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Global Rare Earth and Mineral Dependence in the Energy Transition:

a Comprehensive Analysis of Economic and Strategic Implications

Ana Mendieta Ovejero

Director: Javier Gil Pérez

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ABSTRACT

The global competition for critical minerals and rare earth elements is the key to the energy transition. This thesis examines both current and projected supply and demand with the objective of evaluating whether available resources will satisfy projected demand for critical minerals. Additionally, this work analyses economic, geopolitical, and environmental implications of a strained supply chain. Furthermore, this investigation focuses on the geographical concentration and the incipient exploration of the Arctic, Antarctic, space, and sea bottom as key areas in mining activities. Finally, this thesis proposes a framework of action based on ESG principles, investment diversification, and the collective governance of resources located in Terra nullius.

KEYWORDS

Critical minerals, Rare earth elements, Green energy transition, Supply chain, ESG (Environmental, Social, and Governance), Deep Sea Mining, Space Mining, Arctic exploration, Antarctic exploration, Stated Policies Scenario, Announced Pledges Scenario, Net Zero Emissions Scenario, Critical Mineral Demand Outlook, Critical Mineral Supply Outlook, International Cooperation, Investment Diversification.

ABSTRACT

La competencia por los minerales críticos y las tierras raras es la clave de la transición energética. Este TFG examina su oferta y demanda actual y prevista con la finalidad evaluar si los recursos disponibles satisfarían la demanda futura de minerales críticos. Asimismo, este trabajo aborda las implicaciones económicas, geopolíticas y medioambientales que supone tener una cadena de suministro tensionada. Esta investigación se focaliza en la concentración geográfica y en la incipiente exploración del Ártico, Antártico, espacio y fondo marino como lugares clave en la minería. Finalmente, este TFG propone un marco de actuación basado en los principios ESG, diversificación de inversiones y la gobernanza colectiva de los recursos localizados en Terra nullius.

PALABRAS CLAVE

Minerales críticos, Elementos de tierras raras, Transición a la energía verde, Cadena de suministro, ESG (Ambiental, Social y Gobernanza), Minería en aguas profundas, Minería espacial, Exploración ártica, Exploración antártica, Escenario de Políticas Declaradas, Escenario de Compromisos Anunciados, Escenario de Emisiones Netas Cero, Perspectiva de la Demanda de Minerales Críticos, Perspectiva de la Oferta de Minerales Críticos, Cooperación internacional, Diversificación de inversiones.

1. INTRODUCTION AND MOTIVATION

The global shift towards clean energy is crucial for mitigating climate change and achieving sustainable development goals. Central to this transition is the escalating demand for critical minerals such as lithium, cobalt, nickel, and rare earth elements (IEA, 2024). These minerals are indispensable not only for the production of renewable energy technologies, including wind turbines, solar panels, and electric vehicle batteries, but also for the broader digitalization process and modern technological advancements (IEA, 2024; WEF, 2024).

Critical minerals form the foundation of contemporary technological infrastructure, spanning from smartphones and computers to advanced medical devices and telecommunications systems (IEA, 2024). The rapid pace at which the world is striving to secure supplies of critical minerals and rare earth elements raises significant concerns. This paper aims to investigate whether the burgeoning demand for these critical minerals can be met by current and projected supply levels. Furthermore, it examines the potential economic, environmental, and geopolitical costs associated with accelerating mineral supply to match demand (IEA, 2024).

This thesis seeks to analyze the economic and geopolitical implications of this escalating demand, with a particular focus on supply-demand dynamics, the geographical concentration of resources and refining facilities, and the necessary investments to ensure a stable and sustainable supply chain (WEF, 2024; IEA, 2024). The primary motivation for this thesis is to offer an integrated understanding of how economic, geopolitical, and environmental factors interrelate in the pursuit of critical minerals and a sustainable future. Existing literature often addresses these dimensions in isolation, overlooking the complex interdependencies that exist. For instance, environmental degradation from mining activities can lead to geopolitical tensions over resource control, while geopolitical conflicts can exacerbate environmental and economic vulnerabilities (Energy Global, 2024). This paper seeks to fill this gap by providing an integrated analysis that acknowledges these interconnections. Moreover, it aims to stimulate debate on sustainable practices within the framework of achieving a green transition that is consistent with its goals, ensuring that efforts to combat climate change do not inadvertently lead to new forms of environmental or geopolitical instability (WEF, 2024; IEA, 2024).

2. STATE OF THE ART

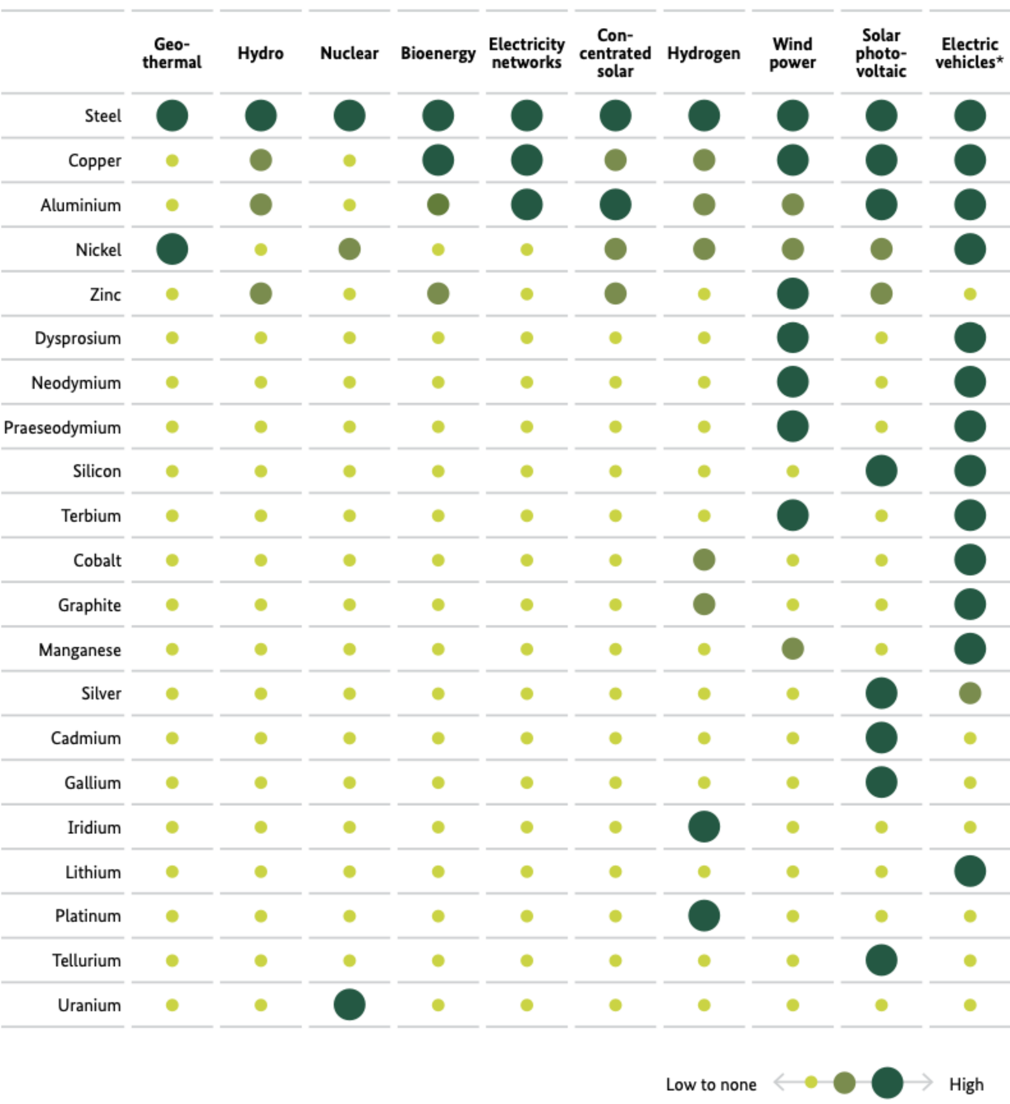
2.1. EVOLUTION OF STRATEGIC AND CRITICAL MINERALS

Throughout history, the designation of strategic and critical minerals has evolved in response to humanity's changing needs. In ancient times, copper and tin were crucial for early industries, laying the foundation for the Bronze Age (USGS, 2020). During the 19th and early 20th centuries, the Industrial Revolution elevated iron and coal to essential status, driving industrial growth and technological advancement (FactSet, 2023). By World War II, oil had become vital for industrial, civil, and military activities, prompting major powers to establish strategic oil reserves (CSIS, 2023). This shift underscored oil's profound influence on global economics and geopolitical dynamics, shaping international relations and economic strategies in unprecedented ways (FactSet, 2023).

Today, there is a global shift away from oil and fossil fuels, driven by environmental concerns and the desire to reduce reliance on oil-producing countries (Klement, 2021). This transition is outlined in the 2015 Paris Agreement, which has spurred investment in renewable energy technologies, facilitating a move towards a low-carbon economy (USGS, 2022). However, this shift does not lead to complete energy independence, as renewable energy technologies rely heavily on critical minerals. These minerals are located in various parts of the world, which, while reducing dependence on OPEC countries, redistributes global energy power dynamics (IEA, 2024). Thus, the move to renewable energy reshapes global dependencies rather than eliminating them, creating new geopolitical and economic landscapes centered around the availability and control of critical minerals (WEF, 2024).

The essential functions of critical minerals are pivotal in supporting sustainable energy solutions and technological progress. Metals such as copper, aluminum, and nickel are indispensable for renewable energy infrastructures, including solar, geothermal, wind, and hydroelectric power (IEA, 2024). Additionally, strategic minerals like cobalt, lithium, graphite, chromite, manganese, and bauxite are essential for energy storage systems, electric vehicle production, transportation infrastructure, and sustainable building construction (IEA, 2024). Furthermore, minerals like lithium, graphite, and cobalt are particularly critical for the energy transition, especially for electric vehicle (EV) batteries and renewable energy storage systems (USGS, 2022). Beyond these well-known critical minerals, others like gallium, germanium, tellurium, and indium are vital for the production of semiconductors and solar cells (CSIS, 2023). Elements such as scandium, yttrium, and lanthanum are used in advanced batteries, fuel cells, and catalysts (IEA, 2024). In the table below, there is a graphical representation of the most typically used minerals and their applications, illustrating the diverse materials required for technological and energy transformations.

Figure 2.1: Materials critical for a transition to a low-carbon economy by technology type



Source: McKinsey & Company (2022).

2.2 POLICY INITIATIVES FOR SECURING CRITICAL MINERALS IN THE GREEN TRANSITION

The global transition to a green economy has prompted countries around the world to implement comprehensive policy frameworks aimed at ensuring the secure and sustainable supply of critical minerals. This section explores the varied and evolving strategies employed by different regions to secure these vital resources, highlighting the interconnected nature of global supply chains and the necessity of international cooperation in this endeavor (IEA, 2023; IEA, 2024).

In the United States, the 2021 Infrastructure Investment and Jobs Act includes a USD 6 billion grant program administered by the Department of Energy. Specifically, half of this funding supports domestic production of materials for the electric vehicle supply chain, while the other half supports battery manufacturing and recycling. Additionally, the Inflation Reduction Act offers a USD 7,500 credit for acquiring clean vehicles, contingent on sourcing critical minerals domestically or from countries with a free trade agreement with the U.S., and manufacturing most battery components in North America, thereby aiming to reduce foreign reliance (IEA, 2024).

Similarly, Australia's Critical Minerals Strategy includes the Modern Manufacturing Initiative, which allocates AUD 120 million for nickel and cobalt refineries, AUD 15 million for REE processing, and AUD 6 million for lithium hydroxide. Consequently, in October 2023, Australia expanded its Critical Minerals Facility with a USD 1.3 billion investment, enhancing its capacity to supply critical minerals (IEA, 2024).

Likewise, Canada's Critical Minerals Strategy, supported by CAD 3.8 billion, includes the CAD 1.5 billion Strategic Innovation Fund, prioritizing innovative critical minerals manufacturing, processing, and recycling projects. Moreover, Canada offers a Clean Technology Manufacturing Tax Credit and a 30% Critical Mineral Exploration Tax Credit to encourage exploration and development (IEA, 2024).

Meanwhile, several mineral-rich countries are adopting protectionist legislation to secure their resources. For instance, Chile's National Mining Policy Framework 2022 addresses copper mining royalties and proposes revising the lithium concession system. Additionally, Mexico's 2022 Mining Reform creates new mining offenses, empowers the water authority to reduce industrial water concessions for mining, and nationalizes its lithium industry. Furthermore, Indonesia has banned nickel exports to develop its midstream value chain, with potential bans on bauxite, tin, and cobalt under consideration. Similarly, Namibia and Zimbabwe have implemented export bans on unbeneficial mineral ores (IEA, 2023; IEA, 2024).

The European Union has also embarked on an ambitious journey towards climate neutrality and digital leadership, recognizing the essential role of critical minerals in this transition. The EU's comprehensive policy framework aims to secure a sustainable supply of these vital resources, thereby bolstering economic resilience and environmental sustainability (European Commission, 2020).

In 2008, the EU launched the Raw Materials Initiative, based on three pillars: securing a reliable international supply, ensuring sustainable domestic supply, and promoting efficient use through recycling. This initiative was further strengthened by the 2020 Action Plan on Critical Raw Materials, which identified five strategic sectors—renewable energy, electric mobility, high-energy industry, information and communications, and defense and space—and fifteen key technologies (European Commission, 2008; European Commission, 2020). The Action Plan outlines ten actions to secure essential minerals, including establishing the European Raw Materials Alliance, setting sustainable financing criteria, conducting research under Horizon Europe, identifying secondary raw material supplies, investing in mining and processing, and deploying earth observation programs for resource exploration (European Commission, 2020).

Building on these initiatives, the REPowerEU plan (May 2022) emphasizes resource access for achieving climate neutrality by 2050 (European Commission, 2022). Furthermore, the European Critical Raw Materials Act sets ambitious objectives for 2030: ensuring at least 10% of the EU's annual critical minerals consumption from domestic extraction, 40% from processing within the EU, and 15% from recycling, while limiting dependency on any single non-EU country to 65% (European Commission, 2023).

To support these goals, Horizon Europe funds research and innovation across strategic value chains, and the updated European Industrial Strategy drives the transition to a green and digital economy, enhances competitiveness, and ensures strategic autonomy (European Commission, 2020). These initiatives exemplify the EU's approach to fostering an open and innovative market. Furthermore, the EU also leads in ESG goals, incorporating these principles into its policies. The Corporate Sustainability Reporting Directive (CSRD), effective January 5, 2023, requires EU businesses to disclose their environmental and social impacts, reinforcing the commitment to sustainability (European Commission, 2023).

In conclusion, the global policy landscape for critical minerals is rapidly evolving, with countries implementing diverse strategies to secure their resources and support the transition to a green economy. Through strategic initiatives and comprehensive policies, regions like the United States, Australia, Canada, and the European Union aim to secure a sustainable and resilient supply of essential resources, promote innovation, and enhance global competitiveness. These efforts underscore the critical role of minerals in achieving climate neutrality and digital leadership, positioning these regions as leaders in the global green transition.

3. THEORETICAL FRAMEWORK

3.1 NEOREALISM

Neorealism is a theory of international relations developed by Kenneth Waltz that emphasizes the anarchic structure of the international system and the inherent competition among states (Waltz, 2000). It posits that the system's lack of a central authority compels states to act in specific ways to ensure their survival, leading to a self-help environment where states must rely on their own capabilities to secure their interests and maintain sovereignty (Waltz, 2000). Central to neorealism is the distribution of power among states, defined in terms of military and economic capabilities (Mearsheimer, 1994/1995). States, as rational actors, seek to maximize their security and power to protect themselves from external threats (Mearsheimer, 1994/1995). A key aspect of neorealism is the balance of power theory, which suggests that states will naturally balance against any state seeking to dominate the international system by forming alliances, building military capabilities, or engaging in strategic partnerships (Waltz, 2000). Additionally, the security dilemma describes a situation where a state's actions to increase its security, such as boosting military capabilities or securing strategic resources, can lead to increased insecurity for others, often resulting in an arms race or competitive behavior ((Waltz, 2000).

Neorealism thus explains the global race for critical minerals by highlighting the anarchic international system and the competitive behaviors of states. It underscores the importance of relative power and security, driving states to secure critical resources to enhance their economic and military capabilities (Waltz, 2000). Furthermore, the security dilemma elucidates the tensions and rivalries that arise from these efforts, as states' actions to secure their interests often lead to increased competition and potential conflict (Mearsheimer, 1994/1995).

3.2 LIBERALISM AND THE GLOBAL RACE FOR CRITICAL MINERALS

Liberalism in international relations contrasts with realism by emphasizing cooperation among states, the role of international institutions, economic interdependence, and democratic values in fostering a more peaceful and stable world (Keohane, 1984). Liberal theorists argue that states can achieve mutual benefits through cooperation rather than competition (Doyle, 1986). Consequently, international institutions like the United Nations and the World Trade Organization play crucial roles in mitigating anarchy and promoting cooperation. These institutions facilitate dialogue, establish norms, and create dispute resolution mechanisms (Keohane, 1984). Additionally, through the lens of liberalism, it is evident that non-state actors, including multinational corporations, NGOs, and civil society, significantly influence international relations by advocating for ESG goals and shaping state behavior (Ruggie, 1998a). For instance, in the global race for critical minerals, the emphasis on ESG goals exemplifies the liberal belief in cooperative solutions to global challenges. Examples of this include initiatives such as the Global Reporting Initiative (GRI), the Extractive Industries Transparency Initiative (EITI), and the European Union's CSRD, which ensure that the extraction and processing of critical minerals adhere to high environmental and social standards (GRI, 2023; EITI, 2023; European Commission, 2023). Moreover, liberal theory highlights the effects of economic interdependence through trade, investment, and global supply chains, thereby reducing the likelihood of conflict (Keohane & Nye, 1977). This is because mutual dependencies incentivize states to maintain peaceful relations due to their interconnected economic interests (Oneal & Russett, 1999). In summary, liberalism provides a framework for understanding the collaborative efforts and regulatory standards driving the global race for critical minerals (Keohane & Nye, 1977).

3.3 POLITICAL ECONOMY THEORY

Political Economy Theory examines how political institutions, economic systems, and social structures intersect to shape policies, power dynamics, and resource distribution by emphasizing how political interests, power relations, and economic imperatives drive policy decisions and impact wealth and resource distribution (Gilpin, 1987).

In the global race for critical minerals, Political Economy Theory offers valuable insights into the interplay between political and economic factors driving competition for essential resources. This theory posits that governments and multinational corporations are key drivers of demand (Blyth, 2009). States leverage their political power to secure access to critical minerals through policies aimed at attracting foreign investments, negotiating trade agreements, and supporting domestic industries (Oatley, 2019). For example, China, the United States, and the European Union have implemented strategies to ensure a stable supply of critical minerals, including investments in mining operations and subsidies for green technologies (European Commission, 2020). By examining the dynamics between political power, economic interests, and institutional frameworks, Political Economy Theory explains how states and multinational corporations vie for control over vital resources.

3.4 RESOURCE ECONOMICS

Resource Economics examines how society allocates, exploits, and conserves natural resources like minerals, water, and forests in order to inform policies to manage resources responsibly (Field, 2008). Developed in the 20th century, notably by Harold Hotelling, this field studies how the price of non-renewable resources evolves over time (Hotelling, 1931).

In the global race for critical minerals, Resource Economics offers a comprehensive understanding of how political and economic factors drive competition. The theory underscores the significance of power dynamics, illustrating how states and multinational corporations deploy policies and investments to secure these essential resources (Tilton, 2003). Additionally, Resource Economics highlights the crucial role of market mechanisms in determining the prices of critical minerals (Slade, 1982). For instance, the establishment of property rights serves as a key attractor for investments and facilitates autonomous, regulated sustainable management. Furthermore, the theory emphasizes the impact of economic incentives on the demand for critical minerals. These incentives not only drive up demand but also affect prices and investment rates. Overall, Resource Economics provides a critical framework for understanding the interplay between political power, economic interests, and market dynamics in the global competition for critical minerals (Tilton, 2003).

4. RESEARCH OBJECTIVES

The general objective of this research is to determine whether future projected demand for critical minerals will meet future projected supply. Additionally, this research aims to provide a holistic understanding of the interconnected implications of the green energy transition. By offering a comprehensive and interconnected perspective, this thesis seeks to bridge the gap between isolated studies on energy security, ESG supply chains, and the broader impacts of transitioning to green energy. The intention is to inform strategies that ensure a resilient, sustainable, and ethical supply chain capable of supporting the global shift to clean energy technologies and the broader process of digitalization.

The research objectives encompass a comprehensive analysis of critical mineral supply chain resilience and its economic, geopolitical, and ESG impacts. This entails a thorough examination of the challenges associated with ensuring a stable supply, including regulatory compliance, investment requirements, and the necessity for innovative solutions in recycling and alternative sourcing of critical minerals. Furthermore, the research will address the ESG impacts of critical mineral mining by scrutinizing ethical concerns and policy dilemmas related to water scarcity, greenhouse gas emissions, biodiversity preservation, human rights violations, corruption, and the displacement of local communities and indigenous peoples. Another crucial objective is to investigate the geopolitical dynamics by assessing how various nations, particularly major players such as China, the United States, and European countries, are strategizing to secure access to these essential resources, alongside the potential conflicts and collaborations that may ensue. Additionally, the research will delve into the potential and implications of next-generation mining exploration, including deep-sea mining, space mining, and Arctic and Antarctic mining, by evaluating the technological, environmental, and geopolitical challenges and opportunities presented by these emerging frontiers. Ultimately, the final objective is to provide policy recommendations aimed at ensuring a sustainable and ethical approach to critical mineral supply chains and the broader green energy transition.

5. METHODOLOGY

The research approach for this thesis is primarily qualitative, with a significant reliance on secondary data sources. The data were collected from reputable institutions, academic journals, industry reports, and authoritative organizations. The research utilized a thematic analysis to identify, analyze, and report patterns within the data, providing a comprehensive understanding of the critical mineral supply chain and its implications for the energy transition and its economic and geopolitical implications.

Data were collected from a variety of credible sources, including reports and publications from the International Energy Agency, World Economic Forum, World Bank, U.S. Geological Survey, United Nations Conference on Trade and Development, McKinsey & Company, and others. These sources provided a comprehensive overview of trends, challenges, and future directions in various aspects of the mining and metals sector, such as resource governance, economic aspects of resource extraction, commodity prices, development banks, supply chain dynamics, geopolitical implications, space mining, deep-sea mining, polar resource extraction, ESG issues, and theoretical frameworks. A thorough literature review was conducted to systematically search, identify, and analyze these publications, serving as a foundation for understanding the current state of knowledge and identifying gaps this thesis aims to address.

The analysis involved a combination of thematic analysis and comparative analysis. Thematic analysis was used to identify recurring themes and patterns across the collected data. Comparative analysis enabled the juxtaposition of different viewpoints and findings from various sources, providing a comprehensive understanding of each topic. The collected data were systematically organized and analyzed to support the thesis's main arguments and conclusions. This included providing a broad overview of trends and challenges in the mining sector,analyzing economic aspects of resource extraction and market adjustments, examining trends and forecasts in commodity prices, exploring supply chain sustainability and risks, highlighting the role of development banks in financing critical projects, discussing resource governance and sustainable development, investigating geopolitical implications of critical mineral supply, reviewing technological and economic prospects of space mining, deep-sea mining, and polar mining, addressing ESG concerns in mining practices, and providing theoretical frameworks for understanding international relations.

Comparative analysis was utilized to contrast different approaches, policies, and outcomes related to critical mineral supply across various regions and contexts. This methodology allowed for the identification of best practices and common challenges, enhancing the understanding of how different governance structures and economic policies impact critical mineral supply chains. Quantitative data analysis was conducted using statistical methods to evaluate trends in commodity prices, supply chain risks, and economic impacts. Data from sources such as the International Energy Agency, USGS, and various market reports were analyzed to derive meaningful patterns and correlations. This approach provided empirical evidence to support the qualitative findings of the research.

Policy analysis was conducted to evaluate existing regulations, frameworks, and initiatives related to critical mineral supply chains. This methodology involved reviewing policy documents, government reports, and international agreements to assess their effectiveness and implications. Key policies analyzed included the European Union's Raw Materials Initiative, the U.S. Inflation Reduction Act, and international space mining regulations. To supplement the secondary data, expert interviews were conducted with professionals and academics in the fields of mining, economics, and environmental science. These interviews provided first-hand insights and contemporary perspectives on the challenges and opportunities within critical mineral supply chains. The qualitative data obtained from these interviews were integrated into the thematic analysis to enhance the depth and validity of the research findings.

Scenario analysis was used to explore potential future developments in critical mineral supply and their implications. This methodology involved analyzing different IEA scenarios based on varying assumptions about technological advancements, policy changes, and market dynamics. Scenario analysis helped in understanding the potential risks and opportunities under different future conditions, providing a strategic perspective on long-term planning for critical mineral supply.

