exist among these entities. End clients, such as automotive companies and battery manufacturers, are now directly investing in mining companies or projects. For instance, the battery manufacturer CATL is heavily integrated into the lithium mining ecosystem. Investment funds, banks, and insurance companies are also increasingly investing in mining companies and projects. This growing blurring of boundaries between financiers, clients, and mining companies has been little studied, raising many questions about the financial ties between states and this booming sector. As noted by the pioneer work of Leruth et al., (2022)[3], China's control over critical minerals and rare earths is found to be more significant than previously thought due to the presence of Chinese non-mining investors.

[3] They used a proprietary software called "Zeno-indices" to better estimate control based on investor share sizes.

Figure 1: Evolution of the number of national strategic policies

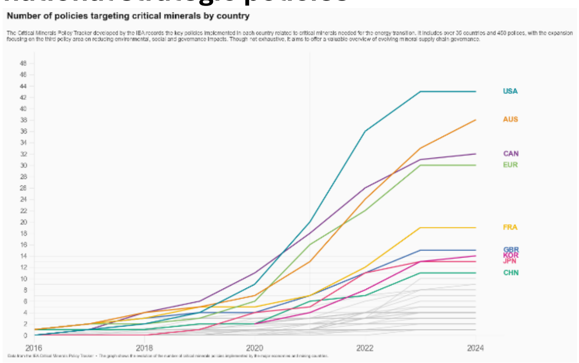
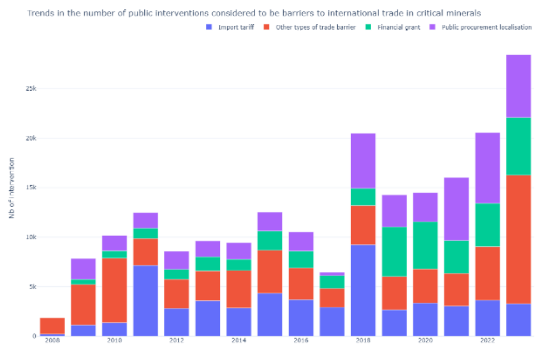


Figure 2: Evolution of the number of trade barriers targeting critical minerals



Caption: The left graph shows the evolution of the number of policies targeting critical minerals by country between 2016 and 2023. The data are derived from the IEA policy tracker[4]. We can observe a greater number of policies implemented by the main industrial economies compared with other countries. The graph on the right shows the upward trend since 2008 in the number of public interventions considered to be barriers to international trade in critical minerals by the Global Trade Alert Database[5].

Despite increasingly detailed analyses of the sources of control, which reveal economic and financial ties between critical mineral-producing and non-producing countries, the understanding of the impact of geoeconomic fragmentation in criticality assessments has seen little evolution. Traditionally, the market concentration indicator has been deemed sufficient for analyzing this risk, assuming all producing countries can trade freely with demanding countries. To overcome this limitation, we have started to weight this indicator by considering the risk associated with mineral-producing countries, using the World Bank's World Governance Index (WGI). The WGI offers a score for institutional quality and good governance, which are seen as proxies for a country's capacity to sustainably manage its mineral resources.[6] However, this indicator may fail to reflect real geopolitical risk, especially since it was conceived before the emergence of discussions on geoeconomic fragmentation, which arose following the successive crises of COVID-19 and the Russia-Ukraine conflict.

Geoeconomic Fragmentation (GEF) is a recently emerging concept that describes the division of the global economy into distinct blocs due to geopolitical tensions, leading to reduced international cooperation, trade barriers, and divergent economic systems. As a new concept in economic literature, there is no consensus yet on how to measure it. Current efforts to quantify geopolitical fragmentation rely on a few key metrics. One such metric is the Geopolitical Risk Index, developed by Dario Caldara and Matteo Iacoviello (2022), which measures the risk of negative geopolitical events by analyzing newspaper content on geopolitical tensions from 1900 to 2024. According to this index, the U.S. is identified as the most geopolitically disruptive nation, suggesting it could be the most likely to halt critical mineral trade with other countries. Another important metric is Geopolitical Distance, which assesses the geopolitical distance between countries based on their foreign policy behavior, particularly their

[4] https://www.iea.org/data-and-statistics/data-tools/critical-minerals-policy-tracker
[5] https://www.globaltradealert.org/
[6] For example, the Democratic Republic of Congo's (DRC) dominant role in cobalt production, coupled with its particularly low WGI score, has led criticality analyses to often deem this source of production unreliable.

voting patterns in the United Nations General Assembly (UNGA). This metric calculates the mean discordance in UNGA voting by squaring the differences between two countries' votes and then standardizing the result, with a value of 0 indicating complete opposition and 10 indicating full agreement.

However, the connection between geoeconomic fragmentation (GEF) and mineral resource production remains underexplored. Recent studies (Adajar et al., 2019; Aiyar et al., 2023; Wang et al., 2023) have begun to touch on this topic, particularly within the friendshoring debate. Notably, the IMF has made a significant contribution by being the first to analyze GEF in relation to the location of critical mineral production using the geopolitical distance indicator (Aiyar et al., 2023). Their research reveals dependencies between critical mineral exporters and importers who are often far apart on the geopolitical spectrum. However, the IMF's analysis is limited to the geographical origins of these minerals and does not address who controls their production. In doing so, it fails to analyze the geopolitical constraints that may be added to the high market concentration caused by international mining companies or the financial or government institutions that control them.

Method

Definition(s) of critical minerals and their key usage for low carbon or digital technologies.

The concept of Critical minerals, also known as Energy transition minerals (ETMs), has emerged to identify minerals essential for renewable energy technologies and infrastructures. The World Bank Group first listed these minerals in 2017, followed by the International Energy Agency (IEA, 2021) with a more detailed list in 2021, reflecting advanced projections for a decarbonized energy mix. These lists result from energy modeling projections of future energy mixes and the mineral content needed for renewable technologies, such as platinum for hydrogen fuel cells or lithium and cobalt for the batteries of Electric Vehicles.

The 32 critical minerals listed[7] by the IEA have very different production structures. While some have been produced for a long time and in many countries (such as iron), others are only produced in a handful of countries. Among the latter, the production of several minerals relies heavily on low-income economies. This is notoriously the case for cobalt, for which the Democratic Republic of Congo produces around 65% of the world's output in 2023. Similarly, China accounts for about 85 % of the world's production of Rare Earth minerals (Lanthanides hereafter).

Mine level production and ownership

We obtain detailed information on 2142 critical mineral mining assets from the S&P Metals and Mining database (last access in July 2023). For each asset, we collect a range of information, including geographical location and development status: active or inactive. Active assets are mines capable of producing minerals. Inactive assets, on the other hand, are mines still at the project stage or having been put on hold, characterized by their non-productive status

[7] Complete list available in the annex section

(as of July 2023). Active assets are associated with production and mineral reserve values for the year 2022, expressed in metric tons.

In addition to the production and reserves data, we extract information on the ownership structure of mining assets, active as well as non-active. For each mining asset, we identify the direct owners, *i.e.*, the institutional entities with an explicit share in the mine's capital, and up to ten of the mine's co-shareholders. Shareholders can include public companies, private companies, state-owned companies, state or local government entities, or private individuals. The vast majority of these entities are composed of private and public mining companies.

Each mining company that holds a share of any mining assets has its own institutional ownership structure. Again, each mining company can have up to 10 institutional owners, each having a share of the mining company. Listed mining companies are the easiest to track as they are legally forced to declare their ownership structure. However, all mining companies do not have a tracked ownership structure, especially if it is owned by private entities. Junior mining companies for instance, generally have no institutional shareholder structure, as they are often formed by a few individuals to minimize the risk of failure due to their highly speculative nature.

Despite being one of the most comprehensive mining asset databases available, the S&P Metals and Mining database cannot be directly compared to common mineral production statistics from the USGS or BGS due to differences in data collection methodologies[8]. The USGS collects data through government channels, surveys, and estimates, covering a wide range of operations, including smaller and private entities. In contrast, S&P focuses primarily on publicly available data from larger, publicly traded companies (S&P, 2023). While the USGS aims to provide a comprehensive national and global overview, encompassing both large- and small-scale operations, public and private, S&P's emphasis is more on major mining projects and large, publicly listed companies (S&P, 2023). Given these differences, the S&P database should be considered as reflecting the production controlled by major mining companies, rather than an exhaustive assessment of global mining production.

Despite being one of (if not) the most comprehensive mining assets database available on the market, S&P Metals and Mining suffers from different gaps that are not easy to estimate nor address. The dataset notably fails to match the production coverage of national geological institutions (mainly USGS[9] and BGS[10]). Depending on the mineral / year, we only get 50-90% of the global mining production identified by major geological institutions. This issue can be attributed to several factors. First, the method of collection of the data is heavily dependent on the mining companies' production and reserves declaration through the publication of reports. Small mining companies and the ones located in countries with less transparency may be harder to identify. Second, geological institutions build a nationwide assessment while S&P focuses only on mining assets. Considering these limitations, this dataset should be considered as the production detained by major mining companies rather than an exhaustive assessment of the world mining production.

[8] https://www.usgs.gov/centers/national-minerals-information-center/historical-statistics-mineral-and-material-commodities

[9] https://www.usgs.gov/programs/mineral-resources-program/science/critical-mineral-resources
[10] https://www.bgs.ac.uk/geology-projects/critical-raw-materials/

Table 1 - Number of active mines and ongoing projects for the major critical minerals

Mineral	Active mines	Projects
Bauxite	84	421
Chromite	58	173
Cobalt	7	318
Copper	383	1799
Graphite	13	41
Iron Ore	685	0
Lanthanides	9	56
Lead	63	1284
Lithium	25	58
Manganese	44	109
Nickel	89	268
Niobium	5	0
Palladium	4	14
Platinum	43	0
Silver	70	30
Tantalum	4	0
Tin	22	78
Tungsten	31	47
Vanadium	10	0
Zinc	213	211

Caption: The list of minerals is taken from IEA 2021; mines are considered active when they have reached one of the production stages defined by S&P; projects are those that have not yet reached the production stage.

