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Critical Raw Materials between strategic importance and vulnerability: A deep analysis of key challenges in Global Value Chains

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TABLE OF CONTENTS

TABLE OF FIGURES

Introduction

70% of international trade relies on participation in Global Value Chains (GVCs). As economies and industries become increasingly interconnected to maximize production capabilities and exploit resources, fragmentation, exacerbated by exogenous and endogenous vulnerabilities, exposes industrial systems to bottlenecks, influencing competitiveness and reliability.

Critical Raw Materials represent the backbone of strategic industries, above all the semiconductor, which drives the future of digital innovation and defense, and energy transition, as electrification aims to futureproof environmental dynamics, shifting from negative ecological tendencies.

In light of recent and sustained industrial trends, where the semiconductor industry is showing extraordinary surges in demand, as it is projected to grow 11.25% by 2025, reaching $697 billion in market value, and the energy transition, where, above all, the electric vehicle market is driving the electrification pathway with boosting growth rates, increasingly higher units sold (20 million by 2025) and market value ($990 billion by 2029).

However, the related supply chains underlie severe vulnerabilities, in part due to production concentrations, often polarized in unstable and extremely unstable countries. The fragile status of the mineral supply chains exposes industries to competitiveness gaps and turbulence, difficult to predict.

Accordingly, this research aims to study the quantitative relationship and its strength degree between production concentration and historical prices of specific mineral commodities.

The research is structured into three chapters. In the first chapter, the study analyzes global economic and trade dynamics, depicting the importance and the complexities of the Global Value Chains (GVCs). Moreover, it presents a brief overview of critical raw materials, defining introductory concepts. In the second chapter, the study deeply analyzes and discusses specific minerals (cobalt, copper, lithium, gallium, and graphite) production trends. Furthermore, it measures the Herfindahl-Hirschman Index (HHI), hereby the concentration index, to comprehend the status of production and supply of mineral commodities. Following the collection of commodities historical prices from Bloomberg, the research studies the relationship and the strength of the association between production concentration, expressed via HHI, and historical prices. In the third and last chapter, the study focuses on understanding industry-specific mechanisms that link and relate to the commodity market studied in chapter two. The research analyzes and discusses key market trends (semiconductor and energy transition), highlighting potential supply distress and competitiveness gaps among economic blocs.

CHAPTER 1. Global Economic and Trade Dynamics

1.1 Global Economic Outlook

The Global Economy is stepping into 2025, facing stabilizing growth and various furious winds to counteract. The World Bank and the International Monetary Fund have conducted an in-depth analysis of relevant trends that will shape the economic landscape, considering, for instance, moderate expansion, reluctant inflation strains, geopolitical difficulties, and regional disparities. The International Monetary Fund (IMF) estimates global GDP growth at 3.3% for 2025 and 2026, a rate empirically lower than the historical average recorded between 2000 and 2019 at 3.7%[1]. Meanwhile, the World Bank estimates a lower % global growth rate of 2.7% for the same timeframe (2025-2026)[2]. While these indicators denote stability, they also indicate a chance of a long-term trend of economic growth slowdown, particularly for emerging markets and developing economies, which contribute roughly 60% of global growth.

Regarding significant economies, the reports point out that strong consumption, labor market resilience, and supporting financial conditions may lead to a 2.7% growth for the United States. Europe, though, appears to be lagging, expecting to grow at just 1% in 2025 due to manufacturing weaknesses and policy uncertainty. Concerning the opposite hemisphere, in Asia, China's economy is expected to grow at 4.6% while India's is about to grow at 6.5%, reinforcing its position as a rising economic force. Despite a slight decline in global inflation, it remains a concern for many economies. The IMF foresees that global headline inflation will drop to 4.2% in 2025 and plunge to 3.5% in 2026, with advanced economies hitting the targets faster than developing economies[1]. Despite central banks putting extraordinary effort into cautiously proceeding with monetary easing to limit inflationary pressures, supply chain disruptions and geopolitical tensions are jeopardizing all the effort, risking making inflationary pressures persist. Global trade is about to rise, although underperforming the average level reached between 2010 and

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[1] International Monetary Fund. (2025). *World economic outlook update: Global growth: Divergent and uncertain*. International Monetary Fund

[2] World Bank. (2025). *Global economic prospects, January 2025*. The World Bank.

2019[2]. The World Bank warns that trade barriers could be five times higher than in the previous decade[2]. As a result, global trade will face substantial risks since protectionist policies, including tariffs and regulatory shifts, may jeopardize global supply chains and investment flows. Retraces of macro data underscore the delicate state of the global economy, which stands on a fragile threshold where risking fragmentation may lead to prolonged instability.

1.2 The Status of Global Trade

According to the UN global trade update, 2024 has been a year of outstanding results. International trade peaked at $33 trillion, a 32% increase from pre-pandemic levels ($25 trillion)[3]. The report shows that the economic value of global trade rose to this unprecedented level due to a rise of $1 trillion in 2024, hence a 3.3% growth from the previous year[3]. The surplus recorded is distributed between an increase in goods and services trade. Goods trade, which involves tangible transactions between countries, surged by $500 billion, marking a growth pattern of 1.5% quarter-over-quarter in Q3 2024. Despite the quarterly growth trend, goods trade remains below the 2022 peak, highlighting a formal shift in global trade dynamics. The sectors that pulled the growth are information and communication technology and apparel. On the other hand, industries that registered a slight decline in terms of trade volumes are automotive, energy and metals, and textile and chemicals. Services trade, which involves intangible transactions between countries, grew by $500 billion. The report states that the services trade in 2024 widely outpaced the trade in goods, registering an annual increase of 7%. Notably, despite geopolitical frictions, commercial barriers, and various trade constraints, globalization, according to the DHL Global Connectedness report, persists in being resilient[4].

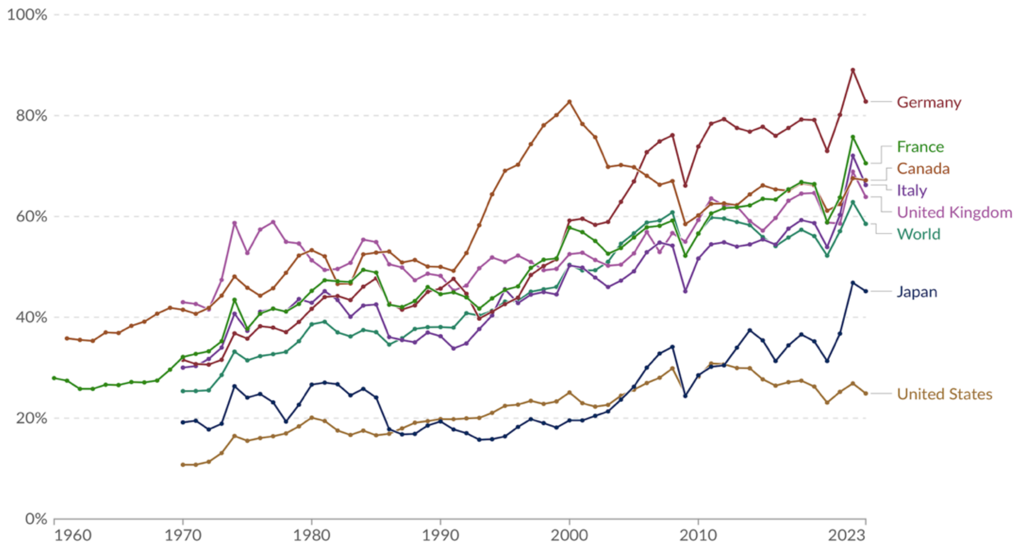
A compelling procedure to analyze global trade is catching and comparing a specific set of ratios. Moreover, as the overview can assess a brief but macroscopic perspective, it’s proper to consider and classify economies in G7 and BRICS. These represent the major

[3] United Nations Conference on Trade and Development (UNCTAD). (2024). *Global trade update, December 2024*. UNCTAD.

[4] Altman, S. A., & Bastian, C. R. (2024). *DHL Global Connectedness Report 2024*. NYU Stern School of Business, Center for the Future of Management.

economies and sources of goods, services, and capital transactions. Metrics analysis is a useful and comprehensive tool that allows whoever pursues research to understand, interpret, compare, and discuss the status of a specific matter. The trade-to-GDP ratio, even labeled as the trade openness ratio, is an indicator (not absolute) of the importance of foreign trade for a country's economy and is a summary measure of a country's openness to the rest of the world. This index can be gauged by summing the value of exports and imports of goods and services and dividing them by gross domestic product. The indicator is expressed as a percentage. According to World Bank national accounts data and OECD national accounts data files, in 2023 (latest data available), global trade accounted for 59% of global GDP[5], slightly higher than the pre-pandemic level (+5.36%) but surely lower than the 2022 level (-6.35%). By considering, as mentioned previously, the major economies classified into G7 countries and BRICS (not considering the most recent countries included, such as Egypt, Ethiopia, Iran, Indonesia, and UAE), the data foresee that 4 out of 7 of the G7 countries, registered the broadest Trade-to-GDP ratio, higher than the world's average. Thus, Germany (82.8%), France (70.6%), Canada (67.2%), and Italy (66.2%) while, lagging, the United Kingdom (63.9%), Japan (45.2%), and lastly the United States (24.9%). (see Figure 1)

Figure 1. *Trade as a share of GDP, G7 countries (Germany, Italy, France, Canada, Japan, UK, USA)*

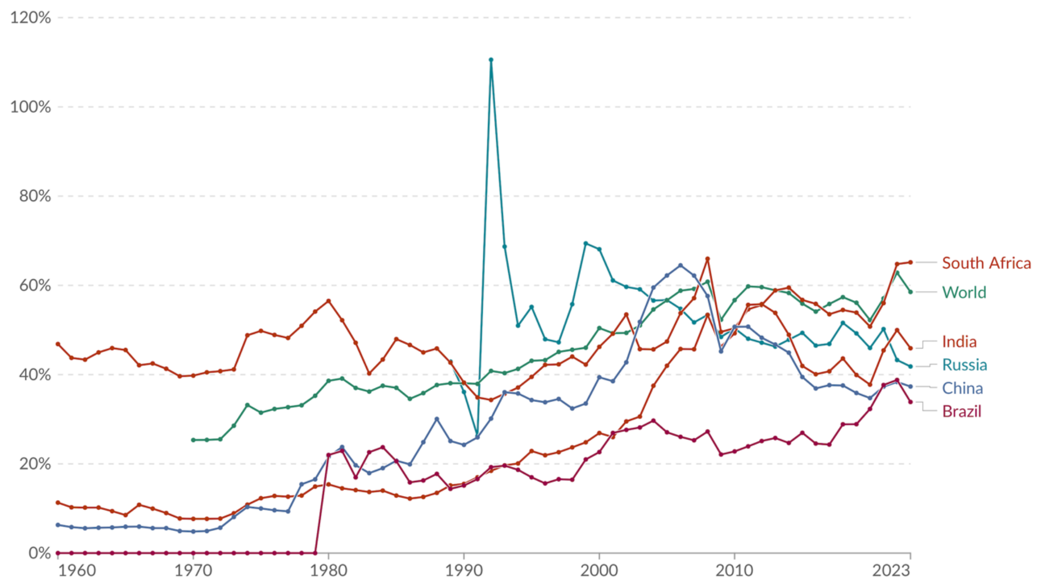


Source: World Development Indicators (WDI), The World Bank (2025).

[5] The World Bank. (2025). *World Development Indicators 2025*.

On the BRICS side, the dataset reports the respective Trade-to-GDP ratios concerning South Africa (65.2%), India (45.9%), Russia (41.8%), China (37.3%), and Brazil (33.9%). (see Figure 2)

Figure 2. *Trade as a share of GDP, BRICS countries (Brazil, Russia, India, China, South Africa)*



Source: World Development Indicators (WDI), The World Bank (2025).

Although the trade-to-GDP ratio can contribute to debate and provide some insights about a country's openness to international trade, the index conceals structural inefficiencies that may distort and bias analysis. According to Bleaney and Tian, the trade-to-GDP ratio does not accurately reflect variations in commercial flows[6]. The researchers identified and discussed factors that influence these variations and lead to distortion among countries. One key issue is the presence of time-invariant factors, which remain stable in the short run and cause country-specific characteristics to influence the trade-to-GDP ratio without reflecting actual changes in trade policies. Country size is one of the variables affecting this metric; larger countries tend to have lower trade-to-GDP ratios because they rely more on domestically produced goods. Additionally, geographical

[6] Bleaney, M., & Tian, M. (2022). *The trade–GDP ratio as a measure of openness*. The World Economy, 46(5), 1319–1332.

distance from trade partners and specialization in production further distort the ratio. On the other hand, time-variant factors, which fluctuate in the short run, can affect the trade-to-GDP ratio without necessarily indicating actual changes in trade patterns. According to the paper, real effective exchange rate (REER) swings contribute to the ratio's volatility. The REER measures a country's currency value against a weighted average of several foreign currencies, adjusted for differences in price levels using a price deflator or cost index. The mechanism behind this effect is straightforward: the exchange rate affects the (export + import) / GDP ratio by altering the value of export and import relative to domestic production. Hence, an appreciation of the REER, which implies strengthening the domestic currency, reduces exports due to a loss in price competitiveness for international buyers. At the same time, imports increase because foreign products become relatively cheaper. As a result, the trade-to-GDP ratio decreases. As a counter scenario, a depreciation of the REER results in the opposite effect: the devaluation of the domestic currency can increase the country's competitiveness, making exports more attractive for foreign buyers while reducing the affordability of imports. This scheme can lead to higher GDP growth, causing the ratio to rise.

In summary, fluctuations in the real effective exchange rate can change the measured value of international trade without any actual change in trade policies. This creates bias, as the trade-to-GDP ratio may misleadingly suggest that a country has become more or less open to trade when, in reality, it is merely an effect of currency fluctuations. If the REER appreciates (depreciates), it may appear that a country is becoming less (more) open, even though no effective shift in trade policy has occurred. Additional time-variant factors include fluctuations in raw materials prices, which can distort the trade-to-GDP ratio, inflating its value. When the price of exported raw materials rises, the value of exports increases as well, even if the volume of traded goods remains unchanged. Consequently, although the trade-to-GDP ratio grows, this does not reflect an increased trade openness but rather a distortion caused by the price effect. This bias is particularly evident when comparing net exporters and net importers of raw materials, as it skews the indicator, making it an unsatisfactory measure of trade openness. Lastly, the paper cites the investment/GDP ratio and economic cycles as misleading factors that can distort the trade-to-GDP ratio.