While this thesis employs a comprehensive methodology, several limitations must be acknowledged. First, the reliance on secondary data sources, although extensive and diverse, inherently restricts the analysis to the available data's scope and depth. This reliance may result in potential biases or gaps in information, particularly in emerging or rapidly evolving areas such as space mining and deep-sea mining. Additionally, the qualitative nature of thematic and comparative analyses, while providing rich insights, may lack the precision and replicability associated with purely quantitative studies. Furthermore, scenario analysis, although useful for exploring future possibilities, relies on assumptions that may not account for unforeseen developments or changes in the global landscape. Finally, the dynamic nature of global mineral markets, geopolitical tensions, and technological advancements means that the findings of this research may need to be updated frequently to remain relevant.

Despite these limitations, the thesis provides a robust framework for understanding the critical mineral supply chain and offers valuable insights into its complexities and implications. The integration of these diverse research methodologies ensured a holistic and multi-faceted approach to understanding the complexities of critical mineral supply chains. Each methodology contributed uniquely to the overall analysis, providing a comprehensive and robust foundation for the thesis. This integrated approach, graphically illustrated in the literature table below, enabled a thorough exploration of the research questions, drawing on both qualitative and quantitative data to offer well-rounded insights and conclusions.

Topic	Key Sources	Utilization
General	WEF (2023a, 2023b, 2024a), World Bank (2020a), USGS (2020, 2022), United Nations Conference on Trade and Development (2023), Energy Global (2024), Kretchmer & Tahsin (2021), IEA (2021, 2022, 2023a, 2023b, 2024), Lovell (2018), McKinsey & Company (2022)	Provided a broad overview of trends and challenges in the mining sector, including the mineral intensity of clean energy transitions and critical mineral reviews.
Governance	Ali et al. (2017), WEF (2023a)	Discussed resource governance and sustainable development.
Economics	Brown (2019), Hotelling (1931), Kretchmer & Tahsin (2021), FactSet (2023), Field (2008)	Analyzed economic aspects of resource extraction, market adjustments, and policy impacts.
Commodity Prices	Slade (1982), Tomek (2000), Labandeira, Labeaga, & López-Otero (2015), Piedmont Lithium (2023), ICSG (2023), Roskill (2023), Lithium Americas (2023), LME (2023), Benchmark Mineral Intelligence (2023)	Examined trends and forecasts in commodity prices, including lithium, cobalt, copper, and nickel, and their implications for market dynamics.
Development Banks	World Bank (2023b), EIB (2023a, 2023b, 2023c), AIIB (2023)	Highlighted the role of development banks in financing critical mineral projects.
Supply Chain	IEA (2023), Majkut et al. (2023), Nassar et al. (2020)	Explored supply chain sustainability, risks, and strategies for building diverse supply chains.
Geopolitics	Buzan (1991), Paltsev (2016), Scholten & Bosman (2016), International Renewable Energy Agency (2023), O'Sullivan, Overland, & Sandalow (2017), CSIS (2023), Goés & Bekkers (2023), Tilton (2003), Bradsher (2021)	Investigated geopolitical implications of renewable energy transitions, critical materials, and the impact of geopolitical conflicts on trade and growth.
Space Mining	Martínez Álvarez (2022), U.S. Government (2015), NASA (2020, 2021), ESA (2021), CNSA (2021), JAXA (2021), SpaceX (2020), Deep Space Industries (2019), Planetary Resources (2018), New Space Economy (2023), Yarlagadda (2022), DiploFoundation (2023), Brunner (2021), Osburg & Lee (2022)	Reviewed technological and economic prospects of space mining, including lunar and asteroid missions, and the implications for future resource extraction.
Deep Sea Mining	ISA (2021, 2023), Thompson et al. (2018), Reitmeier (2023), The Metals Company (2024)	Analyzed the potential and challenges of deep-sea mining, including governance approaches.
Arctic & Antarctic	European Parliament (2010), Jones & White (2021)	Assessed geopolitical and environmental aspects of resource extraction in polar regions.
ESG Concerns	U.S. Energy Information Administration (2022), World Bank (2020b), Brown (2021), EITI (2023), Hamilton (2000), Poynting & Silva (2024)	Addressed environmental, social, and governance (ESG) concerns in mining practices, including water use, indigenous peoples' rights, and transparency initiatives.
Theories	Waltz (2000), Ruggie (1998a, 1998b), Oatley (2019), Oneal & Russett (1999), Doyle (1986), Keohane & Nye (1977), Keohane (1984), Mearsheimer (2001), Gilpin (1987), Blyth (2009)	Provided theoretical frameworks for understanding international relations and political economy.

6. ANALYSIS

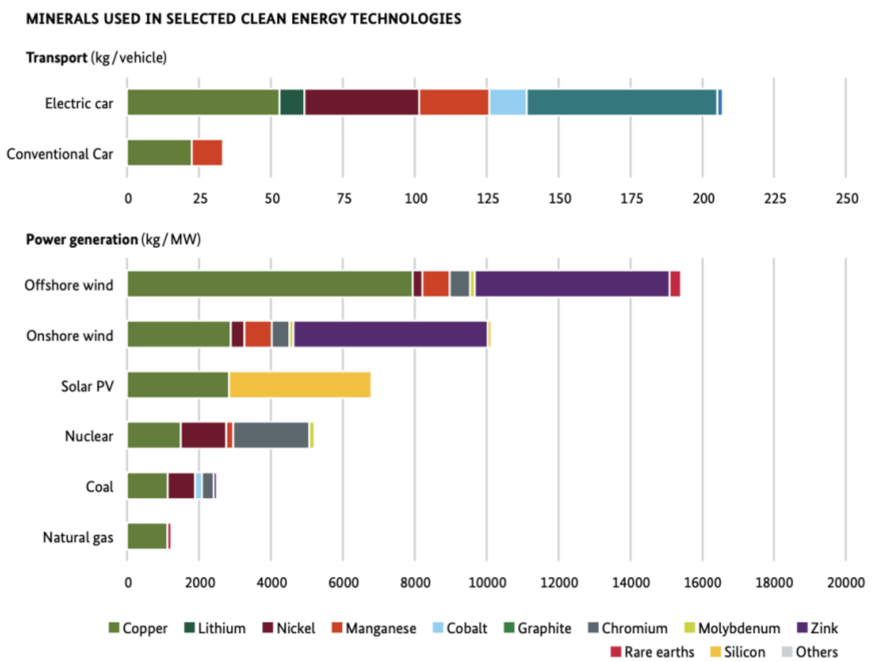
6.1 ECONOMIC IMPLICATIONS OF THE GLOBAL RACE FOR CRITICAL MINERALS

This section examines the current market for clean energy technologies and critical minerals, focusing on present supply and demand and comparing these to projected trends. Utilizing the International Energy Agency's (IEA) STEPS, APS, and NZE scenarios, the analysis aims to understand potential future challenges, market fluctuations, price dynamics and investment trends. This approach seeks to identify deeper implications of the green energy transition and suggest multifaceted policies to address these challenges. The examination includes processes of exploring, developing, extracting, and refining minerals, considering the investments, projects involved, and their geographical distribution.

6.1.1. CURRENT DEMAND: RENEWABLES, BATTERIES AND RAW MATERIALS

The escalating global demand for critical minerals is primarily driven by the green transition, as renewable energy technologies and advanced innovations necessitate these indispensable resources. The IEA has reported an unprecedented deployment of clean energy technologies, encompassing renewable energies, energy storage solutions, and the adoption of electric vehicles (IEA, 2024). The IEA's graph delineates the minerals utilized in clean energy technologies, revealing significant disparities among various types of renewable energy solutions. Electric vehicles represent the green technology with the highest consumption of critical minerals (IEA, 2024). Furthermore, wind power, especially offshore wind, appears to be more resource-intensive compared to other technologies, such as solar power. Offshore wind, in particular, necessitates a considerable amount of critical minerals, potentially rendering it more environmentally detrimental than onshore wind

Figure 2.2: Material intensity of transport and power generation technologies



Notes: kg = kilogramme, MW = megawatt. Steel and aluminium not included.
Source: IEA (2021).

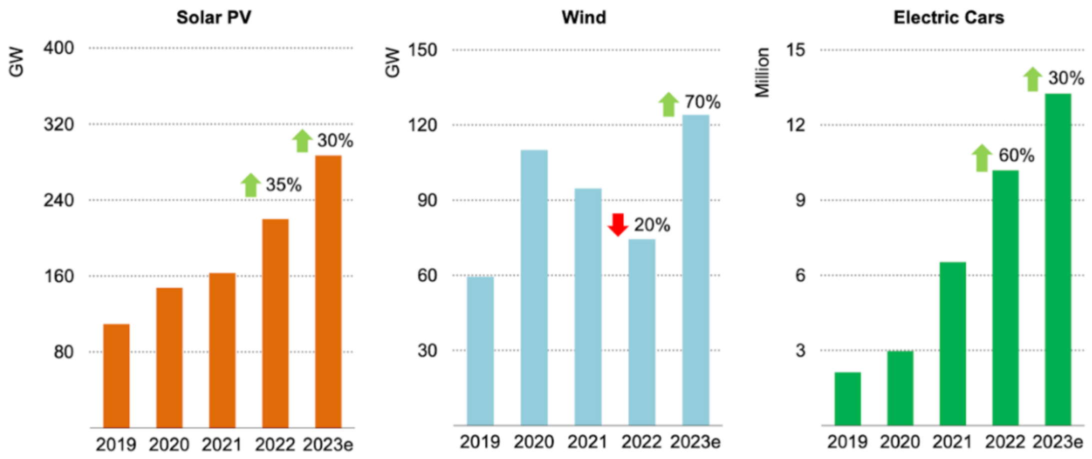
(IEA, 2024).

It is crucial to comprehend that the quantity and type of critical minerals used in each renewable energy technology directly affect its environmental footprint, given that the extraction and refining processes for these minerals are energy-intensive and produce substantial levels of CO_2, alongside other forms of environmental degradation (Ali et al., 2017). It is essential to determine which technologies are more environmentally detrimental and which should be prioritized.

Despite the disparities in the environmental impact of various renewable energy technologies, there is unprecedented growth across all these sectors, as illustrated in the IEA's graphs. There is a dramatic surge in solar photovoltaic (PV) installations, with annual capacity additions persistently surpassing previous records (IEA, 2023a). The first graph indicates that solar PV capacity additions increased by 35% in 2022 and were initially projected to grow by an additional 30% (IEA, 2024). Moreover, subsequent data reveal that the predicted growth was significantly underestimated, as solar power ultimately achieved an impressive 85% growth in 2023, reflecting a consistent upward trajectory (IEA, 2024). This exponential increase in PV installations underscores the escalating demand for critical minerals such as silicon, silver, and other essential materials for solar panel production (IEA, 2023a).

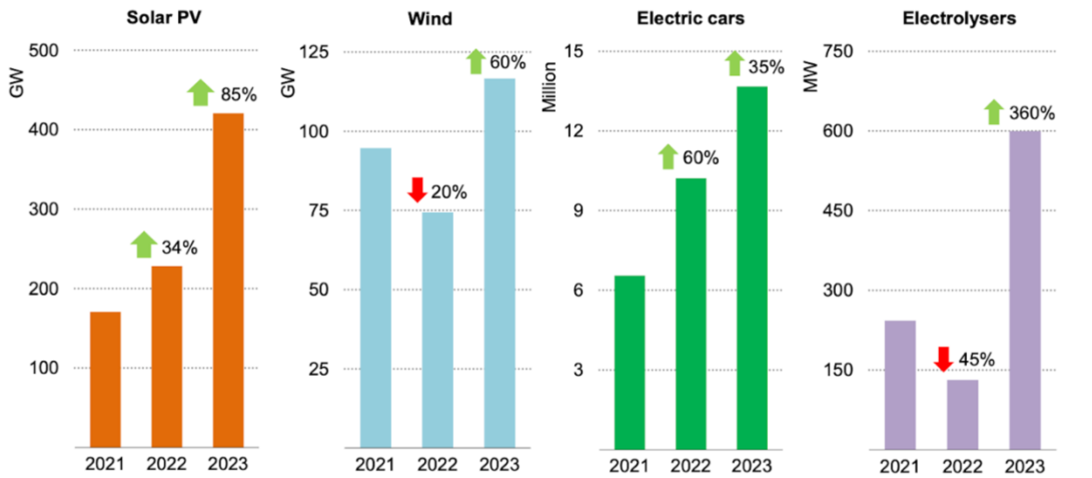
Clean energy technology deployment continued its upward march in 2022, with momentum expected to continue through 2023 and beyond

Annual capacity additions for solar PV and wind and electric car sales



Global clean energy deployment climbed to new heights in 2023

Annual capacity additions for selected clean energy technologies

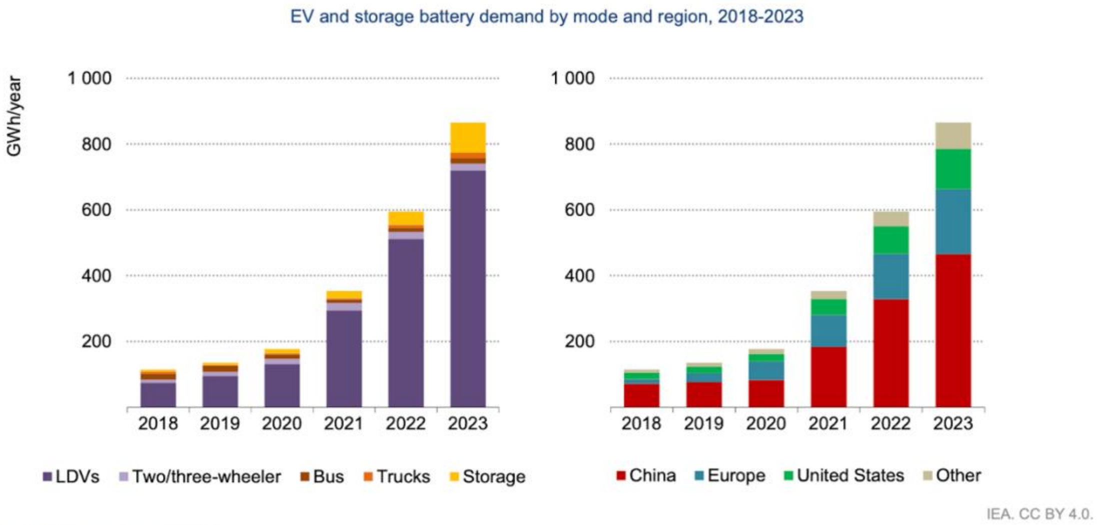


Sources: IEA (2024), Clean Energy Market Monitor – March 2024, and IEA (2024), Global EV Outlook 2024.

Similarly, following a modest decline in 2022, wind power capacity experienced a robust resurgence, marked by a 60% increase in 2023 (IEA, 2024). This recovery and expansion in wind power installations underscore the sustained and prospective demand for essential materials such as neodymium and dysprosium, which are integral to wind turbine functionality. Moreover, the surge in EV sales further elucidates the escalating demand for critical minerals. In 2022, EV sales surged by 60%, surpassing 10 million units, and continued their upward trajectory with an additional 35% increase in 2023, culminating in approximately 13 million units (IEA, 2024). The widespread adoption of EVs drives the demand for lithium, nickel, and cobalt, which are vital constituents of EV batteries (Larcher & Tarascon, 2015). Additionally, the IEA's second graph illustrates the remarkable growth in electrolyzer deployment, essential for hydrogen production. The annual capacity additions for electrolyzers surged by 360% in 2023, highlighting the expanding hydrogen economy (IEA, 2024). This expansion further intensifies the demand for critical minerals utilized in these technologies (IEA, 2024).

To comprehensively understand the total demand outlook for green energy technologies, as well as their environmental and economic impacts, it is essential to also consider battery demand. It is important to remember that renewable energy can only be effectively utilized continuously through the use of batteries. Consequently, an increase in demand for renewable energy will inherently lead to a higher demand for batteries, which are similarly resource-intensive. Most current batteries are predominantly dependent on lithium; however, future advancements in research suggest the emergence of various battery types utilizing other minerals. These include sodium-ion batteries, solid-state batteries which use ceramics or sulfides, magnesium-ion batteries, aluminum-ion batteries, and zinc-air batteries (Jarbratt et al., 2023). While these innovations aim to diversify the material base for battery technology, the current demand for batteries is primarily reflected in the minerals currently utilized. The IEA graph indicates that global battery demand increased by two-thirds in 2022, with a notable rise in applications for light-duty vehicles, buses, other transport modes, and energy storage systems (IEA, 2023a). The substantial increase in global battery demand has been primarily driven by the transport sector, alongside significant growth in power sector storage. This trend underscores the escalating need for lithium, cobalt, and nickel, which are crucial components in battery production, thereby suggesting a potential rise in their prices (IEA, 2024).

Battery demand is dominated by electric cars, although storage is the fastest growing source of demand

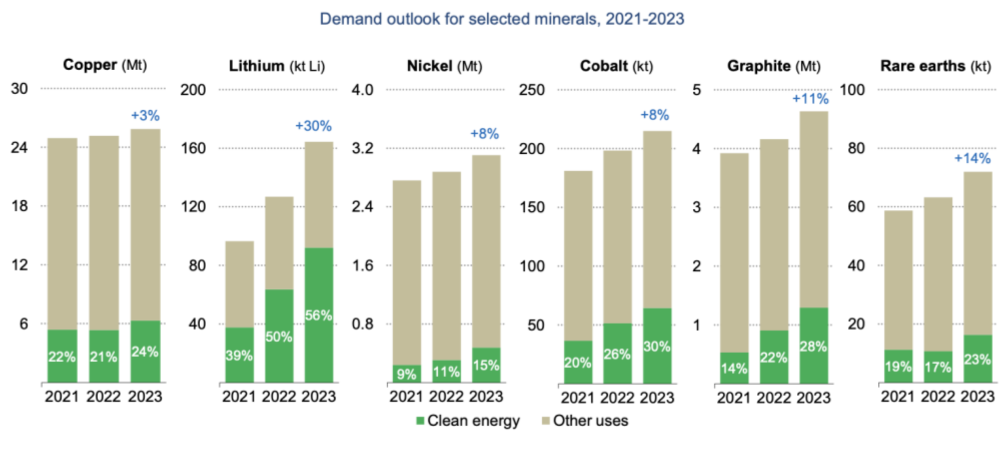


Note: LDVs = light-duty vehicles.
Source: IEA analysis based on EV Volumes.

Moreover, the regional breakdown reveals that China, Europe, and the United States are leading the demand for batteries in the clean energy sector. China's dominant share reflects its substantial investments in EVs and energy storage solutions (IEA, 2024). Europe's demand is also growing, driven by stringent environmental regulations and significant

investments in green technologies (European Commission, 2023). Finally, the United States is seeing increasing adoption of EVs and energy storage systems, further emphasizing the global reliance on critical minerals for battery production (IEA, 2024).
Furthermore, the graph below illustrates the interconnectedness between the global demand for renewable energies and battery systems and the market size for critical minerals and rare earth elements. Over the five-year period from 2017 to 2022, the market size for these minerals has doubled, reflecting the significant surge in demand for critical minerals and the consequent rise in prices (IEA, 2024). Copper's market size increased by 1.5 times, underscoring its continued importance in various industrial applications, particularly in renewable energy infrastructure and electric vehicles (IEA, 2024). Lithium, essential for battery production, experienced a remarkable increase of 6.7 times, indicative of the rapid expansion of the electric vehicle market and energy storage systems (IEA, 2024). Nickel, another crucial component in batteries, saw its market size grow by 3.1 times, highlighting its significance in the green transition (IEA, 2024). Cobalt, vital for high-performance batteries, doubled its market size, growing by 1.9 times (IEA, 2024). Finally, rare earth elements, critical for a wide range of advanced technologies, expanded their market size by 2.5 times (IEA, 2024).
Moreover, the graph below elucidates the actual increase in demand between 2021 and 2023 with greater precision, emphasizing the demand outlook rather than market size. Notably, the one-year period from 2022 to 2023 saw a substantial 30% increase in lithium demand. This surge was primarily driven by clean energy applications, particularly the production of batteries for electric vehicles, with the proportion of lithium used in these applications rising from 39% in 2021 to 56% in 2023 (IEA, 2024). Similarly, the demand for rare earth elements increased by 14% over the three-year period. This reflects the growth in the share of REEs used in clean energy applications, which rose from 19% in 2021 to 23% in 2023 (IEA, 2024). Additionally, graphite demand increased by 11%, with its usage in clean energy applications rising from 14% in 2021 to 28% in 2023. Graphite is critical for battery anodes, and its demand growth mirrors broader trends in battery technology and electric vehicles (IEA, 2024). Lastly, the demand for nickel and cobalt, both key components in battery technologies, each increased by 9%, with the share for clean energy applications growing from 9% in 2021 to 15% in 2023 for nickel, and from 20% in 2021 to 30% in 2023 for cobalt (IEA, 2024). These data underscore the significant and expanding role of clean energy applications in driving the demand for critical minerals, highlighting the necessity for substantial investment and strategic planning to ensure a stable and sustainable supply (IEA, 2024).

Demand for key energy transition minerals continued to grow strongly in 2023, propelled by the expansion of clean energy technologies

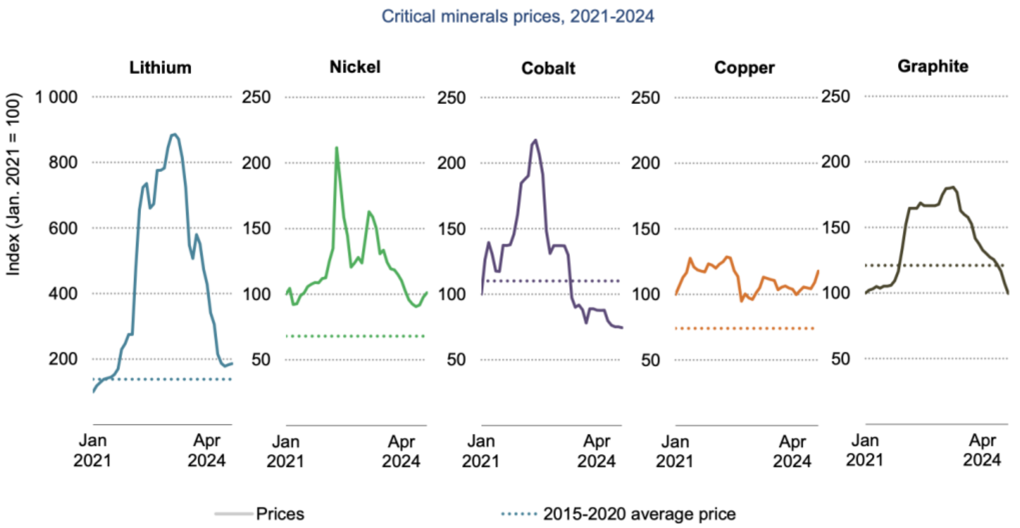


Notes: Rare earths include the four magnet elements: neodymium, praseodymium, dysprosium and terbium. Demand for clean energy applications includes consumption for low-emissions power generation, EV and battery storage, grid networks and hydrogen technologies.

Critical mineral and REE demand augmentation is a fundamentally positive indicator of a world transitioning into a more sustainable energy supply. However, an unexpected demand surge could have challenging impacts, a phenomenon which can be analyzed through supply and demand theory and investment cycles in resource economics (Brown, 2019). Initially, a surge in demand shifts the demand curve rightward, leading to higher equilibrium prices due to the relatively inelastic supply in the short term (Labandeira et al., 2015). This price increase serves as a market signal, incentivizing investment in mining infrastructure and technology, which aligns with the Cobweb Model suggesting that investment decisions are based on current prices, leading to a lagged supply response (Brown, 2019). As new extraction capabilities are developed, the supply curve eventually shifts rightward, reducing prices over time (Brown, 2019). However, this adjustment process is not instantaneous; thus, the initial price spike can adversely affect the affordability of technologies reliant on these minerals. According to the law of diminishing returns, continued investment yields smaller increases in output, making rapid price reductions challenging (Brown, 2019). Consequently, this period of high prices can render energy and digital technologies, fueled by these expensive minerals, less accessible to consumers, potentially categorizing them as luxury items. Additionally, price elasticity of demand plays a crucial role; if demand is elastic, significant price increases could substantially reduce quantity demanded, exacerbating affordability issues (Brown, 2019). Conversely, if demand is inelastic, consumers might continue purchasing these technologies despite higher prices, albeit at a greater economic burden. Factors such as government environmental regulations, fiscal stimulus, and international sanctions also significantly influence the elasticity or inelasticity of green energy solutions. Stricter environmental regulations can limit supply, making prices more inelastic, while fiscal stimulus can boost investment and increase supply elasticity. Conversely, sanctions can disrupt supply chains, increasing inelasticity and driving prices higher. Therefore, while the long-term equilibrium is expected to stabilize with increased supply and lower prices, the short-term effects of a sudden demand surge, compounded by regulatory and geopolitical factors, can lead to economic challenges, emphasizing the need for strategic investment and policy measures to mitigate consumer impact (Kretchmer & Tahsin, 2021).
Moreover, another economic problem regarding critical minerals is their price volatility. Specifically, the graph below depicts the price volatility of critical minerals used in battery production, including lithium, nickel, cobalt, copper, and graphite, from January 2021 to April 2024. It highlights that battery critical minerals have experienced the most significant price fluctuations, reflecting their high demand and market sensitivity (IEA, 2024). For instance, lithium prices saw a dramatic increase, peaking at over 800 in the index by late 2022, compared to its base value in January 2021. This surge was subsequently followed by a steep decline, bringing prices closer to the average historical range by April 2024 (Benchmark Mineral Intelligence, 2023). Similarly, nickel exhibited substantial price volatility, with a notable peak around mid-2022, reaching an index value of approximately 200. This was then followed by sharp declines, indicating significant market instability (LME, 2023). Furthermore, cobalt prices displayed similar patterns of volatility, peaking significantly in early 2022 before declining and stabilizing closer to historical averages by 2024. Cobalt's price trends are reflective of the complex supply chains and geopolitical risks associated with its extraction, particularly from regions with unstable political climates (Roskill, 2023). In contrast, copper, while essential for electrical infrastructure, showed comparatively less volatility, reflecting more established and diversified supply chains (ICSG, 2023). Despite this relative stability, copper prices did increase slightly over the period, indicating rising demand driven by the global push for electrification and renewable energy deployment (ICSG, 2023). Additionally, graphite prices experienced notable volatility as well, with a significant peak in late 2022, followed by a gradual decline. This reflects graphite's role in battery anodes and the growing demand from the

EV market (USGS, 2022). Therefore, the observed fluctuations highlight the pressures on supply chains to meet the rising demand for high-quality battery materials (IEA, 2024).