Definitions of control

The definition of control over the production of a mine is crucial as it determines "who" can decide "how" the critical minerals may be used and traded. While it may seem trivial at first glance to consider the country in which the mine is located as the sole "controller" of its production, the complexity of the ownership structure of mines anchored in a globalized economy actually makes the definition of control much less straightforward. Thus, the assumptions underlying the choice of production control are essential for identifying a potential supply risk resulting from high market concentration among producers of essential minerals. However, as indicated in the literature review section, the definition of mining production control has been largely restricted to the geographical location of the producing mines.

In this study, we choose to analyze critical mineral production by defining three alternative sources of control. The aim is to go beyond simple measures of market concentration based on the geographical location of mines and make comparisons across the different levels of control. Following Leruth et al., (2022) and Prina Cerai, (2024) we define three levels of control as shown in Figure 3 :

- **Geographical control:** Production of critical minerals is attributed to the country hosting the mine. The production of each country's mines is then aggregated to obtain the production controlled by the country. This is the level of production control most widely used in the existing literature.

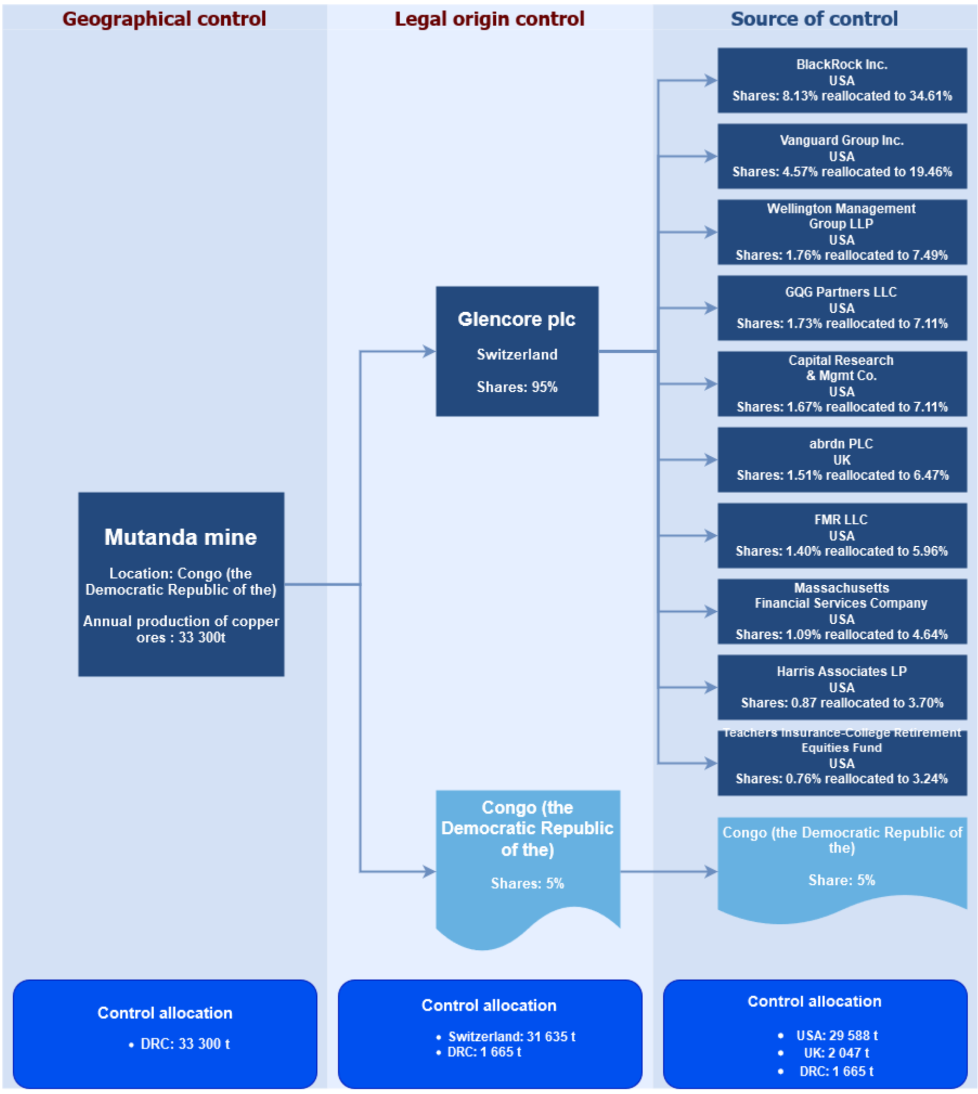
- **Direct ownership**: The production of critical minerals is divided between mining companies according to their share in each mining asset. The headquarters location of these companies is then used to attribute a nationality of the control of that production.

  Example: A mining asset in Zambia produces 1,000 tons of copper annually. Ownership is divided between Company A, holding a 70% stake, and Company B, holding a 30% stake. Company A, headquartered in the UK, is allocated control of 700 tons of copper, while Company B, headquartered in China, is allocated 300 tons.

- **Equity ownership :** The production of critical minerals is attributed to the institutional shareholders of the mining companies that control these key mining assets. The share of production controlled by each institutional shareholder is proportional to their ownership stake in the respective mining company. In the absence of information regarding non-institutional owners, who may hold a majority of the shares, we assume that only institutional shareholders have the capacity to exert control over production. Therefore, ownership shares must be recalculated to determine the 'theoretical control' over production.

  Example: If Institutional Owner 1 holds 20% of the shares and Institutional Owner 2 holds 3% of the shares in a mining company, then Institutional Owner 1 would theoretically control 86.96% of the production, while Institutional Owner 2 would control 13.04% of the production managed by the mining company.

Figure 3: The three categories of mining asset controls



Caption: This figure shows three categories of control: the geographical control, which is defined by the location of the mine, the Direct ownership control, defined by the (main) owners of the mine, and the equity ownership, which can be defined by the owners of the owners of the mine. Most studies on critical minerals have focused on the first and second categories of control, the equity ownership remaining largely unexplored.

In this study, we assume that control is shared among shareholders in direct proportion to each shareholder's percentage interest. While this method of allocating control is widely used in the literature (see Sun et al., (2024) for example), it is nonetheless open to criticism. Indeed, it is questionable whether a shareholder with a small stake (say <5%) really has any control over mine production. Aware of this limitation, Ericsson et al., (2020) proposed to allocate production control only to shareholders with at least 10% of shares. Leruth et al., (2022) for their part, use a specialized software to allocate production control between shareholders according to the relative share held by each.

Market concentration measures

Market concentration refers to the extent to which market shares are concentrated among a small number of firms. It can be used as a proxy for the intensity of competition[11]. A dominant position by a single producer, whether a company or a country, can influence commodity prices or lead to supply restrictions through export quotas or taxes. The increased risk of supply disruption may prompt changes in government policies or regulations and could affect decisions regarding the necessity of strategic reserves (Brown, 2018).

Herfindahl-Hirschman Index (HHI)

The Herfindahl-Hirschman Index (HHI) is widely recognized as the standard for measuring market concentration and is commonly used by institutions and researchers. In our study, we apply the HHI to assess the concentration of major producers of critical minerals, calculated as follows:

$$HHI_m = \sum_{i=1}^{N} S_i^2$$

With S_i^2 the squared number of shares of country i in the production of critical mineral m and N the total number of countries on that market. As defined in the previous section, the shares of minerals produced are calculated based on the country location of the mine, the country of the headquarters of private and public companies that control the production, or the ownership share of each institution controlling the mining companies.

According to the United States Department of Justice (2010), the level of this index, which determines whether a market is concentrated, is generally set at 2500[12]. A value between 1500 and 2500 represents a moderate market concentration and below 1500 no market concentration (Brown, 2018). Recent works such as Bucciarelli et al., (2024) have questioned this threshold in the case of critical minerals. They argue that using a threshold may result in underestimating supply risks in less concentrated markets. Indeed, they find that low levels of HHI concentration generate on average more variations in the prices of critical minerals than higher levels. Therefore, in our analysis, we are taking a cautious approach to the 2500 threshold which motivates us to extend the scope of HHI inside criticality matrixes using the Geopolitical distance as explained below.

Alternative measures of market concentration (tested for robustness check in appendix)

Although the HHI index is today the benchmark indicator for market concentration, alternative measures exist. According to Brown (2018) the entropy measures provide credible alternatives to the HHI and RHT indices. Entropy serves as a metric of uncertainty that spans between equity, where uncertainty is evenly distributed, and strong concentration on a single possible value. The most commonly used index, the Shannon Index, is defined as the sum of the product of relative country shares and their logarithm, such that:

$$S = -\sum_{i=1}^{n} S_i ln S_i$$

[11] See https://www.oecd.org/competition/market-concentration.htm

[12] In 2023, the US department of Justice lowered this threshold in 2023 to 1800.

Geopolitical distance (GPD)

To measure the geopolitical distance between countries, we rely on observable foreign policy behaviors, such as disagreements in their voting patterns in the United Nations General Assembly (UNGA). The UNGA voting dataset (Voeten et al., 2009, version 32), which includes roll-call votes from sessions 1 to 77, covering the period from 1946 to 2022, is used to construct this measure. Various methods exist in the literature for converting observed voting behaviors into bilateral geopolitical distance measures (see for example Häge (2011) and Bailey et al., (2017)).