1.3 Global Value Chains

According to OECD statistics, approximately 70% of international trade depends on participation in Global Value Chains (GVCs)[7]. The growing demand for cross-border exchange of raw materials, parts, and components has led to an exponential rise in transactions involving goods and capital. Global Value Chains constitute a highly complex and advanced international production structure in which different sequential production phases are fragmented and distributed across multiple countries[8]. Traditional international trade involves directly exchanging final goods or services between an exporter and an importer. In contrast, GVCs entail multiple cross-border movements of goods and services, with the value being incrementally added at each production stage before reaching the final consumer. Specialization, which characterizes GVCs, implies that enterprises and countries focus on specific operations in which they have developed a comparative advantage[8]. Baldwin and Venables broadly examine the fragmentation processes that constitute the foundation of GVCs. The researchers distinguish two specific models to describe global production fragmentation: the spider model and the snake model[9]. The spider model concerns production processes in which independent components are manufactured in separate locations and assembled in a specific place to produce the final good. Generally, this model is particularly prevalent in industries such as automotive and electronics, where multiple components are produced in distinct geographical locations before converging in an assembly hub. Each component, essential for the final assembly stage, crosses international borders no more than twice. The first border crossing occurs when the component is manufactured in one country and is subsequently shipped to the final assembly location. The second border crossing takes place when the final product is exported to the consumer market. The peculiarity of this disaggregated production model is that components that do not require sequential

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[7] Organisation for Economic Co-operation and Development (OECD). (n.d.). *Global value and supply chains.* OECD. Retrieved from https://www.oecd.org/en/topics/global-value-and-supply-chains.html

[8] World Bank. (2020). *World development report 2020: Trading for development in the age of global value chains.* World Bank.

[9] Baldwin, R., & Venables, A. J. (2013). *Spiders and snakes: Offshoring and agglomeration in the global economy*. Journal of International Economics, 90(2), 245–254.

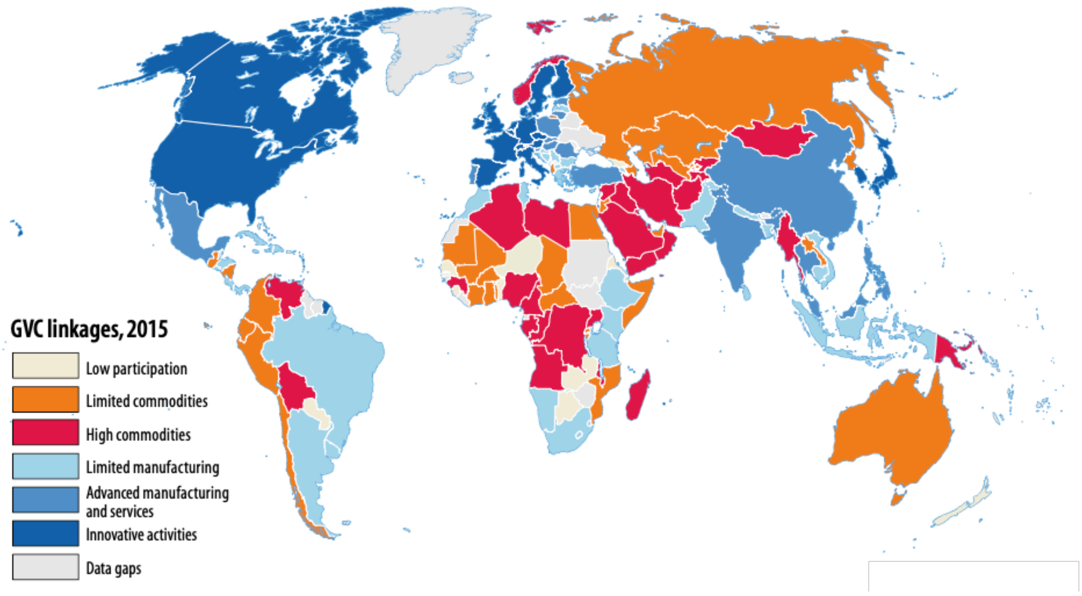
processing can be manufactured where hyper-specialization permits over-minimizing the production cost. However, this model is not risk-free. Since the spider model relies on the efficient shipment of components, the cost-effectiveness is heavily influenced by transportation costs, coordination, and communication costs, as well as tariffs and trade barriers. On the other hand, the paper examines the snake model. Unlike the spider model, the snake model applies to those productions that require sequential processes, where each stage of production depends on the completion of the previous one. The snake model inevitably needs a defined and rigid sequence of operations. What characterizes this production model is that the linear scheme pursued by the product allows it to gain exponential added value at each operational stage until completion. The snake model is particularly evident in industries where cumulative production is essential, such as textiles and semiconductors. However, this model is notably vulnerable to disruptions along the value chain due to the interdependencies between each stage. This sensitivity means that an operational issue or a country-specific (firm-specific) disruption can generate significant complexities, affecting the final product's competitiveness and overall success. Unlike the spider model, which implies minimal cross-border flows, in the snake model, the semi-finished product crosses multiple borders as it moves from a production stage to a successive one. As a consequence of the increased fragmentation, firms not only minimize the production cost by relocating each stage to the most cost-efficient locations, but they also increase the international trade volume, as each transfer between stages constitutes a new trade flow. However, as highlighted in the paper, the snake model operates by managing a trade-off between fragmentation, which involves offshoring and leveraging low-cost or strategic-input production countries, and agglomeration. While firms tend to disperse production phases due to lower separation costs, certain key stages are kept geographically close to benefit from agglomeration effects. In the snake model, agglomeration allows firms to optimize logistical and coordination costs, access specialized labor and know-how, leverage industrial policies favoring localized production, and mitigate risks that could disrupt the value chain.

However, each country contributes differently, marking their role in goods manufacturing or services, along the value chains. As the World Development Report examines, a country's engagement along the value chains can be classified into backward participation and forward participation[8] (see Figure 3). The backward participation concerns those countries that heavily rely on intermediate goods, raw materials, and components imported necessary to craft or incorporate into an intermediate product and export the final or half-final product. This form of participation commonly clusters manufacturing-based economies that necessarily rely on global inputs to produce the final product. One of the features of backward participation is that foreign value-added (FVA) represents a broad share of a country's exports, meaning that a large part of the economic value included in exported goods originates from imports rather than domestic production. As mentioned, countries engaged in backward participation generally import raw materials or technologies from international suppliers to integrate those inputs into production and export the final or half-final goods. Typically, this system is particularly evident in low-cost labor economies where multinational corporations (MNCs) heavily invest in fixed assets through greenfield or brownfield investments to leverage low production costs. Greenfield investments in 2023 peaked at $1.4 trillion, recording the highest value ever realized[10]. This surge was driven by a rise in manufacturing projects, especially in developing economies that accounted for most of the economic variation. Indeed, a 42% increase in manufacturing investment projects was concentrated in Southeast Asia, precisely Vietnam, Indonesia, and Malaysia, which attracted capital for electronics, automotive, and battery production. However, while the integration into value chains can foster the economic status of manufacturing countries, accelerating domestic industrialization, the heavy dependency could switch to a double-edged sword, exposing countries' economies and firm resilience to supply chain disruptions and complexities in retaining the value created[8]. Forward participation refers to countries that supply raw materials, semi-finished goods, or intermediate components utilized in manufacturing exported final products in numerous other countries. One of the key features of forward participation is that, conversely from backward participation, the domestic value-added (DVA) constitutes a soaring share of the country's export value. Countries in this participation form specialize in resource extraction, intensive agriculture, or high-tech components fundamental to global manufacturing processes. However, while forward-participation countries generate great economic returns from commodities and high-tech components trade, undoubtedly inducing beneficial economic upturns, this hyper-reliance

[10] United Nations Conference on Trade and Development. (2024). *World investment report 2024: Investing in sustainable development*. United Nations.

on these critical resources heavily exposes them to price fluctuation and volatility, jeopardizing countries' resilience and economic sustainability. Moreover, these countries could face severe economic downturns due to climate disruption that can affect all the stakeholders involved.

Figure 3*. Countries' participation in GVCs*



Source: World Development Report, The World Bank (2020)

Note: Based on the GVC (Global Value Chains) taxonomy for 2015, developed in Box 1.3 of the World Development Report

1.3.1 Global Supply Chains bottlenecks and vulnerabilities

As discussed, the cross-border exchange of goods represents the backbone of GVCs[9]. Maritime trade, which accounted for 12.3 billion tons in 2023, catalyzes 80% of world trade volume, meaning that almost all global trade relies on shipping routes by sea[11]. However, containerized trade in recent years has faced long-lasting and diverse supply and logistics chain disruptions that jeopardize demand satisfaction, manufacturing

[11] UNCTAD. (2024). *Review of maritime transport 2024: Navigating maritime chokepoints*. United Nations Conference on Trade and Development.

operations, and logistic efficiencies, resulting in dysfunctionalities along the global value chains[11]. The World Bank developed a metric proxy to quantify the stress level in the international container shipping network. The Global Supply Chain Stress Index (GSCSI) highlights supply chain complexities within a prolonged or specific timeframe, contextualizing operational disruptions[12]. The model operates using information collected via an Automized Identification System (AIS) about containerized cargo routes, transit times between ports of loading and discharge, and delays. Effective transit times are compared with a historical baseline from past years' data. When the delay vastly exceeds the norm value, the index records it as a substantial delay. The statistical approach to developing the index implies that the metric quantifies deviation from a norm, typically a normal state in which a system operates. However, the metric considers only the widest deviation stress-relevant, indicating that light variations are not significant enough to be symptomatic of stress but are merely alterations of regular operations. When the delay is detected, the index estimates the trade volume tied up using TEU. Twenty-foot Equivalent Unit (TEU) is a standardized measure utilized to quantify the charging capacity of vessels. Using TEU as a standard measure, the index estimates the delayed capacity, defined as the volume of trade that was expected to be shipped without operational delays but was lost or postponed.

Significant spikes typically observed in the model are generally associated with global shocks, which affect offer contractions, rising prices, and macroeconomic implications (trade value, inflation). The Red Sea crisis, which occurred in mid-October 2023, is a significant event that proved the fragility of supply chains, notably vulnerable to geopolitical shocks. The Suez Canal, one of the world's most vital waterways for global trade, canalizes 30% of global container trade[13]. Houthi attacks on cargo vessels forced ships to reroute, extending trade routes over 4.000 miles (approximately 6.437 km)[14]. According to JP Morgan analysis, shifts from standard trade trajectories increased transit

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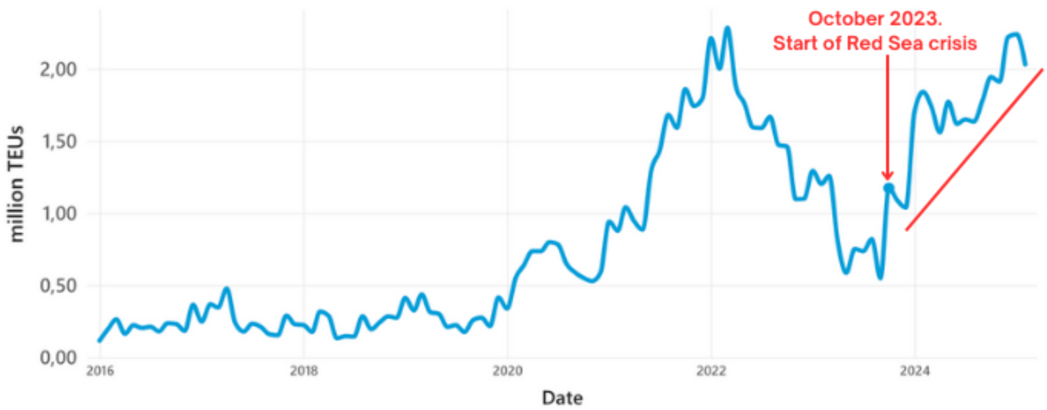
[12] Arvis, J.-F., Rastogi, C., Rodrigue, J.-P., & Ulybina, D. (2024). *A metric of global maritime supply chain disruptions: The Global Supply Chain Stress Index (GSCSI)* (Policy Research Working Paper No. 10839). World Bank.

[13] World Economic Forum. (2021, March). *The Suez Canal in numbers*. https://www.weforum.org/stories/2021/03/the-suez-canal-in-numbers

[14] J.P. Morgan. (2024, January 31). *What are the impacts of the Red Sea shipping crisis?*https://www.jpmorgan.com/insights/global-research/supply-chain/red-sea-shipping

times by 30%, reducing 9% of the global container shipping capacity (see Figure 4), particularly jeopardizing the automotive supply chain and strategically affecting the China-Europe trade partnership[14]. Shipping lanes suffered an increase in freight price, generally correlated with proclaimed stress in GSCSI[12]. The Shanghai Containerized Price Index (SCPI) chart analysis of price trends showcases that since the start of the attacks in mid-October 2023, prices jumped from 967.25 $/TEU to 3763.2 $/TEU at the beginning of July 2024[15], therefore a 289.06% surge.

Figure 4*. Global Supply Chain Stress Index (in millions of TEUs)*



Source: Retrieved from World Bank's Power BI interactive dashboard, modified by the author.

(https://app.powerbi.com/view?r=eyJrIjoiZmQ5YmVjNTItNDExMy00YTNlLTkzZmYtMzk5YjliZjJiZWZlIiwidCI6IjMxYTJmZWMwLTI2NmItNGM2Ny1iNTZlLTI3OTZkOGY1OWMzNiIsImMiOjF9)

Geopolitical adversities do not represent the only source of disruption affecting the global supply chains. Hazardous climate conditions, rising temperatures, and natural disasters jeopardize the commodity market, impacting offer-demand mechanisms and supply chain resilience. During 2024, the Earth's average temperature rose to 15.10 °C, peaking as the highest value recorded ever since[16]. The economic losses from global natural disasters in

[15] Trading Economics. (n.d.). *Containerized freight index*. Retrieved from https://tradingeconomics.com/commodity/containerized-freight-index
[16] Copernicus Climate Change Service (C3S). (2025, January 10). *Global Climate Highlights 2024*. European Centre for Medium-Range Weather Forecasts (ECMWF).