Battery critical minerals have seen the greatest volatility



Notes: Graphite historical average from 2016-2020. Assessment based on the London Metal Exchange (LME) Lithium Carbonate Global Average, LME Nickel Cash, LME Cobalt Cash and LME Copper Grade A Cash prices and China flake graphite – 194 free on board. Nominal prices.
Source: IEA analysis based on S&P Global and Bloomberg.

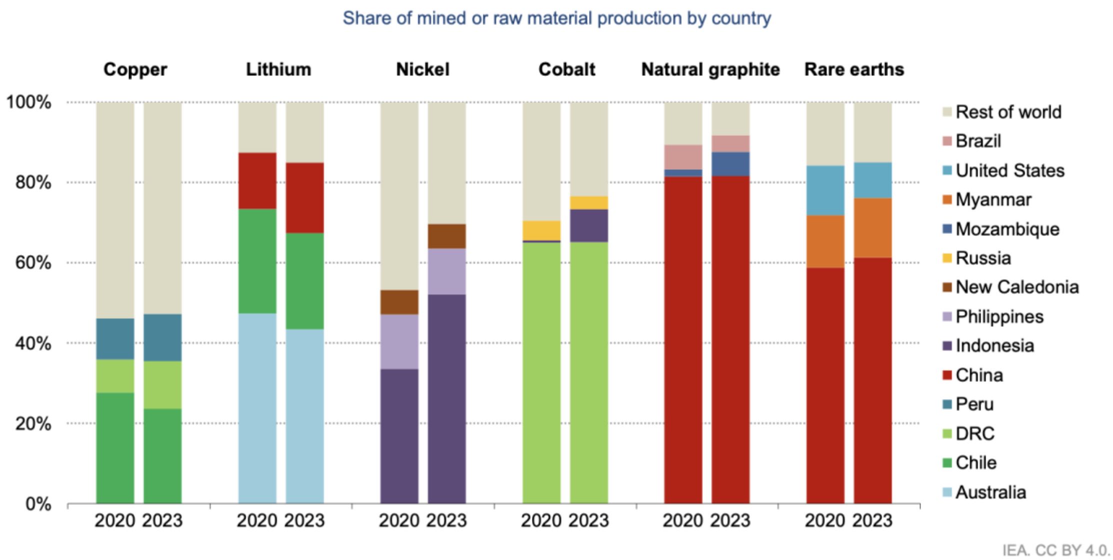
The phenomenon of supply volatility in the market for critical minerals, despite their surging demand, can be attributed to several interrelated factors. Firstly, the supply of critical minerals is relatively inelastic in the short term due to the significant time and investment required to develop new mining operations and increase production capacity (Kretchmer & Tahsin, 2021). Consequently, even small changes in demand can lead to substantial price fluctuations (Labandeira et al., 2015). Additionally, geopolitical risks, especially in regions with unstable political climates, can disrupt supply chains and thereby lead to sudden changes in availability and price spikes (Tomek, 2000). Furthermore, market speculation exacerbates this volatility, as traders and investors buy and sell these commodities based on expected future price movements rather than just current supply and demand (Goés & Bekkers, 2023). Additionally, technological and production changes further contribute to this issue, as sudden shifts in supply capabilities can either unexpectedly increase supply or constrain it, leading to price changes (Brown, 2019). Moreover, environmental, and regulatory factors play a significant role; new regulations can limit output and drive prices up, while deregulation can increase supply and reduce prices (U.S. Energy Information Administration, 2022). In addition, supply chain disruptions, whether caused by natural disasters, logistical issues, or political actions, also precipitate sudden shortages and price spikes (Brown, 2019). Lastly, low inventory levels exacerbate price volatility because any increase in demand or disruption in supply can have a more pronounced impact on prices (Kretchmer & Tahsin, 2021). Collectively, these factors create a market environment where prices of critical minerals are highly sensitive to changes in supply and demand, resulting in substantial volatility despite overall growing demand (Labandeira et al., 2015).

The significant price volatility in the market for critical minerals presents both opportunities and challenges for the green transition. On one hand, this volatility can deter long-term investment strategies, as investors may be reluctant to commit capital to markets characterized by such instability, fearing unpredictable returns (Kretchmer & Tahsin, 2021). This hesitancy can stifle the necessary funding for developing robust and diversified supply chains, which are crucial for maintaining stable prices and ensuring the availability of these critical resources (Labandeira et al., 2015). Moreover, the economic burden of adapting to volatile markets can lead to increased operational costs for companies in the renewable energy sector, potentially translating to higher prices for end consumers and impeding the adoption of clean technologies (Brown, 2019). Additionally, financial instability may also lead to a more fragmented market, where only the most financially resilient companies can survive, reducing competition and innovation (Brown, 2019). Furthermore, reliance on countries with unstable political climates, such as the DRC for cobalt, underscores the necessity for supply chain diversification (Tomek, 2000). Without stable and reliable supply chains, prices of critical minerals are likely to continue fluctuating, leading to increased costs for clean energy technologies and hindering their widespread adoption (U.S. Energy Information Administration, 2022). Ultimately, if investment in the extraction and processing of these minerals does not keep pace with demand, the long-term effect will likely be even higher prices due to constrained global supply, exacerbating affordability issues for clean energy technologies (Kretchmer & Tahsin, 2021). Addressing these economic and financial challenges requires coordinated policy efforts to stabilize markets, incentivize long-term investments, and build resilient supply chains (Goés & Bekkers, 2023).

6.1.2 CURRENT SUPPLY: GEOGRAPHICAL CONCENTRATION & SUPPLY CHAIN CHALLENGES

The current critical minerals and REEs supply necessitates examination from a dual perspective. On one hand, there is the supply of raw minerals extraction, which is highly concentrated in a limited number of countries with significant geological deposits (Nassar et al., 2020). On the other hand, the supply of refined minerals is equally crucial. Refinement involves sophisticated industrial processes to remove impurities from the extracted minerals, thereby enhancing their properties and rendering them suitable for application in various products (Nassar et al., 2020). Both aspects are integral to understanding supply chain dynamics and the challenges associated with ensuring a steady and secure provision of critical minerals for global industries (IEA, 2024).

Production growth has been accompanied by rising levels of geographical concentration, with the trends particularly pronounced for nickel and cobalt



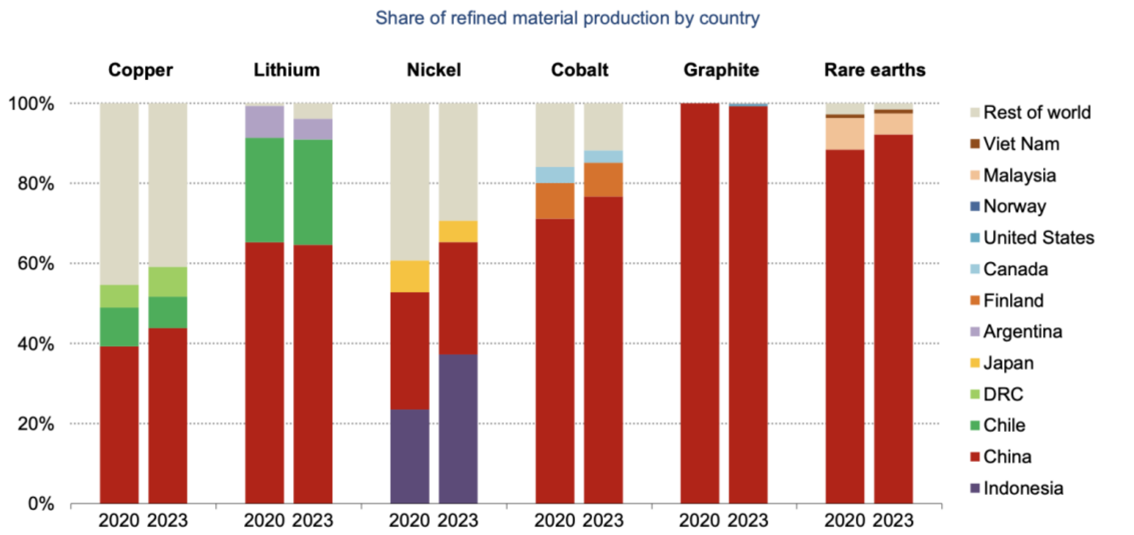
Notes: DRC = Democratic Republic of the Congo. Graphite extraction is for natural flake graphite. Rare earths are magnet rare earths only.

The graph presents a comparative analysis of the share of mined material production for critical minerals by country, focusing on data from 2020 and 2023. This analysis encompasses key minerals, including copper, lithium, nickel, cobalt, natural graphite, and rare earth elements, and highlights the increasing geographical concentration of mining operations, particularly for nickel and cobalt (IEA, 2024).

The graph underscores China's significant role as a leading extraction hub, particularly in the production of natural graphite, and REEs (IEA, 2024). This high level of concentration presents substantial risks to global supply chains, especially given the strategic importance of REEs in various high-tech and clean energy applications (USGS, 2022). Moreover, geographical concentration is also a critical issue for cobalt production which is predominantly concentrated in The DRC, with very modest contributions from Russia and an increasing trend in production from Indonesia (Roskill, 2023). This heavy reliance on a single nation raises concerns about supply security, especially given the potential for political instability and other disruptions (Roskill, 2023). Furthermore, nickel production is also notably concentrated, with the majority occurring in Indonesia and the Philippines (IEA, 2024). Fortunately, in the context of lithium production, China's contributions are more balanced relative to other major producers, with Australia and Chile also holding substantial production volumes (IEA, 2024). Chile, in particular, emerges as the global leader in copper supply, followed by Peru and the DRC (ICSG, 2023). Notwithstanding lithium, a more positive prospect. The general geographical concentration in production underscores the vulnerability of supply chains to geopolitical and economic instabilities in these regions (IEA, 2024).

Furthermore, when examining refined material production, geographical concentration becomes even more pronounced. Specifically, China has emerged as the leader in refining across all categories, including (IEA, 2024). Graphite refining is almost entirely dominated by China, with its share approaching 100% in 2023 (USGS, 2022). Similarly, rare earth elements exhibit a significant concentration, with China overwhelmingly leading the refining process. Likewise, lithium refining is predominantly controlled by China, despite notable roles played by Chile and Argentina in the refining process (Roskill, 2023). As for nickel refining, China’s influence is again substantial, with significant contributions from Indonesia and Japan (IEA, 2024). Additionally, cobalt refining follows a similar trend, with China as the primary player, with contributions from Finland and, to a lesser extent, the United States (Roskill, 2023). Finally, in the case of copper, while China holds the dominant share, contributions from Peru and Chile help to slightly diversify the refining activities. This slight diversification helps mitigate some risks, but it still leaves a significant concentration in China's favor (ICSG, 2023). Overall, the data underscores the increasing geographical concentration of refined critical minerals, with China playing a dominant role across all categories (IEA, 2024).

The level of geographical concentration for refined products has increased in recent years



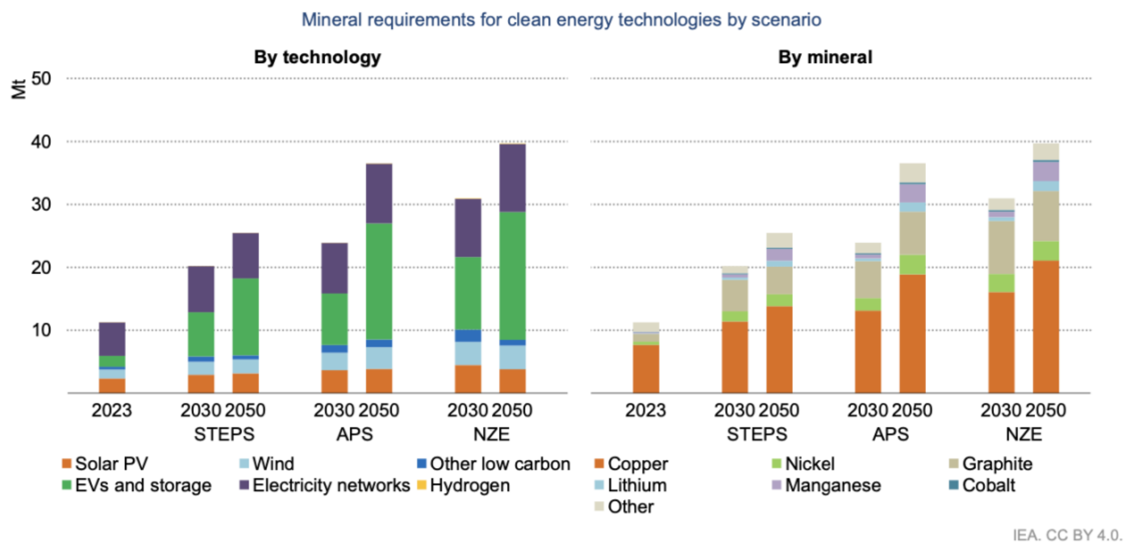
Note: Graphite is based on spherical graphite for battery grade. Rare earths are magnet rare earths only.

The geographical concentration of critical minerals in both extraction and refining processes has profound implications for global supply chains. Specifically, China has emerged as a dominant player in refining graphite, rare earth elements, lithium, nickel, cobalt, and copper. This concentration presents substantial risks because any disruption—due to political instability, economic fluctuations, or strategic policy changes—could severely impact the availability and price stability of these essential minerals, which are crucial for high-tech and clean energy applications (Majkut et al., 2023).

Consequently, to mitigate these risks, it is imperative to achieve a globally diversified supply chain because it reduces dependence on any single extraction source or refining capability, thereby minimizing the risk of disruption. Ideally, no single country should control more than 30% of the global supply of any critical mineral. This diversification ensures that geopolitical issues, natural disasters, or economic policies in one region do not disproportionately affect the global supply (Goés & Bekkers, 2023). Achieving this level of diversification requires the involvement of at least three to five major producers for each mineral, geographically dispersed to minimize regional risks (Majkut et al., 2023). In this context, international collaboration becomes crucial for ensuring a secure supply chain. Cooperative agreements and partnerships can help manage risks related to trade policies, tariffs, and geopolitical tensions. For instance, distributing lithium production and refining across Australia, Chile, China, Argentina, and the United States could enhance resilience (U.S. Energy Information Administration, 2022). This approach supports the sustainable growth of high-tech and clean energy sectors, ensuring that critical minerals remain accessible and affordable despite regional disruptions and political instability(WEF, 2023a).

6.1.3 PROJECTED DEMAND & SUPPLY

Mineral demand for clean energy technologies doubles between today and 2030 in the STEPS and APS and grows by almost three times in the NZE Scenario



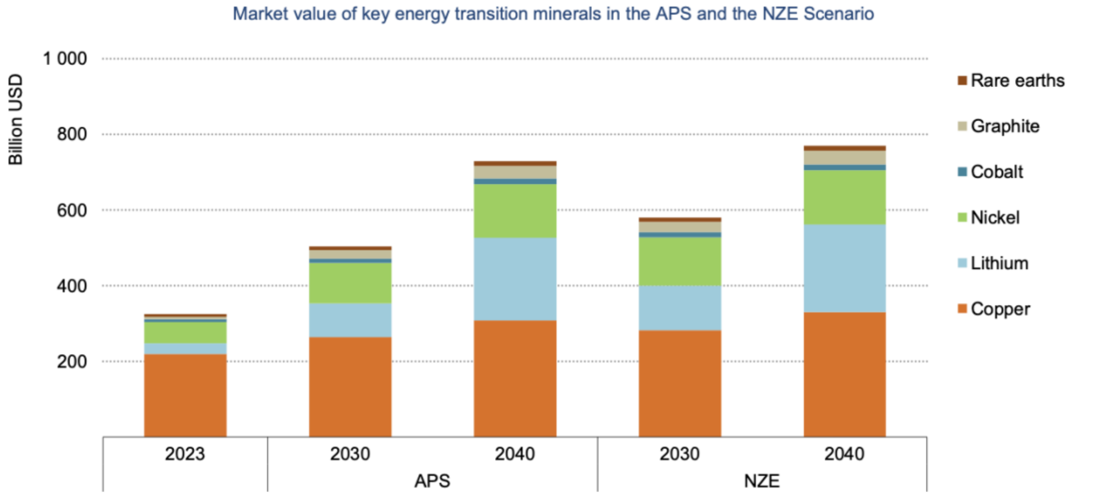
Note: Includes most of the minerals used in various clean energy technologies but does not include steel and aluminium.

The graph under review provides a detailed projection of mineral demand associated with clean energy technologies, delineating the evolution of this demand from 2023 to 2050 across three different scenarios: the STEPS Scenario, the APS Scenario, and the NZE Scenario. It disaggregates the mineral requirements by both technology type and specific minerals, offering a comprehensive view of how the green energy transition will influence mineral demand (IEA, 2024).

The STEPS scenario, which aligns with current policies and less ambitious climate goals, projects a steady growth in mineral demand driven by the deployment of solar photovoltaics, wind power, electric vehicles, and energy storage systems (IEA, 2024).

Conversely, the APS scenario anticipates an aggressive adoption of clean energy technologies, predicting a substantial increase in the demand for essential minerals. Notably, the demand for minerals in clean energy technologies is expected to double by 2030 in both the STEPS and APS scenarios and nearly triple by 2050 under the NZE scenario (IEA, 2024). Moreover, as depicted in the graph, the market value of key transition minerals under the APS is estimated at approximately 250 billion USD in 2023, escalating to 600 billion USD by 2040. Furthermore, the NZE scenario forecasts an even more pronounced increase, projecting the market value to reach around 700 billion USD by 2040 (IEA, 2024). This significant market growth in the NZE scenario particularly underscores the increased reliance on minerals such as lithium, which is anticipated to experience the most substantial proportional market growth due to its critical role in energy storage systems (IEA, 2024).

The combined market value of key energy transition minerals more than doubles by 2040 in climate-driven scenarios, reaching USD 770 billion in the NZE Scenario



Note: 2023 annual average price levels are assumed to estimate the market size for the projection period.

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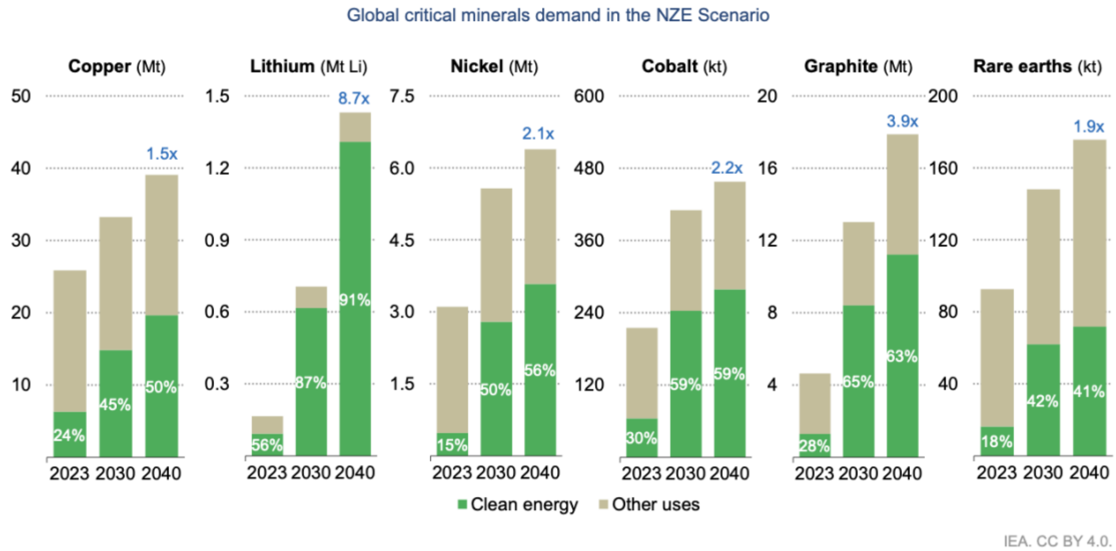
Furthermore, the graph below provides detailed data on the expected demand for copper, lithium, nickel, cobalt, graphite, and REEs under the NZE scenario. The demand for these minerals is projected to grow substantially by 2040, with lithium seeing the most dramatic increase, multiplying by 8.7 times (IEA, 2024). Graphite demand is projected to quadruple, driven by its use in battery anodes. Nickel, cobalt, and REEs, all crucial for battery production, are expected to more than double in demand by 2040, while copper demand is projected to increase by 1.5 times (IEA,

2024).

Limiting global warming to 1.5 °C, as in the NZE Scenario, means very rapid growth in demand for key minerals

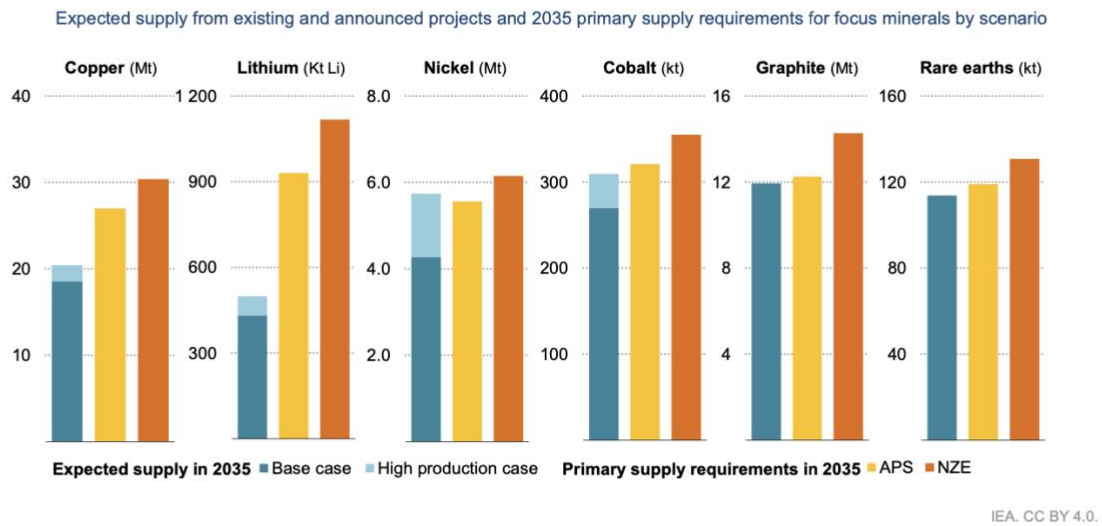


Notes: The figures for copper are based on refined copper. Those for rare earth elements are for magnet rare earth elements only. Growth rates (in blue) are

This analysis highlights several critical points. Firstly, the rapid growth in mineral demand across all scenarios underscores the urgency of securing a stable and sustainable supply of these resources. As the world transitions to a low-carbon economy, the availability of these minerals will be crucial in determining the affordability and pace of the energy transition (IEA, 2024). Secondly, the data suggests that current and announced policies may be insufficient to meet the projected mineral demand, emphasizing the need for more ambitious and effective strategies (IEA, 2024).

However, it is crucial to contrast this data with projected supply. There is difficulty in estimating supply, given that it has many multifaceted factors involved in the stages of exploration and development, mining, ore processing, and smelting and refining, which are all time-intensive and capital-intensive (IEA, 2024). Notwithstanding, the IEA graph below shows expected supply taking into account announced projects, and contrasts it with supply requirements under APS and NZE scenarios (IEA, 2024).