Following Aiyar et al., (2023) we base our geopolitical distance measure on the S score initially developed by Häge (2011). This metric computes the mean discordance in United Nations General Assembly (UNGA) voting by squaring the total difference between two countries and then standardizes the result, where a value of -1 indicates complete opposition and 1 indicates full agreement (Aiyar et al., 2023). The GPD can be therefore computed as follows:

$$GPD_{a,b} = -1 \times \left[1 - \frac{\sum_v (X_{av} - X_{bv})^2}{\frac{1}{2} \sum_v (d_{max})^2} \right]$$

Where X_{av} denotes voting behavior (v) of country a and X_{bv} the voting behavior (v) of country b. X refers to votes (yea=1, abstain=2, and nay=3), and v indexes voting during sessions in a calendar year (adjusted for sessions toward the end of the year that could potentially run into January of the n year). d_{max} stands for the maximum possible distance between the country pairs (which is 3–1=2 in this case).

Figure 4 – Average Geopolitical Distance of countries

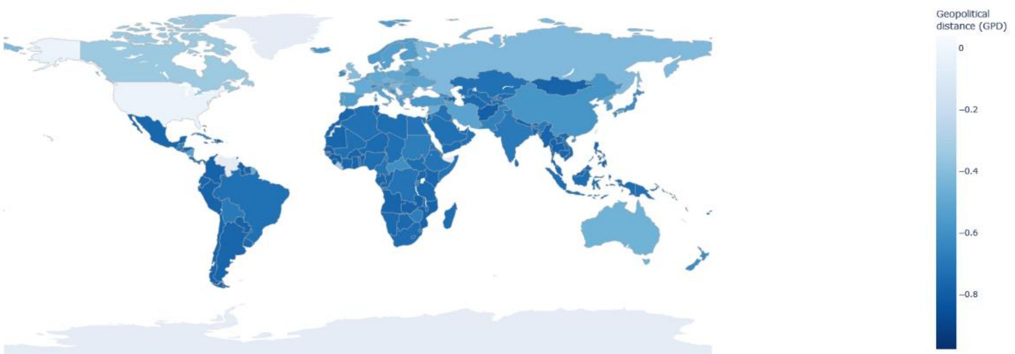


Figure 4 ranks the world's countries based on their average geopolitical distance from the rest of the world. A score closer to -1 indicates a lower average geopolitical distance. The lowest geopolitical distances are found in Africa, South America, and Southeast Asia. In contrast, Western nations, Russia, and, to a lesser extent, China have higher average geopolitical distance scores. As of the 2022/2023 UN voting session, Israel and the USA have the highest geopolitical distance scores.

Results

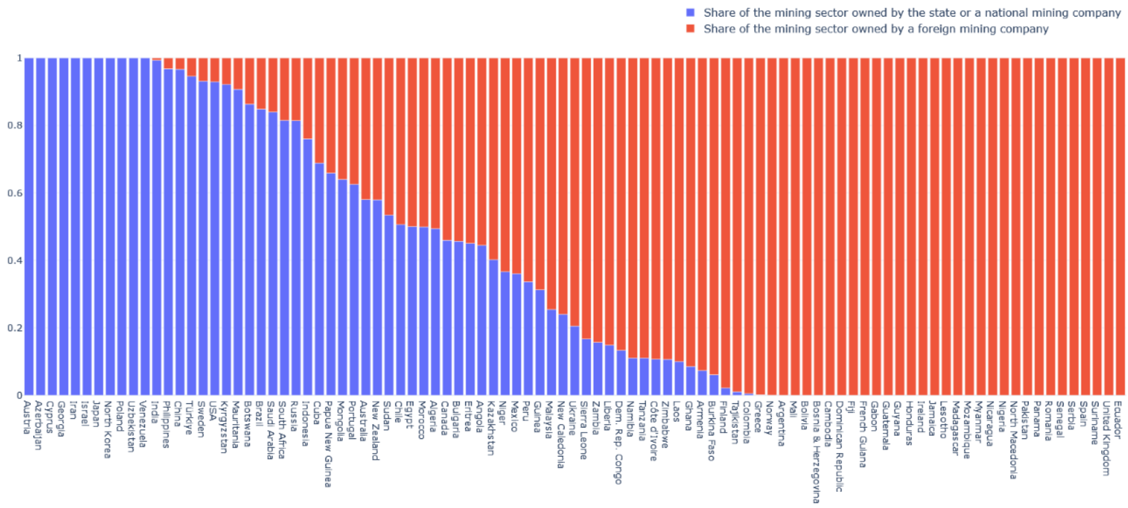
Forms of ownership in each country mineral sector

In this first part of the results, we analyze the ownership structure of each country's mining sector. Figures 5 and 6 compare the average share of the mining sector controlled by foreign entities (whether companies or states) with the share controlled by domestic entities. Figure 5 considers foreign entities based on the Direct ownership control, while Figure 6 defines foreign entities according to the Equity ownership (EO) definition. The proportion of each mineral controlled by foreign entities is aggregated using a simple average, meaning the economic size associated with the production of each mineral is not considered.

Both Figures 5 and 6 reveal contrasting patterns between national and foreign control. Notably, around two-thirds of the countries producing critical minerals have more than 50% of their mining sector controlled by foreign entities. Additionally, about one-third of these countries have no control at all over their critical mineral production. This lack of domestic control is even more pronounced when foreign entities are defined according to the EO definition.

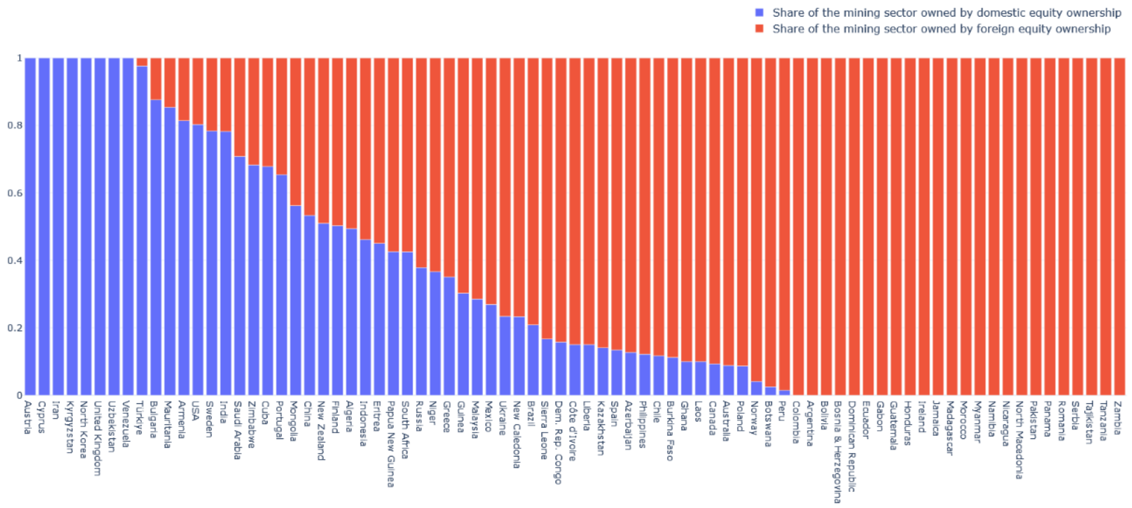
In contrast, only a few countries have managed to maintain significant control over their critical mineral production. Among them are nations under U.S. sanctions, such as Venezuela, Iran, and Cuba. Also included are major economic powers like the United States, China, and, to a lesser extent, Japan, which have been proactive in securing the supply of critical minerals. It is important to note that a significant portion of the foreign entities involved in China's mining sector are based in Hong Kong.

Figure 5 – Direct ownership share in each country mineral sector.



Caption: This graph shows the share of domestic Direct ownership (in blue) in each country's mineral sector of our dataset.

Figure 6 – Equity ownership share in each country mineral sector.



Caption: This graph shows the share of domestic Equity ownership (in blue) in each country's mineral sector of our dataset.

Market concentration of critical minerals producers

Table 2 presents the HHI scores across the three different levels of production control. HHI (geographic) reflects market concentration based on geographic distribution of mines, HHI (Direct) represents market concentration based on the Direct of producers, and HHI (EO) indicates market concentration based on the nationality of the institutional owners of mining companies. For all three measures, a value of 10000, the maximum possible HHI, means that the market is entirely dominated by a single country.

This table also introduces two columns that explain the differences between the different concentration levels. "Diff Direct/GEO" indicates the percentage difference between HHI values for Direct and those for geographical distribution. "Diff EO/GEO" indicates the percentage difference between institutional ownership and geographic HHI values. Positive values indicate a higher concentration for Direct than for geographic distribution, while negative values indicate the opposite.

Table 2 shows that, on average, the concentration scores for critical minerals are high, but they vary significantly depending on the level of control. Among the 20 critical minerals analyzed, 11 exceed the 2,500 market concentration score threshold for the geographic control hypothesis, reinforcing previous findings of high geographical concentration among critical mineral producers. Notably, Graphite, Iron, and Tin are close to this threshold. In contrast, industrial minerals such as Copper, Nickel, and Zinc typically exhibit the lowest market concentration.

Direct concentration tends to reduce the concentration of mineral producers across countries. For example, Lithium and Cobalt, known for their high geographical concentration, have particularly diversified ownership structures. This observation supports Sun et al. (2024), who argue that foreign direct investment (FDI) from countries without native deposits of a critical mineral can effectively mitigate the supply risk for that mineral. Legal constraints, such as mandatory government participation—either directly or through state-owned mining companies—can foster this diversification in mining ownership. Additionally, the significant investments required to develop mining projects often lead to a multi-stakeholder structure.

Conversely, analyzing market concentration using the Equity ownership (EO) often increases the concentration of the mineral producer market for certain industrial minerals, such as Copper and Nickel, while reducing it for other types of minerals. For the minerals emerging with the energy transition, diversified Equity ownership reflects ongoing efforts to secure and advance the development of new critical minerals, like those used in batteries (Cobalt, Graphite...). In contrast, industrial minerals typically exhibit a concentrated ownership structure, often dominated by major financial institutions such as trust funds, which tend to lock in and maintain high levels of control.

