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THE FUTURE OF THE MINERALS MARKET FOR ELECTRIC VEHICLE PRODUCTION: CHALLENGES AND OPPORTUNITIES

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EV – Electric vehicle
DRC – Democratic Republic of Congo
ICE – Internal combustion engine
BEV – Battery electric vehicles
PHEV – Plug-in hybrid electric vehicles
kWh – Kilowatt hour
LCE - Lithium carbonate equivalent
IEA – International energy agency
NGO – Non-governmental organization
ESG – Environmental, social and governance
ASM – Artisanal small-scale mining
ELCA – Environmental life cycle assessment
S-LCA – Social life cycle assessment
CIS – Commonwealth of Independent States
US – United States

1 INTRODUCTION

As a more sustainable and environmentally friendly transportation option, electric vehicles (EVs) are growing in popularity as a means of addressing global climate change and reducing dependence on fossil fuels. Given the urgent need for clean energy transportation options worldwide to tackle the challenges of climate change (Liu et al., 2022), EVs are becoming increasingly attractive. However, the production of EVs relies on a range of minerals, including lithium, cobalt, nickel, graphite, copper, manganese, aluminium and two rare earth metals neodymium and dysprosium (Habib et al., 2020). An EV in total requires six times more minerals than a normal internal combustion engine vehicle (Mullan et al., 2022). These minerals are often sourced from specific countries, such as Chile and Argentina for lithium, the DRC (Democratic Republic of Congo) for cobalt, Russia and Indonesia for nickel, and China for graphite, copper, manganese, aluminium, neodymium, and dysprosium (International Energy Agency, 2022).

Major corporations in the mining and production of these minerals include Albemarle Corporation (USA), SQM (Chile), and Ganfeng Lithium (China) for lithium, Glencore (Switzerland) and Vale (Brazil) for cobalt and nickel, and Syrah Resources (Australia), Imerys (France), and China Molybdenum (China) for graphite. End producers like Tesla (United States) then purchase these minerals through various methods, such as direct contracts, intermediaries, joint ventures, or partnerships, to use in the production of EVs. It is worth noting that the methods of purchasing minerals can vary depending on the specific mineral in question, as well as the market conditions and other factors. Some minerals, such as lithium, are more likely to be purchased through long-term contracts, while others, such as copper, are more commonly purchased on the spot market or through futures contracts. EVs are increasingly becoming a popular choice in the vehicle market and are steadily gaining market share across all vehicle segments. The launch of various EV models is attracting a wider range of consumers. Moreover, as the technology continues to mature, many countries are updating their incentives for EVs to promote their adoption (Wang et al., 2022). Thus, the growing demand for electric vehicles is resulting in a heightened demand for the minerals used in their production, raising concerns about supply and price impacts. The mass production of EVs may strain the mineral supply if current mining and production methods cannot keep up, leading to the need for a strong strategy to secure raw materials. Raw materials can come from newly extracted and refined metals or from recycled end-of-life batteries and production waste. The reliance on newly extracted materials poses challenges, as they are expected to make up most supply by 2030, making battery manufacturers vulnerable to commodity material prices. Recent supply chain disruptions have caused a significant increase in key material prices by over 20%, leading to higher lithium-ion battery costs in 2021. Long-term, geopolitical, and labour issues may also limit material supplies (Breiter et al., 2022).

The rapid rise in demand for EV batteries raises concerns about the fragility and sustainability of the supply chain, both socially and environmentally. As a result, both governments and private organizations are taking steps to address these issues. As an example, in January 2020, the World Economic Forum and the Global Battery Alliance launched ten guiding principles for a sustainable battery supply chain, which were agreed upon by 42 organizations from various industries, including automotive, mining, energy, and chemicals. These principles aim to promote circular recovery of battery materials, eliminate child and forced labor, and support responsible trade and anti-corruption practices.