2024 amounted to $368 billion[17]. Tropical cyclones, flooding, and severe convective storms accounted for approximately 80% of the financial losses[17]. Scholars have conducted vast research to understand the economic relationship between climate alterations and food market responses[18]. The findings indicate a non-linear relationship between temperature variations and food price returns. Food price returns measure the percentage change in food price over a given period, capturing how several factors, such as climate anomalies and supply chain disruptions, affect its fluctuation. The result suggests that food prices demonstrate asymmetrical responses when specific temperature thresholds are exceeded. When temperature anomalies range from 0.5 °C to 0.9 °C, the impact on food prices remains minimal. However, once the temperature rises above the 1.1° C threshold, food prices steeply rise, peaking when extreme anomalies occur (>1.5° C). Researchers applied a Distributed Lag Non-linear Model (DLNM) to capture delayed responses to climate anomalies. The model shows that food prices gradually grow, peaking 6 months after the anomaly appears. At the 9-month circa, further price shifts occur due to supply chain adjustments and market dynamics. After 9 to 12, the price effect weakens as the market stabilizes and supply chains adapt.

1.4 Critical Raw Materials: Overview

The commodity market may serve as a proxy, in addition to trade volume data, for obtaining a global outlook. Expansion or contraction in commodity derivatives prices reflects global trends that prompt investors to engage in the market, speculate, and allocate capital. Energy transition and technological advancements have shifted market dynamics in recent years, redirecting capital flows toward growth opportunities and specific industrial commodities. By analyzing the trend of the notional value of hard commodities, which include industrial and precious metals, it is possible to make

[17] Aon. (January 21, 2025). *Economic loss from natural disaster events worldwide in 2024, by peril (in billion U.S. dollars)* [Graph]. In Statista. Retrieved March 2025, from: https://www.statista.com/statistics/510922/natural-disasters-globally-and-economic-losses-by-peril/

[18] Cheng, S., Li, X., & Cao, Y. (2023). *Global evidence of the exposure-lag-response associations between temperature anomalies and food markets*. Journal of Environmental Management, 325, 116592.

assumptions and understand key market dynamics. The notional value refers to the total value of a position in a financial instrument and is determined by multiplying the contract size by the underlying price (spot price). Specifically, the notional value of industrial metal derivatives is expected to grow at a CAGR of 4.10% from 2024 to 2029, indicating a faster rise compared to other commodity derivatives[19]. Continuing the analysis of the compound annual growth rate for the period 2024-2029, the commodity market outlook shows that, in decreasing order, energy product derivatives are expected to grow at 2.28%, while precious metals are projected to grow at 1.92% and agricultural product derivatives at 1.88%[19]. The report highlights that specific commodities such as copper, aluminum, and lithium may experience a surge in demand and value due to investments in key sectors, particularly the energy transition.

Critical raw materials (CRMs) refer to a diverse array of metals and minerals that are strategically and economically significant for global economies[20]. Their versatile applications underscore their importance, as they play an indispensable role across various industry sectors such as environmental technologies, consumer electronics, health, steel-making, defense, space exploration, and aviation. The classification and use of the term "critical" is subjective and may vary across global economies, thus, this overview will consider the criteria used by the European Union. According to the EU framework, the criticality of materials is assessed based on two key criteria: economic importance (EI) and supply risk (SR)[20]. The economic importance parameter evaluates how essential a material is to the EU economy. To quantify this, the EU inspects end-use applications by identifying the industries or sectors in which the material is utilized and determining their contribution to the generation of the EU's economic value added. Sector classification follows the NACE Rev.2 (2-digit level). A high EI score indicates that the material is essential, implying that any shortage could have significant economic repercussions. The EI indicator is then adjusted to reflect whether fungible substitutes for industrial operations can replace the material. The Substitution Index for Economic Importance (SIEI) serves as a proxy to demonstrate whether an alternative material is viable for the same industry application and, subsequently, whether the cost-effectiveness

[19] Statista. (2024, July). *Commodities: Market data & analysis*. Statista Market Insights.
[20] European Commission. (2014). *Report on critical raw materials for the EU*. Report of the Ad hoc Working Group on defining critical raw materials.

of the trade-off is substantial compared to the original material. The index ranges between two polarized values from 0 to 1, where 0 indicates that the material is highly critical and 1 indicates that the material can be easily replaced. The second parameter used to capture the criticality is the supply risk. The vulnerability assessment plays a vital role in identifying potential supply disruptions that could threaten the EU's demand for essential materials in value-adding industrial sectors. The SR indicator aims to assess the measures by which the EU could be exposed to potential supply bottlenecks. The two key components used to determine the indicator are the Herfindahl Hirschman Index (HHI) and the Worldwide Governance Index (WGI). The first component (HHI) serves as a proxy for the concentration of extraction and processing activities among specific suppliers and functions as a tool for evaluating the EU's reliance on imports from those countries. The second component (WGI) is used to assess the risk linked to supplier countries based on internal factors like political stability, regulatory quality, and corruption control.

In summary, a combination of factors such as substitutability, end-of-life recycling rates, acting as a risk-reducing filter, gauges the proportion of metals that can be retrieved from end-of-life scraps, the concentration level, and the economic importance, it is possible to assess the criticality of the material. The application of this methodology for determining the scope of criticality enables the EU to establish a list of Critical Raw Materials. Since the first list was drafted in 2011, the number of critical and strategic elements grew by +142.86%, increasing from 14 to 34 in 2023[21]. The latter list updated considers CRMs[21]: aluminum/bauxite, coking coal, lithium, phosphorus, antimony, feldspar, light rare earth elements (LREE), scandium, arsenic, fluorspar, magnesium, silicon metal, baryte, gallium, manganese, strontium, beryllium, germanium, natural graphite, tantalum, bismuth, hafnium, niobium, titanium metal, boron/borate, helium, platinum group metals (PGM), tungsten, cobalt, heavy rare earth elements (HREE), phosphate rock, vanadium, copper, nickel. The nature of global trends, where minerals are vital for achieving technological and environmental goals and acquiring or maintaining competitiveness on the international economy's chessboard, makes CRM supply chains extremely vulnerable

[21] Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs. (2023). *Study on the critical raw materials for the EU 2023 – Final report*. Publications Office of the European Union.

to economic, ecological, and social issues[22]. The intrinsic endowments of extraction areas in countries with proclaimed low governance, high water stress, and climate risks exacerbate the fragile status of supply chains and prompt policymakers to design and implement risk mitigation strategies. The Critical Raw Material Act (CRMA) illustrates the EU's response to these issues by setting precise targets to ensure a secure, resilient, and sustainable supply of critical raw materials[23]. The EU aims to reduce dependency on countries with weak governance by diversifying and enhancing domestic extraction and processing. Furthermore, the regulation encourages EU member states to endorse end-of-life recycling and sustainable sourcing practices and to allocate financial resources to strategic projects that could contribute to EU supply resilience.

[22] International Energy Agency. (2021). *The role of critical minerals in clean energy transitions* (World Energy Outlook Special Report). IEA.

[23] European Union. (2024). *Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, and (EU) 2018/1724*. Official Journal of the European Union, L 125/1.

CHAPTER 2. CRMs Production and Price Dynamics

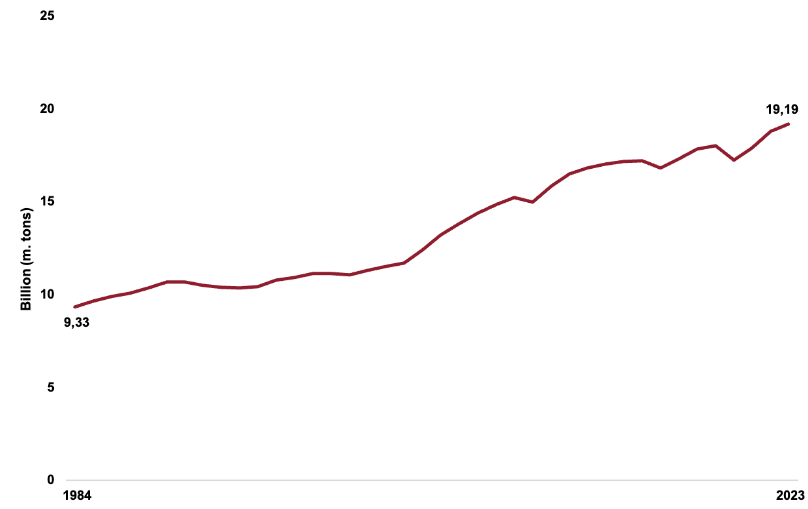
2.1 Critical Raw Materials Production

Critical raw materials are essential inputs for manufacturing a wide range of goods. These commodities are indispensable for realizing and delivering clean energy technologies for the green transition (e.g., nickel, lithium, and cobalt for battery production, among other clean energy technologies), advanced technologies for the digital transition (e.g., gallium for semiconductors), and defense and space applications (e.g., titanium and tungsten).
The analysis of production patterns offers an interesting methodological approach to understanding the dynamics and trends in the mineral industry. This study aims to leverage the World Mining Data database to investigate historical patterns in mineral production and assess relevant trends[24]. The "World Mining Data" platform is a public resource developed by the Austrian Ministry of Finance. The data have been collected from various official sources, including the British Geological Survey (BGS) and the United States Geological Survey (USGS). The regularly updated database contains information on the production value in metric tons (1 metric ton = 1.000 kg) and US dollars for 65 mineral commodities from 168 countries.
Before diving into specifics, the initial analysis and elaboration of the data reveal that, during the relevant time series considered in this dataset (1984-2023), the percentage of mineral production has more than doubled, with a growth rate of approximately +105.62%, peaking in 2023 at 19.19 billion metric tons (see Figure 5). Data analysis allows us to quantify the volume of specific minerals extracted within the time series from 1984 to 2023. This investigation involves classifying the minerals into five categories based on their composition and nature. Primarily, the classification organizes metals into: Iron and Ferro-alloys (e.g., chromium, cobalt, manganese, and nickel); Non- Ferrous Metals (e.g., aluminum, copper, zinc, lead, and lithium); Precious Metals (e.g., gold, platinum group metals, and silver); Industrial Minerals (e.g., gypsum, phosphate rock,

[24] *World Mining Data. (2025). Total World Mineral Production.*

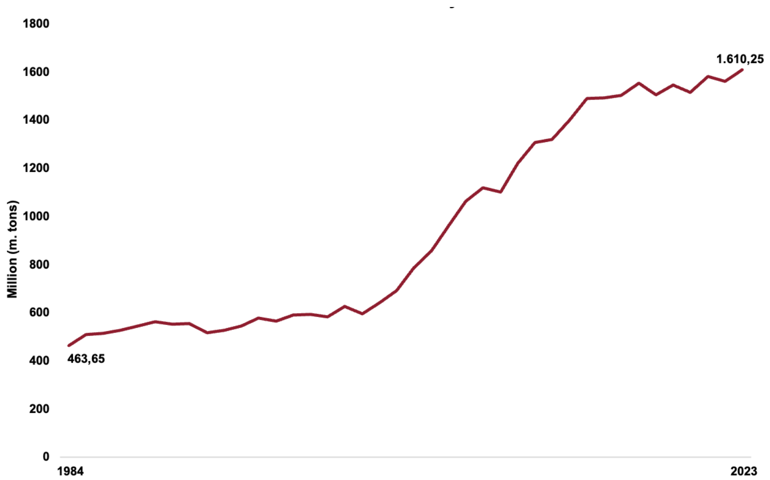
and limestone); and Mineral Fuels (e. g., coal, petroleum, natural gas, and uranium). To analyze the production trends of categorized minerals over time, a sequence of graphs has been constructed from the database to illustrate the extraction volumes. These visual representations of extraction in millions of metric tons aim to demonstrate the volume's growth and peak over a 39-year time series (see Figures 6 to 10).

Figure 5. *Global minerals production (1984-2023 in billions of m. tons)*



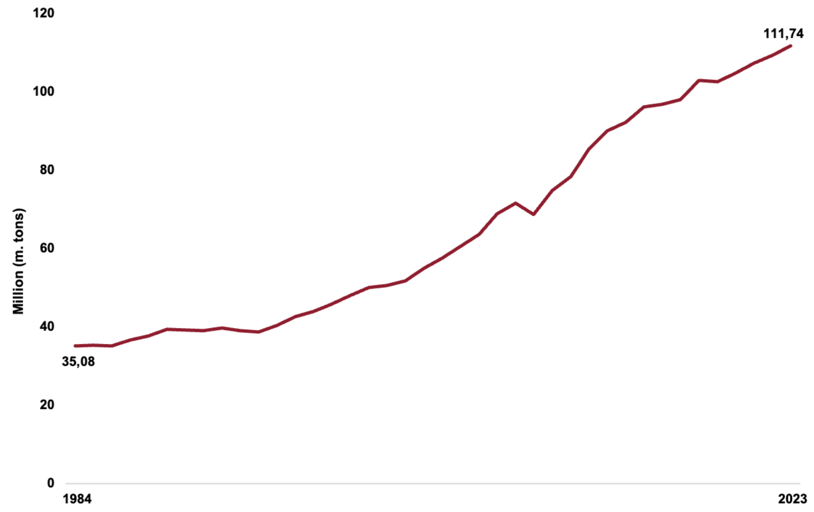
Source: World Mining Data. (2025). Total World Mineral Production

Figure 6*. Iron and Ferro-Alloys (1984-2023 in millions of m. tons)*



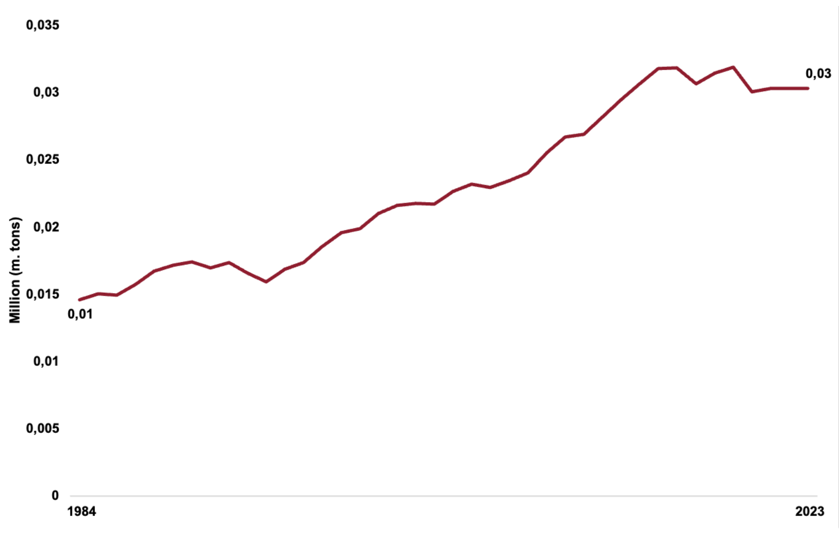
Source: World Mining Data. (2025). Total World Mineral Production