The entropy measure of market concentration, used as a robustness check, yields results consistent with the HHI concentration for all three ownership types. Figures 7, 8, and 9 in the annex illustrate the entropy scores for minerals based on geographical ownership, Direct of ownership, and equity ownership, respectively. Copper, silver, zinc, and nickel exhibit the highest entropy scores, indicating a high degree of diversification among producers. In contrast, niobium, tungsten, lanthanides, and platinum show the lowest entropy scores, suggesting a significant concentration among their producers. Overall, the patterns identified by the entropy scores align across the three types of ownership.

Table 2 - HHI production scores for the three control levels

Mineral	HHI (geographic)	HHI (Direct)	HHI (EO)	Diff Direct/GEO	Diff EO/GEO
Bauxite	3060	1577	3422	-48%	11%
Chromite	3078	2762	2572	-10%	-16%
Cobalt	5641	1490	2020	-73%	-64%
Copper	1109	844	2403	-23%	116%
Graphite	2458	4317	1854	75%	-24%
Iron	2459	1405	2410	-42%	-2%
Lanthanides	5163	5316	5073	2%	-1%
Lead	1768	1733	2250	-1%	27%
Lithium	3470	2283	4608	-34%	32%
Manganese	2231	1292	1566	-42%	-29%
Nickel	988	1050	2163	6%	118%
Niobium	10000	10000	3701	0%	-62%
Palladium	3754	5458	2280	45%	-39%
Platinum	6095	7068	2128	15%	-65%
Silver	1222	899	2877	-26%	135%
Tin	2354	2827	2171	20%	-7%
Tungsten	6191	6829	2624	10%	-57%
Uranium	2278	1495	1374	-34%	-39%
Vanadium	5007	3697	5631	-26%	12%

Zinc	1246	1333	1967	7%	57%
Average	3478,6	3183,75	2754,7	-8%	-21%

Figure 7: Production by country (Geography):

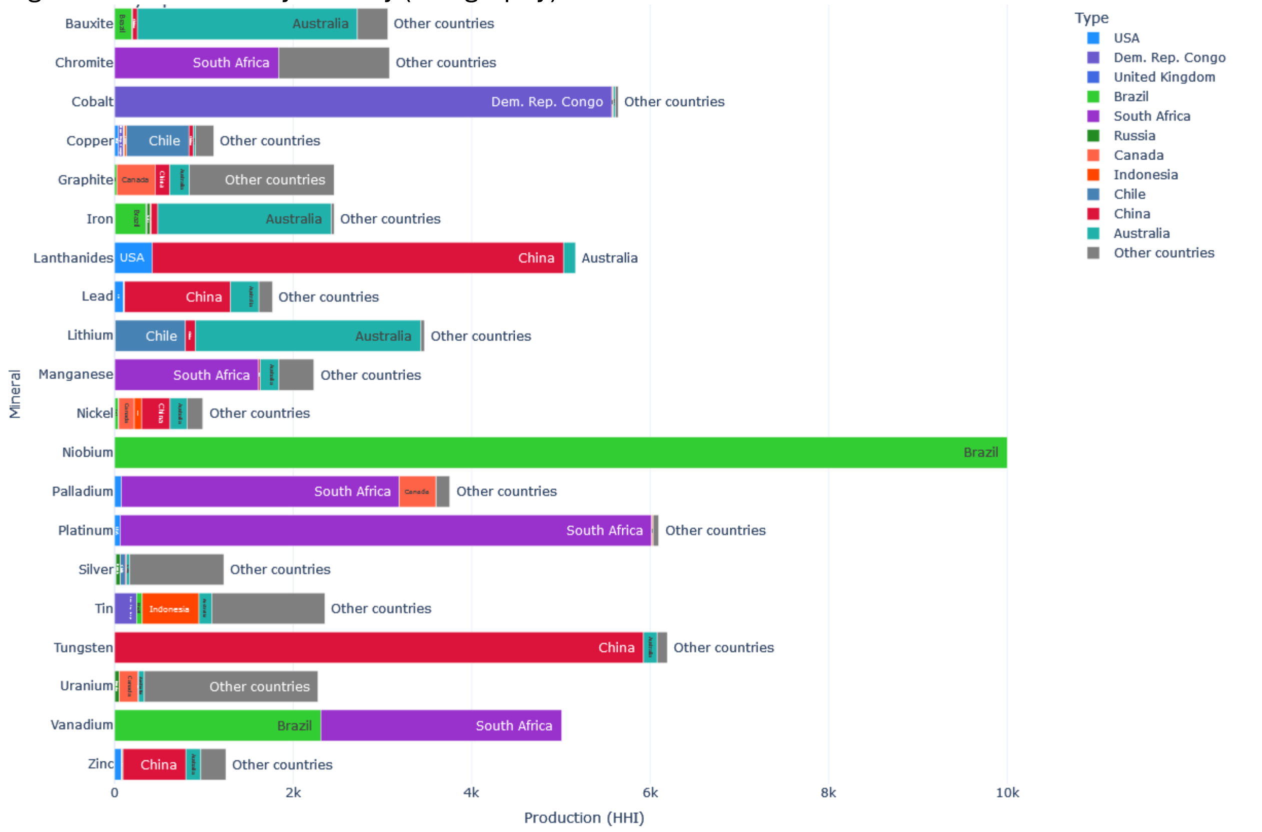


Figure 8: Production by country (Direct Ownership):

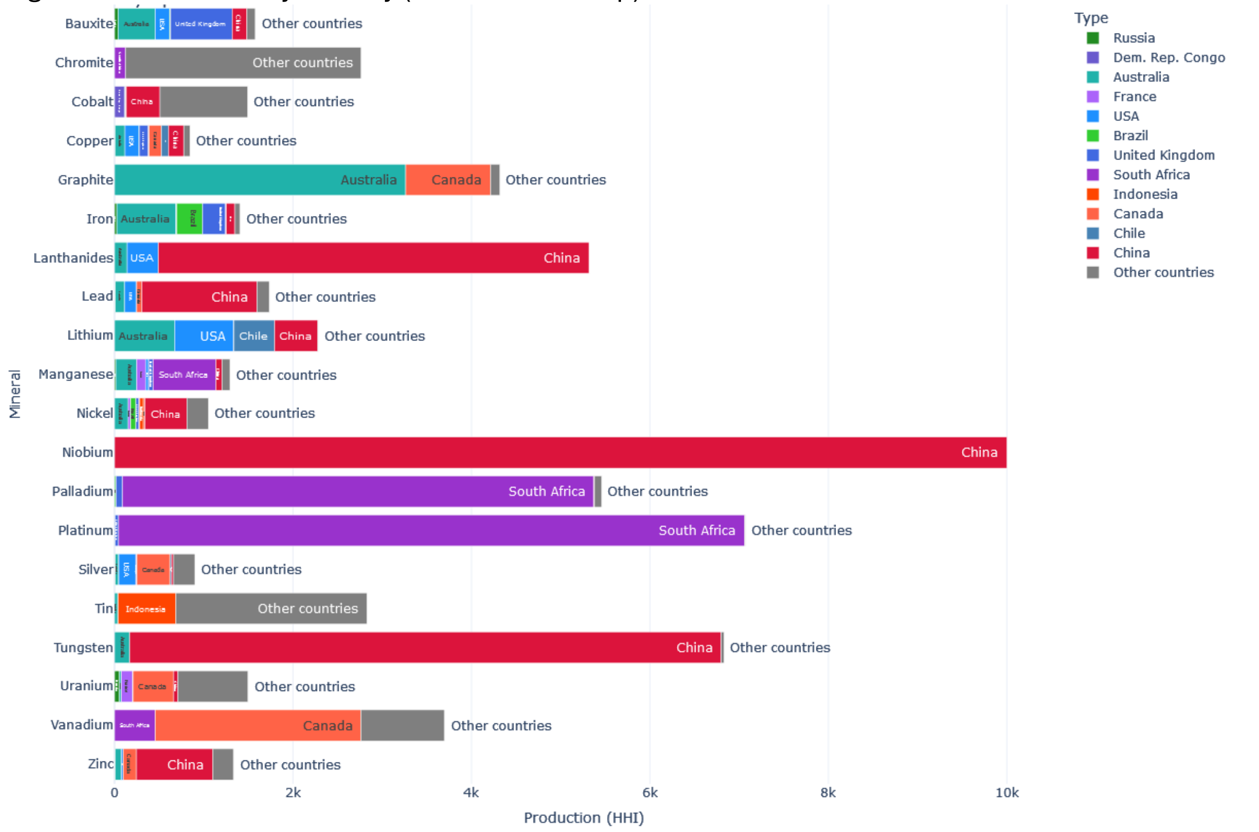
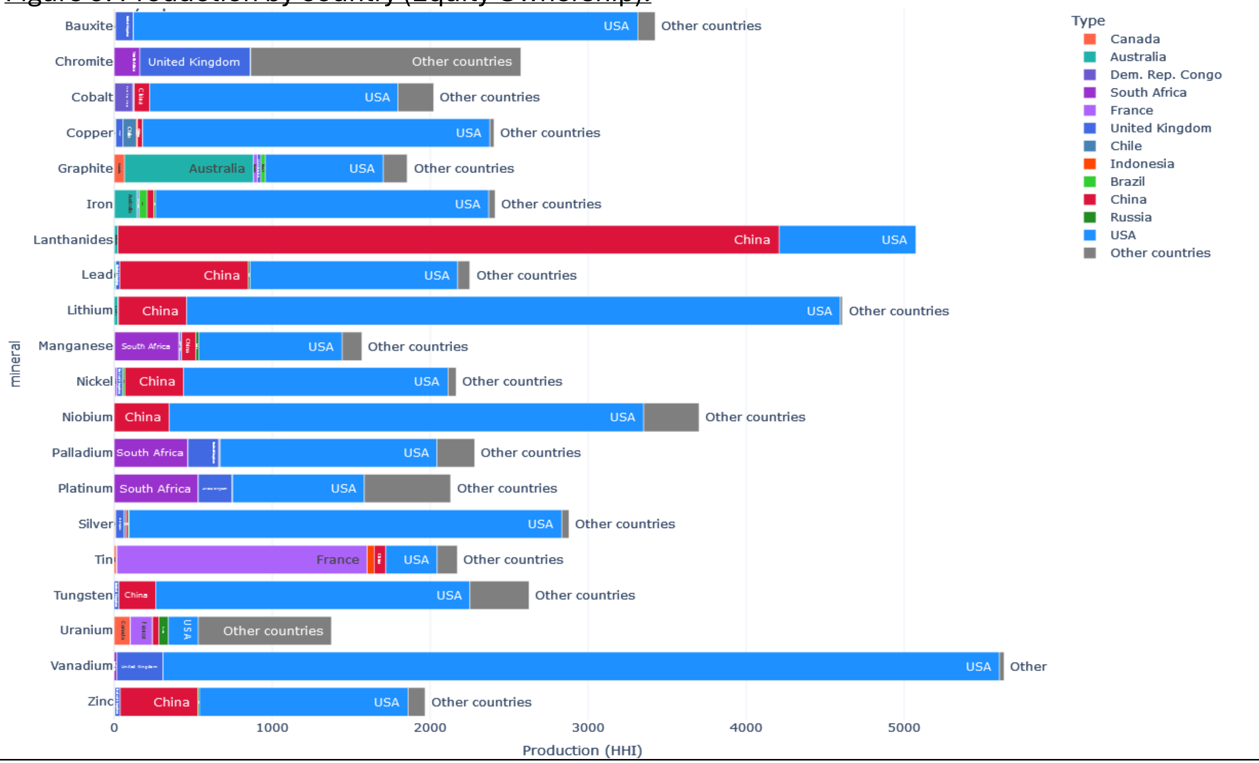