Expected supply from announced projects is within range of projected 2035 requirements to reach national and global climate goals, with the major exceptions of copper and lithium

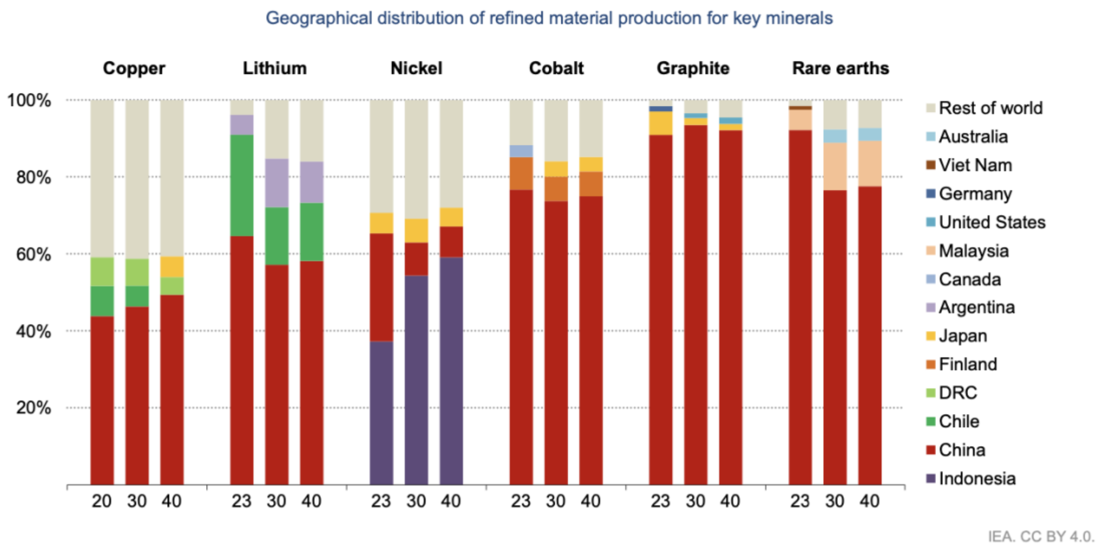


Notes: Expected supply is based on mined or raw material output, except for graphite where the figure includes expected spherical graphite and synthetic graphite supplies. Primary supply requirements are calculated as "total demand net of secondary supply", also accounting for losses during refining operations. The figures for rare earth elements are for magnet rare earth elements only.

For copper, the expected supply in both the base and high production scenarios falls short of the primary supply requirements in the APS and NZE scenarios, highlighting a significant challenge in meeting future demand crucial for electrical infrastructure and renewable energy technologies such as wind turbines and solar panels (IEA, 2024). Similarly, lithium's expected supply in 2035 is considerably lower than the primary supply requirements in the APS and NZE scenarios, even under high production assumptions. This gap underscores the critical need for increased lithium production to support the burgeoning demand for battery technologies, which are crucial for the green transition (IEA, 2024). Similarly, rare earth elements follow the trend, with the expected supply not projected to meet the demand requirements in the APS and NZE scenarios, largely affecting the affordability and pace of innovation of digital technologies. Moreover, while the projected supply for nickel, cobalt, and graphite appears more promising, it remains insufficient. In none of the scenarios does the base case for these minerals meet the projected supply requirements. Only in the high production case for nickel does the supply meet demand in the APS scenario, under the more carbon-intensive pathway.

The data from the IEA reveals a concerning reality: under no current scenario will the projected demand for critical minerals meet the expected supply by 2035. The insufficiency in supply, particularly stark for copper and lithium, poses significant challenges for the affordability and equitable distribution of green energy and technology (IEA, 2024). Without substantial increases in strategic investments and production capacities, the critical minerals deficit could hinder progress towards global climate goals and exacerbate disparities in access to clean energy solutions (IEA, 2024). Moreover, the situation becomes even more worrying given the projected geographical distribution of projects and refined material production for critical minerals, reflected in the graph below (IEA, 2024).

As many refining projects are being developed in today's dominant producers, refined material production is also set to remain highly concentrated in a few countries



Notes: The figures for graphite are based on battery-grade spherical graphite and synthetic graphite supplies. The figures for rare earth elements are for magnet rare earth elements only. The figure depicts the value of the top three producing countries in a given year.

Given the current distribution of projects, the geographical concentration of refined material production for critical minerals and projected future projects is likely to remain highly concentrated, with China continuing its role as the dominant leader in refined material production across nearly all critical minerals except nickel and REEs (IEA, 2024). For copper and lithium, China's dominance in refining is expected to increase, although contributions from Chile, Peru, and Argentina will also play a role, albeit to a lesser extent (IEA, 2024). Notably, nickel is the only mineral where the current and projected refined supply is more diversified, with Indonesia set to play a significant role in maintaining the overall balance and Japan also contributing (IEA, 2024).

The future outlook for critical mineral supply chains appears increasingly dominated by China, with notable exceptions in nickel and lithium production and refinement. As demand for these essential minerals continues to grow, the existing challenges of geopolitical risks, potential supply disruptions, and price volatility are likely to intensify (IEA, 2024). Although some diversification efforts are underway, the overall reliance on China for refining critical minerals such as REEs, graphite, and cobalt remains a significant vulnerability (IEA, 2024). Consequently, the conclusions drawn from the current outlook regarding the fragility of these supply chains and the urgent need for diversification remain pertinent (IEA, 2024).

6.1.4 INVESTMENT ALONG THE SUPPLY CHAIN

Under no predicted scenario does current supply adequately meet projected demand for critical minerals. This disparity implies that policymakers must either adapt demand volumes or significantly expand supply to ensure a greener future without leaving substantial portions of the population without access to energy (IEA, 2021). Given the existing socio-political and international legal frameworks, governments have prioritized rapid transition to a greener future over a slower, more affordable pace in adopting renewable energy technologies. Consequently, rather than exploring the implications of a potential decrease or slowdown in demand for critical minerals, this section will focus on the drivers of supply. The objective is to identify strategies to build a more resilient supply chain, thereby aligning projected supply as closely as possible with projected demand (IEA, 2023).

In the IEA's NZE Scenario, mitigating foreseeable supply shortages for critical minerals hinges on achieving the necessary investment levels in both mining and processing. Between 2022 and 2030, mining production alone would require an investment of USD 360 billion to USD 450 billion to meet projected production levels (IEA, 2024). Most of these anticipated investments are expected to be directed towards Africa, Central and South America, and the Asia Pacific region (IEA, 2024). Additionally, the processing segment of the value chain necessitates between USD 90 billion and USD 210 billion over the same period to align with the projected demand (IEA, 2024). Therefore, ensuring these investment levels is crucial to building a resilient supply chain and meeting the ambitious targets set under the NZE Scenario, thereby preventing critical supply shortages that could hinder the global transition to sustainable energy systems (IEA, 2021).

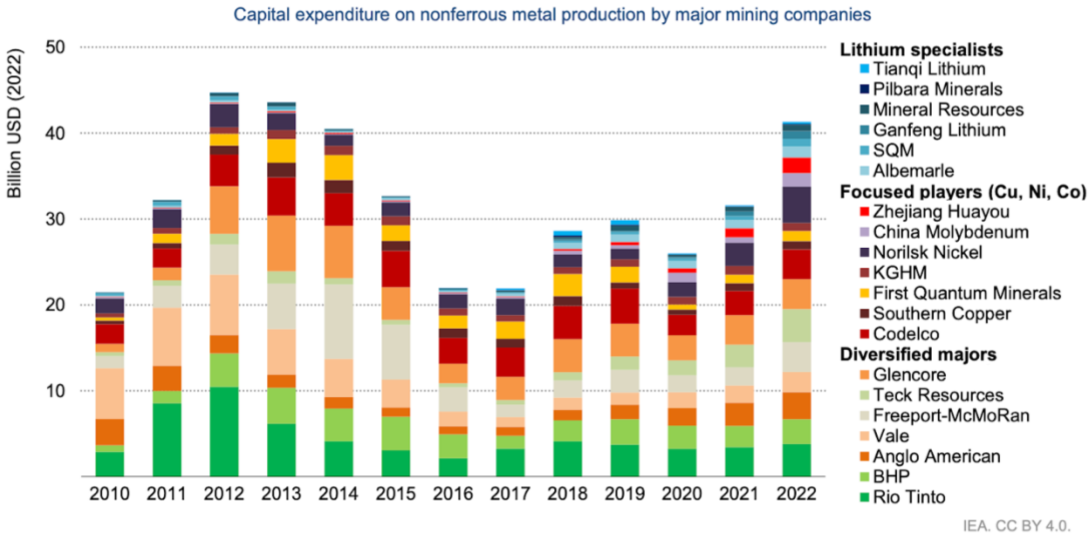
The supply chain for critical minerals begins with exploration and development, involving geological surveys, drilling, and feasibility studies, often costing hundreds of millions of dollars. In 2022, exploration spending increased by 20%, with significant growth in lithium exploration, particularly in Canada and Australia. Lithium spending saw a 90% rise, emphasizing its importance in battery technologies for electric vehicles and energy storage. Uranium exploration increased by 60% due to renewed interest in nuclear power, and nickel exploration rose by 45%, driven by Canada's attractive investment opportunities.

The next phase is mining, where ores are extracted from the earth, requiring substantial capital investment in infrastructure. Large-scale mining operations can cost billions to establish. China has significantly invested in overseas mines, especially for battery metals like lithium, nickel, and cobalt, reaching USD 10 billion in the first half of 2023. Following mining, ore undergoes smelting and refining to produce pure metals. This stage is energy-intensive and costly, with smelting and refining plants costing between $500 million to over $1 billion.

In the fabrication stage, refined metals are converted into usable forms such as cathodes and billets, with investments often reaching hundreds of millions. The semi-production phase further processes these products into wire rods, shapes, and tubes, requiring specialized machinery and skilled labor. The production phase transforms semi-finished products into final goods like cables and motors, with investment in production facilities costing several hundred million dollars. Finally, in the end-use phase, these materials are integrated into industries such as energy, transport, and construction, driving up costs as companies invest in infrastructure and technologies to utilize these critical minerals effectively (IEA, 2023).

Understanding this supply chain highlights the immense financial and logistical challenges involved in meeting the global demand for critical minerals. Each step, from exploration to end use, necessitates substantial investment, making the entire process not only complex but also capital-intensive. This underscores the need for strategic investments, effective licensing agreements, and robust international cooperation to ensure a stable and sustainable supply of these essential resources (IEA, 2021). The only possible way forward to meet projected supply for projected demand scenarios is to drive significant investments in all phases of exploration, extraction, and refining of critical minerals. This necessity leads us to the next point: an analysis of current investment levels versus the required investment levels to achieve these ambitious goals.

Investment in critical mineral mining rose by 30% in 2022 as strengthening momentum for energy transitions offers prospects for robust demand growth



Notes: Co = cobalt; Cu = copper; Ni = nickel. For diversified majors, capex on the production of iron ore, coal and other energy products was excluded.
Source: IEA analysis based on company annual reports and S&P Global.

The graph on the left illustrates capital expenditure on nonferrous metal production by major mining companies from 2010 to 2022, highlighting a 30% surge in investment in 2022 following a 20% increase in 2021. This rise underscores the strengthening momentum for energy transitions and robust demand growth for critical minerals (IEA, 2023a).

Historical data from 2010 to 2022 shows fluctuating investment levels, with peaks around 2012 and a steady increase from 2020 onwards, reflecting a renewed focus on critical minerals driven by global decarbonization efforts (IEA, 2023a). This renewed focus is exemplified by the record USD 1.6 billion raised by critical minerals start-ups in 2022, marking a 160% year-on-year increase despite challenges in the wider venture capital sector (IEA, 2023a). The first quarter of 2023 maintained strong investment levels for critical minerals, underscoring their strategic importance (IEA, 2023a). This contrast highlights how investment in critical minerals was less stable before 2020, with more recent years showing a more consistent and robust commitment to supporting the supply chain for these essential resources.

Another important indicator of optimal investment levels is the investment in EV batteries and critical minerals. As previously discussed, EVs represent the most resource-intensive form of renewable energy in terms of critical mineral consumption (IEA, 2023a).

EV battery cell makers are following the same pathway; top players increased their raw material investments significantly in recent years

Top 7 battery cell makers' involvement in the raw material supply chain

Market player	Long-term offtake			Investment in mining			Investment in refining		
	Lithium	Nickel	Others	Lithium	Nickel	Others	Lithium	Nickel	Others
CATL				O (blue) O (red)	O (red)	O (red)	O (blue) O (red)	O (blue) O (red)	O (blue) O (red)
LGES	O (blue) O (red)	O (red)	O (red)	O (red)			O (red)	O (blue) O (red)	O (red)
BYD				O (blue) O (red)			O (blue) O (red)		
Panasonic	O (red)	O (red)	O (blue) O (red)						
SK On	O (red)	O (blue)	O (blue)	O (red)				O (red)	
Samsung SDI		O (blue) O (red)	O (blue)						
CALB									

Notes: Top 7 cellmakers accounted for 86% of market share in 2022. O (blue) = before 2021; O (red) = after 2021.
Source: IEA analysis based on company announcements and news articles.

EV makers are becoming serious about critical mineral supplies; there has been a notable pick-up in strategic investment into the raw material sector since 2021

Top 10 EV makers' involvement in the raw material supply chain

Market player	Long-term offtake			Investment in mining			Investment in refining		
	Lithium	Nickel	Others	Lithium	Nickel	Others	Lithium	Nickel	Others
BYD				O (blue) O (red)			O (blue) O (red)		
Tesla	O (blue) O (red)	O (blue) O (red)	O (blue) O (red)				O (red)		
VW Group	O (blue) O (red)				O (red)	O (red)		O (red)	
General Motors	O (red)	O (red)	O (red)	O (red)				O (red)	O (red)
Stellantis	O (red)	O (red)	O (red)	O (red)	O (red)	O (red)			
Hyundai			O (red)						
BMW	O (blue) O (red)		O (blue)				O (red)		
Geely Auto									
RNM Alliance	O (blue) O (red)		O (red)		O (red)	O (red)			
Mercedes-Benz	O (red)								

Notes: VW = Volkswagen. Top 10 EV makers accounted for around 70% market share in 2022. O (blue) = before 2021; O (red) = after 2021.
Source: IEA analysis based on company announcements and news articles.

The first graph highlights the top seven battery cell makers' engagement in the raw material supply chain, focusing on long-term offtake agreements and investments in mining and refining. Companies like CATL, LGES, and BYD are particularly active in securing supplies of lithium and nickel, essential for battery production. Notably, LGES and SK On have made significant investments in mining and refining, indicating a proactive approach to supply chain stability (IEA, 2023a). Panasonic also shows substantial involvement in securing nickel and lithium through both offtake agreements and investments in refining, reflecting the growing demand for batteries driven by the transition to EVs (IEA, 2023a). Meanwhile, the second graph provides a broader view of the top ten EV manufacturers' strategic investments in the raw material supply chain. Companies such as Tesla, VW Group, and General Motors have made notable strides in securing long-term offtake agreements and investing in mining and refining critical minerals like lithium and nickel (IEA, 2023a). Tesla has been active in securing these supplies both before and after 2021, demonstrating its long-term strategy to mitigate supply risks. VW Group and General

Motors also show significant investments in the raw material sector, emphasizing the importance of these minerals in their EV production plans (IEA, 2023a). Overall, the graphs highlight the strategic investments by leading EV battery cell makers and EV manufacturers in the raw material supply chain, underscoring their efforts to ensure a stable supply of critical minerals. These investments signify a significant industry shift towards securing essential materials for battery production, reflecting a broader trend of increasing involvement in the raw material sector (IEA, 2023a).

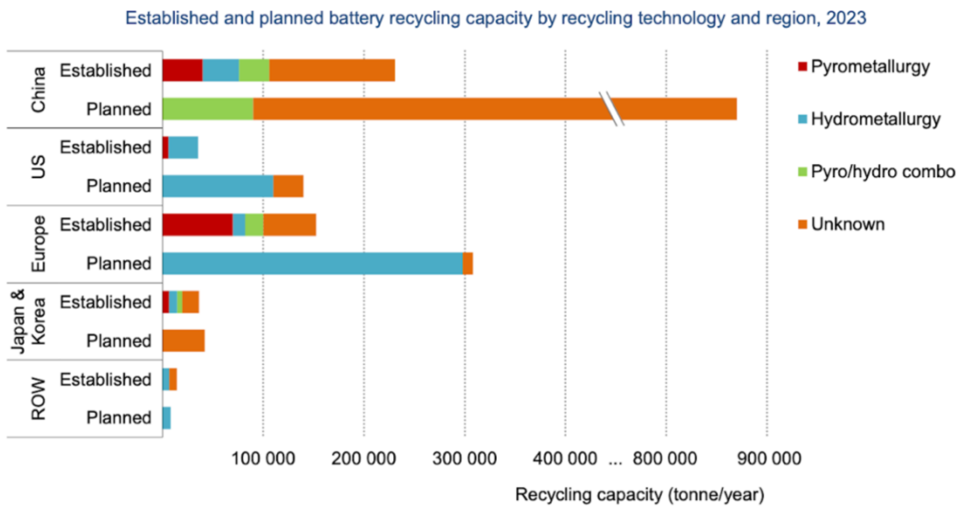
6.1.3.1GREEN FINANCE AND VENTURE CAPITAL'S IMPACT

Green finance has emerged as a pivotal force in driving investments into critical minerals, aligning financial flows with sustainable development goals to support initiatives that address environmental concerns and ensure the stability and sustainability of supply chains (WEF, 2024a). Green finance encompasses various financial instruments and strategies aimed at promoting sustainable development, prioritizing innovative solutions that can diversify supply chains, enhance efficiency, and support the global transition to a low-carbon economy. Key drivers include green bonds, sustainability-linked loans, and venture capital (EIB, 2023c).

Venture capital plays a crucial role in the mining sector by supporting start-ups and companies focused on developing new technologies for the extraction, refining, and recycling of critical minerals. In 2022, despite broader economic challenges, critical mineral start-ups raised a record USD 1.6 billion, marking a 160% year-on-year increase. This surge in funding brought the critical minerals category to 4% of all venture capital funding for clean energy (IEA, 2024). Notably, the first quarter of 2023 continued to see strong investment flows into this sector, even as other VC segments, such as digital start-ups, faced significant downturns (IEA, 2024).

Moreover, battery recycling has emerged as the largest recipient of venture capital funding within the critical minerals sector. Investments in battery recycling technologies are crucial for creating a circular economy, reducing dependence on newly mined raw materials, and mitigating environmental impacts associated with battery disposal (IEA, 2024). This focus on recycling not only addresses sustainability concerns but also enhances the efficiency and security of supply chains (IEA, 2024).

A significant amount of battery recycling capacity is being developed mainly in China, Europe and the United States



Notes: ROW = rest of world. Based on 53 identified battery recycling projects.
Source: IEA analysis based on Baum et al. (2022), Lithium-Ion Battery Recycling - Overview of Techniques and Trends, BNEF and company announcements.

China, the United States and the European Union are leading the investment in critical mineral recycling capabilities, in order to reduce dependence on mining. In China, both established and planned recycling capacities show a considerable reliance on pyrometallurgy, with planned capacity significantly outstripping established capacity (IEA, 2024). The United States and Europe both utilize hydrometallurgy, and have substantial planned capacities indicating a growing focus on expanding recycling efforts (IEA, 2024). Japan and Korea exhibit modest but noteworthy capacities, primarily in planned projects, while the rest of the world shows relatively smaller scales of both established and planned recycling capacities (IEA, 2024).

Another driver of investment towards sustainable alternatives are international development banks, such as the World Bank, the Asian Development Bank (ADB), the Asian Infrastructure Investment Bank (AIIB), the African Development Bank (AfDB), and notably the European Investment Bank (EIB), among others, which are increasingly necessary in shaping the future availability of critical minerals. By channeling significant investments into the mining and processing sectors, these institutions are addressing the challenges of securing a sustainable and diversified supply of essential minerals(World Bank, 2020).

The European Investment Bank (EIB), as the EU's financial arm, has adopted a proactive stance in this domain. It has been creative and proactive in issuing Climate Awareness Bonds and Sustainability Awareness Bonds, mobilizing substantial private sector investment into green projects, and creating strategies such as the European Battery Alliance to establish a robust battery cell manufacturing value chain within Europe, thereby reducing dependency on external sources for critical minerals (EIB, 2023c). Moreover, the EIB has been particularly active in forging strategic partnerships to enhance investment in critical raw material value chains. For instance, the EIB recently signed a landmark agreement with Rwanda to strengthen investment in critical raw materials, aiming to identify investment opportunities, scale up investments, and increase recycling (EIB, 2023b). Furthermore, the EIB's overall investment strategy includes significant allocations to projects in Africa, Central and South America, and the Asia Pacific, with the aim of reaching the required production levels of critical minerals as projected in various scenarios, including the NZE Scenario (EIB, 2023a). Between 2022 and 2030, the EIB estimates that mining production will require an investment of USD 360 billion to USD 450 billion, while the processing segment will need between USD 90 billion and USD 210 billion (EIB Investment Report, 2023).

Furthermore, the Asian Infrastructure Investment Bank (AIIB) has significantly bolstered its investment efforts in the critical minerals supply chain, recognizing its essential role in supporting the global transition to clean energy. As of 2023, the AIIB has committed substantial financial resources, amounting to over USD 500 million, to enhance infrastructure projects that improve mining operations and processing facilities across Asia and the Pacific regions (AIIB, 2023). Notably, the AIIB has allocated USD 200 million to develop sustainable lithium extraction techniques in Indonesia, a country pivotal to the global nickel supply chain due to its rich deposits of high-grade nickel ores (Mining Weekly, 2023). Additionally, the AIIB has invested USD 150 million in a partnership with the Philippines to expand refining capabilities for cobalt and nickel, ensuring these critical minerals meet the growing demands of the electric vehicle and renewable energy sectors (World Bank, 2023). By targeting these strategic areas, the AIIB aims to create a more resilient and diversified supply chain, mitigating the risks of geopolitical instability and market volatility.

Additionally, the Inflation Reduction Act (IRA), of the United States, despite it not coming from a development bank, significantly bolsters investment in the critical mineral supply chain. Since its enactment, over $45 billion in battery investments across at least 75 facilities have been announced, covering all segments from extraction to manufacturing

(U.S. Department of the Treasury, 2023). This includes substantial investments in lithium, graphite, and nickel production, which are essential for the EV industry. The IRA also provides tax credits and incentives aimed at expanding domestic production capacities and reducing reliance on foreign sources. For instance, the Department of Energy awarded $2.8 billion from the Bipartisan Infrastructure Law to 20 manufacturing and processing companies across 12 states to boost domestic production of battery materials, including enough lithium to supply 2 million EVs annually and enough graphite for 1.2 million EVs annually (U.S. Department of the Treasury, 2023).

The collective efforts of these development banks and regulations are gradually transforming the critical minerals market. By increasing investment and fostering international cooperation, they are mitigating the risks associated with supply shortages and price volatility. This, in turn, ensures that the global transition to a low-carbon economy remains on track, with a stable and diversified supply of critical minerals to support the necessary technological advancements.

6.2 ESG IMPLICATIONS IN THE CRITICAL MINERAL & REES' SUPPLY CHAIN

Achieving sustainable development goals and supporting the rapid deployment of clean energy technologies will significantly increase the demand for critical minerals. According to the IEA, meeting this heightened demand by 2030 necessitates the development of 164 new mines (IEA, 2021). This anticipated surge in mining activity underscores the importance of addressing environmental, social, and governance (ESG) implications within the global supply chain for these essential resources. Environmentally, mining operations are linked to extensive water usage, greenhouse gas emissions, biodiversity loss, and increased pollution of water, land, and air (IEA, 2021). Socially, the industry grapples with issues such as worker safety incidents, human rights abuses, and negative impacts on local communities and Indigenous Peoples, including displacement, lack of engagement, and failure to respect rights (IEA, 2021). Additionally, mining can cause damage through tailings dam failures and local air, water, and noise pollution (World Bank, 2020a). On a broader societal level, mining activities can lead to corruption, misallocation of public resources, erosion of governance and the rule of law, contributions to armed conflict, and adverse impacts on women (World Bank, 2020a). Understanding the ESG implications in the global supply chain for critical minerals is crucial for developing sustainable and equitable solutions. This section will explore the comprehensive impact of mining activities on the environment, workers, local communities, and broader societies. Addressing these multifaceted challenges will be essential for ensuring a stable, sustainable, and ethically sound supply chain for the critical minerals that are foundational to the global energy transition.

6.2.1 WATER SCARCITY

One of the most substantial material risks to critical mineral supply chains is water scarcity, which can slow down or completely halt production. In fact, approximately 40% of major mining companies have reported that water risks could lead to operational shutdowns, disrupt production capacity, and constrain growth (IEA, 2023). This is because the need for water spans from exploration to processing and transportation, being water a vital input for standard operations such as cleaning, cooling, dust control, and pumping (Brown, 2021). Additionally, some mineral supply chains are particularly susceptible to water-related risks. For instance, lithium brine extraction and copper processing are highly vulnerable due to their locations in arid regions, and nickel processing is at risk due to its high water requirements (Brown, 2021). Currently, over 50% of lithium and copper production is concentrated in areas with high water stress levels, such as northern Chile and Australia (IEA, 2023). As more mines are developed to support the clean energy transition, the risk of supply disruptions due to water scarcity is likely to increase (Goés & Bekkers, 2023).