***Figure** 7. Non-Ferrous Metals (1984-2023 in millions of m. tons)*



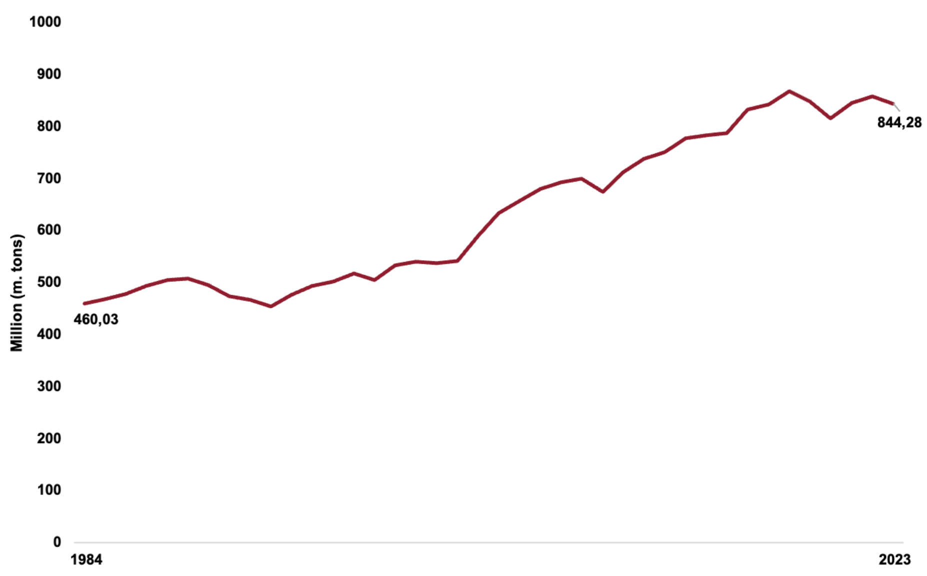
Source: World Mining Data. (2025). Total World Mineral Production

***Figure 8.** Precious Metals (1984-2023 in millions of m. tons)*



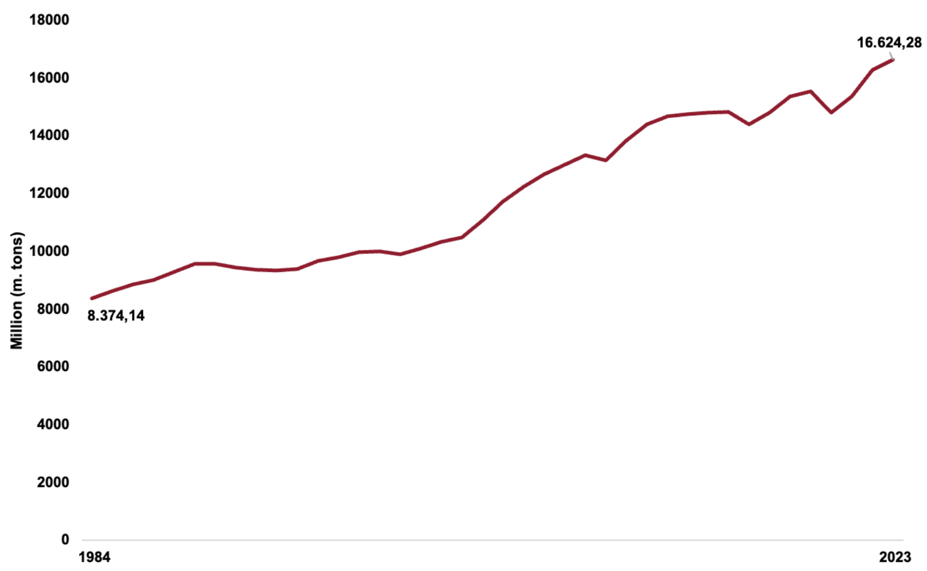
Source: World Mining Data. (2025). Total World Mineral Production

Figure 9. *Industrial Minerals (1984-2023 in millions of m. tons)*



Source: World Mining Data. (2025). Total World Mineral Production

Figure 10*. Mineral Fuels (1984-2023 in millions of m. tons)*



Source: World Mining Data. (2025). Total World Mineral Production

Empirically, the commodities that increased the most, considering the CAGR, are Iron and Ferro Alloys (3.24%) and Non-Ferrous Metals (3.01%). Production of Iron and Ferro Alloys jumped by 247.30% from 1984 to 2023, peaking in 2023 at 1.61 billion metric tons. In contrast, Non-Ferrous Metals, whose production increased by 218.48% during the same period, reached 111.74 million metric tons in the same year. These surges, highlighted by the line trends on the graphs, reflect global industrial tendencies that predominantly rely on these two categories of minerals.

However, the research will later focus on specifics, as particular attention is necessary in investigating the geographic source of these minerals that may lead to geopolitical disputes and commercial constraints. The analysis of total mineral production (excluding bauxite) according to the political stability of producers, as measured by the Worldwide Governance Index, indicates an evident polarization (see Figure 11)[24]. Having introduced the WGI in the previous chapter as a practical tool to assess supply risk and quantify material criticality, it is fundamental to clearly define the principles categorizing countries into four groups: stable, fair, unstable, and extremely unstable. The Worldwide Governance Index evaluates countries by reflecting perceptions of governance[25]. The metrics used to construct the model are periodically sourced and filtered from various organizations and expert assessments or surveys. The WGI utilizes approximately 31 sources through the Unobserved Components Model (UCM). The UCM is based on three fundamentals: standardization, ensuring meaningful data combination; weighting, monitoring the reliability and precision of analyzed sources; and error margin, always considering a statistical standard error. Combining these standards allows the model to proxy a country's governance status and score six governance dimensions. Through these six measures, the model aims to assess how governments are selected, monitored, and replaced, the extent of government capacity to draft and implement policies, and the acknowledged status of social and economic interactions. This score assessment is practically conducted through metrics such as voice and accountability, gauging the scope of democratic participation based on freedom of expression, political participation, political pluralism, and civil liberties. Political stability and absence of violence/terrorism

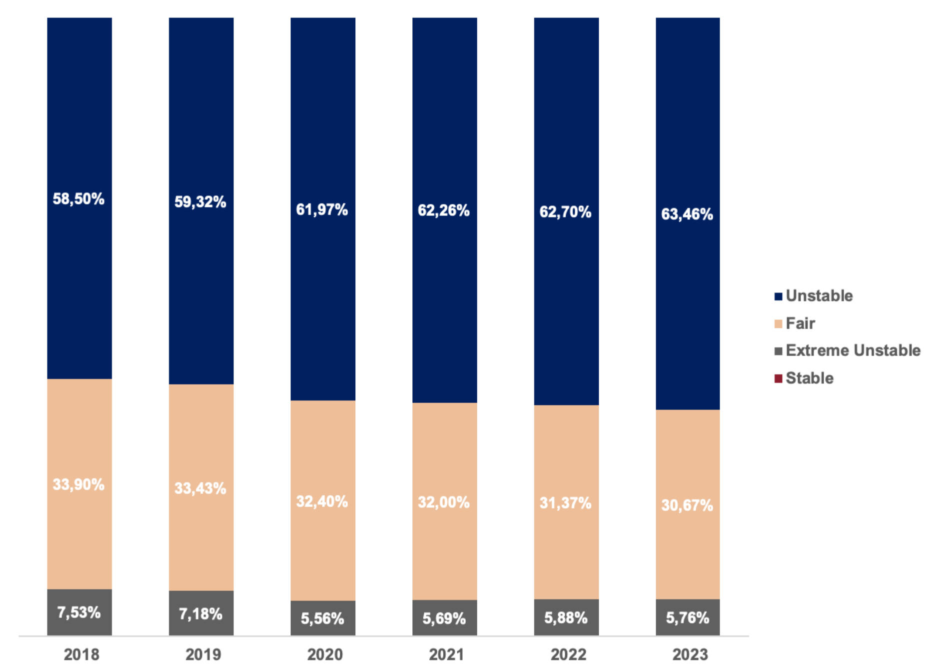
[25] Kaufmann, D., Kraay, A., & Mastruzzi, M. (2011). *The Worldwide Governance Indicators: Methodology and Analytical Issues.* Hague Journal on the Rule of Law, *3*(2), 220–246.

measure the probabilities of government destabilization or overthrow due to violent, unconstitutional retaliations or terrorist acts. Government effectiveness and regulatory quality determine the quality of civil and public services, resulting from the government's ability to formulate and implement policies that foster development in various sectors. The last two dimensions are the rule of law and control of corruption, which capture how agents respect and adhere to societal laws (e.g., contract enforcement, respect for property rights, prevention of crime and violence) and how public authorities interact with the private sector, influencing policies to protect elites and private interests. The interpretation of the resulting data relies on multiple scores represented in two formats, assigned to each of the six dimensions. The first is the governance score, or standard normal unit, attributing a score ranging from -2.5 to 2.5, where 0 represents the global average. Statistically, higher values indicate better governance. The second parameter is the percentile rank (0-100), which indicates a country's ranking among others; extreme values represent the lowest rank (0) and the highest rank (100). However, since the analysis is perception-based, the model emphasizes the margin of error, which may distort governance scores. Each country's score comes with a 90% confidence interval, with a specific standard error estimated for each governance dimension, reflecting the quality and quantity of sources and adjusting the final output accordingly. Hence, the World Mining Data (WMD) database classifies countries by political stability, grouping them into governance score intervals: < -1.25 as extremely unstable; $-1.25 < GS < 0$ as unstable; $0 < GS < +1.25$ as fair; $> +1.25$ as stable.[26]

The polarization analysis, conducted considering a time frame from pre-pandemic to 2023, shows that unstable and extremely unstable countries combined, provided almost 67.63% on average of the total minerals production. In the graphical representation, though, the stable countries' values are not reported since there is reason to believe that their contribution is petty throughout the years, supplying on average 0.07% of total minerals production (2018-2023).

[26] World Mining Data. (n.d.). *Regional and sectoral groups - Political stability of producer countries*. World Mining Data. Retrieved April 2025, from: https://www.world-mining-data.info/?World_Mining_Data___Regional_and_Sectoral_Groups___Political_Stability_of_Producer_Countries

__Figure 11.__ Minerals production by the political stability of producer countries



Source: World Mining Data. (2025). Total World Mineral Production

2.1.1 Strategic Minerals Concentration

The theme of production concentration was introduced in the preceding paragraph. However, sampling minerals by purposes in selected industries, such as energy and clean technology, digital transition, defense, and space applications, could provide a deeper understanding of the production concentration status of those minerals that play a pivotal and strategically relevant role. The chosen minerals are copper, lithium, gallium, cobalt, and graphite. There is justification for considering these minerals since benchmarks indicate that their application in the mentioned fields is highly significant.

We can trace specific consumption needs to produce technologies in the considered industries to justify this choice of analysis. Starting with the applications in energy and clean technology and examining the International Energy Agency's (IEA) report on minerals' criticality in the clean energy transition, it is possible to quantify mineral usage in electric vehicles (EVs) and clean energy production plants[27]. The mineral usage is expressed in two ratios: kg/MW for clean energy production plants and kg/vehicle for electric vehicles. According to the report, the kg/MW ratio reflects the quantity of materials, typically minerals and metals, necessary to generate 1 megawatt (MW) of power through a specific energy technology. This parameter highlights the material intensity of a technology, meaning that the higher the value, the greater the amount of materials required to produce 1 MW of power. The report reveals that offshore wind turbines, compared to alternative clean energy production plants, demand an average of 15.000-20.000 kg/MW, confirming their mineral-intensive nature compared to other clean energy sources. A significant portion of the materials used in offshore wind turbines is copper, which constitutes roughly 52% of the structure and accounts for the highest mineral requirement (approximately 8.000 kg/MW). In contrast, alternative clean energy production plants, such as onshore wind, which also require substantial mineral implementation, use 63.5% less copper than offshore ones (approximately 2.900 kg/MW).

The kg/vehicle ratio is a practical measure to quantify the approximate load of materials needed to manufacture an electric vehicle, particularly in comparison to a conventional automobile. The report states that an EV requires roughly 250-280 kg of essential materials to ensure the battery's resilience and reliability. Among these materials, copper accounts for 30%, graphite for 25%, nickel for 13%, cobalt for 5%, and lithium for 3%, while the remaining 24% consists of other critical materials.

According to the Center for Strategic and International Studies (CSIS), advanced semiconductors heavily rely on gallium integration, among various materials[28]. Gallium is an indispensable and non-substitutable component, as its application spans the defense industry and advanced electronics, enhancing its strategic and technological value. While gallium does not account for the largest share of chip materials, its properties and applications are crucial for fostering the high performance of electronics. Gallium is extensively used in producing gallium arsenide (GaAs) and gallium nitride (GaN),

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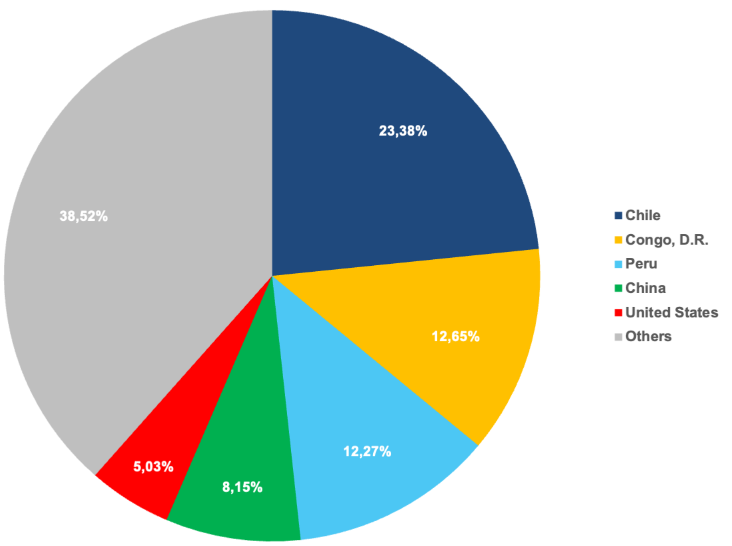
[27] International Energy Agency (IEA). (2022). *The role of critical minerals in clean energy transitions*. International Energy Agency.