Figure 9: Production by country (Equity Ownership):



In Figures 7, 8, 9, we decompose the market concentration indicator (HHI) by analyzing the respective weight of each controlling country. This allows us to identify which countries dominate each critical mineral market. The HHI index, as shown in Table 2, is derived from the sum of the shares controlled by each country.

The decomposition of ownership concentration by Direct ownership reveals that a few countries dominate the critical mineral mining industry. These countries—Australia, Canada, China, Russia, South Africa, the United Kingdom, and the USA—share a common trait: they are major mining powerhouses with well-established ecosystems of mining companies. Each hosts the headquarters of some of the world's most influential mining firms. Australia, Canada, and South Africa inherited their mining industries from the British Empire. China, Russia, and the USA developed their significant mining sectors, particularly during the Cold War, to support their heavy industries. The UK, while somewhat distinct, has inherited powerful mining companies as a result of its colonial period.

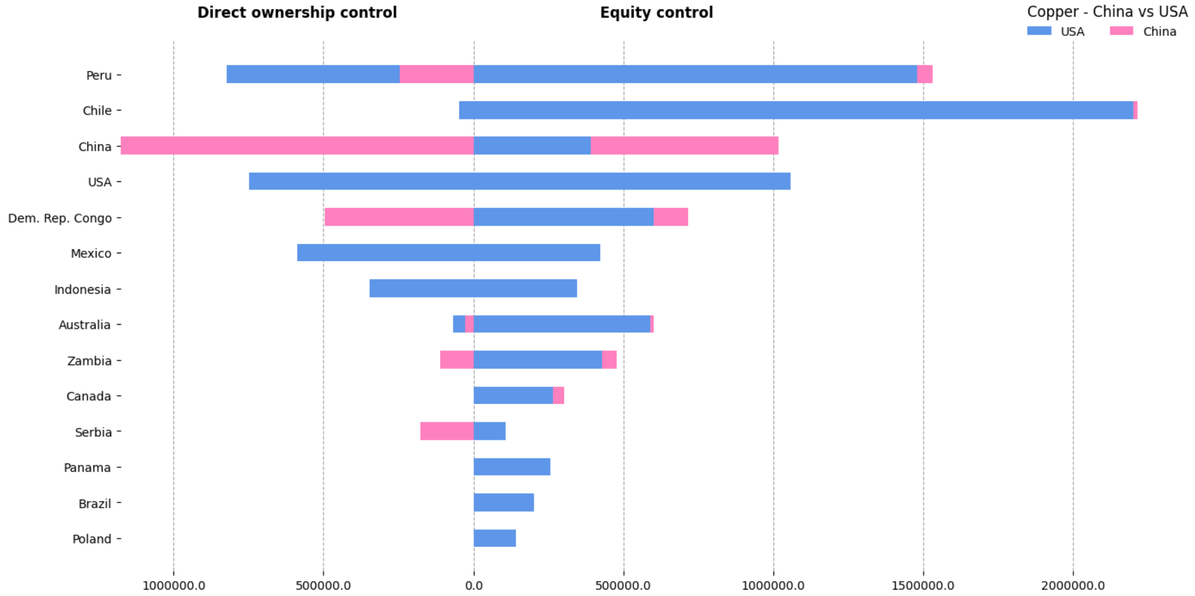
The decomposition of ownership concentration by Equity ownership (EO) reveals the financial dominance of the USA. While China has a significant financial presence in several mineral markets, America's financial power provides it with indirect control over a substantial portion of global critical mineral production. The USA's dominance is evident across most markets, with the exception of Tin and Lanthanides, where it faces more competition. Outside of these exceptions, China appears relatively marginal in terms of institutional ownership within the critical mining industry.

Case study – Copper

Figure 10 highlights the differences in control of copper production between China and the USA. The left part indicates the value of copper production (in tons) controlled by direct investment in copper mining assets over the world. The right part indicates the value of copper production (in tons) controlled by shares in copper focused mining companies.

In terms of Direct control, China is at par with the USA, particularly in African countries, while the USA maintains a stronger presence in Latin America. However, when examining control through the Equity ownership (EO), the USA emerges as clearly dominant. U.S. financial companies even hold shares in Chinese firms, highlighting the significant financial influence of U.S. funds in the global market, including within Chinese listed mining companies.

Figure 10 – Difference in production control of copper between China and the USA



Market concentration of critical mineral reserve owners

Table 3 – HHI reserves scores for the three control levels

Mineral	HHI (Geographic)	HHI (Direct ownership)	HHI (EO)	Diff Direct/GEO	Diff EO/GEO
Bauxite	2209	1557	2605	-29%	17%
Chromium	10000	4165	5795	-58%	-42%
Cobalt	3869	2041	2361	-47%	-38%
Copper	1183	907	2671	-23%	125%
Graphite	3377	8285	2803	145%	-16%
Iron	1491	1379	2023	-7%	35%
Lanthanides	7765	8559	6990	10%	-9%
Lead	797	798	1871	0%	134%
Lithium	3814	2967	4029	-22%	5%
Manganese	3120	1737	1922	-44%	-38%
Nickel	1039	882	1592	-15%	53%
Palladium	6300	6733	4059	6%	-35%
Platinum	5441	6759	2236	24%	-58%
Silver	772	1095	2731	41%	253%
Tin	1640	2139	1420	30%	-13%
Tungsten	7079	6470	5831	-8%	-17%
Zinc	697	738	1450	5%	107%
Average	3564	3365	3081	-6%	-14%

In Table 3, we analyze the reserves of critical minerals using the same approach as for production, distinguishing between the three levels of control. This analysis includes reserves from both currently active mines and future mining projects. It is important to note that not all mining projects in our dataset have reserve estimates, as these estimates are typically associated with more advanced projects in the later stages of development.

The analysis of reserve concentration from current and future mining assets reveals, on average, slightly higher concentration levels compared to production, along with significant heterogeneity across different minerals. Notably, battery minerals like Graphite, Lithium, and Manganese, as well as cross-cutting technology minerals like Lanthanides (rare earth elements), exhibit considerably higher concentration levels in reserves compared to production. Conversely, some minerals, such as Bauxite and Tin, show a decrease in concentration levels when reserves are compared to production.

The decomposition of the ownership structure of reserves in Figures 11, 12, and 13 reveals shifts in key players as ownership concentration increases. At the geographic level, major players in production maintain their strong positions, largely due to their extensive geological capabilities. However, significant changes in ownership emerge when considering Direct and Equity ownership (EO). In terms of Direct, we observe China's growing share over Cobalt and Lanthanides reserves. Australia takes the lead in Graphite reserves, while Russia becomes dominant in Palladium. On the EO level, U.S. share remains unmatched. Nevertheless, there is a notable increase in Chinese control over Tungsten reserves, and Bolivia emerges as a key player in Lithium reserves, where the Bolivian government holds significant shares in every foreign firm involved in mining projects within its vast Lithium deposits.

The shift in countries' shares for certain minerals can be attributed to several factors in the current structure of the global production system for critical minerals. First, the current race for critical minerals has incentivized many countries to pursue new mining projects, even if they are not currently exploiting those minerals. For example, countries with large reserves, like Bolivia with its significant Lithium reserves, may not yet be actively producing these minerals. Additionally, in the earliest stages of mining projects, many junior companies are involved. These companies specialize in developing uncertain or speculative mining projects. Since the majority of junior companies are Anglo-Saxon, this naturally reinforces the shares of countries like the USA, Canada, and the UK in the global mining landscape.

Finally, it is important to note that this analysis of mining projects should be viewed as a potential future scenario for critical mineral production. A mining project may never reach the production stage due to various economic, technical, and socio-environmental factors, which can lead to its cancellation. Even if a project progresses to active mining, large reserves do not always translate into large-scale production. The same factors—economic conditions, technical challenges, and social or environmental concerns—can limit the development of a mine's productive capacity. Additionally, reserves in currently active mines may not be economically viable to extract if the mineral's price drops or if other socio-technical issues arise that affect the mine's operations.