Moreover, water is a critical resource not only for the extraction of minerals but also for the production of clean energy technologies themselves. It is extensively used in cooling processes and other stages of energy production, highlighting its multifaceted importance(Brown, 2021). A specific example of water dependence of green energy technologies is hydroelectric dams. While being a significant source of renewable energy, they also have profound environmental impacts, particularly on water temperature and local ecosystems. The operation of these dams can alter the natural flow and temperature of rivers, affecting aquatic habitats and biodiversity. The water released from hydroelectric dams is often significantly warmer than the natural river water, which can disrupt the life cycles of fish and other aquatic organisms, leading to a decline in local biodiversity. (U.S. Energy Information Administration, 2022)

To ensure the robustness of supply chains, it is crucial to implement a variety of actions to secure an abundant water supply. This may include investing in mining activities in regions with more abundant water resources and employing innovative technologies such as cloud seeding. Cloud seeding, a weather modification technique, involves dispersing substances like silver iodide into the atmosphere to stimulate cloud formation and increase precipitation. This method is currently used in the Arab-Peninsula states to enhance rainfall and could be a viable strategy to mitigate water scarcity in mining regions (Poynting & Silva, 2024).

Addressing water scarcity and ensuring sustainable water management practices will be essential for maintaining stable and efficient supply chains for critical minerals. This will require collaborative efforts, substantial investments in water-efficient technologies, and strategic planning to mitigate the risks associated with water scarcity (IEA, 2023).

6.2.2. GREENHOUSE GAS EMISSIONS

The transition to green energy is essential for reducing global carbon emissions and achieving climate goals. However, the extraction and processing of critical minerals necessary for clean energy technologies also entail significant environmental impacts (World Bank, 2020a). Although green technologies are less carbon-intensive compared to traditional fossil fuels, some critical minerals like cobalt and nickel can have substantial carbon footprints. For instance, while natural gas processing is more carbon-intensive, its extraction is less carbon-intensive compared to nickel and cobalt, as illustrated by recent data (IEA, 2021).

Greenhouse gas emissions from critical mineral production occur at multiple stages along the supply chain. This is because the industry relies on energy-intensive processes and equipment, often powered by fossil fuels (World Bank, 2020a). In 2021, the average GHG emissions for the production of critical minerals ranged from 4.6 tonnes of carbon dioxide equivalent (CO2-eq) per tonne of refined copper to 75.8 tonnes CO2-eq per tonne of neodymium oxide (IEA, 2021). These emissions vary significantly depending on the processes used, energy efficiency, and whether renewable energy sources power the operations (World Bank, 2020a). Although emissions from the critical minerals industry are relatively small compared to other sectors due to lower production volumes, they are expected to increase alongside the projected growth in demand, including indirect emissions from purchased energy (IEA, 2023).

Nevertheless, clean energy technologies have lower levels of GHG emissions compared to conventional technologies, even when considering full life-cycle emissions (IEA, 2023). For example, the total life-cycle GHG emissions of electric vehicles are around half those of internal combustion engine cars on average, with the potential for a further 25% reduction when powered by low-carbon electricity (World Bank, 2020a). Consequently, reducing GHG emissions in mining and processing critical minerals is vital to ensuring a sustainable, responsible, and reliable supply (IEA 2021).

Furthermore, increasing regulatory pressures, such as carbon taxes, can lead to higher operational costs for mines, especially those that rely on fossil fuels (World Bank, 2020). These increased costs might limit supply if they render some operations uneconomical given the carbon price or the cost of mitigation measures (IEA, 2023). Although a carbon tax could eventually benefit the mining industry by shifting demand towards renewable energies, there would likely be near-term consequences for supply, particularly for mines with high GHG intensities, including those in remote areas far from clean energy infrastructure (World Bank, 2020a). Additionally, high GHG emissions along the critical mineral supply chain may become a prohibitive barrier to developing new operations in regions lacking cost-efficient renewable energy sources or GHG abatement technologies (IEA, 2023). This is especially pertinent for minerals requiring energy-intensive processes and for developing resources in non-grid-connected or insufficiently renewable-powered areas (World Bank, 2020a). Despite many companies in the industry making commitments to reduce GHG emissions, concrete progress remains limited (IEA, 2023).

In conclusion, the current framework of carbon emission pricing plays a complex role in the development of green energy technologies. While it encourages investment in green technologies by penalizing carbon-intensive industries, it also increases costs for the extraction of critical minerals essential for the green transition (World Bank, 2020a). To align future supply with projected demand and secure energy availability for all, it is crucial to maximize investment in all phases of exploration, extraction, and refining of critical minerals. This approach is necessary to meet projected demand scenarios without compromising the affordability and equitable distribution of green energy technologies (IEA, 2023).

6.2.3. BIODIVERSITY

Mining activities, essential for extracting critical minerals required for the global transition to green energy, often have severe environmental impacts. These impacts vary depending on the type of mine (open-pit versus underground), the geological mineral source (lithium hard rock versus brine deposits), and the geographical context (tropical rainforests versus degraded lands) (IEA, 2023.) For example, mining in tropical rainforests results in higher biodiversity impacts compared to operations on degraded land. The environmental consequences of mining can be direct, indirect, and cumulative, ranging from habitat loss and fragmentation at the site level to water contamination and particulate matter emissions at the regional level, and contributing to climate change on a global scale. These activities require extensive land use, which often disrupts natural habitats and ecosystems, including migration routes. Additionally, mineral transport and processing are significant drivers of land-use changes. As ore grades decline and mineral demand increases, the impact of critical mineral supply on land use and biodiversity will likely intensify (IEA, 2023.)

The critical importance of tackling adverse biodiversity impacts derived from critical mineral mining lies in two main reasons. Firstly, the primary purpose of transitioning to critical minerals is to prioritize the environment by moving away from fossil fuel consumption. However, if the process of extracting these minerals further destroys the environment, it defeats the purpose of the green transition (IEA, 2023). Secondly, biodiversity loss has many interconnected implications. The destruction of a food chain, changes in water acidity levels, the loss of forests that provide oxygen, and the impact on other primary sector activities like fishing, agriculture, and housing, are just a few examples. It is imperative to manage mining activities effectively to prevent further environmental degradation, ensuring that the pursuit of a sustainable energy future does not come at the cost of irreparable harm to our ecosystems (IEA, 2023).

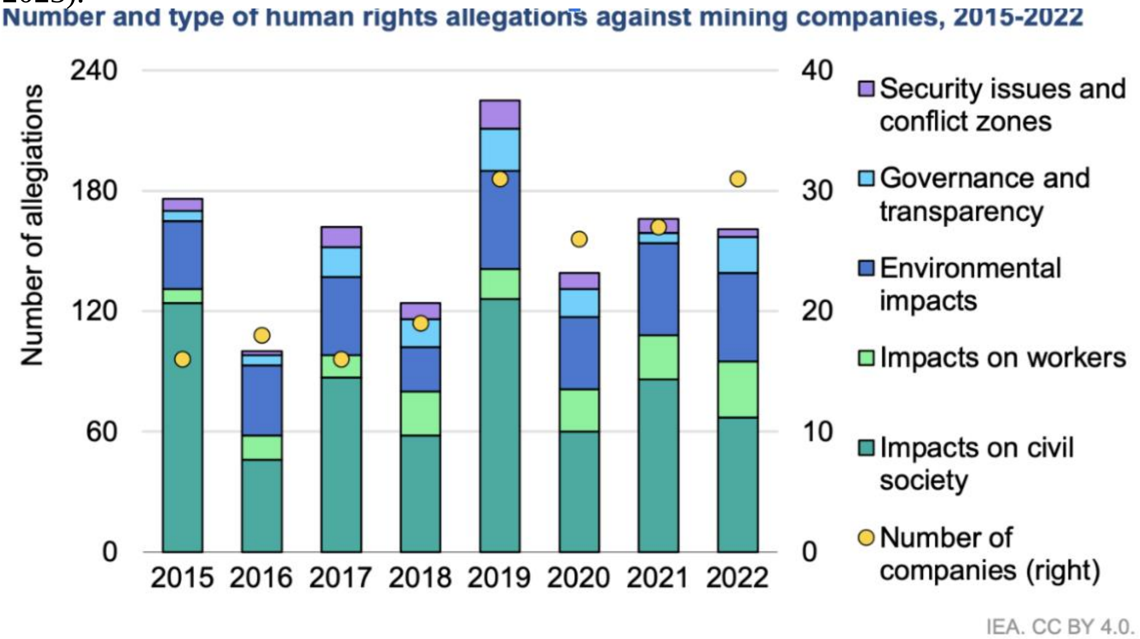
Furthermore, regulation addressing the impact of mining activities on biodiversity is crucial for environmental protection yet also presents potential challenges for mineral supply (IEA, 2023). The Global Initiative for Non-Financial Disclosure, which includes the Taskforce on Nature-Related Financial Disclosures and the Corporate Social Responsibility Directive in the EU, plays a key role in this regulatory framework. The IGF Framework recommends that governments implement policies and build capacity to manage biodiversity and ecosystem services, requiring mining entities to identify and mitigate risks and impacts to achieve no net loss across the mine life cycle through the mitigation hierarchy (IEA, 2023). Impact assessments, which often include biodiversity provisions, are a common regulatory tool. For instance, the EU Environmental Impact Assessment Directive mandates biodiversity assessments for mining projects under certain conditions. The EU Directive on public access to environmental information, aligned with the Aarhus Convention, ensures public access to this information. Additionally, Australia's Environment Protection and Biodiversity Conservation Act and South Africa's Biodiversity Act provide guidelines for activities that may adversely affect biodiversity. Initiatives like Nature Action 100 further mobilize institutional investors to establish a common agenda around nature and biodiversity, targeting 100 prominent companies, including 13 mining firms (IEA, 2023). While these regulations are essential for safeguarding the environment, they can also lead to supply shocks by complicating and lengthening the approval processes for new mining projects. The additional scrutiny and requirements can make it more difficult for mining companies to obtain necessary permits, potentially delaying the development of new mines and impacting the overall supply of critical minerals needed for the green transition (IEA, 2023).

In conclusion, the intricate balance between the environmental protection and the efficient functioning of the critical mineral supply chain is crucial. Regulatory frameworks, while essential for safeguarding biodiversity, can introduce potential supply chain disruptions by complicating and extending the approval processes for mining projects (IEA, 2023). These regulations are necessary to prevent environmental degradation, but they also pose challenges for timely and adequate mineral supply, essential for the green transition (IEA, 2023). Effective management and innovative solutions are imperative to ensure that the supply chain for critical minerals can meet the rising demand without compromising environmental and biodiversity goals. The global effort must focus on creating a resilient and sustainable supply chain that aligns with both ecological and economic objectives (IEA, 2023).

6.2.4. HUMAN RIGHTS

Mining activities for critical minerals, essential for the global transition to green energy, come with significant challenges that impact supply chains. The mining industry, in particular, has historically been associated with adverse human rights impacts at many stages along the mineral value chain. Common violations include labor violations, such as child labor or forced and compulsory labor, which are notably prevalent in artisanal and small-scale mining; violations of the right to health, with some cases of torture, or cruel, inhuman and degrading treatment or sexual violence perpetrated by security forces of the state or private companies (IEA, 2023). Human rights violations pose several risks to supply chains. Companies that engage in or are associated with human rights violations face substantial legal risks, including lawsuits, fines, and potential shutdowns of operations (IEA, 2023). Moreover, human rights abuses can severely damage a company’s reputation, leading to loss of consumer trust and investor confidence. This can result in financial instability and interruptions in operations (IEA, 2023). Poor working conditions can lead to accidents and health issues, causing work stoppages and reduced productivity. Proper working conditions and respect for labor rights are essential for a stable and efficient workforce (IEA, 2023). Additionally, adhering to human rights norms involves additional costs for training, monitoring, and compliance, increasing the financial burden on mining companies and potentially affecting their profitability and operational efficiency (IEA,

2023).



Notes: The data cover only reported allegations against companies operating globally significant producing mines of cobalt, copper, lithium, manganese, nickel and zinc. All allegations are publicly reported, specific incidents including attacks against human rights defenders or legal/regulatory action against companies. Allegations are not independently verified. Each allegation can be related to multiple categories.
Sources: IEA analysis using data from Business & Human Rights Resource Centre (2023), Transition Minerals Tracker.

Overall, while mining activities for critical minerals are fundamental to advancing green energy technologies, they present considerable challenges related to human rights and operational efficiency. Addressing these human rights violations is not only a moral imperative but also crucial for maintaining a stable and resilient supply chain. Ensuring proper working conditions and compliance with human rights norms can mitigate legal risks, protect company reputations, and enhance overall productivity and financial stability, ultimately supporting a sustainable transition to green energy (IEA, 2023).

6.2.5. COMMUNITIES AND INDIGENOUS PEOPLES

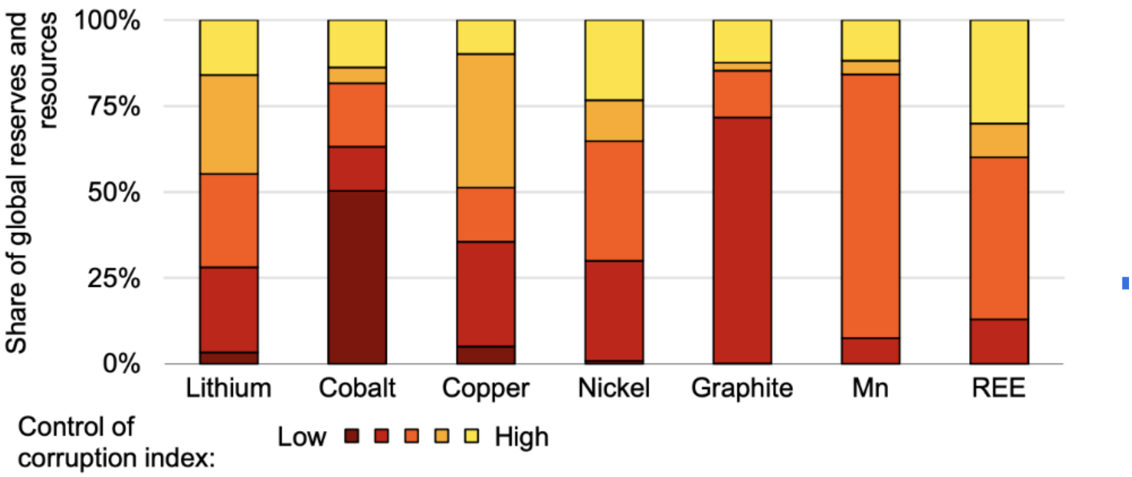
Another significant factor posing ESG and supply chain risks is the impact of mining activities on local communities and Indigenous Peoples. While mining can bring positive changes, such as job creation, it also has adverse effects, including habitat loss, displacement, water and air pollution, deforestation, and adverse health outcomes (IEA, 2023). These negative impacts can lead to social unrest, as displacement and disruption of local livelihoods often cause protests and violent confrontations, halting mining operations and increasing costs (IEA, 2023). Furthermore, negative impacts on communities can result in the loss of the social license to operate, leading to blockades, strikes, and litigation. These disruptions can have severe consequences for supply chains. Halting mining operations due to social unrest or legal challenges disrupts the steady supply of critical minerals, causing delays and increased costs in production (IEA, 2023). Additionally, stricter regulatory controls imposed in response to environmental degradation and pollution can increase operational costs and further delay production (IEA, 2023). Engaging with communities and respecting their rights is crucial for maintaining peaceful operations and stable supply chains. For instance, obtaining free, prior, and informed consent (FPIC) from Indigenous Peoples is legally required in many contexts (World Bank, 2020). Failure to obtain FPIC can lead to legal challenges and delays in project approvals, further impacting the supply chain. Therefore, effective engagement and adherence to legal and environmental standards are essential to mitigate these risks and ensure the stability and sustainability of mining operations and their supply chains (IEA, 2023).

6.2.6. CORRUPTION

Corruption, defined as the abuse of entrusted power for private gain, significantly impacts the critical minerals supply chain. It manifests through bribery, embezzlement, and fraud at various stages, including contract awards, extraction licenses, and community compensation. The mining stage is particularly vulnerable due to high investment levels and state involvement (Transparency International, 2023).

The control of corruption index reveals that many countries with significant mineral resources, such as cobalt, copper, and nickel, rank low, indicating high corruption risks (World Bank, 2023). Corruption leads to delays in developing new mining projects as officials investigate allegations or revise terms. Smaller incidents, like demands for 'grease payments,' cause operational shutdowns and disrupt the supply chain (World Bank, 2023).

Control of corruption index for global critical minerals reserves and resources

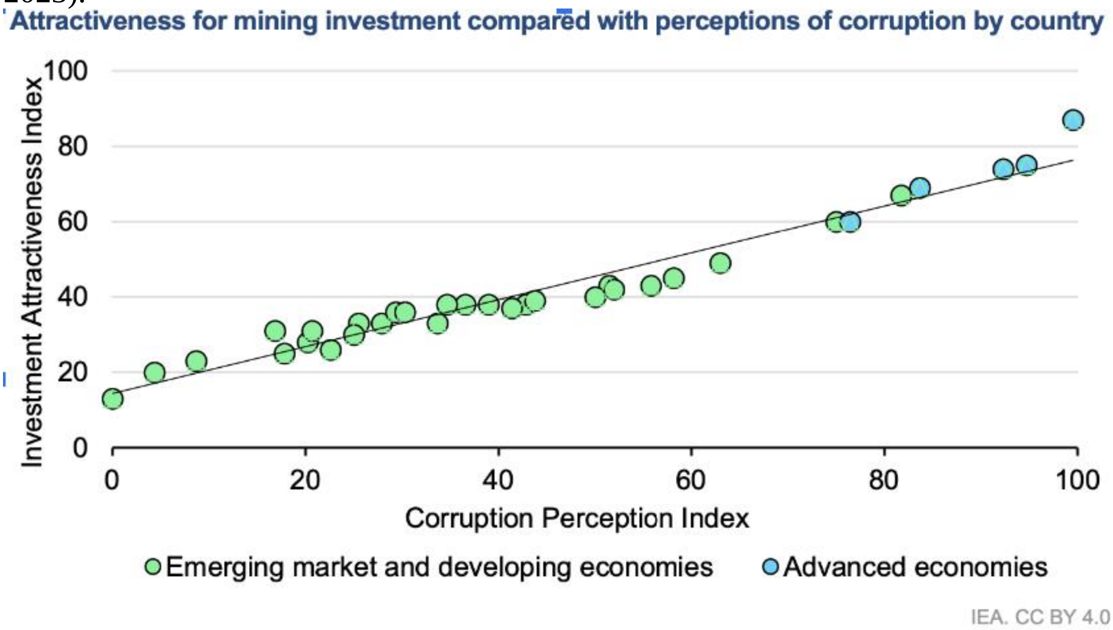


Note: Mn = manganese; REE = rare earth elements.

Sources: IEA analysis based on the World Bank Worldwide Governance Indicators and Owen, Lebre and Kemp (2022), Energy Transition Minerals (ETMs): A Global Dataset of Projects.

Corruption also affects investment. The graph comparing mining investment attractiveness and corruption perceptions shows that countries with lower corruption levels attract more investment, while highly corrupt countries struggle (WEF, 2023). This trend hampers supply chain stability and restricts economic growth by making certain regions less appealing for investment. Furthermore, corruption diverts resources from essential public investments in infrastructure, health, and education, undermining the benefits mining could bring to local communities. This fosters distrust and opposition, complicating project development (WEF,

2023).



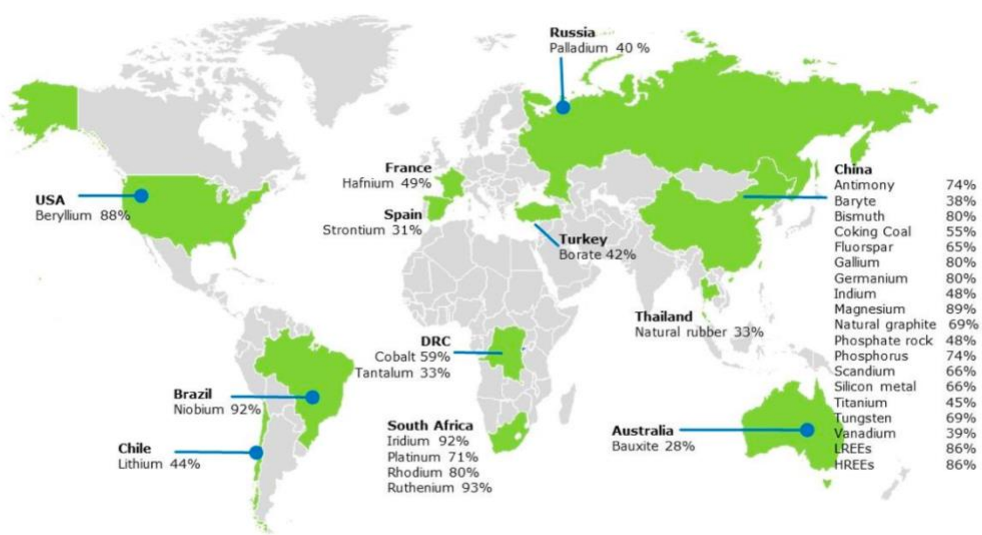
Note: The Corruption Perceptions Index ranks countries around the world based on how corrupt their public sectors are perceived to be. The results are given on a scale of 0 to 100, where 0 is highly corrupt and 100 is highly clean.
Sources: IEA analysis based on Fraser Institute's Annual Survey of Mining Companies 2022 and the Corruption Perceptions Index.

In conclusion, corruption in the critical minerals supply chain poses significant challenges to ensuring a stable and reliable supply. Addressing this issue requires robust governance, transparency, and accountability to foster investment and sustainable development, essential for supporting the global transition to green energy technologies.

6.3. GEOPOLITICAL IMPLICATIONS

6.3.1. GEOGRAPHICAL CONCENTRATION

Figure B: Countries accounting for largest share of global supply of CRMs



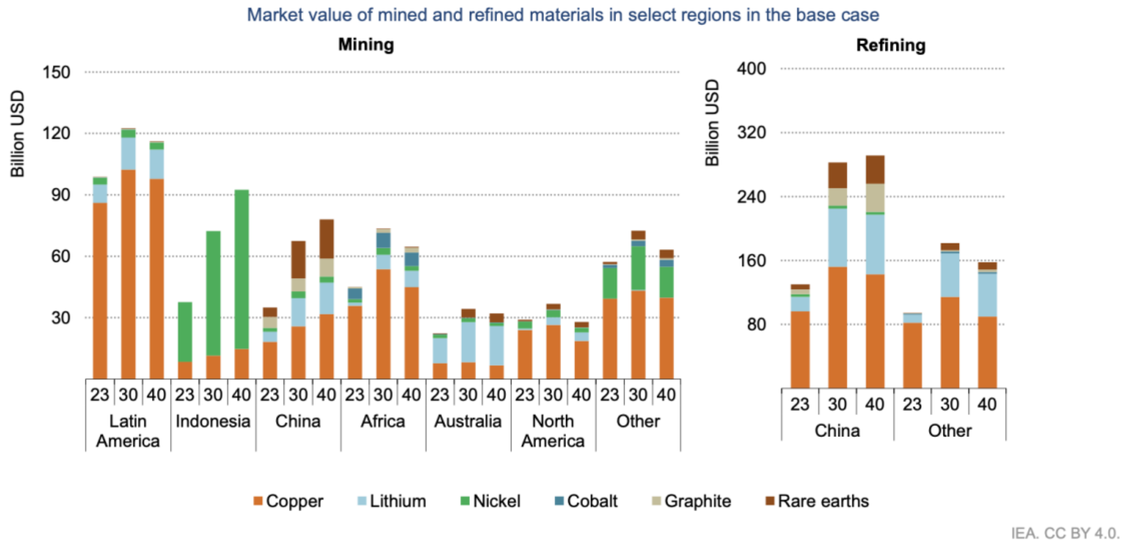
An analysis of global supply confirms that China is the largest supplier of several critical raw materials. Other countries are also important global suppliers of specific materials. For instance, Russia and South Africa are the largest global suppliers for platinum group metals, the USA for beryllium and Brazil for niobium.

Figure B, extracted from the "Study on the EU's List of Critical Raw Materials (2020) Final Report," depicts the current global distribution of critical minerals, including copper, lithium, nickel, cobalt, as well as other less commonly encountered yet equally necessary minerals for clean energy technologies and digitalization processes. This map highlights

the DRC as a crucial supplier, providing 59% of the world's cobalt and 33% of tantalum, both vital for electronics and battery production (European Commission, 2020). Brazil leads in niobium supply (92%), a critical material for steel production. Russia is a major supplier of palladium (40%), essential for catalytic converters in the automotive industry. South Africa dominates the supply of platinum group metals, including iridium (92%), platinum (71%), rhodium (80%), and ruthenium (93%), which are crucial for various industrial applications. The USA is the largest supplier of beryllium (88%), used in the aerospace and defense industries. Chile is a major supplier of lithium (44%), critical for battery technologies, and Australia significantly contributes to the global supply of bauxite (28%), essential for aluminum production, alongside other countries that provide substantial reserves of various minerals (European Commission, 2020).
Yet, an analysis of the global supply confirms that China is the dominant supplier of a wide range of critical raw materials, controlling substantial portions of the global supply for materials such as antimony (74%), bismuth (80%), gallium (80%), germanium (80%), magnesium (89%), natural graphite (69%), and rare earth elements (86%) (European Commission, 2020). This extensive control underscores China's critical role in the global supply chain for these materials. The geographical concentration of critical minerals in China poses significant risks to global supply chain resilience. Any geopolitical tensions, trade restrictions, or supply disruptions in these regions can have widespread impacts, highlighting the urgent need for diversification of supply sources. The strategic implications of this dependence are profound, as control over these resources can influence global power dynamics and economic stability (European Commission, 2020).
Fortunately, the graph below illustrates a positive outlook for the diversification of mining projects globally for key minerals in the years 2023, 2030, and 2040. In terms of mining, Latin America is projected to maintain a high market value primarily driven by copper, with substantial contributions from lithium and nickel. The market value in Latin America is anticipated to grow steadily from 2023 to 2040. Similarly, Indonesia shows significant market value, predominantly fueled by nickel production. In Africa, the market value for mining is expected to rise substantially, driven by a combination of copper, cobalt, and graphite. Australia and North America also exhibit growth in their mining market values, albeit at a more moderate pace compared to the other regions. China's mining market value is expected to increase, although not as sharply as that of Latin America or Indonesia, with a diversified portfolio that includes copper, lithium, and rare earths (IEA,

2024).