[28] Baskaran, G., & Schwartz, M. (2024). *From mine to microchip: Addressing critical mineral supply chain risks in semiconductor production*. Center for Strategic and International Studies.

serving as optimal and non-substitutable materials in creating particularly efficient devices that can manage high frequencies and powers. The report specifies that gallium nitride possesses a wide bandgap (approximately 3.4 eV), enabling it to handle significantly higher voltages and powers than silicon without overheating. GaN is characterized by low internal resistance and high electronic mobility, minimizing energy loss and enhancing device efficiency. These features make it an ideal material for high-frequency devices, such as those utilized in 5G stations, high-resolution radar, and LiDAR sensors embedded in autonomous vehicles. Conversely, gallium arsenide enables rapid signal transmission through elevated electron mobility. The characteristics of GaAs range from reduced electrical noise to radiation resistance, making it the ideal material for manufacturing radar antennas, RF amplifiers in mobile phones and satellites, and infrared devices and modules for high-precision optical communications.

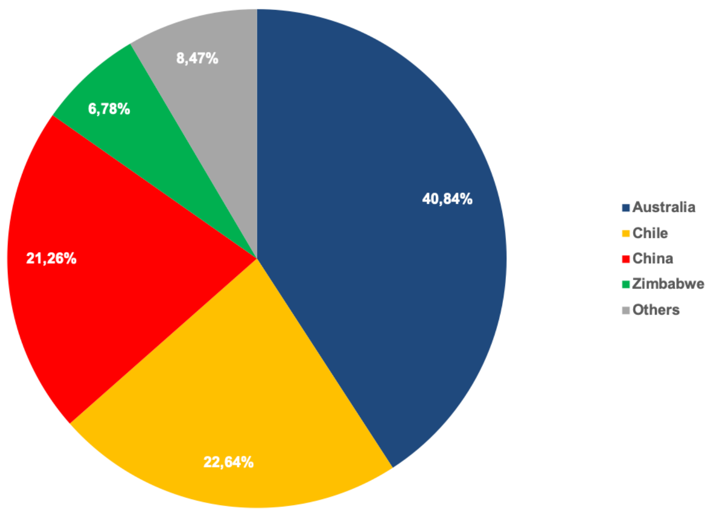
Having briefly established the relevance of these materials to specific industries, an analysis of the World Mining Data database allows us to highlight the current production concentration and relevant trends. The following graphical representations illustrate the weight percentage of metric tons of minerals produced by individual countries in 2023. (Figures 12-16)

Figure 12. *Copper production by country in 2023*



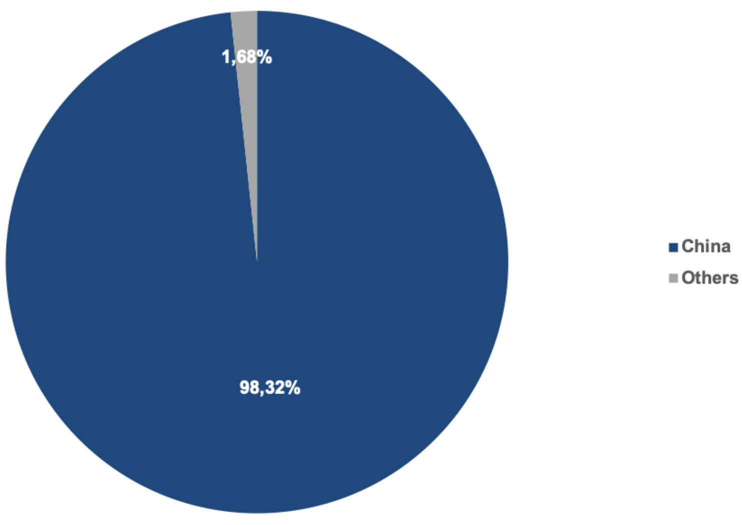
Source: World Mining Data (2025). Production of mineral raw materials of individual countries by minerals

Figure 13. *Lithium production by country in 2023*



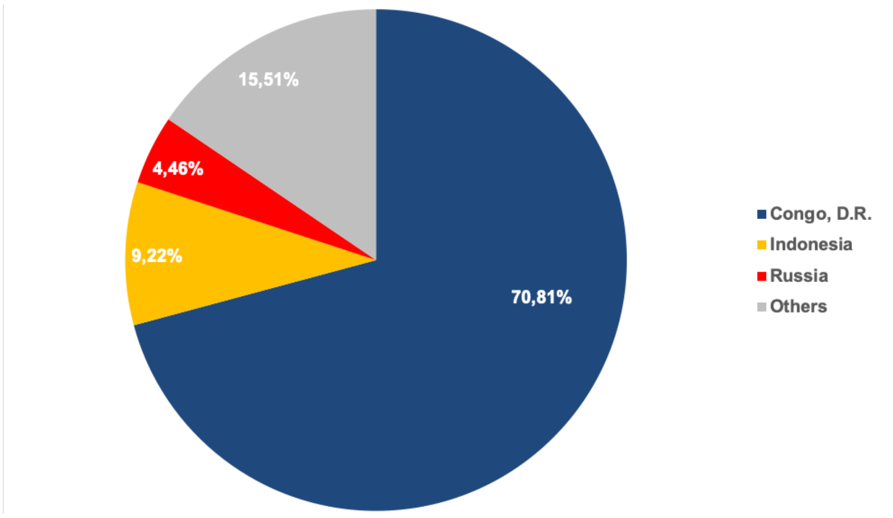
Source: World Mining Data (2025). Production of mineral raw materials of individual countries by minerals

Figure 14. *Gallium production by country in 2023*



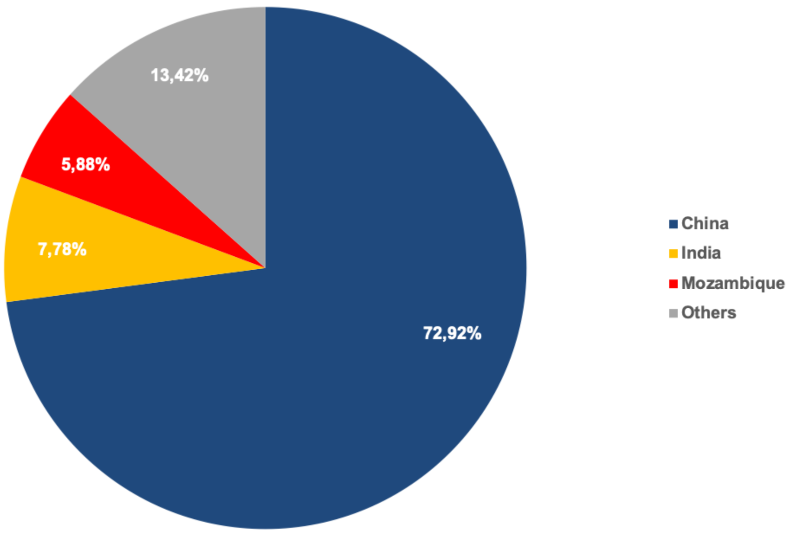
Source: World Mining Data (2025). Production of mineral raw materials of individual countries by minerals

Figure 15. *Cobalt production by country in 2023*



Source: World Mining Data (2025). Production of mineral raw materials of individual countries by minerals

Figure 16. *Graphite production by country in 2023*



Source: World Mining Data (2025). Production of mineral raw materials of individual countries by minerals

The analysis was conducted by elaborating and modelling bulk data from the World Mining databases on the production of mineral raw material of individual countries by minerals[29], and the world production of critical raw materials by political stability[30].
To improve readability and highlight major contributors, it is appropriate to group all countries accounting for less than a specific percentage threshold under the "Others" category. The percentage threshold has been defined based on the mineral in question and the production values (e.g., regarding the graphical representation of cobalt production, all countries accounting for less than 4.45% have been categorized under "Others"). This criterion enhances the overall distribution visualization without compromising data representation. Since the graphs extracted from the database appear self-explanatory, before proceeding with commentary dense with percentage calculations and analysis, a preliminary observation concerns growth trends in production recorded between the pre-pandemic period (2019) and 2023. Throughout the considered timeframe, all the selected minerals experienced significant production increases. Copper production increased by 8.85%, Cobalt production rose by 58.7%, lithium soared by 160.25%, gallium increased by 90.64%, and graphite grew by 2.47%. The following analysis aims to leverage the 2023 relative HHI indicator to more effectively capture the complexity and seriousness of critical minerals production concentration. The Herfindahl-Hirschman Index (HHI), briefly mentioned in the last paragraph of the first chapter, is a common measure used in economics to determine the concentration status of particular markets. In this case, the HHI serves as a tool to establish the status of mineral production concentration. By using this index, the research aims to explore whether strategic minerals production is polarized in specific countries (e.g., unstable or extremely unstable countries), assess the implications of a hypothetical concentration status, and understand the pivotal impacts on global supply chain dynamics. The HHI is calculated by squaring the weight percentage of all producer countries for the mineral in question and summing the resulting figures. The interpretation of the results should indicate wide diversification with a value tending to 0, or substantial concentration with a value approaching 1. The calculation involved minerals previously highlighted for strategic importance. The analysis of Critical Raw

[29] World Mining Data (2025). *Production of mineral raw materials of individual countries by minerals*
[30] World Mining Data (2025). *World Production of Critical Raw Materials by Political Stability*

Materials (CRM) production concentration could provide clear evidence of economic and geopolitical fragilities, leading to dependencies and jeopardized supply chains.

Although copper production appears relatively distributed among a cluster of 58 producer countries, as indicated by an HHI of 0.1, it is still proportionally concentrated in nations classified as unstable and extremely unstable. In 2023, copper production peaked at 22.45 million metric tons, with 55.69% concentrated in unstable (41.55%) and extremely unstable (14.14%) countries.

Regarding lithium production, the measured HHI value is 0.27, a threshold that indicates high production concentration, an assertion supported by the visual representation results showing 84.27% of the total 2023 lithium production clustered among Australia (40.84%), Chile (22.64%), and China (21.26%). Additionally, data analysis reveals that although 64.29% of total lithium production comes from countries categorized as stable, with only 35.09% being produced by unstable and extremely unstable countries, growth trends present interesting results. Indeed, production from unstable and extremely unstable countries is rapidly increasing, experiencing a 43.18% rise over four years with a CAGR of 15.18% (2019-2023), while, in contrast, production from stable countries is declining, reporting a 23.49% decrease from 2019 to 2023, gauging a CAGR of -5.14% (2019-2023). The exploratory data analysis highlighted some patterns of particular interest. Among unstable nations, Zimbabwe, contributing 6.78% (0.33 million metric tons) of lithium production in 2023, recorded a staggering growth rate of 1179.25% (2019-2023). Furthermore, an equally intriguing trend evident from the database analysis is China's push in mineral production, demonstrated by a growth rate of 459.47% (2019-2023), achieving a CAGR of 53.80%. These findings confirm the hypothesis of structural growth in lithium production, which is defined as critical according to the EU criticality assessment[21] due to its production polarization. This reflects the industrial importance already assessed in the study of the growth rate since, as the research recalls, the Non-Ferrous Metals recorded the second highest surge in production (218.48%)[24] and CAGR (3.01%)[24], manifesting the strategic relevance of these materials for various implementations discussed previously in this paragraph. Accordingly, these insights potentially create space for future projections, which can reshape the production landscape and cluster closely the production localizations. The methodology applied to develop a forecast analysis involved defining the prediction model and the growth rates.

The setup model included input data from countries considered for their total production contribution in 2023 (99.38%): China, Australia, Chile, Zimbabwe, Argentina, Brazil, and Canada. Since the CAGR incorporates the compounding effect, showing the average annual growth, it has been used as a proxy for the growth rate over a 4-year lithium production horizon (2024-2028). Thus, the subsequent growth rates for the countries mentioned above are 53.80% (China), 17.89% (Australia), 25.98% (Chile), 89.12% (Zimbabwe), 8.02% (Argentina), 55.85% (Brazil), and 45.89% (Canada). The results suggest that China is set to catch up to its competitor-producing countries and establish itself as the largest lithium producer within four years (2024-2028). Consequently, the production distribution landscape could shift, with China and the lagging Zimbabwe outpacing competitors, representing 33.11% and 29.69% of the 2028 total lithium production, respectively.

Several points must be expressed regarding gallium production, as the results indicate a clear monopoly; the measured HHI of 0.96 signals a monopolistic environment. China dominates gallium production, accounting for 98.32% of total mineral production in 2023.

A similar assertion about production concentration depicts a scenario concerning cobalt production. The measured HHI of 0.51 indicates significant concentration. According to the 2023 data extraction and analysis, the Democratic Republic of Congo produced nearly three-quarters of the world's total cobalt production (70.81%).

Based on its application and importance, the final material considered is graphite. The measured HHI value of 0.54 indicates substantial concentration. This mineral, classified as an industrial metal, is primarily produced in unstable and extremely unstable countries. Data analysis shows that in 2023, combined unstable (92.77%) and extremely unstable (5.98%) countries contributed nearly the entirety of global graphite production (98.75%). In 2023, China's contribution to global graphite production reached approximately 1.65 million metric tons.