Figure 11: Reserves by country (Geography):

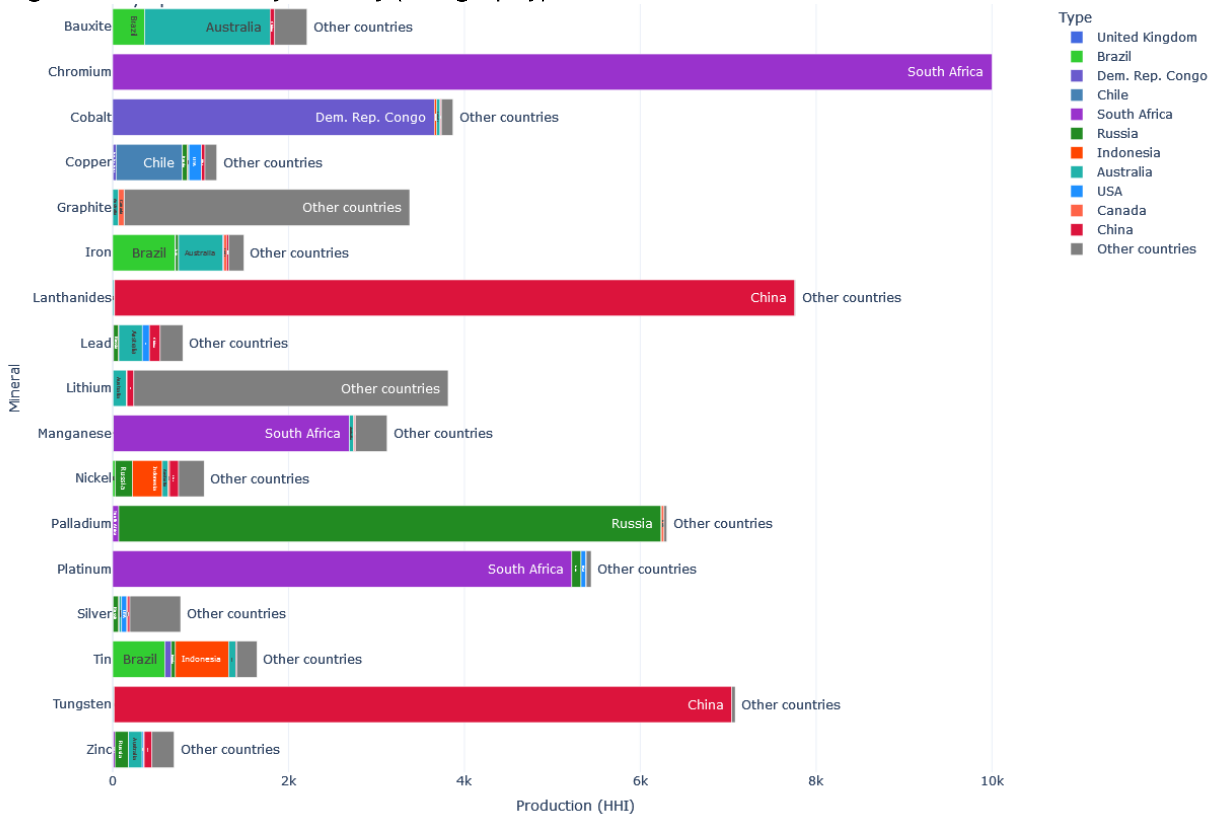


Figure 12: Reserves by country (Direct Ownership):

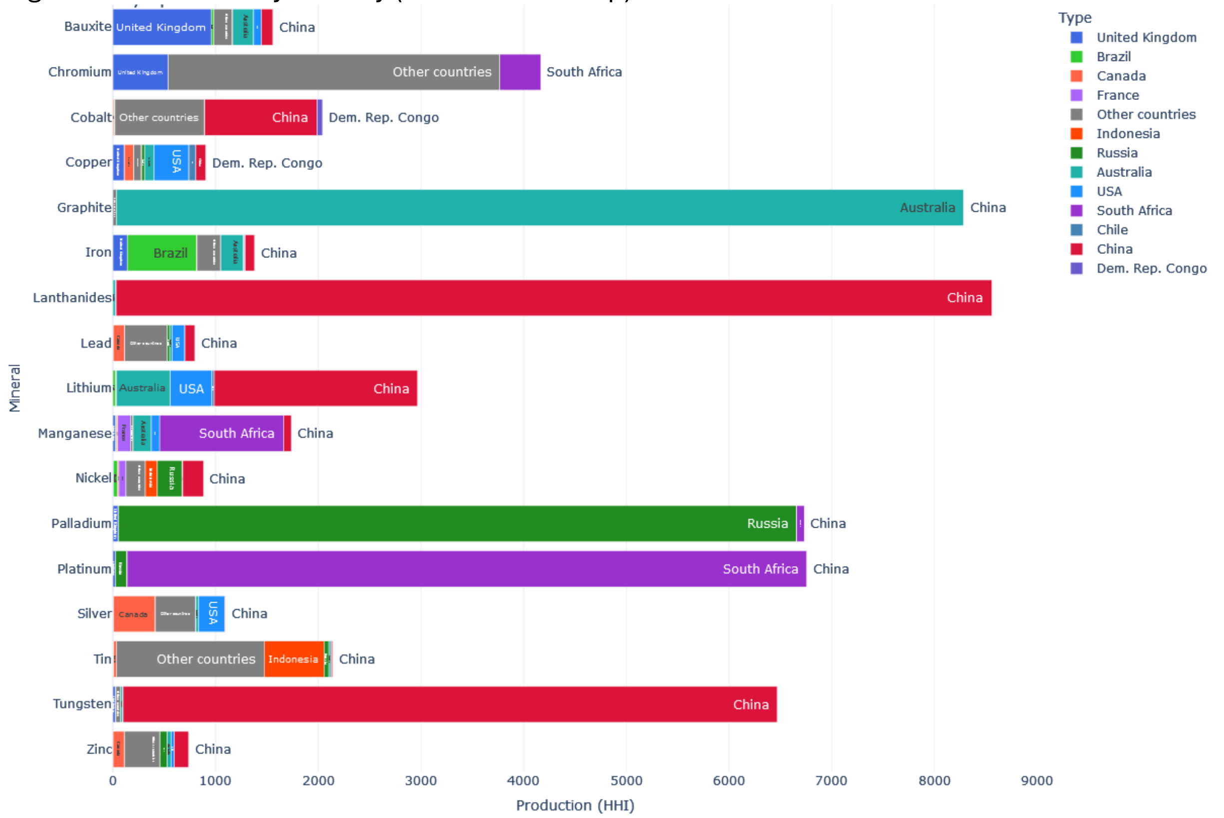
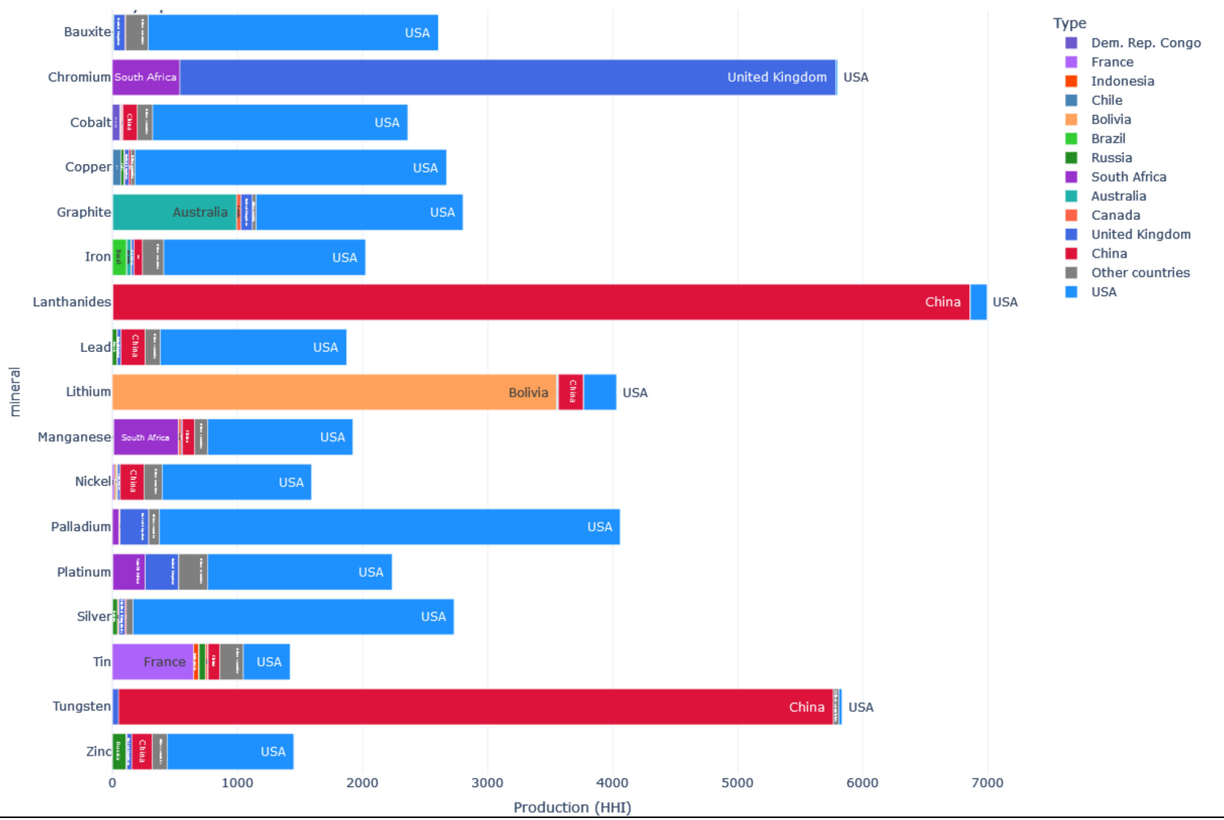


Figure 13: Reserves by country (Equity Ownership):