Latin America, Africa and Indonesia see a growing market value from their mining operations; nearly 50% of the market value from refining is concentrated in China by 2030



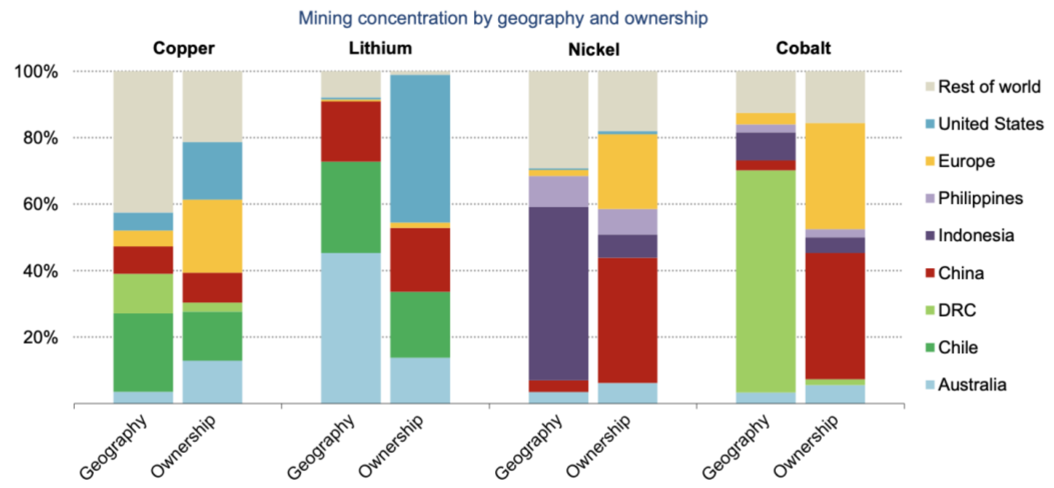
Note: Market value was calculated by multiplying each region's production volume in the base case with today's market price for final products.

However, the challenge arises with the refining of minerals. In terms of refining, China is projected to dominate the market, with its value nearly doubling from 2023 to 2040 (IEA, 2024). For rare earth elements, graphite, and cobalt, China not only currently leads but is also expected to maintain its dominance in the future. This underscores the strategic importance of diversifying refining sources for these minerals (IEA, 2024). In the case of copper and lithium, China's dominance in refining is anticipated to grow, although Chile, Peru, and Argentina will also contribute to a lesser extent. This highlights the urgent need for diversification to ensure the stability and sustainability of supply chains for these crucial materials (IEA, 2024). Nickel presents a somewhat different scenario, with both the current and projected refined supply being more diversified due to substantial contributions from Indonesia and Japan. This diversification in nickel refining contrasts sharply with the high concentration observed in other critical minerals, offering a model for reducing dependency on a single country (IEA, 2024). The geographical distribution of refined materials further emphasizes China's dominance. This control over refining capabilities means that even if raw materials are extracted elsewhere, they often need to be sent to China for refining, adding another layer of dependency (IEA, 2024). Future project pipelines indicate that this concentration is likely to persist, with projects reflecting that dominance is expected to continue well into the future (IEA, 2024). The positive aspect is that refining capabilities are considerably easier to distribute geographically than extraction sources (IEA, 2024).

Furthermore, China's investment strategy plays a crucial role in maintaining its dominance in the global supply chain for critical minerals. As the world's largest metal refining hub, China relies heavily on imports for large volumes of raw materials, often from a limited number of sources, such as the DRC for cobalt (European Commission, 2020). To mitigate this dependency, China has been investing significantly in mining assets in Africa and Latin America, with Chinese companies investing USD 4.3 billion in lithium assets between 2018 and mid-2021, double the investment of companies from the United States, Australia, and Canada combined during the same period (IEA, 2024). Additionally, China has begun investing in overseas refining and downstream facilities to secure strategic access to raw materials (IEA, 2024). The Asian Infrastructure Investment Bank (AIIB), backed by China, supports these strategic investments by providing significant funding for infrastructure projects related to mining and mineral processing, thereby enhancing

China's investment capabilities in key regions (AIIB, 2021). This financial support extends China's influence over the global supply chain, reinforcing its dominant position and ensuring continued control over essential resources (IEA, 2024). Beyond asset acquisition, China is also developing infrastructure to support mining operations and refining capabilities, exemplified by the Belt and Road Initiative, which aims to establish the necessary infrastructure to sustain China's dominance in critical minerals (World Bank, 2020a). This extensive investment in infrastructure and refining capabilities ensures that China remains at the forefront of the global supply chain for critical minerals (IEA, 2024). Notwithstanding the concerning picture of global supply chain domination by a single country—China—a closer examination of ownership structures reveals a more nuanced scenario. The graph on the left illustrates the concentration of mining activities for critical minerals, including copper, lithium, nickel, and cobalt, analyzed both by geography and asset ownership. The data indicates significant differences in mining concentration depending on whether the analysis focuses on the geographical location of the mines or the ownership of the mining assets. This distinction suggests that while China may dominate in terms of geographical concentration, the global ownership of these mining assets is more diversified, potentially mitigating some of the risks associated with supply chain dependence (IEA, 2024).

Mining concentration looks different if viewed through the lens of asset ownership, with US and European companies playing a greater role



Notes: Ownership based on company headquarters location. For projects run by multiple companies, production is assigned to the company with the largest share. For copper, data are on the top 20 mining companies in 2023 representing 57% of production. For lithium, data cover 100% of production in 2023; for nickel, 93% of production; and for cobalt 97% of production.
Sources: IEA analysis based on S&P Global and Wood Mackenzie.

In terms of geography, copper mining is notably diversified, with substantial contributions from Chile, the DRC, and China. Conversely, ownership data shows a significant presence of companies based in the United States and Europe, highlighting the global reach and influence of Western corporations in the copper mining sector (IEA, 2024). However, lithium mining presents a different pattern. Geographically, Australia dominates the landscape, contributing the majority of global production. Yet when analyzing ownership, there is a noticeable shift, with significant stakes held by companies from the United States, Europe, and China. This suggests that while the physical extraction is concentrated in Australia, the control and benefits of lithium mining are more internationally distributed (IEA, 2024). Nickel mining exhibits a similar duality. Geographically, the production is heavily centered in Indonesia, the Philippines, and Russia, but in terms of ownership, companies from the United States, Europe, and Australia play a prominent role, indicating a considerable level of foreign investment and control in these regions (IEA, 2024). In the case of cobalt, mining is predominantly concentrated in the DRC geographically, yet in terms of ownership, China and Europe lead the investments (IEA, 2024).

The graph underscores the significant role of Western and Chinese companies in controlling the production of critical minerals, even when the physical mining activities are concentrated in other regions. Given the high levels of geographical concentration of the mining and refining processes, the displacement of ownership introduces voices from more actors into the global landscape. According to Liberal Peace Theory and Complex Interdependence Theory, this diversification of ownership can induce peace and resilience into global supply chains by fostering interdependence among nations (Keohane & Nye, 1977). The duality of geographical concentration and distributed ownership has profound implications for global security and geopolitical dynamics. Control over these essential resources can influence market trends and power balances, potentially leading to strategic advantages or vulnerabilities for nations dependent on these minerals. The involvement of multiple stakeholders in the critical minerals market can affect global supply chains and economic stability, creating potential points of contention in international relations (Ali et al., 2017).

The dependency on critical minerals and rare earth elements is reshaping global power dynamics, with China emerging as the leading global player in these resources. This geographical concentration has substantial geopolitical implications, making countries reliant on China vulnerable to supply disruptions due to geopolitical tensions or policy changes (European Commission, 2020). The COVID-19 pandemic demonstrated China's ability to disrupt global supply chains, as seen with extensive delays and shortages resulting from its zero-COVID policy (CSIS, 2023). While China dominates in geographical concentration, the ownership of critical mineral assets is more diversified, with significant stakes held by companies from the United States, Europe, and other regions. This diversification in ownership mitigates some risks associated with supply chain dependence and introduces more stakeholders into the global landscape, fostering interdependence among nations (Ali et al., 2017). From a neorealism perspective, China's dominance in critical minerals enhances its strategic leverage, compelling other states to navigate their foreign policies and economic strategies around this dependency, thereby exacerbating the security dilemma (Waltz, 2000). Countries reliant on these resources perceive their dependency as a vulnerability, prompting them to seek alternatives to mitigate risks. This dynamic could lead to increased competition for securing alternative sources and refining capabilities, potentially escalating geopolitical tensions (Mearsheimer, 2001).

Moreover, from a resource economics perspective, China's control over critical minerals allows it to exert significant influence over global supply chains, impacting the allocation and utilization of these resources (Hotelling, 1931). However, unlike oil, critical minerals can be refined anywhere with the proper infrastructure. This presents an opportunity to diversify supply chains and reduce China's strategic leverage by investing in refineries outside China. Such investments would enhance global supply chain resilience and reduce vulnerability to geopolitical instability (WEF, 2023a).

6.3.2. RACE FOR CRITICAL MINERALS IN UNEXPLORED TERRITORY

The global race for critical minerals has reached a new frontier, as countries and companies alike turn their attention to unexplored and remote territories such as the deep sea, outer space, and the Arctic and Antarctic regions. As traditional sources become more strained and geopolitically risky, the need to diversify supply and secure new reserves has never been more pressing.

6.3.2.1 DEEP SEA MINING

One of the most promising new frontiers for critical mineral extraction is the deep sea. The ocean floor is rich in polymetallic nodules, seafloor massive sulfides, and cobalt-rich ferromanganese crusts, all of which contain high concentrations of critical minerals and rare earth elements, making them highly attractive resources. However, there are two significant challenges associated with deep-sea mineral extraction: environmental concerns and issues related to property rights.

Regarding property rights, the exploration and extraction of resources from the marine seabed and subsoil are regulated by the widely accepted 1982 United Nations Convention on the Law of the Sea (UNCLOS). This convention designates areas such as the territorial sea, contiguous zones, and exclusive economic zones (EEZs) to delineate which country has authority over which maritime space. While these sea borders are generally accepted, countries can request expansions and changes, a process that is becoming more frequent due to the increasing interest in underwater resources (United Nations, 1982). Consequently, we can expect more discussions and disputes over these boundaries in the future.

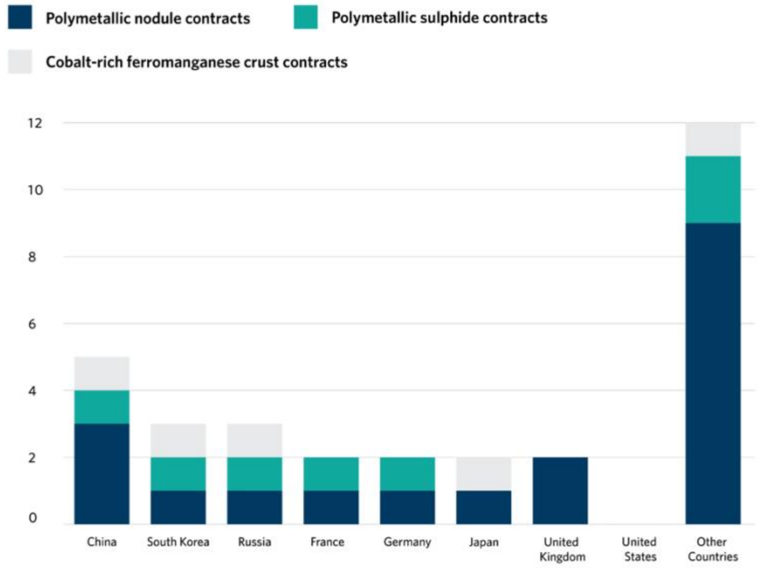
Beyond the EEZs lies the continental shelf, which is declared as the common heritage of mankind and is governed by the International Seabed Authority (ISA) and is open to peaceful use by all states, whether coastal or landlocked (United Nations, 1982). The ISA oversees the exploration and exploitation of resources in the seabed and subsoil, authorizing and supervising activities through an official written work plan that details how exploration and exploitation will be conducted. These activities must comply with the general policies and production limits established in Articles 150 and subsequent articles of the convention (United Nations, 1982). To date, the ISA has granted numerous exploration licenses and signed fifteen-year contracts with twenty-two contractors for the exploration of polymetallic nodules, polymetallic sulfides, and cobalt-rich ferromanganese crusts in deep seabed areas (ISA, 2021). Companies like DeepGreen, now The Metals Company, and nations such as Japan, China, and South Korea are at the forefront of this new industry (The Metals Company, 2024).

However, the environmental impact of deep-sea mining operations is a significant concern. Disturbing the seabed can destroy habitats and disrupt marine ecosystems. Sediment plumes generated by mining activities can spread over vast areas, affecting species that rely on clear water. Additionally, the potential release of toxic substances trapped in the seabed poses a risk to marine life (Reitmeier, 2023). Despite these concerns, several companies and countries are moving forward with exploration and testing. As the race for deep-sea mining intensifies, the geopolitical stakes also rise. Countries and corporations are vying for control over these valuable resources, which could become pivotal in securing the materials needed for the global transition to green energy.

Deep-sea mining activities present significant challenges to the international system, particularly when viewed through neorealism and resource economics theories. Neorealist theory emphasizes the importance of power dynamics and state security in an anarchic international system. The competition for valuable resources crucial for the green energy transition intensifies geopolitical tensions, with major powers like China vying for control. This rivalry turns critical minerals into significant leverage in international diplomacy (Thompson et al., 2018).

China has been the most active player in deep-sea mining, strategically investing in developing the necessary technology for deep-sea exploration and mineral extraction. Additionally, China is exerting significant diplomatic efforts to establish a rules-based system under the ISA. China's influence is particularly notable because other major powers, such as the United States, are not participants in the ISA. As illustrated in the ISA's graph, China holds the majority of the ISA Exploration Contracts. This concentration of influence and control raises significant concerns, as it further intensifies global dependence on critical minerals from a single country with a non-democratic regime (ISA,

Figure 2. China Holds the Most ISA Exploration Contracts



Source: International Seabed Authority.

2023).

Geostrategic pressures and climate urgency are driving higher levels of political pressure on the ISA, as nations push for favorable regulatory frameworks. This dynamic, as articulated by political economic theory, risks fragmenting international standards and compromising environmental regulations (Thompson et al., 2018). Resource economics theory further highlights the economic efficiencies and market dynamics of deep-sea mining, noting that the rush to secure minerals can cause long-term ecological damage and challenge sustainability (Field, 2008). Additionally, the strategic importance of critical minerals is reshaping the geopolitical landscape, potentially leading to new alliances and trade blocs (Thompson et al., 2018). For instance, the European Union has formed partnerships with African nations rich in seabed resources, such as Namibia, to jointly explore and develop these resources.

Balancing the economic benefits with the need for robust international cooperation and regulatory frameworks is essential for ensuring sustainable and equitable access to deep-sea mineral resources (WEF, 2023). This requires a concerted effort to establish comprehensive governance mechanisms that align with neorealist and resource economics principles. To secure diversified, fair, equitable, and resilient global supply chains while minimizing environmental damages, it is crucial to invest in diplomatic efforts in conversations ensuring that licensing agreements are granted to countries capable of complying with ESG goals in their drilling operations and also within their national frameworks. This approach would reflect and upgrade global ESG standards and the green transition. By aligning financial incentives with sustainable practices, we can foster a more balanced and responsible approach to the exploration and exploitation of deep-sea minerals, thereby securing a stable and resilient supply chain for critical minerals, which ultimately ensures the availability of an equitable and affordable green energy supply.

6.3.2.2 SPACE MINING

Space mining has recently emerged as another area of interest regarding critical mineral exploration. Asteroids and other celestial bodies are known to contain vast reserves of valuable metals and minerals. For example, near-Earth asteroids are believed to be rich in platinum-group metals, gold, and various other precious resources (New Space Economy, 2023). Although the idea of mining these celestial bodies has existed for some time,

advancements in space technology have now made it a more realistic and attainable prospect (Brunner, 2021).
Space mining involves several steps, including identifying suitable asteroids, sending robotic probes to extract the minerals, and transporting them back to Earth. The challenges are immense, ranging from the high cost of space missions to the technical difficulties of mining in a zero-gravity environment. However, the rewards could be equally substantial, given that a single asteroid could potentially contain more platinum than has ever been mined in human history (Yarlagadda, 2022).
Several private companies, such as Planetary Resources, Deep Space Industries, and SpaceX, have been established with the goal of pioneering space mining. Planetary Resources aimed to develop robotic asteroid mining technologies (Planetary Resources, 2018), Deep Space Industries focused on developing spacecraft to explore and extract resources from asteroids (Deep Space Industries, 2019), and SpaceX has significantly advanced space technology through its reusable rockets and ambitious missions, making space mining more feasible and economically viable (SpaceX, 2020). These companies have laid the groundwork for space mining, showcasing the potential and commercial viability of extracting resources from celestial bodies. In addition to private companies, national space agencies are also playing a crucial role in the development of space mining. NASA, China National Space Administration and Japan Aerospace Exploration Agency have all demonstrated the feasibility of extracting material from asteroids (CNSA, 2021; JAXA, 2021). Moreover, the European Space Agency (ESA) is also making efforts to include partnerships with private companies to develop technologies for extracting and utilizing space resources (ESA, 2021).
The potential of space mining carries profound geopolitical implications, particularly when viewed through the lens of neorealism. Leading nations and corporations in space mining could gain substantial economic and strategic advantages, potentially dominating the global supply of precious metals and minerals (New Space Economy, 2023). This dominance would not only enhance their economic power but also shift the balance of power in international relations. The strategic significance of controlling space resources parallels the historical importance of terrestrial resources like oil and gas. Consequently, new international alliances and partnerships may form, reshaping global political dynamics (Osburg & Lee, 2022). For instance, space mining could lead to new blocs or coalitions based on shared interests in space exploration and resource extraction, further complicating existing geopolitical alignments.
Moreover, the accelerated development of space technologies, with dual-use potential, could result in advancements in both civilian and military capabilities, raising significant concerns about the militarization of space (Brunner, 2021). The strategic importance of space mining capabilities could lead to the deployment of space-based surveillance and resource control systems, potentially escalating conflicts. Preventing an arms race in outer space is crucial to maintaining global security and stability. From a neorealist perspective, the pursuit of these capabilities is driven by the imperative to maximize relative gains and ensure national security in an uncertain and competitive international environment.
Furthermore, The current regulatory environment, primarily shaped by the Outer Space Treaty, lacks robustness, exacerbating geopolitical tensions. The absence of comprehensive international legal frameworks to address property rights, resource sharing, and environmental protection creates a vacuum that major powers are likely to exploit (DiploFoundation, 2023). An example of this is the U.S. Space Act of 2015, which grants American companies the rights to own and sell resources extracted from space, significantly stimulating interest in space mining (U.S. Government, 2015). This unilateral approach raises concerns similar to those associated with deep-sea resource appropriation due to its lack of democratic oversight and equitable governance. Moreover, many countries that have signed the Outer Space Treaty have yet to ratify the agreement (United

Nations, 1967). This situation is problematic as it reflects a lack of commitment to act in good faith on an international level. Diplomatic efforts to establish fair and sustainable practices could lead to tensions and complex negotiations, as states jockey for advantageous positions. It is imperative that nations invest in diplomatic efforts to develop a universally acceptable framework that ensures space remains a resource for all humankind and is not militarized (DiploFoundation, 2023).

6.3.2.3 ARCTIC AND ANTARCTIC MINING

The Arctic and Antarctic regions represent untapped reservoirs of critical minerals, with the Arctic believed to hold substantial reserves of oil, natural gas, and various minerals, including rare earth elements. Due to the retreat of sea ice caused by climate change, these resources are becoming more accessible. This increased accessibility has led to heightened interest from countries bordering the Arctic, such as Russia, Canada, Denmark, and the United States (European Parliament, 2010). Consequently, the geostrategic implications are significant, as extracting these resources could shift the global balance of power in energy and minerals, providing substantial economic and strategic advantages to countries with Arctic territories. However, the potential environmental risks are vast. Drilling and mining in such a fragile ecosystem could have catastrophic consequences for local wildlife and indigenous communities (Jones & White, 2021).

The significance of the Arctic extends beyond its resource wealth, particularly through the Northern Sea Route (NSR). This shipping lane along Russia’s northern coast is becoming increasingly navigable due to melting sea ice (European Parliament, 2010). The geostrategic implications of the NSR are considerable, offering a shorter passage between Europe and Asia and potentially revolutionizing global trade. The NSR reduces shipping times and diminishes reliance on traditional routes through the Suez Canal, which are susceptible to geopolitical instability and piracy (Thompson et al., 2018). Consequently, the NSR represents a strategic asset for Russia and an opportunity for allied nations. A new trade route can reduce commercial flow prices, positively impacting global supply chains linked to critical mineral use for green energies and digitalization. Therefore, allied nations should encourage diplomatic action to collectively dominate the trade route and resource exploitation, involving northern players like Denmark, Finland, Norway, Sweden, Canada, and the USA, alongside Russia (European Parliament, 2010).

Following the strategic importance of the NSR, Russia has been particularly aggressive in its Arctic ambitions, seeing the region as a strategic area of significant economic and military potential. It has invested heavily in icebreaker ships and other infrastructure to support mineral extraction and shipping routes (Jones & White 2021). By securing control over key Arctic resources and shipping lanes, Russia aims to enhance its economic and military influence in the region. For example, Russia has commissioned a fleet of nuclear-powered icebreakers to ensure year-round navigation of the NSR, facilitating the transport of extracted minerals and hydrocarbons (European Parliament, 2010). This infrastructure is crucial to Russia's broader goal of becoming a dominant player in the Arctic, both economically and militarily. Furthermore, Russia's establishment of new military bases and extensive military exercises in the region have intensified the militarization of the Arctic, adding a layer of tension and prompting concerns among other Arctic nations and NATO members (European Parliament, 2010).

The Arctic’s geopolitical landscape is further complicated by China’s growing interest, framed within its Polar Silk Road initiative. This adds another dimension to the geopolitical dynamics due to significant investments in Arctic infrastructure and research (Jones & White 2021). The geostrategic implications of China's involvement are substantial, as it seeks to expand its influence and secure access to Arctic resources. Consequently, international cooperation is essential to manage the geopolitical tensions and ensure the sustainable development of the Arctic's resources. A collaborative approach would help balance economic interests with environmental protection and geopolitical stability, ensuring that the benefits of Arctic resource extraction are distributed equitably and responsibly.

In response to Russia's and China's increasing presence in the Arctic, the European Union and other Western players are strategically counteracting their influence through a multifaceted approach. This strategy can be analyzed through the lenses of neorealism and liberal institutionalism, which together offer a comprehensive understanding of the actions being taken (European Parliament, 2010).

From a neorealist perspective, the balance of power theory is evident in the increased military presence and strategic investments by Western nations. NATO's augmented military activities and joint exercises in the Arctic are designed to enhance security and deter potential threats from Russia. Similarly, Canada and the United States are expanding their Arctic capabilities by investing in icebreaker fleets and infrastructure, ensuring they maintain strategic mobility and presence in the region. These efforts are aimed at preventing any single power, particularly Russia or China, from achieving dominance in the Arctic.

Concurrently, the European Union's comprehensive Arctic policy emphasizes sustainable development, environmental protection, and international cooperation, reflecting principles of liberal institutionalism. By promoting these values, the EU aims to create a framework for peaceful and sustainable exploitation of Arctic resources. EU member states like Denmark and Sweden are investing in scientific research and infrastructure development to bolster their presence and influence, thereby supporting a cooperative international order.

While the Arctic region is becoming a focal point for geopolitical competition and resource extraction, the Antarctic has traditionally been governed by a different set of principles aimed at preserving its pristine environment. The Antarctic, governed by the Antarctic Treaty System (ATS), has been historically established as a scientific preserve and bans military activity on the continent. The ATS, along with its associated agreements, explicitly prohibits mineral resource activities, except for scientific research (Antarctic Treaty System, 2023). This prohibition reflected the international community's commitment to preserving the Antarctic environment and avoiding the geopolitical tensions that could arise from competing territorial claims (Scholten & Bosman, 2016).