2.2 Critical Raw Material Price Fluctuations: Literature Review

Since the subject is increasingly discussed for its contemporary relevance, it is debated how the mid-transition, during which soaring investments are redirected into clean energy technologies, fosters geo-fragmentation[31]. The evolutionary shift to a more sustainable industry and consumption exacerbates geographical and political bottlenecks, inducing structural market shocks. Literature has explored how external variables may affect price formation and volatility in commodity markets and has expressed concerns about the impact of trade restrictions and structural shocks. The OECD working paper[32] examined risks linked to macroeconomic factors that may affect critical mineral markets, jeopardizing the interconnected dynamics of global supply chains. The paper discovered how diverse forms of demand, aggregate, contemporaneous (metal-specific), and precautionary, affect commodity price volatility. Since the paper conducted an effect analysis on three crucial materials, aluminum, nickel, and copper, the last material mentioned has been sampled from the paper narrative to demonstrate the price effect determined from different demand shocks. According to the paper, an aggregate demand shock is a synchronized peak in global economic activity that boosts the physical production of specific minerals, driving price trends. Generally speaking, this can be explained as an expansive macro-industrial cycle where companies in the telecommunications and automotive sectors increase commodity buying. Although the physical output of minerals rises, prices increase even more, as the supply cannot keep pace with the surging demand. The energy transition could create an aggregate demand shock if green investments are promoted simultaneously, leading to a sudden surge in metals and minerals necessary for green industry-specific applications. According to the study results, when the global economy transitions into a coordinated expansive phase, the copper price, among other commodities analyzed, suddenly rises and consequently descends. Shortly after the shock, the copper price registers a 1% increase. However, the

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[31] Espagne, E., Oman, W., Mercure, J.-F., Svartzman, R., Volz, U., Pollitt, H., Semieniuk, G., & Campiglio, E. (2023). *Cross-border risks of a global economy in mid-transition* (IMF Working Paper No. 2023/184). International Monetary Fund.
[32] Miller, H., & Martínez, J.-P. (2025). *The changing dynamics in global metal markets: How the energy transition and geo-fragmentation may disrupt commodity prices* (OECD Environment Working Papers No. 258). OECD.

price rally is absorbed in three months, resulting in an effect statistically indistinguishable from 0. The explanation of the outcome lies in the capacity of the market to absorb the demand peak since copper has a resilient and flexible offer structure compared to other minerals studied in the paper (aluminum and nickel). Consequently, the research argued that contemporaneous demand (metal-specific) shocks occur. The result of an improvised and significant demand for specific minerals sharply pushes price curves upward immediately after the shock occurs. The demand shock creates a price-availability loop, where price volatility and inventory levels influence each other. The effects on downstream activities impact production costs and cascade to the finished product price, slowing clean energy technology adoption and tightening companies' margins. In this case, the paper discovered that copper price, following an improvised surge in demand, "sticks", as defined, to the market. The stickiness effect, argued in the research, explains the price reaction to the rigid offer, which struggles to re-establish an equilibrium. Price gets stuck since the shock drains the entirety of the mineral reserves, blocking the offer, which cannot react promptly, and making the spot and future market internalize a higher marginal cost as long as the market is capable of enhancing productivity or the demand plummets. Lastly, the paper analyzed the precautionary demand shock. This bump is driven not by a concrete rise in demand but rather by sentiment regarding the future minerals supply-demand equilibrium. Thus, a geopolitical crisis or expectations of influential trade shocks could squeeze prices, generating long-lasting increases. The Nickel case, discussed in the paper, clearly represents how rumors of possible sanctions on Russian nickel imports, during March 2022, affected material prices, increasing them by up to +270% in three trading sessions on the London Metal Exchange (LME). In this last case studied in the paper, the copper price reacts as sentiment about tariffs, embargoes, and geopolitical tensions rises. A 1% shock increases real prices by ten months, reaching a maximum peak price of +4.8%.

Therefore, the discussed literature focused on understanding the causal effect determined by demand shocks on commodity prices. However, the study in the preceding paragraph and the results collected have constructed the fundamentals of the scope of the subsequent research. Furthermore, it remarked the importance of conducting detailed research on production trends, and understanding concrete or close concentration status through the calculation and interpretation of the Herfindahl-Hirschman Index, which the study recalls being an effective tool applied to determine whether, in this case, the strategic minerals production is polarized in specific countries, or, otherwise, how the production distribution is scattered across countries.

2.2.1 Methodological approach, data collection, and research limitations

Following the logical progress of the research, thus, the study in this paragraph aims to understand whether a correlation, and its intensity grade, exists between production concentration, expressed via HHI, and price volatility of the considered commodities (Copper, Lithium, Gallium, Cobalt). Besides, whether the correlation appears to be statistically significant, the analysis aims to explore the relationship between the two variables through a simple linear regression. The research methodology employs a quantitative approach, underpinned by data collection and elaboration. As the research recalls, the production concentration indexes have been measured based on the countries' production data provided on the World Mining Data dataset, previously used for the above CRMs production concentration assertion and description. Accordingly, a first dataset has been constructed, measuring, collecting, and organizing HHI data per year, which the research recalls being a 5-year time series (2019-2023), and per minerals. Consequently, the research progressed by collecting monthly commodity prices data from January 2019 to December 2023, and extracting them from the Bloomberg terminal. The period price selection was coherent with the HHI's time series as reported in the World Mining Data database. The process of terminal screening led to choosing the subsequent price indicators, expressed as Bloomberg's tickers. For Cobalt, the ticker from which historical prices have been extracted was <LMCODY LME COMDTY>. The LME Cobalt, as stated by LME itself, is crucial for the global metal markets as it is, as defined, the only physically settled contract for the electric vehicles sector that allows cobalt's price risk management, offering the metal's producers a terminal market in times of oversupply. This ticker underlines the physical contract, which implies the physical delivery of the metal, regulated for cobalt on the London Metal Exchange (LME). Specifically, the underlying metal, Cobalt, comes with a 99.80% purity. According to the contract's specifications, its lot size is 1 metric ton, and its price quotations are in USD/m. ton.

For Copper, the ticker from which historical prices have been extracted was <LMCADS03 LME COMDTY>. The LME Copper represents a future contract physically regulated, implying the effective metal delivery through the LME-approved warehouses. The contract measurement is expressed in metric tons, and its price quotations are in USD/m. ton.

For Gallium and Lithium, Bloomberg reports financial information referring to external agencies that regulate these two commodity prices.

Price Reporting Agencies (PRAs) are indispensable in gathering, validating, and publishing price assessments for commodities that do not trade transparently on exchanges[33]. Since these commodities are not yet priced through order books on platforms like the London Metal Exchange (LME) or the Chicago Mercantile Exchange (CME), PRA assessments serve as crucial references for producers, traders, industrial consumers, and tax authorities. Rather than setting prices, PRAs strive to accurately describe the commercial value by utilizing recent third-party transactions, firm bids and offers, and wider market insights. Before any figure is published, each observation is aligned to a common Incoterm and a uniform product standard, then a second analyst reviews the resulting price band to check for consistency. The choice of delivery basis is critical: an EXW quote reflects only the factory-gate value, an FOB quote incorporates inland transport to the port and loading costs, whereas a CIF quote folds in ocean freight and insurance. The ticker from which Gallium historical prices have been extracted is <GACNDQSD AMTL INDEX>. This indicator refers to the Asian Metal Gallium Price Index, which monitors the gallium price, which comes with 99.99% purity. This quality standard turns out to be crucial in the semiconductor market. The price quotation, which comes in CNY/kg (currency subsequently adjusted on Bloomberg from CNY to USD), also includes the FOB price. The presence of the Free on Board (FOB) incoterm indicates that the price includes the transportation cost to the port of loading. Regarding Lithium, chemical grades are

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[33] Taquiri, J., Lassourd, T., & Viola, A. (2024). *Determining the price of minerals: A transfer pricing framework for lithium*. International Institute for Sustainable Development & Organisation for Economic Co-operation and Development.

standardized to battery-quality lithium carbonate or hydroxide with at least 99.5 % purity, and spodumene concentrate is referenced to 6 % Li_2O[33]. In this study, spot prices were collected for Lithium Carbonate 99.5% traded in China. The ticker from which Lithium historical prices have been extracted is <L4CNMJGO AMTL Index>. The Bloomberg terminal sources Lithium's financial data from the Asian Metal Market. Even in this case, the price quotation has been adjusted at a currency level, converting it from CNY to USD. The lot size is expressed in metric tons.

However, despite analyzing Graphite previously in the research, in this study has been omitted since price quotations have not been accessible through the Bloomberg terminal due to restrictions applied by its suppliers.

Once the price quotations of the above-mentioned commodities have been collected, the data have been cleared, and units of measurement and currencies have been homogenized to guarantee a correct and effective analysis coherence (CNY to USD and Kg to m. ton). A "Master" Excel sheet, purposely created, has precisely organized the last monthly prices of commodities along with the respective HHI values. To enhance the effectiveness of the analysis, commodity prices have been log-transformed. Log transformation helps mitigate the effects of extreme values (outliers), stabilizing the variance and reducing heteroscedasticity. Without log-normalization, high volatility periods, which increase price dispersions, as discussed in the literature above regarding sudden or sentiment-based demand shocks, could invalidate statistical tests. To conduct the statistical tests, the created database has been uploaded to SPSS software, where, before performing the necessary analysis, variables have been checked and transformed into numerical type and scale measure when required.

As the research recalls, the analysis aims to understand whether a correlation exists between log-normal commodity price volatility and production concentration, expressed via HHI. Subsequently, whether the correlation is statistically significant, deeply explore the relationship between the two variables using simple linear regression.

The Pearson's correlation coefficient (r) is a parametric measure of the strength and slope of the linear relationship between two quantitative and continuous variables. The coefficient quantifies the degree of linear association between two variables, X and Y, assuming values within a range of -1 to 1.

$r = +1$: Assuming this extreme value, it reports a perfect positive linear correlation, where with an increase in X, Y increases proportionally.
$r = -1$: Assuming this extreme value, it reports a perfect negative linear correlation, where with an increase in X, Y decreases proportionally.
$r = 0$: Assuming this value, it reports no linear relation

$$r = \frac{\sum(X_i - \overline{X})(Y_i - \overline{Y})}{\sqrt{\sum(X_i - \overline{X})^2 \sum(Y_i - \overline{Y})^2}}$$

The correlation strength is assumed by the nature of the values given by the statistical analysis. Correlation degree can be interpreted as strong when r assumes values ≥ 0.5; as moderate when r assumes values included $0.3 \leq r < 0.5$; and as weak or unimportant when r assumes values < 0.3.
The r statistical significance can be determined through a unilateral or bilateral t-test, considering a null hypothesis $H_0 = 0$. The associated p-value determines whether the correlation observed is statistically significant, considering a set $\alpha\ level$ (e.g., $\alpha = 0.05$).
A simple linear regression, on the other hand, is a statistical model that estimates the linear relationship between an independent variable (X) and a dependent variable (Y).

$$y = \beta_0 + \beta_1 x + \varepsilon$$

According to the theoretical notions, β_0 is described as the intercept or the expected Y value when X=0. β_1 is described as the angular coefficient, or a change in Y over a change in X. ε is described as residuals or prediction error.
Correlation and simple linear regression share common factors. Pearson's coefficient (r), which measures the strength and direction of a linear relation between two variables X and Y, is strictly linked to the determination coefficient (R^2), which measures the proportion of variance of the dependent variable Y explained by the predictor X in a linear regression model. The determination coefficient assumes values ranging $0 \leq R^2 \leq 1$, where the higher the value, the higher the predictive ability of the model.

However, the research took into consideration some methodological limitations. Neither the correlation coefficient nor the linear regression assumes a causal relationship between the two variables determined for the statistical tests. Moreover, study limitations could be determined by the temporal scope of the databases that the study employed to extrapolate data and gauge the HHI values. The World Mining Data database had short-horizon data on mineral production by countries (2019-2023). Accordingly, the extrapolation of historical commodity prices was temporally adapted to the availability of the HHI time series.

2.2.2 Results discussion

The first analysis aimed to understand the relationship between the log-transformed prices of copper and its relative HHI value. The correlation analysis revealed an inverse and statistically significant relationship between the two variables. The statistical outcome denotes a negative Pearson's coefficient (r) of -0.621, pointing out a negative and moderately strong linear correlation, explaining that, to an increase in production concentration, expressed via HHI, the association assumes that the copper price on a logarithmic scale tends to decrease. Moreover, the measured p-value < 0.001 marked the statistical significance of the relationship.
Since the relationship between the two variables was statistically significant, the analysis progressed with a simple linear regression (see Figure 17). Defined the nature of the variables, hence production concentration (HHI) as the predictor and commodity log-price as the dependent variable, the analysis revealed that the determination coefficient (R^2) of 0.385, within the association, assumes that the concentration degree (HHI Copper) explains 38.5% of the variance in the log(copper) price. Moreover, the angular coefficient, expressed as β, of -0.002, suggests that each unit increase in HHI corresponds to a decrease of 0.002 units in the log-transformed copper price. Thus, 38.5% of the copper price fluctuations can be statistically associated with the production concentration. However, the remaining 61.5% of the variance is explained by other factors not included in the model. Accordingly, despite the model trying to statistically highlight the influential implications of the production concentration as a significant, but not largely

exhaustive, predictor, the studied results underline that the HHI is not singularly exhaustive in comprehending copper price dynamics.

The second analysis aimed to understand the relationship between the log-transformed price of cobalt and its relative HHI values. The correlation analysis revealed a positive and statistically significant relationship between the two variables. The statistical outcome denotes a positive Pearson's coefficient (r) of 0.505, pointing out a positive and moderate linear correlation, explaining that, to an increase in production concentration, expressed via HHI, the association assumes that cobalt price on a logarithmic scale tends to increase as well. Furthermore, the measured p-value <0.001 marked the statistical significance of the relationship.

Since the relationship between the two variables was statistically significant, the analysis progressed with a simple linear regression (see Figure 18). Defined the nature of the variables, hence production concentration (HHI) as the predictor and commodity log-price as the dependent variable, the analysis revealed that the determination coefficient (R^2) of 0.255, within the association, assumes that the concentration degree (HHI Cobalt) explains 25.5% of the variance in the log(cobalt) price. Moreover, the angular coefficient, expressed as β, of 0.0004, suggests that each unit increase in HHI corresponds to an increase of 0.0004 units in the log-transformed cobalt price. The regression coefficient interpretation, however, despite reflecting a statistically significant and positive relationship, denotes an economically negligible increase in log(cobalt) price as an unimportant consequence of an increase in the HHI value. Thus, 25.5% of the cobalt price fluctuations can be statistically associated with the production concentration. However, the remaining 74.5% of the variance is explained by factors not included in the model. Accordingly, despite the model trying to statistically highlight the influential implications of the production concentration as a significant, but not exhaustive, predictor, the studied results underline that the HHI is not singularly exhaustive to comprehend the cobalt price dynamics.

The third analysis aimed to understand the relationship between the log-transformed price of lithium and its relative HHI value. The correlation analysis revealed a negative and statistically significant relationship between the two variables. The statistical outcome denotes a negative Pearson's coefficient (r) of -0.558, pointing out a moderately strong and negative correlation, explaining that, to an increase in production concentration, expressed via HHI, the association assumes that lithium price on a logarithmic scale tends to decrease accordingly. Furthermore, the measured p-value <0.001 marked the statistical significance of the relationship.

Since the relationship between the two variables was statistically significant, the analysis progressed with a simple linear regression (see Figure 19). Defined the nature of the variables, hence production concentration (HHI) as the predictor and commodity log-price as the dependent variable, the analysis revealed that the determination coefficient (R^2) of 0.312, within the association, assumes that the concentration degree (HHI Lithium) explains 31.2% of the variance in the log(lithium) price. Moreover, the angular coefficient, expressed as β, of -0.002, suggests that each unit increase in HHI corresponds to a decrease of 0.002 units in the log-transformed lithium price. Thus, 31.2% of the lithium price fluctuations can be statistically associated with the production concentration. However, the remaining 68.8% of the variance is explained by factors not included in the model. Accordingly, despite the model trying to statistically highlight the influential implications of the production concentration as a significant, but not largely exhaustive, predictor, the studied results underline that the HHI is not singularly exhaustive to comprehend the copper price dynamics.