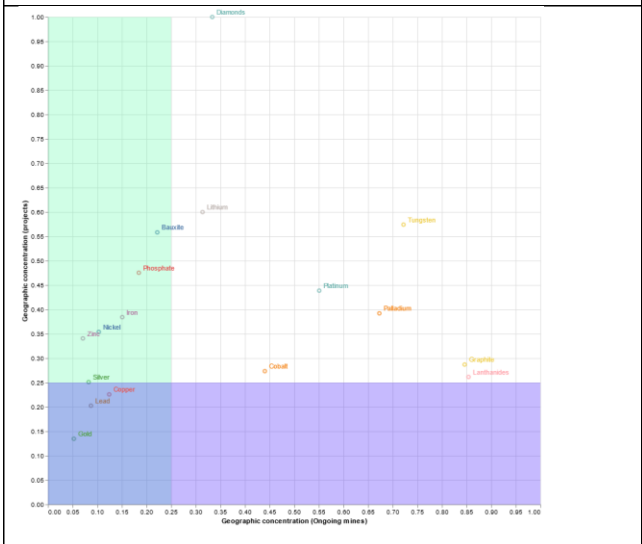
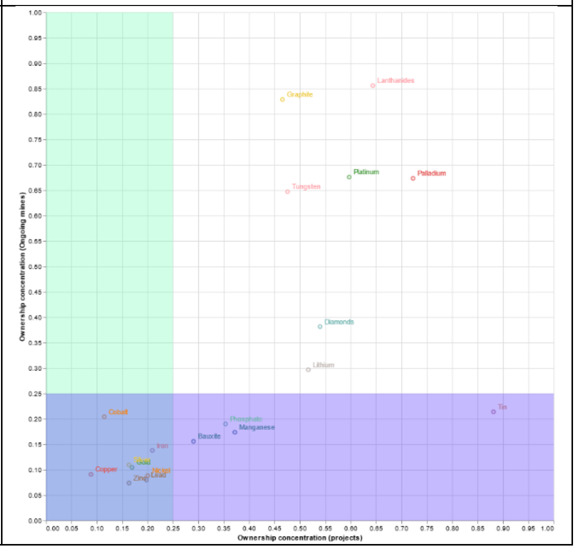
Market concentration of owners of critical mineral reserves for undeveloped mining assets

In this section, we dissociate the reserves identified in currently operating mining assets and the ones from not yet active mining projects. The shift between both types of reserves may provide an idea of future trends in the production of critical minerals. It would also help to identify actors (old or new) that would be able to capture a dominant position on a given market. Figure 14 (left) indicates the HHI concentration for geographic ownership of currently operating mines on the X axis and for mining projects on the Y axis Figure 14 (right) investigates in a similar way the HHI concentration of reserves according to direct ownership concentration definition. The color bars show the level under which the market concentration is considered acceptable according to the 2500 threshold.

Figure 14 (left) shows that the market concentration resulting from future mining projects is likely to be significantly higher than the concentration estimated from current reserves for a wide range of minerals, including Bauxite, Nickel, and Zinc. However, some minerals experience a notable decrease in market concentration, although they still remain above the 2,500 threshold. This is particularly true for Lanthanides and Graphite. In the case of Lanthanides, the high concentration suggests that a small number of countries are specializing in their production. For Graphite, whose market concentration was already very high, this decrease indicates that many countries are actively developing new projects to secure these strategically important minerals.

Figure 14 (right) indicates only marginal changes in the market concentration of critical minerals between the reserves of currently operating mines and those of upcoming projects. This suggests that while there may be shifts in the countries where these minerals are exploited, the entities involved in their extraction are likely to maintain similar market shares as they do today. Implicitly, this also suggests that the Directs of the main players currently dominating the critical minerals market will remain largely unchanged as new mining projects come online.

Figure 14 - Difference in HHI concentration between reserves located in active mines and those under development.

Geographic concentration of Reserves – Active mines vs mining projects	Direct Ownership concentration of Reserves - Active mines vs mining projects
	

Caption: The graph on the left shows the HHI concentration (geographical) for active mines (x axis) and for mining projects (y axis). The graph on the right shows the HHI concentration (Direct ownership) for active mines (x axis) and for mining projects (y axis).

Geoeconomic fragmentation (GEF)

The breakdown of the ownership structure of mining assets by country reveals that a limited number of countries holds significant shares over the production and reserves of critical minerals. As we ascend the ownership hierarchy, it becomes increasingly evident that the current trend in geoeconomic fragmentation may play a driving role in countries critical mineral strategies. The geopolitical risk to critical mineral supplies cannot be directly captured by the Herfindahl Hirschman index alone. The geoeconomic fragmentation of the global economy—exacerbated by recent events such as COVID-19, the war in Ukraine, and the Israel-Palestine conflict—has become a focal point of numerous studies, including those by the IMF (2023). This geopolitical tilt among major economies is raising concerns about the resilience of global supply chains, particularly for strategic common goods like critical minerals. The control over the means of production of these minerals could provide a significant advantage to one of the world's major geopolitical players. Given the strategic importance of critical minerals in supporting the global energy transition, this geo-economic fragmentation could pose a serious threat to global efforts toward a low-carbon development.

In Figure 15, we use the Geopolitical Distance (GPD) in conjunction with the Herfindahl-Hirschman Index (HHI) to provide a new perspective on market concentration for critical minerals. High market concentrations can present varying levels of risk to a country's supply, depending on whether the dominant producers are aligned with or opposed to the country's geopolitical stance. On the Y axis, each mineral is associated with its three concentration measures of control over production. The size of the dots indicates the value of the HHI score. The X axis represents the normalized average geopolitical distance of the producers on each mineral market according to the different levels of controls.

Figure 15 – HHI concentration and average Geopolitical Distance

Caption: This graph compares the HHI concentration of critical minerals and the average Geopolitical Distance of countries that control the production. In this graph, the size of the bubbles is proportional to the HHI concentration score of each mineral.

On average, producers identified by Direct and Equity ownership (EO) have a higher average Geopolitical Distance (GPD) from the rest of the world compared to geographic producers. This suggests that the host countries of critical mining assets are generally less geopolitically distant than the institutional owners. These host countries often include nations in South America and Africa, which have some of the lowest GPD scores. Conversely, high levels of production control frequently involve a significant proportion of countries aligned with specific geopolitical blocs, which tend to have higher average GPD values relative to the rest of the world.

An increased level of ownership concentration heightens geopolitical risk as the group of "mining experts" becomes more dominant in the ownership structure. The second layer of control mainly comprises mining company entities. International mining companies can sometimes develop nationally located subsidiaries, driven by economic interests such as lower tax rates or regulatory requirements. This is particularly common in many developing countries, where mining companies operating mines must be nationally based.

Lanthanides are the most threatened minerals due to geopolitical distance. These minerals are predominantly extracted in China, the USA, and Australia. The primary institutional owners of lanthanide mines are China and the USA, and the main institutional owners of the companies exploiting these minerals are also in China and the USA. These two countries have effectively locked down the production ownership structure of these minerals.

Discussion

This study of the market concentration of the main producers of critical minerals complements the analyses traditionally carried out on the basis of the geographical location of mining assets. Varying the assumptions made about production control revealed significant heterogeneity between critical minerals. The results first confirmed previous studies that market concentration based on the geographic location of mining assets was on average high. We confirm here that minerals critical to batteries, such as cobalt and lithium, are produced in particularly concentrated ways, while more common minerals (copper, iron, etc.) have a more diversified production basis.

The switch of focus to other definitions of control, based on the ownership structure of mining assets, alters the classical discourse of market concentration based on the location of the mining assets. First, the use of direct owners' control (Direct) leads to an average decrease in the market concentration of critical minerals markets. This is particularly notable in the case of cobalt, where the concentration of producers has been considerably reduced by this change in the definition of control. Secondly, analysis by equity ownership shows that some minerals that do not make the headlines are much more concentrated than expected. This is particularly true of certain minerals such as copper, nickel and silver, where production is controlled by a small number of ultimate owners, highlighting a rarely raised risk for the supply of these minerals.

However, the decomposition of concentration indicators with these alternative definitions of control over the production of critical minerals shows new emerging supply risks. With regard to the Direct ownership, western entities, especially from the United States and United Kingdom, and Chinese entities are the dominant actors of most critical minerals markets. The breakdown of the equity ownership reveals a more surprising fact, namely that Western entities have the largest control over the production of critical minerals. This requires a nuance of claims that Western countries lag behind China and others in terms of control over production. These claims usually lump together mining and processing of minerals. Our results show that at least at the mining of minerals stage, while China holds a dominant position over key minerals (cobalt, lanthanides...), it does not match the Western players whose mining companies and financial capacities remain dominant.

The comparison between the alternative definition of ownership for estimating market concentration and geopolitical risk highlights a geopolitical risk that is not taken into account by conventional analyses of market concentration based on the geographical location of mining production. Even if, on average, Direct and Equity ownership concentrations are lower than Geographic concentration, the composition of these higher levels of concentration is problematic. The decomposition of concentration indicators suggested strong geopolitical antagonisms between the main producers of certain critical minerals, especially based on their ownership structure. Analysis of the geopolitical distance between these producers for different definitions of control confirms that there is a significant geopolitical risk lurking in the ownership structure of mining assets. This risk is amplified by the low diversity of entities controlling production, particularly visible for certain ores such as Vanadium, Niobium or Graphite.

The geopolitical distance separating a small number of countries that control the production (extraction) of critical minerals raises serious questions about their approach to the energy transition. The growing tensions between some of these countries could lead to trade in critical minerals being fragmented into blocks. The proliferation of bilateral and multilateral agreements such as the Mineral Security Partnerships and the Belt and Road Initiative are a possible step in this direction. The friendshoring of critical mineral production, either by direct control or geopolitically close could reduce access to critical minerals for the non-aligned countries. This could increase the average price of minerals and consequently slow down the development of green industries.