However, as global demand for critical minerals continues to rise, there is growing pressure to reconsider the current stance on the prohibition of mineral resource activities in Antarctica. Geological surveys and remote sensing have indicated that Antarctica's mineral wealth could be substantial, with significant deposits of various minerals, including coal, iron ore, copper, gold, and oil and gas reserves (Jones & White 2021). Consequently, nations with interests in Antarctica, such as the United States, Russia, China, Argentina, Chile, Brazil, and several European countries, are aware of the strategic and economic advantages that could be gained from accessing these resources. Speculatively, their intentions might include securing a share of this mineral wealth to bolster their own economic growth and technological advancements. However, any move to exploit these resources would require a major shift in international policy. For instance, the Madrid Protocol, which currently prohibits mineral extraction, would need to be amended or renegotiated to allow for such activities. This process would necessitate the agreement of all parties to the treaty, making it politically complex and potentially contentious (Antarctic Treaty System, 2023). Therefore, these countries would need to navigate a delicate balance between environmental protection and economic interests, carefully negotiating to ensure that their actions do not provoke geopolitical tensions or environmental degradation (Scholten & Bosman, 2016).

The geopolitical implications of Antarctic mineral extraction are also significant. The potential for resource conflicts and territorial disputes could increase tensions among nations with competing claims and interests in the region. The strategic importance of

Antarctica, coupled with its resource potential, could lead to a new era of geopolitical rivalry and competition, reminiscent of the historical "scramble for Africa," but in a much more environmentally sensitive context (Scholten & Bosman, 2016).

Furthermore, as nations contemplate the exploitation of Antarctica's vast mineral wealth, it is essential to consider the broader environmental and geopolitical ramifications of such activities, especially given that environmental damage extends beyond immediate habitat disruption and poses future geostrategic problems. The Antarctic plays a crucial role in regulating the Earth's climate, and significant industrial activity could have far-reaching impacts on global weather patterns and sea levels (Jones & White 2021). The pristine ice and snow of Antarctica serve as a barometer for climate change, and any industrial activity could accelerate ice melt and contribute to rising sea levels, affecting coastal communities worldwide (Jones & White 2021). This environmental degradation could lead to geopolitical instability as nations grapple with the effects of climate change, including increased migration, food and water scarcity, and heightened competition for natural resources (Ali et al., 2017). Moreover, as the ice melts, new maritime routes could open, making control over these strategic passages a point of contention among global powers. Nations with advanced technological capabilities and significant economic resources may vie for dominance in the Antarctic, potentially leading to a militarization of the region (Jones & White 2021). Additionally, the environmental damage from resource extraction could result in international disputes over responsibility and reparations. According to Jones & White (2021) countries adversely affected by the environmental consequences of Antarctic mining activities might seek compensation or sanctions against the offending nations, further complicating diplomatic relations. The cumulative effect of these factors underscores the urgent need for robust international governance and cooperative strategies to manage the exploitation of Antarctic resources responsibly. Jones and White (2021) emphasize that "ensuring that environmental and geopolitical stability are maintained requires a coordinated international approach." This highlights the importance of maintaining strong environmental and geopolitical stability through effective international cooperation.

7. CONCLUSIONS AND PROPOSALS

7.1 PROJECTED SUPPLY SHORTAGES: INVESTMENT IMPERATIVE

The escalating global demand for critical minerals, driven by the rapid expansion of renewable energy technologies, electric vehicles, energy storage systems, and digitalization, underscores a critical challenge in the green transition (WEF, 2023a). From 2017 to 2022, the market for key minerals expanded significantly, resulting in increased market volatility and higher costs for manufacturers and consumers. This volatility has deterred long-term investments and hindered the development of robust supply chains (IEA, 2023). Projections indicate that the demand for these minerals will double by 2030 in both the Stated Policies Scenario and the Announced Pledges Scenario and nearly triple by 2050 in the Net Zero Emissions by 2050 scenario (IEA, 2023). Despite this rising demand, current investment levels remain insufficient to meet the projected needs by 2035, posing a significant risk to progress toward global climate goals and equitable access to clean energy solutions.

Addressing these investment gaps is imperative. The IEA's NZE scenario suggests that mining production alone will require between $360 billion to $450 billion by 2030, with an additional $90 billion to $210 billion needed for processing (IEA, 2024). Although current investments are increasing, they are still insufficient to meet these requirements. Green finance, including venture capital and initiatives by international development banks, will play a pivotal role in driving the necessary investments (WEF, 2023). The rise in venture capital funding for critical mineral recycling start-ups is promising, but efforts must be significantly scaled up to align with future demand (IEA, 2023). Without substantial increases in strategic investments and production capacities, the critical minerals deficit could make energy and technology unaffordable, hindering the broad adoption of clean energy solutions (WEF, 2024a).

7.2. SUPPLY CHAIN RISKS: GEOGRAPHICAL CONCENTRATION

The analysis of the current supply of critical minerals reveals substantial risks associated with geographical concentration and supply chain dependencies. Both the extraction and refinement processes underscore critical vulnerabilities within global supply chains, highlighting significant concerns for the stability and resilience of mineral supply necessary for various industries (WEF, 2023a).

In terms of global extraction concentration, the production of critical minerals is dominated by a few major players. China has established near-monopolistic control over the extraction of natural graphite and rare earth elements. Similarly, the DRC dominates cobalt production, while Indonesia and the Philippines control a significant portion of nickel production. Although lithium and copper extraction is more geographically diversified, with major contributions from Australia, Chile, and Peru, they still exhibit regional dependencies that could disrupt supply chains in the event of localized issues (IEA, 2024).

This geographical concentration of essential minerals presents several risks. Geopolitical tensions, trade restrictions, or policy changes could lead to severe disruptions in the global supply of these critical materials, potentially hampering technological and green energy advancements worldwide. Additionally, monopolistic and oligopolistic market structures typically lead to price increases. Moreover, control over mineral resources can be leveraged as a political tool, further complicating international relations and economic stability.

Another pressing concern is China's dominance in the refining of critical minerals. This concentration in refining indicates that even if raw materials are extracted globally, they frequently require processing in China, thereby increasing reliance on a single nation. Consequently, any geopolitical tensions or policy changes in China could disrupt global supply chains, adversely affecting the production of high-tech and clean energy products. This risk was evidenced during China's zero-COVID policies, which already caused significant disruptions (CSIS, 2023). Furthermore, China’s strategic investments in mining and refining assets worldwide, coupled with its investments in key technology for exploring in the deep sea, and sky, position it as a pivotal player in the critical minerals market (FactSet, 2023). This dominance enables China to influence global market trends and economic stability, thereby creating strategic vulnerabilities for countries dependent on these supplies (Jones & White 2021).

The energy transition and equitable access to energy depend on a resilient supply chain for critical minerals. Consequently, it is crucial that no single country controls more than 30% of the supply (Hotelling, 1931). Achieving this necessitates developing multiple producers and refining capacities across diverse regions. Furthermore, cooperative agreements and strategic partnerships are essential to manage trade policy risks and geopolitical tensions. Distributing production and refining more evenly will reduce dependence on China's refining capabilities. This approach will ultimately ensure a balanced and secure supply chain, thereby supporting a sustainable energy transition (WEF, 2023a).

7.3. ESG CONSIDERATIONS

The rapidly escalating demand for critical minerals underscores the imperative to address the extensive ESG implications associated with their supply chains.

Firstly, mining operations for critical minerals have profound environmental impacts, including substantial water usage, greenhouse gas emissions, biodiversity loss, and pollution of water, land, and air (IEA, 2023). The industry's reliance on water, particularly in arid regions, makes it highly susceptible to water scarcity, which can halt production and disrupt supply chains. The increased demand for minerals like lithium and copper, often found in water-stressed areas, further exacerbates this issue (IEA, 2023). Moreover, mining operations contribute significantly to greenhouse gas emissions, with processes often powered by fossil fuels. The carbon footprint of critical minerals such as cobalt and nickel highlights the paradox of using high-emission processes to support low-emission technologies (IEA, 2023). Furthermore, regulatory pressures like carbon taxes can elevate operational costs, potentially making some mining operations economically unfeasible and affecting the affordability of green technologies (WEF, 2023). This regulatory dilemma should be debated, as it pits environmental protection against the economic feasibility of sustainable energy solutions (Ali et al., 2017).

In addition, the impact of mining on biodiversity is particularly concerning. The destruction of habitats, disruption of ecosystems, and pollution resulting from mining activities contribute to a loss of biodiversity that contradicts the environmental goals of the green transition. The consequences of these environmental issues include diminished ecosystem services, increased climate vulnerability, and long-term ecological damage (IEA, 2023). Furthermore, regulatory frameworks aiming to protect biodiversity, while necessary, can also delay the approval of new mining projects, thereby complicating the timely supply of critical minerals. This regulatory dilemma requires careful consideration, as it balances the urgent need for critical minerals with the imperative to protect biodiversity (IEA, 2023).

Socially, the mining industry faces numerous challenges, including worker safety incidents, human rights abuses, and adverse effects on local communities and Indigenous Peoples. Addressing these concerns is essential for maintaining a stable workforce and ethical supply chains, as failure to do so can result in labor strikes, decreased productivity, and legal actions, further increasing costs (IEA, 2023). Additionally, mining activities often lead to displacement, habitat loss, and pollution, causing social unrest and confrontations that can halt operations and escalate expenses (IEA, 2023). Engaging with communities and obtaining their free, prior, and informed consent is crucial for maintaining the social license to operate and ensuring smooth supply chain functioning (IEA, 2023). Ignoring these aspects can lead to project delays, increased security costs, and loss of social capital, ultimately affecting the profitability and viability of mining projects (IEA, 2023).

Furthermore, governance issues, particularly corruption, pose significant risks to the critical minerals supply chain. High levels of corruption in many resource-rich countries hinder investment and development of new mining projects, destabilizing supply chains and limiting economic growth (WEF, 2023). Moreover, corruption diverts resources from essential public investments, undermining the potential benefits of mining for local communities and fostering distrust and opposition (IEA, 2023).

7.4 CHALLENGES OF MINING IN UNCLAIMED TERRITORIES

The global race for critical minerals has reached unprecedented frontiers, encompassing unexplored territories such as the deep sea, outer space, and the polar regions of the Arctic and Antarctic.

The pursuit of deep-sea mining presents significant geopolitical consequences, as countries and corporations compete for control over valuable resources crucial for the global transition to green energy. This competition intensifies tensions and may lead to conflicts over maritime boundaries and exclusive economic zones (Thompson et al., 2018). Moreover, China's leading role in deep-sea exploration technology has positioned it as the primary beneficiary of ISA contracts and a major rule-setter in this domain. As nations push for regulatory frameworks that favor their interests, the governance of deep-sea mining under the ISA may come under scrutiny, potentially leading to a fragmentation of international standards (ISA, 2023). Additionally, the pressure to secure these minerals could result in compromised environmental regulations, causing long-term ecological damage that transcends national boundaries (IRENA, 2023). The strategic importance of these resources may also lead to the formation of new alliances and trade blocs, further reshaping the global geopolitical landscape (Thompson et al., 2018). Therefore, robust international cooperation and comprehensive regulatory frameworks are essential to managing the geopolitical and environmental impacts of deep-sea mining effectively (WEF, 2023).

In parallel, The potential of space mining holds significant geopolitical implications. Specifically, leading nations and corporations in space mining could gain substantial economic and strategic advantages, potentially dominating the global supply of precious metals and minerals (Brunner, 2021). Consequently, new international alliances and partnerships may form, reshaping global political dynamics (ESA, 2021). Moreover, the accelerated development of dual-use space technologies is raising concerns about the militarization of space and a potential arms race (Brunner, 2021). This concerning issue, coupled with country initiatives to legislate in favor of obtaining space resources, has sparked a diplomatic battlefield over the use and ownership of space. However, the current regulatory environment, primarily shaped by the Outer Space Treaty, lacks robustness, necessitating comprehensive international legal frameworks to address property rights, resource sharing, and environmental protection (Yarlagadda, 2022).

Furthermore, The Arctic and Antarctic regions present significant geopolitical implications due to their potential for critical mineral extraction. In the Arctic, diminishing sea ice from climate change has made vast reserves of oil, natural gas, and minerals more accessible, attracting intense interest from bordering nations like Russia, Canada, Denmark, and the United States (European Parliament, 2010). Moreover, the melting sea ice is opening new trade routes, such as the Northern Sea Route, which offers a shorter passage between Europe and Asia and has significant strategic and economic potential (European Parliament, 2010). Russia, in particular, has aggressively pursued its Arctic ambitions, heavily investing in infrastructure and icebreaker ships to support extraction and shipping routes (Jones & White, 2021). This competition among key players for influence in the strategically crucial Arctic region could lead to geopolitical tensions and increased militarization, as nations seek to secure their (Jones & White, 2021). Conversely, the Antarctic remains largely protected under the ATS, which prohibits mineral resource activities to preserve its pristine environment (Antarctic Treaty System, 2023). However, the rising global demand for critical minerals has sparked calls for reconsidering this stance, posing potential environmental and geopolitical risks (Jones & White, 2021). The pressure to explore and possibly exploit Antarctic resources challenges the existing international agreements, potentially leading to conflicts over resource control (IRENA, 2023). The strategic importance of both polar regions, combined with the environmental and geopolitical stakes, underscores the need for robust international cooperation to manage these areas sustainably and prevent conflicts (European Parliament, 2010).

7.5 PROPOSAL ON STRATEGIC INVESTMENTS AND INTERNATIONAL COOPERATION:

Achieving environmental goals while maintaining peace and strategic sovereignty necessitates targeted investments. Strategic investments are critical for expediting the acquisition of critical minerals and enhancing supply chain resilience through diversified activities in exploration, extraction, refining, and innovation, particularly in critical mineral recycling research (WEF, 2023b).

To this end, public investments must be diversified across all stages of the critical mineral supply chain, encompassing exploration, extraction, refining, and recycling. Concurrently, private investment should be incentivized to focus on the supply chain rather than solely on the development of renewable technologies (WEF, 2023b). This comprehensive

approach ensures that the foundational components of green technologies are robustly supported (IRENA, 2023).
Furthermore, investments should be tailored to the specific needs of each country or region. This entails a thorough assessment of each country's energy mix, renewable energy consumption, and potential for expansion, promoting less resource-intensive renewable energy sources where feasible (e.g., prioritizing solar over wind). It is imperative for countries to consider the costs, supply chain robustness, and criticality of the required minerals for the promoted renewable technologies.
To facilitate these initiatives, countries could implement fiscal incentives, including subsidies, tax breaks, and favorable regulatory frameworks, to encourage private investments across all phases of the critical mineral supply chain. Additionally, fostering international alliances and partnerships for cross-border investments and shared technological advancements is essential (WEF, 2023) Establishing refining capabilities in diverse locations and integrating them into strategic national plans will further mitigate reliance on external sources.
Moreover, investment in advanced machinery and innovative extraction technologies is crucial to augment domestic capacities. Increasing funding for research and development in recycling technologies will diminish dependence on new mining operations, thereby reducing external dependencies (Rademaker, Kleijn, & Yang, 2013). Furthermore, promoting circular economy principles will enhance sustainability and resource efficiency. By adopting these comprehensive measures, countries can ensure a balanced and resilient supply chain for critical minerals. Consequently, this strategy will support a sustainable energy transition while significantly reducing dependence on external sources (European Commission, 2023b).

7.6 PROPOSAL ON DIPLOMATIC STRATEGIC FOR UNCLAIMED TERRITORIES

Given the ongoing race to secure access to critical minerals in unexplored territories, it is imperative for countries to invest in diplomatic efforts to ensure equitable access and responsible practices. To achieve this, international agreements must govern the exploration and extraction of critical minerals in regions beyond national jurisdiction. This governance should include the oversight of activities in unclaimed territories, the issuance of permits, monitoring compliance with environmental standards, and enforcing regulations to prevent monopolization of resources (DiploFoundation, 2023).
Countries should promote international frameworks that grant licenses only to companies adhering to stringent ESG standards. These standards should ensure compliance not only in their operations but also within their home countries, thereby fostering sustainable and equitable mineral extraction. Moreover, it is crucial to invest in exploratory efforts to make missions as ownership-diversified as possible, ensuring that no single country or group of countries gains dominant control over these valuable resources (WEF, 2023).
Additionally, nations must anticipate and prepare for conflicts over property rights and the governance of new sea routes. These conflicts are likely to arise as the strategic importance of these routes becomes more apparent. By investing in diplomatic initiatives, countries can be better equipped to address these disputes in the international arena, promoting peaceful and cooperative resolutions (Ali et al., 2017).
In summary, securing access to critical minerals in unexplored territories requires a multifaceted approach. This includes diplomatic efforts to establish and enforce international agreements, promoting stringent ESG standards, diversifying ownership in exploratory missions, and preparing for potential conflicts over new sea routes (IEA, 2023).

7.7 ESG PROPOSAL

Achieving a sustainable future necessitates the adoption of sustainable practices, ensuring that efforts toward greater sustainability are not counterproductive. Given the interconnectedness of the global community, it is imperative to establish a global commitment to ESG standards across the critical mineral supply chain. To this end, supporting initiatives such as the Global Reporting Initiative and facilitating public debate are crucial steps toward this goal (GRI, 2023).

Moreover, implementing governance standards requires addressing the policy dilemmas generated by ESG implementation. This includes balancing the urgent need for renewable energy with the imperative to protect the environment, uphold social equity, and maintain robust governance standards (IEA, 2023). Furthermore, it is essential to navigate the economic considerations introduced by carbon taxes and other regulations aimed at environmental protection.

Engaging in transparent discussions about the economic, social, and environmental costs of the green transition is vital for informing policies that support an equitable and effective transition. Consequently, granting the public a voice in the implementation of ESG standards will help prevent backlash and ensure that these standards are robust and widely accepted. By fostering inclusive dialogue and cooperation, we can create a framework that not only promotes sustainability but also addresses the diverse concerns and needs of all stakeholders involved. This holistic approach is essential for achieving a sustainable future that is both environmentally sound and socially equitable (IEA, 2023).

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9. ANNEX

Material	Application	Share	NACE sector	VA
Aggregates	Construction	100%	C23 - Manufacture of other non-metallic mineral products	57,255
Aluminium	Construction	23%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Aluminium	Mobility (Transport and Automotive)	21%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Aluminium	Mobility (Transport and Automotive)	21%	C30 - Manufacture of other transport equipment	44,304
Aluminium	Packaging	17%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Aluminium	High Tech Engineering	12%	C28 - Manufacture of machinery and equipment n.e.c.	182,589
Aluminium	Consumer Durables	6%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Antimony	Flame retardants	43%	C20 - Manufacture of chemicals and chemical products	105,514
Antimony	Lead-acid batteries	32%	C27 - Manufacture of electrical equipment	80,745
Antimony	Lead alloys	14%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Antimony	Plastics (catalysts and stabilisers)	6%	C20 - Manufacture of chemicals and chemical products	105,514
Antimony	Glass and ceramics	5%	C23 - Manufacture of other non-metallic mineral products	57,255
Arsenic	Zinc production	71%	C24 - Manufacture of basic metals	55,426
Arsenic	Glassmaking	18%	C23 - Manufacture of other non-metallic mineral products	57,255
Arsenic	Chemicals	7%	C20 - Manufacture of chemicals and chemical products	105,514
Arsenic	Alloys	5%	C24 - Manufacture of basic metals	55,426
Arsenic	Electronics	0%	C26 - Manufacture of computer, electronic and optical products	65,703
Baryte	Weighting agent in oil and gas well drilling fluids or "muds"	60%	C23 - Manufacture of other non-metallic mineral products	57,255
Baryte	Filler in rubbers, plastics, paints & paper	30%	C22 - Manufacture of rubber and plastic products	75,980
Baryte	Chemical industry	10%	C20 - Manufacture of chemicals and chemical products	105,514
Bauxite	Refining to alumina	90%	C24 - Manufacture of basic metals	55,426

Material	Application	Share	NACE sector	VA
Bauxite	Refractories	3%	C23 - Manufacture of other non-metallic mineral products	57,255
Bauxite	Cement	3%	C23 - Manufacture of other non-metallic mineral products	57,255
Bauxite	Abrasives	2%	C23 - Manufacture of other non-metallic mineral products	57,255
Bauxite	Chemicals	2%	C20 - Manufacture of chemicals and chemical products	105,514
Bentonite	Pet litter	34%	C23 - Manufacture of other non-metallic mineral products	57,255
Bentonite	Foundry molding sands	22%	C24 - Manufacture of basic metals	55,426
Bentonite	Civil engineering	13%	C23 - Manufacture of other non-metallic mineral products	57,255
Bentonite	Food and wine production	3%	C11 - Manufacture of beverages	32,505
Bentonite	Pelletizing of iron ore	8%	C24 - Manufacture of basic metals	55,426
Bentonite	Oil absorbents	8%	C20 - Manufacture of chemicals and chemical products	105,514
Bentonite	Paper	3%	C17 - Manufacture of paper and paper products	38,910
Bentonite	Specialties and drilling fluids	7%	B09 - Mining support service activities	3,400
Bentonite	Others	2%	C20 - Manufacture of chemicals and chemical products	105,514
Beryllium	Electronic and telecommunications equipments	42%	C26 - Manufacture of computer, electronic and optical products	65,703
Beryllium	Transport and Defence : Vehicle electronics	17%	C26 - Manufacture of computer, electronic and optical products	65,703
Beryllium	Transport and Defence : Auto components	17%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Beryllium	Transport and Defence : Aerospace components	10%	C30 - Manufacture of other transport equipment	44,304
Beryllium	Energy application	8%	C26 - Manufacture of computer, electronic and optical products	65,703
Beryllium	Industrial components : Moulds	3%	C28 - Manufacture of machinery and equipment n.e.c.	182,589
Beryllium	Industrial components : Metal	3%	C24 - Manufacture of basic metals	55,426
Beryllium	Others	0%	0	0
Bismuth	Chemicals	62%	C20 - Manufacture of chemicals and chemical products	105,514
Bismuth	Low-melting alloys	28%	C32 - Other manufacturing	39,160
Bismuth	Metallurgical additives	10%	C24 - Manufacture of basic metals	55,426
Borate	Glass	55%	C23 - Manufacture of other non-metallic mineral products	57,255

Material	Application	Share	NACE sector	VA
Borate	Frits and Ceramics	17%	C23 - Manufacture of other non-metallic mineral products	57,255
Borate	Fertilisers	15%	C20 - Manufacture of chemicals and chemical products	105,514
Borate	Chemicals manufacture	4%	C20 - Manufacture of chemicals and chemical products	105,514
Borate	Construction materials (flame retardants, plasters, wood preservatives)	4%	C20 - Manufacture of chemicals and chemical products	105,514
Borate	Metals	4%	C24 - Manufacture of basic metals	55,426
Borate	Other	0%	0	0
Cadmium	Batteries	80%	C27 - Manufacture of electrical equipment	80,745
Cadmium	Pigments	11%	C20 - Manufacture of chemicals and chemical products	105,514
Cadmium	Coatings	7%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Cadmium	Stabilizers	2%	C20 - Manufacture of chemicals and chemical products	105,514
Cadmium	Others	0%	0	0
Cerium	Autocatalysts	35%	C20 - Manufacture of chemicals and chemical products	105,514
Cerium	Glass&Ceramics	33%	C23 - Manufacture of other non-metallic mineral products	57,255
Cerium	Polishing powders	11%	C26 - Manufacture of computer, electronic and optical products	65,703
Cerium	Fluid Cracking Catalysts	8%	C19 - Manufacture of coke and refined petroleum products	17,289
Cerium	Metal (excl. Batteries)	6%	C24 - Manufacture of basic metals	55,426
Cerium	Batteries	6%	C27 - Manufacture of electrical equipment	80,745
Cerium	Lighting	1%	C27 - Manufacture of electrical equipment	80,745
Chromium	Products made of Stainless Steel	74%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Chromium	Products made of Alloy Steel	19%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Chromium	Casting Molds	3%	C24 - Manufacture of basic metals	55,426
Chromium	Products made of chromium chemicals	3%	C20 - Manufacture of chemicals and chemical products	105,514
Chromium	Refractory bricks and mortars	1%	C23 - Manufacture of other non-metallic mineral products	57,255

Material	Application	Share	NACE sector	VA
Chromium	Other uses	0%	0	0
Cobalt	Superalloys, hardfacing/HSS and other alloys	36%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Cobalt	Hard materials (carbides and diamond tools)	14%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Cobalt	Pigments and Inks	13%	C20 - Manufacture of chemicals and chemical products	105,514
Cobalt	Catalysts	12%	C20 - Manufacture of chemicals and chemical products	105,514
Cobalt	Tyre adhesives and paint dryers	11%	C20 - Manufacture of chemicals and chemical products	105,514
Cobalt	Magnets	7%	C27 - Manufacture of electrical equipment	80,745
Cobalt	Other – Biotech, Surface Treatment, etc	6%	C20 - Manufacture of chemicals and chemical products	105,514
Cobalt	Battery	3%	C27 - Manufacture of electrical equipment	80,745
Coking coal	Coke for steel production	82%	C24 - Manufacture of basic metals	55,426
Coking coal	Coke for other applications	9%	C23 - Manufacture of other non-metallic mineral products	57,255
Coking coal	Other uses (tar, benzole, electricity and heat)	8%	C20 - Manufacture of chemicals and chemical products	105,514
Copper	Automotive	6%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Copper	Digital appliances	14%	C26 - Manufacture of computer, electronic and optical products	65,703
Copper	Jewellery	5%	C32 - Other manufacturing	39,160
Copper	Ships, trucks and armored vehicles	10%	C20 - Manufacture of chemicals and chemical products	105,514
Copper	Subparts of interior	2%	C31 - Manufacture of furniture	26,171
Copper	Oxides and dopants	3%	C20 - Manufacture of chemicals and chemical products	105,514
Copper	Electrolytic refined copper	2%	C24 - Manufacture of basic metals	55,426
Copper	Components and household	22%	C27 - Manufacture of electrical equipment	80,745
Copper	Tubes, plates, wire	21%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Copper	Machinery	15%	C28 - Manufacture of machinery and equipment n.e.c.	182,589
Diatomite	Food industry	48%	C11 - Manufacture of beverages	32,505