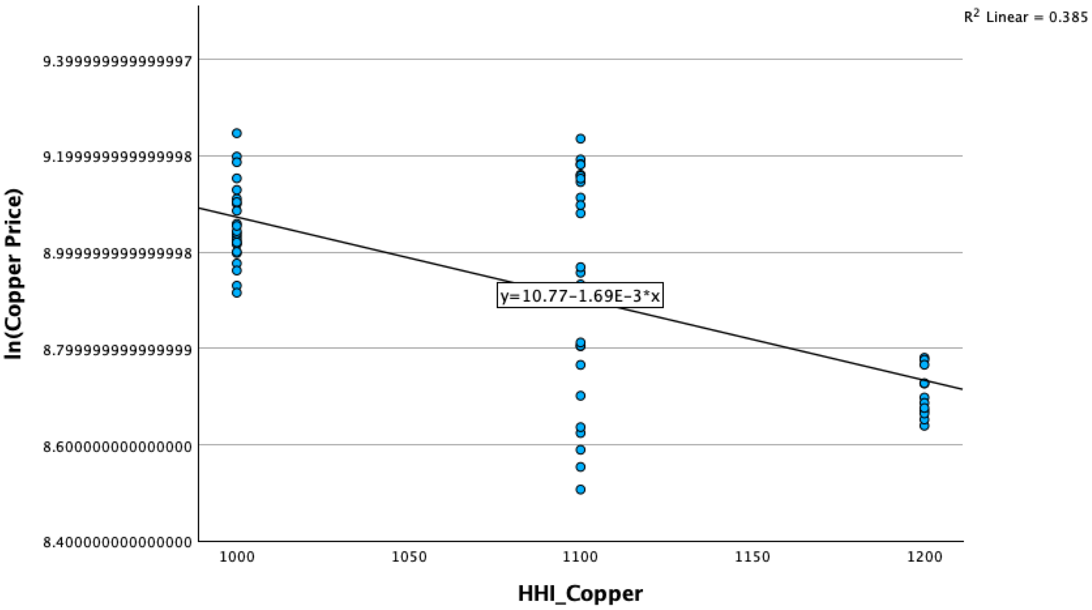
The fourth and last analysis aimed to understand the relationship between the log-transformed price of gallium and its relative HHI value. The correlation analysis revealed a positive and statistically significant relationship between the two variables. The statistical outcome denotes a positive Pearson's coefficient (r) of 0.842, pointing out an extremely strong and positive correlation, explaining that, to an increase in production concentration, expressed via HHI, the association assumes that gallium price on a logarithmic scale tends to increase accordingly. Furthermore, the measured p-value <0.001 marked the statistical significance of the relationship.

Since the relationship between the two variables was statistically significant, the analysis progressed with a simple linear regression (see Figure 20). Defined the nature of the variables, hence production concentration (HHI) as the predictor and commodity log-price as the dependent variable, the analysis revealed that the determination coefficient (R^2) of 0.710, within the association, assumes that the concentration degree (HHI Gallium) explains 71% of the variance in the log(gallium) price. Moreover, the angular coefficient, expressed as β, of 0.001, suggests that each unit increase in HHI corresponds to an increase of 0.001 units in the log-transformed gallium price. Thus, 71% of the gallium price fluctuations can be statistically associated with the production concentration. The remaining 29% of the variance is explained by factors not included in the model. Accordingly, the model highlighted an extremely significant correlation and dependency between the two analyzed variables, denoting the influential impact of production concentration on ln(gallium) price. The studied results underline that the HHI might be an exhaustive, yet not singular, factor to comprehend the gallium price dynamics.

2.2.3 Conclusion

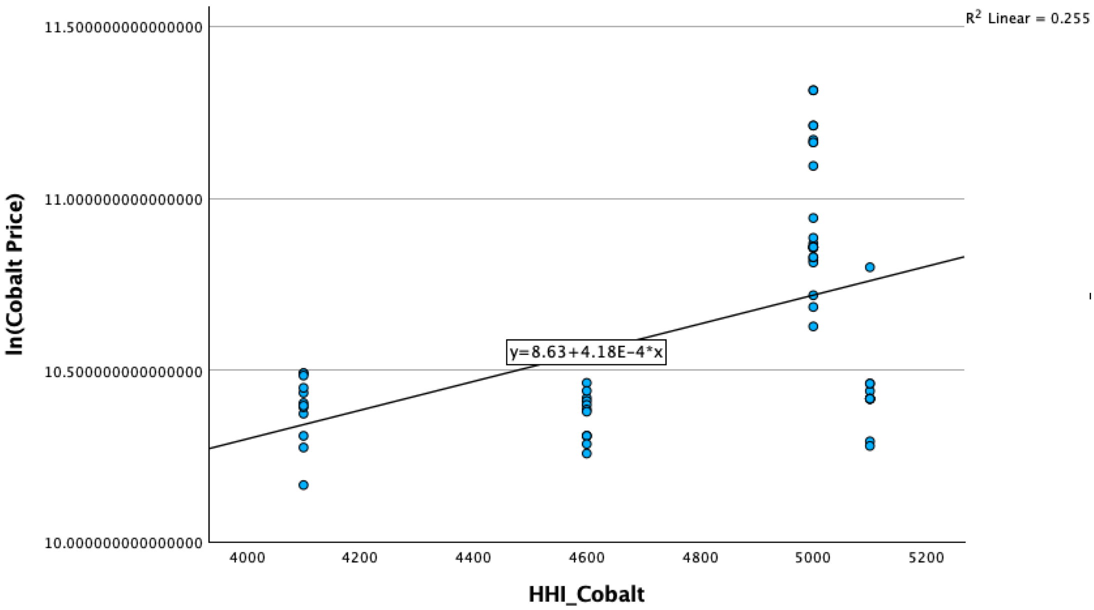
This research has studied the relationship between production market concentration, measured by the Herfindahl-Hirschman Index (HHI), and the logarithmic prices of four selected critical commodities (Copper, Cobalt, Lithium, and Gallium). The key findings after analyzing the correlation between the variables, first, and the linear regression right after, revealed a heterogeneous relationship among the variables studied. Gallium showed a strong positive correlation ($r = +0.842$) and high explanatory power in regression ($R^2 = 0.710$), Lithium and copper exhibited moderate negative correlations ($r = -0.558$ and $r = -0.621$) with moderate regression fit ($R^2 = 0.312$ and 0.385, respectively), indicating that the degree of market concentration, for instance, partially drives price reductions through extended supply dynamics. However, Cobalt, despite exhibiting a positive and significant correlation ($r = +0.505$), had weaker explanatory power ($R^2 = 0.255$). The study demonstrated that all models revealed a statistically significant relationship between concentration and price fluctuation (p-value <0.001), which, assuming a varying degree of consistency within the associations, the research refutes to assess that the correlation consistency is attributable to random patterns. However, as discussed previously in the research, despite indicating some interesting outcomes, the analysis does not mark a concrete causal interaction among variables, which underlie several other influential factors, as well as demand shocks, as discussed in the literature above[32], macroeconomic, and geopolitical dynamics. Nonetheless, the resulting research outcomes highlighted the influential role that production market concentration plays in influencing price fluctuations and, consequently, impacting the status of global supply chains. Moreover, the cascading effect on global value chains may jeopardize production, especially for companies strongly reliant on these CRMs. The same effect may also impact the demand side, which bears the end cost of the disruptions.

Figure 17. *Linear regression: HHI and ln(copper) price*



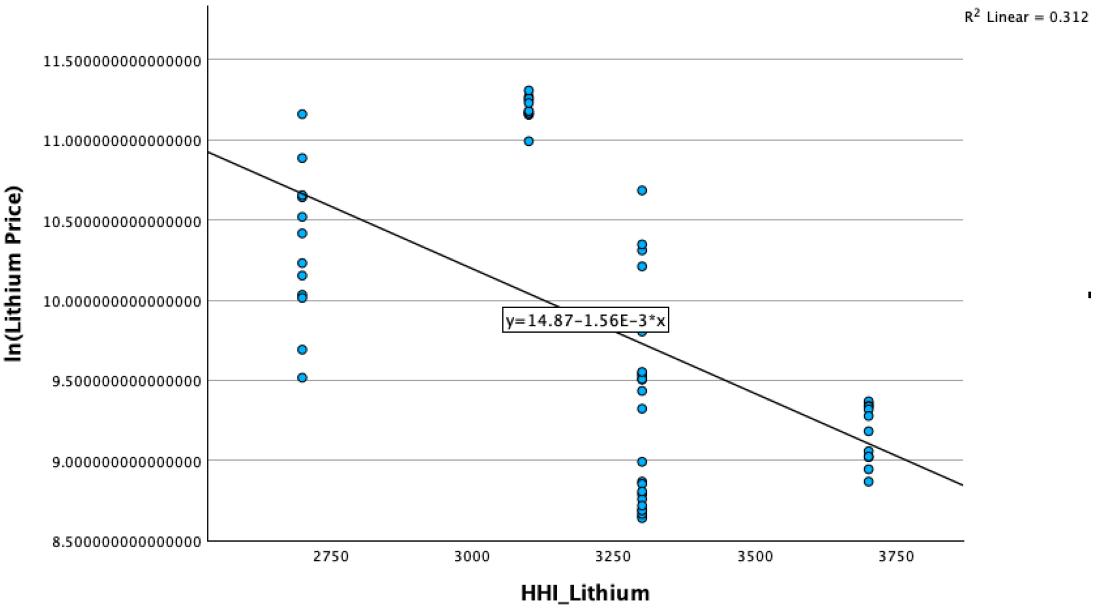
Source: Author's data analysis through SPSS statistics software

Figure 18. *Linear regression: HHI and ln(cobalt) price*



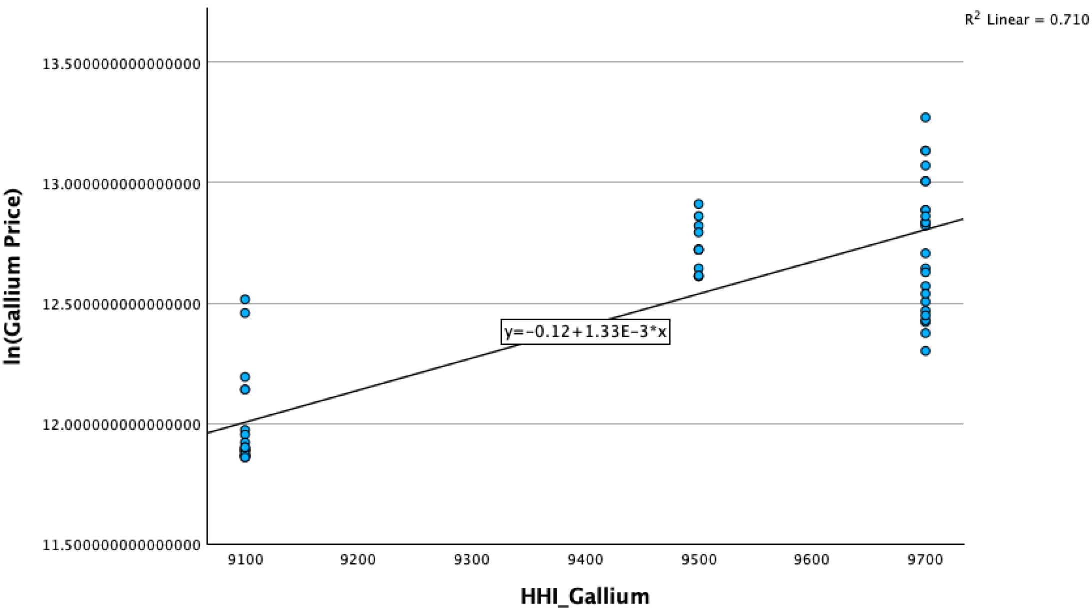
Source: Author's data analysis through SPSS statistics software

Figure 19. *Linear regression: HHI and ln(lithium) price*



Source: Author's data analysis through SPSS statistics software

Figure 20. *Linear regression: HHI and ln(gallium) price*



Source: Author's data analysis through SPSS statistics software

CHAPTER 3. CRMs and Industrial Implications: relevance and vulnerabilities

3.1 CRMs and Digital Innovation

The analysis conducted in the preceding chapter denoted a complex multifactor matrix. It appears clear how the nature and the dynamic intercourse of mining outcomes generate a sense of strategic importance, which is often associated with wide sectoral dependencies. The binomial coexistence between sustainability, technological innovation, and advancements underlies consequence-based factors influencing market and political variables. Since key points have been previously addressed throughout the research, there is reason to recall how raw materials, whose criticality has been highlighted, play a strategically relevant role.
Global Value Chains' fragility exposure is progressively amplified, whether production or any phase along the smiling curve, is highly concentrated in a few locations[34]. Nonetheless, despite trade's chance to minimize countries' economic exposure to volatilities through diversification, in certain scenarios it results quite difficult considering the status of GVCs. Besides, the geo fragmentation, partially explained by GVCs dynamics and physical resource availability, evidences competitiveness gaps among geoeconomic and political blocs.
In this paragraph, the discussion focuses on understanding industry-specific mechanisms that link and relate to the commodity market studied above.
2024 has been a year of solid results for the semiconductor market. The World Semiconductor Trade Statistics reported a double-digit growth in the semiconductor market, which rose by 19% and recovered from a -8.2% recorded in 2023[35]. Accordingly,

[34] Research Institute for Global Value Chains, Asian Development Bank, Institute of Developing Economies – Japan External Trade Organization, & World Trade Organization. (2023). *Global Value Chain Development Report 2023: Resilient and sustainable GVCs in turbulent times*.
[35] World Semiconductor Trade Statistics. (2024, December 3). *Global semiconductor market poised for strong growth in 2024 and 2025* (Fall 2024 Forecast Release).

the global semiconductor market value during 2024 surged to $627 billion, with analysts forecasting it to increase by 11.2% in 2025, hitting $697 billion. Regionally, the Americas rallied by 38.9% ($186,6 billion), outpacing Asia Pacific, Japan, and Europe, respectively reporting a 17.5% ($341 billion), 1.4% ($47 billion) increase, and -6.7% ($52 billion) decrease[35].

Analyzing the semiconductor-related stock market is a useful indicator for comprehending industry dynamics and investors' willingness to allocate capital.

In its report regarding the global semiconductor industry, Deloitte studied how the sector showcased its growth by aggregating the top ten semiconductor companies' market capitalization while temporally comparing and discussing the results. The aggregate market capitalization recorded a 93% increase from mid-December 2023 to mid-December 2024, a value that consequently jumped by 235% from mid-November 2022[36].