The overwhelming financial dominance of the United States and to a lesser extent United Kingdom and China opens up financial opportunities linked to the energy transition. The role of ultimate owners suggests that these will reap a substantial share of the monetary benefits of the critical minerals boom. Even when they are absent from the exploitation of critical minerals on their soil or via their mining companies, the financial ownership makes them major indirect players that receive significant shares of the profits of the energy transition. This means that they can benefit from the exploitation of critical minerals without bearing its heavy environmental and social costs. This unequal ecological exchange, largely underestimated by past analyses, is particularly important for low- and middle-income countries, especially Africa and Latin America, which hope to be able to draw on their mineral wealth for their development. Conversely, this dominant position means that the economic and financial health of major countries is particularly important for the near-term development of the global mining sector.

The geoeconomic dynamics of major's players in the green race could generate supply risk issues. Geopolitical distance calculations show that countries controlling key mineral production can reduce market risks by maintaining strong and stable relations with the developing world. This is particularly relevant because many major deposits are located in "middle" countries—those not closely aligned with any major power bloc, such as many African and Latin American nations. However, as the concentration of mineral production increases, the number of countries controlling the production decreases, making the geopolitical relationships between these dominant players and the "middle" countries critical. The marginal behavior of dominant actors in their UN votes, particularly those with direct ownership or equity control in mining production, represents an underestimated threat to global supply stability.

The consequences of foreign control over mining assets often extend beyond the loss of control over the resources themselves, impacting entire territories with significant environmental and community repercussions. The bargaining power of a state with foreign mining companies can be limited due to information asymmetry and corruption, which can undermine compliance with mining codes (Kuswanto et al., 2017). This lack of accountability for the social and environmental damages caused by foreign companies is a significant issue. Moreover, equity ownership often allows these companies to reap financial benefits from mining without addressing the consequences of their operations. Ultimately, the dominance of foreign ownership in critical mineral assets can help undermine resource-based development strategies, which many developing countries see as key to capitalizing on the energy transition.

Finally, it is important to mention some of the limitations associated with this exercise. Firstly, control over production is difficult to determine. It is not only defined by the ownership structure, but by a complex set of factors, ranging from management to the binding contracts that the company may face. For example, mining companies of Chinese origin but listed on US or UK financial markets may be subject to a degree of control even if no Chinese entity holds a significant stake. Secondly, the extent to which a government can exert direct influence over the behavior of multinational companies, which many of the mining and financial companies in sample are, may be limited. Lastly, our study comes up against the limitations of the S&P database, particularly concerning smaller mining assets and/or mines located in countries with low transparency.

Conclusion

This study offers a novel perspective on the market concentration of critical minerals by incorporating various definitions of control, extending beyond traditional geographic analyses. The findings reveal considerable variability in market concentration among different minerals. While geographic location analyses previously highlighted high concentrations, this study confirms that battery minerals such as cobalt and lithium exhibit particularly concentrated markets. In contrast, more common minerals like copper and iron demonstrate a more diversified production landscape. Geoeconomic fragmentation considerably raises the supply risks of this sector at the core of the low-carbon transition.

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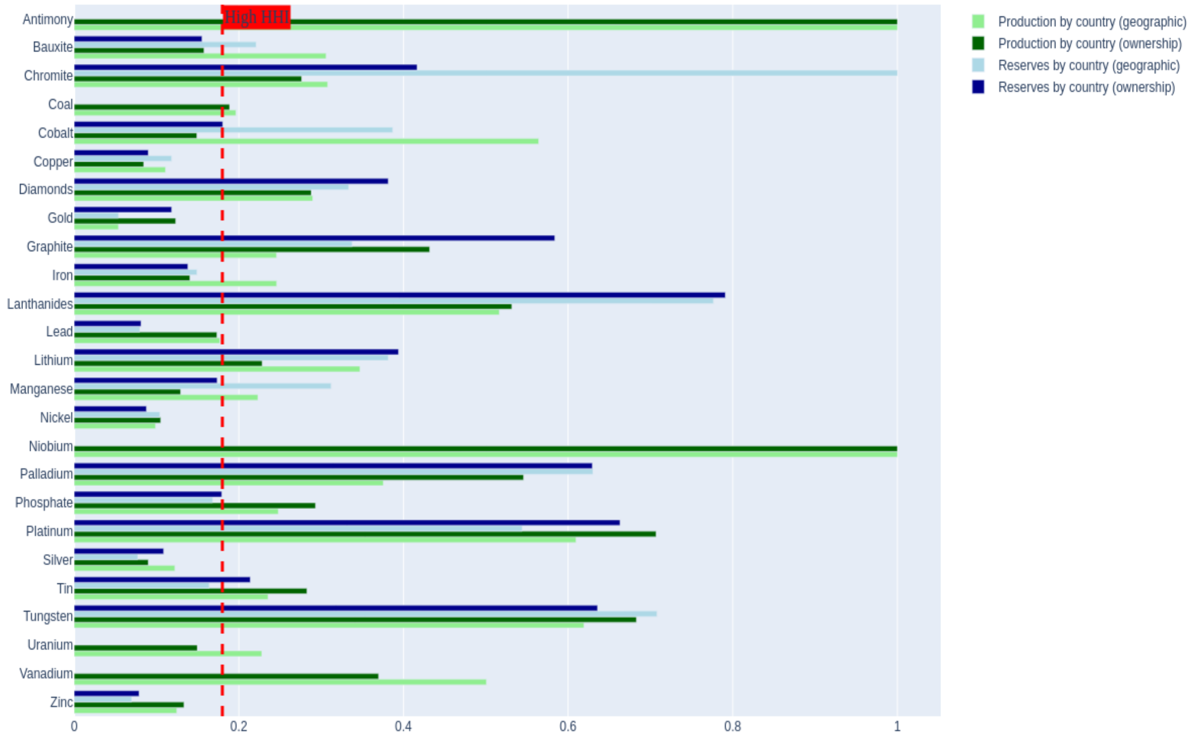
Appendix

Market concentration (Production and Reserves)



Robustness - Other concentration indicators

Figure X: Entropy of production by mineral (Geographic ownership)

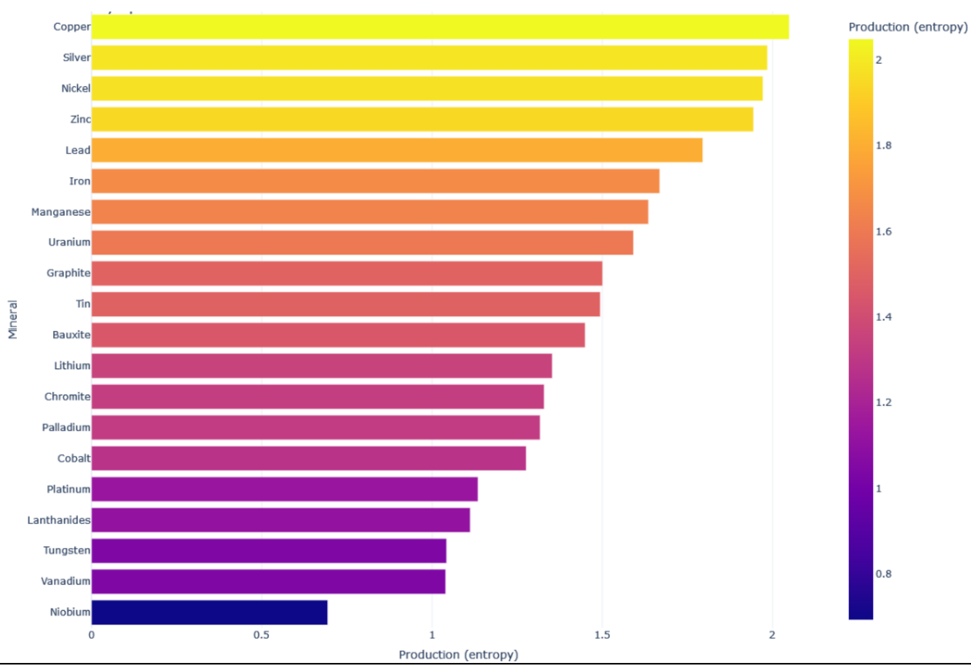


Figure Y - Entropy of production by mineral (Direct ownership)

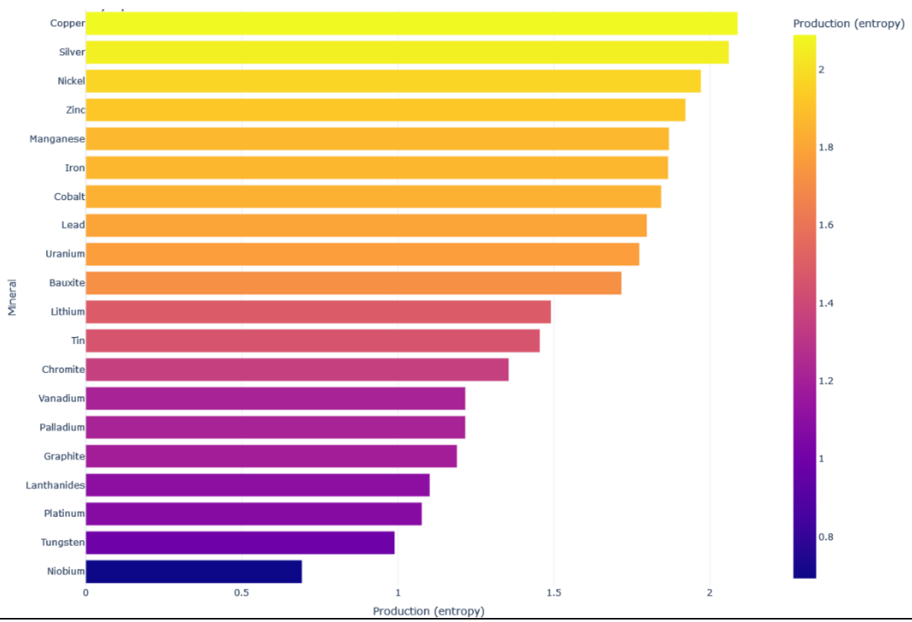


Figure Z - Entropy of production by mineral (Equity ownership ownership)