Material	Application	Share	NACE sector	VA
Diatomite	Pelletizing iron ore	23%	C23 - Manufacture of other non-metallic mineral products	57,255
Diatomite	Activated raw granules	13%	C23 - Manufacture of other non-metallic mineral products	57,255
Diatomite	Pet litter	7%	C23 - Manufacture of other non-metallic mineral products	57,255
Diatomite	Civil engineering	6%	C23 - Manufacture of other non-metallic mineral products	57,255
Diatomite	Drilling fluids	2%	B09 - Mining support service activities	3,400
Diatomite	Foundry molding sands	1%	C24 - Manufacture of basic metals	55,426
Dysprosium	Magnets	100%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Erbium	Glass - Optical applications	74%	C23 - Manufacture of other non-metallic mineral products	57,255
Erbium	Lighting	26%	C27 - Manufacture of electrical equipment	80,745
Europium	Lighting	100%	C27 - Manufacture of electrical equipment	80,745
Feldspar	Ceramics (tiles, sanitaryware, tableware, glazes)	45%	C23 - Manufacture of other non-metallic mineral products	57,255
Feldspar	Glass (container, float, fiberglass, specialties)	6%	C23 - Manufacture of other non-metallic mineral products	57,255
Feldspar	Constructions, brick, tiles	46%	C23 - Manufacture of other non-metallic mineral products	57,255
Feldspar	Others	3%	0	0
Fluorspar	Steel and iron making	36%	C24 - Manufacture of basic metals	55,426
Fluorspar	Refrigeration and air conditioning	9%	C27 - Manufacture of electrical equipment	80,745
Fluorspar	Refrigeration and air conditioning	9%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Fluorspar	Aluminium making and other metallurgy	15%	C24 - Manufacture of basic metals	55,426
Fluorspar	Solid fluoropolymers for cookware coating and cable insulation	11%	C27 - Manufacture of electrical equipment	80,745
Fluorspar	Fluorochemicals	10%	C20 - Manufacture of chemicals and chemical products	105,514
Fluorspar	UF6 in nuclear uranium fuel	6%	C24 - Manufacture of basic metals	55,426
Fluorspar	HF in alkylation process for oil refining	3%	C19 - Manufacture of coke and refined petroleum products	17,289
Gadolinium	Magnets	38%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Gadolinium	Metal (excl. Batteries)	30%	C24 - Manufacture of basic metals	55,426

Material	Application	Share	NACE sector	VA
Gadolinium	Lighting	25%	C27 - Manufacture of electrical equipment	80,745
Gadolinium	Magnetic Resonance Imaging - MRI	8%	C21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations	80,180
Gadolinium	Other	0%	0	0
Gallium	Integrated circuits	70%	C26 - Manufacture of computer, electronic and optical products	65,703
Gallium	Lighting	25%	C27 - Manufacture of electrical equipment	80,745
Gallium	CIGS solar cells	5%	C26 - Manufacture of computer, electronic and optical products	65,703
Germanium	Infrared optics	47%	C26 - Manufacture of computer, electronic and optical products	65,703
Germanium	Optical fibres	40%	C27 - Manufacture of electrical equipment	80,745
Germanium	Satellite solar cells	13%	C26 - Manufacture of computer, electronic and optical products	65,703
Germanium	Others	0%	0	0
Gold	Jewellery	86%	C32 - Other manufacturing	39,160
Gold	Electronics	11%	C26 - Manufacture of computer, electronic and optical products	65,703
Gold	Other industrial applications	2%	C32 - Other manufacturing	39,160
Gold	Dental	1%	C32 - Other manufacturing	39,160
Gypsum	Plasterboard and Wallboard	51%	C23 - Manufacture of other non-metallic mineral products	57,255
Gypsum	Building plaster	26%	C23 - Manufacture of other non-metallic mineral products	57,255
Gypsum	Cement production	17%	C23 - Manufacture of other non-metallic mineral products	57,255
Gypsum	Agriculture	6%	C23 - Manufacture of other non-metallic mineral products	57,255
Hafnium	Superalloy	61%	C24 - Manufacture of basic metals	55,426
Hafnium	Catalyst precursor	7%	C20 - Manufacture of chemicals and chemical products	105,514
Hafnium	Plasma cutting tips	15%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Hafnium	Nuclear control rod	11%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Hafnium	Oxide for Optical	3%	C26 - Manufacture of computer, electronic and optical products	65,703
Hafnium	Semiconductors	3%	C26 - Manufacture of computer, electronic and optical products	65,703

Material	Application	Share	NACE sector	VA
Hafnium	Others	0%	0	0
Helium	Controlled atmospheres	23%	C24 - Manufacture of basic metals	55,426
Helium	Cryogenics	22%	C32 - Other manufacturing	39,160
Helium	Balloons	14%	C32 - Other manufacturing	39,160
Helium	Pressurisation and purging	9%	C32 - Other manufacturing	39,160
Helium	Analysis	9%	C32 - Other manufacturing	39,160
Helium	Welding	8%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Helium	Semiconductors, optic fibres	8%	C26 - Manufacture of computer, electronic and optical products	65,703
Helium	Leak detection	7%	C33 - Repair and installation of machinery and equipment	52,332
Ho, Tm, Lu, Yb	Glass - Optical applications	100%	C26 - Manufacture of computer, electronic and optical products	65,703
Hydrogen	Ammonia production	50%	C20 - Manufacture of chemicals and chemical products	105,514
Hydrogen	Refineries	30%	C19 - Manufacture of coke and refined petroleum products	17,289
Hydrogen	Methanol production	13%	C20 - Manufacture of chemicals and chemical products	105,514
Hydrogen	Metal processing	6%	C24 - Manufacture of basic metals	55,426
Hydrogen	Others	1%	C32 - Other manufacturing	39,160
Indium	Flat panel displays	60%	C26 - Manufacture of computer, electronic and optical products	65,703
Indium	Solders	11%	C26 - Manufacture of computer, electronic and optical products	65,703
Indium	PV cells	9%	C26 - Manufacture of computer, electronic and optical products	65,703
Indium	Thermal interface material	7%	C26 - Manufacture of computer, electronic and optical products	65,703
Indium	Batteries	5%	C27 - Manufacture of electrical equipment	80,745
Indium	Alloys/compounds	4%	C24 - Manufacture of basic metals	55,426
Indium	Semiconductors & LEDs	3%	C26 - Manufacture of computer, electronic and optical products	65,703
Indium	Other	0%	0	0
Iridium	Electrochemical	48%	C20 - Manufacture of chemicals and chemical products	105,514
Iridium	Other	0%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603

Material	Application	Share	NACE sector	VA
Iridium	Electronics	39%	C26 - Manufacture of computer, electronic and optical products	65,703
Iridium	Chemical	13%	C20 - Manufacture of chemicals and chemical products	105,514
Iron ore	Steel in Construction	35%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Iron ore	Steel in Automotive	20%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Iron ore	Steel in Mechanical engineering	15%	C28 - Manufacture of machinery and equipment n.e.c.	182,589
Iron ore	Steel in Metalware	14%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Iron ore	Steel in Tubes	11%	C24 - Manufacture of basic metals	55,426
Iron ore	Steel in Domestic appliances	2%	C28 - Manufacture of machinery and equipment n.e.c.	182,589
Iron ore	Steel in Other transport	2%	C30 - Manufacture of other transport equipment	44,304
Iron ore	Other	0%	0	0
Kaolin clay	Ceramics	47%	C23 - Manufacture of other non-metallic mineral products	57,255
Kaolin clay	Paper	29%	C17 - Manufacture of paper and paper products	38,910
Kaolin clay	Fiberglass	6%	C23 - Manufacture of other non-metallic mineral products	57,255
Kaolin clay	Refractories	5%	C23 - Manufacture of other non-metallic mineral products	57,255
Kaolin clay	Catalysts	4%	C19 - Manufacture of coke and refined petroleum products	17,289
Kaolin clay	Others	4%	0	0
Kaolin clay	Paints and adhesives	4%	C20 - Manufacture of chemicals and chemical products	105,514
Kaolin clay	Rubber and plastics	1%	C22 - Manufacture of rubber and plastic products	75,980
Kaolin clay	Cement	1%	C23 - Manufacture of other non-metallic mineral products	57,255
Lanthanum	Fluid Cracking Catalysts	67%	C19 - Manufacture of coke and refined petroleum products	17,289
Lanthanum	Glass&Ceramics	13%	C23 - Manufacture of other non-metallic mineral products	57,255
Lanthanum	Batteries	10%	C27 - Manufacture of electrical equipment	80,745
Lanthanum	Polishing powders	5%	C26 - Manufacture of	65,703

Material	Application	Share	NACE sector	VA
			computer, electronic and optical products	
Lanthanum	Metal (excl.Batteries)	3%	C24 - Manufacture of basic metals	55,426
Lanthanum	Lighting	2%	C27 - Manufacture of electrical equipment	80,745
Lead	Batteries	84%	C27 - Manufacture of electrical equipment	80,745
Lead	Rolled and extruded products	6%	C24 - Manufacture of basic metals	55,426
Lead	Lead compounds	4%	C20 - Manufacture of chemicals and chemical products	105,514
Lead	Shot/ammunition	4%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Lead	Cable sheathing	1%	C27 - Manufacture of electrical equipment	80,745
Lead	Alloys and solders	1%	C24 - Manufacture of basic metals	55,426
Limestone	Cement & concrete, plaster & mortar, roadworks	31%	C23 - Manufacture of other non-metallic mineral products	57,255
Limestone	Manufacture of basic metals	8%	C24 - Manufacture of basic metals	55,426
Limestone	Paper, plastics and rubber	31%	C20 - Manufacture of chemicals and chemical products	105,514
Limestone	Agriculture	5%	C20 - Manufacture of chemicals and chemical products	105,514
Limestone	Others (Glass & ceramics,chemicals, water treatment)	6%	C23 - Manufacture of other non-metallic mineral products	57,255
Limestone	Paint, coating, adhesives	6%	C20 - Manufacture of chemicals and chemical products	105,514
Limestone	Flue Gas Desulfurisation	9%	E39 - Remediation activities and other waste management services	1,301
Limestone	Feed	4%	C10 - Manufacture of food products	155,880
Lithium	Glass and ceramics	66%	C23 - Manufacture of other non-metallic mineral products	57,255
Lithium	Lubricating greases	9%	C20 - Manufacture of chemicals and chemical products	105,514
Lithium	Cement production	9%	C23 - Manufacture of other non-metallic mineral products	57,255
Lithium	Steel casting	5%	C24 - Manufacture of basic metals	55,426
Lithium	Pharmaceutical products	4%	C21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations	80,180
Lithium	Rubber and plastics production	4%	C22 - Manufacture of rubber and plastic products	75,980
Lithium	Al-Li alloys	2%	C25 - Manufacture of fabricated metal products,	148,351

Material	Application	Share	NACE sector	VA
			except machinery and equipment	
Lithium	Batteries and products containing batteries	1%	C27 - Manufacture of electrical equipment	80,745
Magnesite	Steel making	57%	C24 - Manufacture of basic metals	55,426
Magnesite	Paper industry	12%	C17 - Manufacture of paper and paper products	38,910
Magnesite	Cement making	9%	C23 - Manufacture of other non-metallic mineral products	57,255
Magnesite	Agriculture (1 of 2)	7%	C20 - Manufacture of chemicals and chemical products	105,514
Magnesite	Agriculture (2 of 2)	7%	C10 - Manufacture of food products	155,880
Magnesite	Ceramics	5%	C23 - Manufacture of other non-metallic mineral products	57,255
Magnesite	Glass making	3%	C23 - Manufacture of other non-metallic mineral products	57,255
Magnesite	Others	0%	0	0
Magnesium	Transportation (Automotive)	50%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Magnesium	Packaging	21%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Magnesium	Desulfurisation agent	12%	C24 - Manufacture of basic metals	55,426
Magnesium	Construction	13%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Magnesium	Transportation (Air, Marine, Train)	4%	C30 - Manufacture of other transport equipment	44,304
Magnesium	Other applications	0%	0	0
Manganese	Steel (construction)	25%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Manganese	Steel (automotive)	14%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Manganese	Steel (mechanical engineering)	13%	C24 - Manufacture of basic metals	55,426
Manganese	Steel (structural steelworks)	11%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Manganese	Steel (tubes)	10%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351

Material	Application	Share	NACE sector	VA
			except machinery and equipment	
Lithium	Batteries and products containing batteries	1%	C27 - Manufacture of electrical equipment	80,745
Magnesite	Steel making	57%	C24 - Manufacture of basic metals	55,426
Magnesite	Paper industry	12%	C17 - Manufacture of paper and paper products	38,910
Magnesite	Cement making	9%	C23 - Manufacture of other non-metallic mineral products	57,255
Magnesite	Agriculture (1 of 2)	7%	C20 - Manufacture of chemicals and chemical products	105,514
Magnesite	Agriculture (2 of 2)	7%	C10 - Manufacture of food products	155,880
Magnesite	Ceramics	5%	C23 - Manufacture of other non-metallic mineral products	57,255
Magnesite	Glass making	3%	C23 - Manufacture of other non-metallic mineral products	57,255
Magnesite	Others	0%	0	0
Magnesium	Transportation (Automotive)	50%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Magnesium	Packaging	21%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Magnesium	Desulfurisation agent	12%	C24 - Manufacture of basic metals	55,426
Magnesium	Construction	13%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Magnesium	Transportation (Air, Marine, Train)	4%	C30 - Manufacture of other transport equipment	44,304
Magnesium	Other applications	0%	0	0
Manganese	Steel (construction)	25%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Manganese	Steel (automotive)	14%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Manganese	Steel (mechanical engineering)	13%	C24 - Manufacture of basic metals	55,426
Manganese	Steel (structural steelworks)	11%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Manganese	Steel (tubes)	10%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351

Material	Application	Share	NACE sector	VA
Nickel	Metal goods (Steel)	21%	C24 - Manufacture of basic metals	55,426
Nickel	Transport (Steel)	19%	C30 - Manufacture of other transport equipment	44,304
Nickel	Electrical and Electronics (Steel)	11%	C27 - Manufacture of electrical equipment	80,745
Nickel	Building and construction (Steel)	10%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Niobium	Automotive (Steel)	23%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Niobium	Construction (Steel)	45%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Niobium	Stainless Steel	10%	C24 - Manufacture of basic metals	55,426
Niobium	Oil & Gas	17%	C24 - Manufacture of basic metals	55,426
Niobium	Special Steel	3%	C30 - Manufacture of other transport equipment	44,304
Palladium	Autocatalyst	87%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Palladium	Electronics	4%	C26 - Manufacture of computer, electronic and optical products	65,703
Palladium	Chemical	4%	C20 - Manufacture of chemicals and chemical products	105,514
Palladium	Dental	2%	C32 - Other manufacturing	39,160
Palladium	Jewellery	2%	C32 - Other manufacturing	39,160
Palladium	Other	0%	0	0
Palladium	Investment	0%	0	0
Perlite	Building construction products	59%	C23 - Manufacture of other non-metallic mineral products	57,255
Perlite	Filter aid	24%	C11 - Manufacture of beverages	32,505
Perlite	Horticultural aggregate	11%	C23 - Manufacture of other non-metallic mineral products	57,255
Perlite	Fillers	6%	C23 - Manufacture of other non-metallic mineral products	57,255
Phosphate rock	Mineral fertilizer	86%	C20 - Manufacture of chemicals and chemical products	105,514
Phosphate rock	Animal feed	10%	C10 - Manufacture of food products	155,880
Phosphate rock	Detergents, chemicals, food additives	4%	C20 - Manufacture of chemicals and chemical products	105,514
Phosphorus	Chemicals	90%	C20 - Manufacture of chemicals and chemical products	105,514

Material	Application	Share	NACE sector	VA
Phosphorus	Metals	1%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Phosphorus	Electronics	5%	C26 - Manufacture of computer, electronic and optical products	65,703
Phosphorus	Agrochemicals	4%	C20 - Manufacture of chemicals and chemical products	105,514
Platinum	Autocatalyst	77%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Platinum	Jewellery	10%	C32 - Other manufacturing	39,160
Platinum	Chemical	6%	C20 - Manufacture of chemicals and chemical products	105,514
Platinum	Other	0%	0	0
Platinum	Medical and Biomedical	4%	C32 - Other manufacturing	39,160
Platinum	Investment	0%	0	0
Platinum	Petroleum	2%	C19 - Manufacture of coke and refined petroleum products	17,289
Platinum	Electronics	1%	C26 - Manufacture of computer, electronic and optical products	65,703
Platinum	Glass	1%	C23 - Manufacture of other non-metallic mineral products	57,255
Potash	Fertiliser	92%	C20 - Manufacture of chemicals and chemical products	105,514
Potash	Chemical manufacture	8%	C20 - Manufacture of chemicals and chemical products	105,514
Praseodymium	Magnets	27%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Praseodymium	Ceramics	17%	C23 - Manufacture of other non-metallic mineral products	57,255
Praseodymium	Batteries	13%	C27 - Manufacture of electrical equipment	80,745
Praseodymium	Metal (excl. Batteries)	12%	C24 - Manufacture of basic metals	55,426
Praseodymium	Catalysts	11%	C20 - Manufacture of chemicals and chemical products	105,514
Praseodymium	Polishing powders	11%	C26 - Manufacture of computer, electronic and optical products	65,703
Praseodymium	Glass	9%	C23 - Manufacture of other non-metallic mineral products	57,255
Praseodymium	Other	0%	0	0
Rhenium	Aerospace	83%	C30 - Manufacture of other transport equipment	44,304
Rhenium	Catalysts in petroleum industry	17%	C19 - Manufacture of coke and refined petroleum products	17,289

Material	Application	Share	NACE sector	VA
Rhenium	Others	0%	0	0
Rhodium	Autocatalyst	84%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Rhodium	Glass	10%	C23 - Manufacture of other non-metallic mineral products	57,255
Rhodium	Chemical	6%	C20 - Manufacture of chemicals and chemical products	105,514
Rhodium	Other	0%	0	0
Rhodium	Electronics	0%	C26 - Manufacture of computer, electronic and optical products	65,703
Ruthenium	Chemical	30%	C20 - Manufacture of chemicals and chemical products	105,514
Ruthenium	Electronics	48%	C26 - Manufacture of computer, electronic and optical products	65,703
Ruthenium	Electrochemical	22%	C20 - Manufacture of chemicals and chemical products	105,514
Ruthenium	Other	0%	0	0
Samarium	Magnets	97%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Samarium	Medical and optical applications	3%	C26 - Manufacture of computer, electronic and optical products	65,703
Sapele wood	Construction material	80%	C16 - Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	27,967
Sapele wood	Furniture	10%	C31 - Manufacture of furniture	26,171
Sapele wood	Boats	10%	C30 - Manufacture of other transport equipment	44,304
Scandium	Solid Oxide Fuel Cells (SOFCs)	91%	C27 - Manufacture of electrical equipment	80,745
Scandium	Al-Sc alloys	9%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Scandium	Others	0%	0	0
Selenium	Metallurgy	40%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Selenium	Glass manufacturing	25%	C23 - Manufacture of other non-metallic mineral products	57,255
Selenium	Electronics	10%	C26 - Manufacture of computer, electronic and optical products	65,703
Selenium	Pigments	10%	C20 - Manufacture of chemicals and chemical products	105,514
Selenium	Agricultural/ biological products	10%	C20 - Manufacture of chemicals and chemical	105,514

Material	Application	Share	NACE sector	VA
Tantalum	Chemicals	12%	C20 - Manufacture of chemicals and chemical products	105,514
Tantalum	Carbides	10%	C28 - Manufacture of machinery and equipment n.e.c.	182,589
Tantalum	Mill products	4%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Tellurium	Solar power	40%	C26 - Manufacture of computer, electronic and optical products	65,703
Tellurium	Thermo-electric devices	30%	C26 - Manufacture of computer, electronic and optical products	65,703
Tellurium	Metallurgy	15%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Tellurium	Chemical manufacture	10%	C20 - Manufacture of chemicals and chemical products	105,514
Tellurium	Rubber vulcanising	5%	C22 - Manufacture of rubber and plastic products	75,980
Terbium	Lighting	68%	C27 - Manufacture of electrical equipment	80,745
Terbium	Magnets	32%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Tin	Solders	47%	C26 - Manufacture of computer, electronic and optical products	65,703
Tin	Chemicals	18%	C20 - Manufacture of chemicals and chemical products	105,514
Tin	Tinplate	13%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Tin	Others	10%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Tin	Lead acid batteries	6%	C27 - Manufacture of electrical equipment	80,745
Tin	Copper alloys	6%	C24 - Manufacture of basic metals	55,426
Titanium	Paints	54%	C20 - Manufacture of chemicals and chemical products	105,514
Titanium	Polymers	24%	C22 - Manufacture of rubber and plastic products	75,980
Titanium	Aerospace	8%	C30 - Manufacture of other transport equipment	44,304
Titanium	Medical equipment	6%	C28 - Manufacture of machinery and equipment n.e.c.	182,589
Titanium	Automotive	3%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603

Material	Application	Share	NACE sector	VA
Titanium	Hand held objects	2%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Titanium	Alloys	2%	C24 - Manufacture of basic metals	55,426
Titanium	Various	1%	C21 - Manufacture of basic pharmaceutical products and pharmaceutical preparations	80,180
Tungsten	Mill and cutting tools	33%	C28 - Manufacture of machinery and equipment n.e.c.	182,589
Tungsten	Mining and construction tools	23%	C28 - Manufacture of machinery and equipment n.e.c.	182,589
Tungsten	Other wear tools	18%	C28 - Manufacture of machinery and equipment n.e.c.	182,589
Tungsten	Catalysts and pigments	8%	C20 - Manufacture of chemicals and chemical products	105,514
Tungsten	Lighting and electronic uses	6%	C26 - Manufacture of computer, electronic and optical products	65,703
Tungsten	High speed steels applications	6%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Tungsten	Aeronautics and energy uses	5%	C28 - Manufacture of machinery and equipment n.e.c.	182,589
Tungsten	others	0%	0	0
Vanadium	High-strength low-alloy steels (HSLA)	60%	C24 - Manufacture of basic metals	55,426
Vanadium	Special steel	30%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Vanadium	Super alloys for high-end uses	3%	C29 - Manufacture of motor vehicles, trailers and semi-trailers	160,603
Vanadium	Chemicals	3%	C20 - Manufacture of chemicals and chemical products	105,514
Vanadium	Cast Iron for rigid structures	2%	C30 - Manufacture of other transport equipment	44,304
Vanadium	Stainless steel	1%	C28 - Manufacture of machinery and equipment n.e.c.	182,589
Vanadium	Energy storage	1%	C27 - Manufacture of electrical equipment	80,745
Yttrium	Lighting	50%	C27 - Manufacture of electrical equipment	80,745
Yttrium	Ceramics	38%	C23 - Manufacture of other non-metallic mineral products	57,255
Yttrium	Alloys	8%	C24 - Manufacture of basic metals	55,426
Yttrium	Glass	4%	C23 - Manufacture of other non-metallic mineral products	57,255
Yttrium	Others	0%	0	0

Material	Application	Share	NACE sector	VA
Zinc	Galvanising	52%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Zinc	Zinc alloys	17%	C24 - Manufacture of basic metals	55,426
Zinc	Brass and bronze	15%	C24 - Manufacture of basic metals	55,426
Zinc	Zinc compounds (incl. dust and powder)	10%	C20 - Manufacture of chemicals and chemical products	105,514
Zinc	Zinc semi-manufactures	6%	C25 - Manufacture of fabricated metal products, except machinery and equipment	148,351
Zirconium	Ceramics	43%	C23 - Manufacture of other non-metallic mineral products	57,255
Zirconium	Refractories	15%	C23 - Manufacture of other non-metallic mineral products	57,255
Zirconium	Foundry	15%	C24 - Manufacture of basic metals	55,426
Zirconium	Chemicals	12%	C20 - Manufacture of chemicals and chemical products	105,514
Zirconium	Others	10%	C26 - Manufacture of computer, electronic and optical products	65,703
Zirconium	Pigments	3%	C20 - Manufacture of chemicals and chemical products	105,514
Zirconium	Superalloys, Nuclear	2%	C24 - Manufacture of basic metals	55,426