As reported, this staggering growth has been supported by a surging demand for gen AI chips, whose market is forecasted to be worth over $150 billion and is likely to peak at $500 billion in 2028[37].

The semiconductor market, with its double-digit growth year-over-year and capitalization almost doubled in one year, is not only an indicator of technological progress and staggering innovation, but also appears as a warning signal. The acceleration mechanism is reliant on production capacity and critical raw materials availability. In an over-fragmented market, competitiveness is key, particularly for economic blocs.

In this section, the research discusses the status of European competitiveness. Mario Draghi, among a series of strategic sectors, addressed the status of the European semiconductor industry. The European contribution to the semiconductor value chain is a mere 10%[38]. Europe's wafer production accounts for just 7% of global production capacity; meanwhile, more than 75% of the production is concentrated in Asia, specifically Taiwan, South Korea, and China[38]. For the sake of the research, along with short investments redirected to innovation, the dependency paradox mostly weakens the

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[36] Kusters, J., Bhattacharjee, D., Bish, J., Nicholas, J. T., Stewart, D., & Ramachandran, K. (2025, February 4). *2025 Global Semiconductor Industry Outlook*. Deloitte Insights.

[37] Varas, A., Varadarajan, R., Goodrich, J., & Yinug, F. (2021). *Strengthening the global semiconductor value chain: Insights from COVID-19, lessons for the future*. Boston Consulting Group & Semiconductor Industry Association.

[38] Draghi, M (2024). *The Future of European Competitiveness: In-depth Analysis and Recommendations.* European Union Report

European semiconductor value chains. In 2023, China's Gallium production accounted for 98% of global mineral production. The caveat in the analysis of future implications is the monopoly production status (HHI 0.96)[29], which explicitly affects European odds on catching up to competitor economic blocs. Without stable access to the mineral, as the demand for chips steadily rises, the 20% production share aimed to be reached by the EU by 2030 seems unrealistic[36]. The EU hereby projects to increase continental mineral production, limited to the availability of specific materials, by 40%, and increment 25% of EU consumption from recycled materials[23]. This dependency status heavily exposes Europe to systemic risks, supply disruption, and distorted competition.

3.2 CRMs and Green Energy Transition

Establishing and mentioning key policy objectives to analyze the sustainable transition towards green energy production technologies and electric vehicles (EVs) is crucial. Taking a step backward on the green transition policies, the United Nations (UN) came up in 2015 with the Paris agreement, manifesting the willingness to develop an effective and progressive response to climate change through industrial initiatives and investments. The convention acknowledged the mentioned issues and endorsed the commitment as per Art. 2 of the agreement:

"[...] Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change;
Increasing the ability to adapt to the adverse impacts of climate change and foster climate resilience and low greenhouse gas emissions development, in a manner that does not threaten food production [...]"[39]

According to the International Energy Agency (IAE) prediction model, to achieve net zero by 2050 and keep faith with the ambitious outcomes set in the Paris Agreement, a

[39] United Nations. (2015). *Paris Agreement*. United Nations Framework Convention on Climate Change.

serious electrification process, among various projects, is necessary[40]. Electrification is one of the key pillars of the net-zero emission path. Accordingly, this process implies a wide transformation in the final consumption and switching to efficient and effective electricity generation technologies. Regarding IEA projections, by 2050, electricity will likely represent 20% of total energy consumption, supplied by 90% by renewable sources[40]. However, transitioning to greener energy production and consumption requires progressively higher infrastructure and industrial investments, an essential financial commitment to guarantee achieving the results discussed. IEA estimates that the energy sector expenditure should jump to $5 trillion by 2030[40].

The electrification projections can be addressed simultaneously by increasing the in-scale adoption of electric vehicles (EVs). Since the Paris Agreement was sealed in 2015, the global electric vehicle market (in units sold) recorded an exponential surge by 3261,7% (2015-2024)[41]. Indeed, the EV market is showcasing year-over-year rising growth rates. In 2024, the global EV market reached 17 million units sold, a 25% rally compared to the data regarding 2023 sales (13.5 million). Estimations forecast a consequent 25% increase in 2025, assuming a 20 million peak rise in units sold. Regionally, China in 2024 registered a solid 40% rise in EV sales, totalizing 11 million units sold, compared to the 6.6 million units reached during 2023. China's incremental EV sales confirm its market leadership position, representing 50% of the global share of electric vehicles sold in 2024. Europe in 2024 recorded a 20% increase in units sold (4 million), representing 20% of the global share of EVs sold. Following, in descending sales order, the USA recorded a weak 10% increase in 2024 EV sales (1.6 million), while ASEAN (Association of Southeast Asian Nations), Latin America, and Africa recorded a 0.4, 0.6, and 0.011 million increase in units sold, respectively.

Regarding financial parameters, the global electric vehicle market in 2024 has been valued at roughly $784.2 billion, a 2.81% YoY increase from 2023[42]. The exponential surge, already expressed in electric vehicles sold, is visible in the industry value rally, a

40 International Energy Agency. (2021). *Net zero by 2050: A roadmap for the global energy sector.* IEA

41 International Energy Agency. (2025). *Global EV Outlook 2025: Expanding sales in diverse markets*. IEA.

42 Statista. (2025). *Electric Vehicles - Worldwide*. Statista. https://www.statista.com/outlook/mmo/electric-vehicles/worldwide

1617.56% jump from 2016 to 2024. According to analysts' forecasts, the EV market is expected to grow at a CAGR of 6.01% (2025-2029), peaking at $990.4 billion in 2029[42]. As analyzed in the previous chapter, green energy technologies require copious quantities of materials and minerals, higher than the average for traditional technologies reliant on fossil fuels. Mentioning briefly what was described in chapter two, approximately, an electric vehicle requires 6x minerals compared to a conventional one[27].

As the demand and investments in green energy production technologies and facilities rise, demand for critical raw materials increases accordingly.

The IEA analyzed the 2023 (latest data available) demand for essential minerals necessary for green energy production technologies and forecasted future demand based on three distinct scenarios.

The "Stated Policies scenario" (STEPS) provides forecasts based on today's policy settings. The "Announced Pledges scenario" (APS) provides forecasts based on assumptions where governments meet national energy and climate targets, including longer-term net-zero emissions. The "Net Zero Emissions by 2050 scenario" (NZE) provides forecasts assuming commitment to reaching net-zero carbon dioxide emissions by 2050 and meeting key energy-related UN Sustainable Development Goals (SDGs).

In 2023, the total demand for key energy transition minerals reached 34.124 kt (1 kt = 1.000 m. ton), with 24.36% (8.314 kt) utilized for clean technologies[43]. Since the research introduced and analyzed four specific minerals (copper, cobalt, lithium, and graphite) pivotal for the green transition, it proceeded with the demand analysis. Analyzing the most recent data (2023) on key transition minerals demand reveals that copper's total demand for 2023 amounted to 25.915 kt. Of this, 25% (6.372 kt) has been absorbed for green tech production, primarily used for electricity networks (69%) and solar PV (19%). Furthermore, the analysis showed that among the cluster of minerals included in the database (copper, cobalt, lithium, nickel, rare earth elements, and graphite), copper accounted for the largest share of total demand (76%) and, correspondingly, the highest portion designated for green tech production (76.6%). The mineral intensity, highlighted by the data analysis, which makes copper essential for the energy transition, indicates that

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[43] International Energy Agency. (2025). *Critical Minerals Dataset.* IEA

fulfilling this demand, according to the UN global trade update, requires 80 new mines and $250 billion in investments by 2030[44].

About cobalt, its total demand for 2023 was 215 kt, representing 0.63% of the total demand for key energy transition minerals and 2.6% of the total portion used for green tech production. Specifically, the portion of cobalt demand allocated to green technology (30%) was utilized for electric vehicle production (97%)[43].

Regarding lithium, database analysis indicated that its total demand for 2023 was 165 kt, representing 0.48% of the total demand for key energy transition minerals and 1.98% of the total portion allocated for green tech production. Over half of lithium's share of demand for clean technologies (56%) has been used for electric vehicle production (90.2%).

The analysis shows that graphite's total demand for 2023 amounted to 4.632 kt, representing 13.6% of the total demand for key energy transition minerals and 15.5% of the total portion allocated for green tech production. The share of graphite demand utilized by clean technologies stands at 28%, primarily used (88.8%) in electric vehicle production.

Regarding future demand implications, considering the three mentioned scenarios, which follow forecasting criteria based on demand-driven assumptions on today's policy setting, governments' energy and climate targets, and net-zero commitment, the database analysis highlights a clear surge in key energy transition minerals, assuming a forecasting period from 2030 until 2050 at five-year intervals. The share of minerals demand for clean technologies is expected to experience a staggering growth. Assuming that economies move forward to fulfill the net-zero objectives, the portion of total demand for clean technologies will rally at +227% (27.168 kt) by 2030, reaching +287% (32.188 kt) by 2050, indicating that more than half of the minerals demand will be allocated for clean technologies implementations (53% on average between 2030-2050, assuming net-zero commitment).

The forecasted demand analysis highlighted an interesting pattern, which the research assumes is linked to industry dynamics. Lithium, nickel, and graphite, among all the

[44] United Nations Conference on Trade and Development. (2025). *Focus on critical minerals: Copper in the new green and digital economy* (Global Trade Update, May 2025). UNCTAD.

analyzed materials in the database, and indistinctively in all three scenarios, recorded the highest growth rates during the entirety of the forecasting period. Lithium demand, assuming the net-zero commitment, for instance, is expected to surge to +569% by 2030, peaking to +1.609% by 2050. Nickel and graphite demand is expected to peak at +548% and +510% by 2050, respectively. Almost the totality of these materials' usage is allocated to electric vehicle production. Hence, this exponentially growing pattern signals how the EV sector will constantly boost its industry value and importance.

However, the surge in key energy transition minerals underlies supply concentration issues, which can erode the status of the green industries, exposing value chains to shock vulnerabilities such as export restrictions, disrupting the supply-demand equilibrium. Considering the criticalities linked to the key energy transition minerals supply chain, alternative solutions may mitigate supply shocks.

Critical minerals recycling can significantly impact the primary supply on various levels. Assuming operation under the Announced Pledges scenario, mineral recycling could reduce mining activities by 40% for cobalt and copper, and by 25% for lithium and nickel by 2050[45]. Recycling serves as a strategic mechanism for countries to manage oversupply dependencies and limit mineral extraction investment expenditures, which would otherwise rise by 30%. Furthermore, recycling can help mitigate the overall cost of the green transition, estimated to reach between $600 and $800 billion by 2040, depending on the scenario. Recycling also ensures an effective domestic secondary source of materials for countries with a high diffusion of green technologies but limited resource availability. For instance, Europe, which, as researched by Draghi, can satisfy only 7% of its mineral demand through domestic extraction[38], could benefit from recycling, as this activity may fulfill roughly 30% (higher than the global average) of its lithium and nickel demand by 2050[45]. However, despite being a source of supply shock mitigation, a diversification alternative, and a strategic lever for mineral-intensive sectors, recycling alone cannot eliminate the need for primary extraction. Mining operations will still play a crucial role in keeping pace with surging demand and decarbonization goals.

[45] International Energy Agency. (2024). *Recycling of critical minerals: Strategies to scale up recycling and urban mining*. IEA.

Conclusion

Global Value Chains (GVCs) represent the backbone of international trade, enabling industrial development. However, GVCs face a series of fragilities that jeopardize their resilience, exposing industries to increasing disruptions. Critical Raw Materials, crucial for strategically relevant industries such as the semiconductor and the energy transition, play a leading role in shaping GVCs' resilience due to their geological presence and industrial importance.

This research aimed to examine and analyze the Critical Raw Materials supply chain, focusing on understanding the industrial relevance while exploring production concentration vulnerabilities.

Specifically, the core of the study intended to: study and discuss production trends of specific minerals, whose relevance has been assessed for their industrial importance; comprehend the status of production concentration through the calculation and interpretation of the Herfindahl-Hirschman index (HHI); measure the correlation and its intensity degree between production concentration (HHI) and specific commodities' historical prices.

To address these objectives, the study has employed a quantitative approach, measuring HHI values from countries' production raw data while collecting historical commodity prices. The quantitative approach was summoned by asserting the statistical relationship between the two variables.

Production trends evidence a clear concentration among the analyzed materials (HHI lithium = 0.27; HHI gallium = 0.96; HHI cobalt = 0.51; HHI graphite = 0.54), values often exacerbated by high concentration in countries marked for substantial instabilities (HHI copper = 0.1, where 55.69% of production concentrated in unstable countries)

This study established that production concentration (HHI) differentially influences critical mineral prices, revealing heterogeneous linkages. Gallium exhibited a strong positive association ($\beta = +0.001$, $R^2 = 0.710$), while Copper ($\beta = -0.002$, $R^2 = 0.385$) and Lithium ($\beta = -0.002$, $R^2 = 0.312$) showed price-reducing effects. Cobalt's relationship is statistically significant but economically marginal ($\beta = +0.0004$, $R^2 = 0.255$). All models reject random variability since all the associations were statistically significant ($p < 0.001$)

The analysis revealed a significant correlation, but it's important to note that correlation does not imply causation. Moreover, the impact of production concentration on prices resulted in commodity-specific effects. Price fluctuations are affected by various factors that can be either exogenous or endogenous, including demand fluctuations, import and export restrictions, macroeconomic trends, and geopolitical events. Importantly, market concentration imposes substantial strain on global supply chains: vulnerabilities on the supply side jeopardize production stability for firms that depend on critical raw materials (CRMs). In contrast, those on the demand side face disruption costs due to price fluctuations. These results highlight concentration's impactful, though not exclusive, role in influencing commodity markets and the resilience of value chains.

Therefore, by mapping HHI-commodity price dynamics, in light of the discussed evidence, this research aimed to transform concentration from a simple risk variable into a quantifiable factor for supply chain risk management.

Given the geological constraints of mineral extraction, naturally bound to finite physical deposits in specific locations, and despite ongoing efforts to develop alternatives (e.g., recycling, material life-cycle reintegration), these strategies cannot fully neutralize the need for primary extraction. This need remains tied to rising demand. In this structural context, our work establishes rigorous academic and managerial foundations for monitoring complex supply chain dynamics. Quantifying concentration-price linkages through the HHI framework paves the way for predictive models integrating complementary variables (geopolitical stability, trade policies, technological shocks), ultimately enabling proactive GVC resilience strategies.

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