Additionally, the International Council on Mining and Metals has also established a set of Mining Principles focusing on environmental, social, and governance requirements for its members, including leading mining companies such as Alcoa, BHP, and Rio Tinto. These principles emphasize the importance of engaging with local stakeholders, avoiding involuntary resettlement, respecting workers' rights, providing fair pay and working hours, and more (Gerdes, 2020).

Mining is the process of obtaining minerals, coal, and other resources from the earth's crust. Mining activities can have a significant impact on the environment, including deforestation, soil erosion, and water pollution. To address these issues, technological solutions such as mineral recycling have been introduced as an alternative to traditional mining methods. Recycling minerals from discarded EVs and batteries is considered an effective way to conserve resources, reduce demand for virgin minerals, and minimize environmental impact. The process involves collecting end-of-life EVs and batteries, disassembling them, and extracting valuable minerals such as lithium, cobalt, nickel, and manganese. These minerals can then be reused in the production of new batteries. The recycling of minerals not only conserves resources but also reduces greenhouse gas emissions and other environmental pollutants associated with mining, refining, and transportation of new minerals. Several companies have been established to recover and recycle minerals from EVs, including Umicore, TerraCycle, and Circular Energy Storage, among others (World Economic Forum, 2021).

The motivation for this research stems from the urgent need to reconcile the environmental promise of EVs with the sustainability challenges posed by their mineral-intensive supply chains. As nations and industries push toward decarbonization, understanding and addressing the resource demands of EV production is critical to ensuring a truly sustainable transition to clean energy transportation.

The thesis explores the usage and challenges of EV production minerals, and the impact of its challenges on the global supply chain of EVs in both the economic and social views. The increasing demand for EVs is putting pressure on the supply of minerals used in their production. The mass production of EVs may strain the mineral supply if current mining and production methods cannot keep up, leading to the need for a strong strategy to secure raw materials. The reliance on newly extracted materials poses challenges, such as geopolitical and labour issues that may limit material supplies and result in supply chain disruptions and price increases. The global problem is to find a sustainable solution to ensure the long-term availability of minerals for EV production and the stability of the EV supply chain. The purpose of this thesis is to analyze the role of minerals in EV production and evaluate their implications and impact in the global supply chain.

The methodology for this research follows a multi-faced approach to analyze the role of minerals in EV production, considering their geographic, economic, and environmental aspects. Initially, a thorough literature review was conducted, drawing from various academic sources, industry reports, and government publications. This review provided foundational insights into the types of minerals used in EVs, particularly those essential for batteries, structural components, and motors. Following this, the minerals were categorized based on their function in EV production. Data on the geographical distribution of these minerals was then collected and analyzed. Market dynamics, including pricing, supply, and demand, were explored through historical data from commodity exchanges and specialized market reports. The analysis aimed to understand how rising demand for EVs is impacting the availability and pricing of these critical minerals. The thesis examined the implications for other industries that depend on the same resources, such as electronics and aerospace. The next stage involved evaluating the supply chain of these minerals, from extraction to their use in EV production. This involved exploring the roles of mining companies, processors, and refiners, as well as the involvement of stakeholders such as governments, regulatory bodies, and non-governmental organizations (NGO). Data from corporate reports and industry publications helped map the supply chain and identify key players and technologies driving it. The thesis also delved into the environmental and economic impacts of mineral extraction in key regions. Finally, the thesis proposes the future opportunities and challenges facing the mineral market for EV production. This included an analysis of emerging technologies aimed at improving the sustainability of mineral extraction and processing, as well as policy implications for governments, corporations, and other stakeholders involved in the global EV supply chain. This approach provides a whole view of the mineral landscape, integrating technical, economic, and environmental perspectives into the evolving dynamics of EV production. The research question guiding this study is: How does the increasing demand for minerals in EV production affect the sustainability and resilience of the global supply chain, and what strategies can ensure long-term resource availability while minimizing environmental and social impacts?

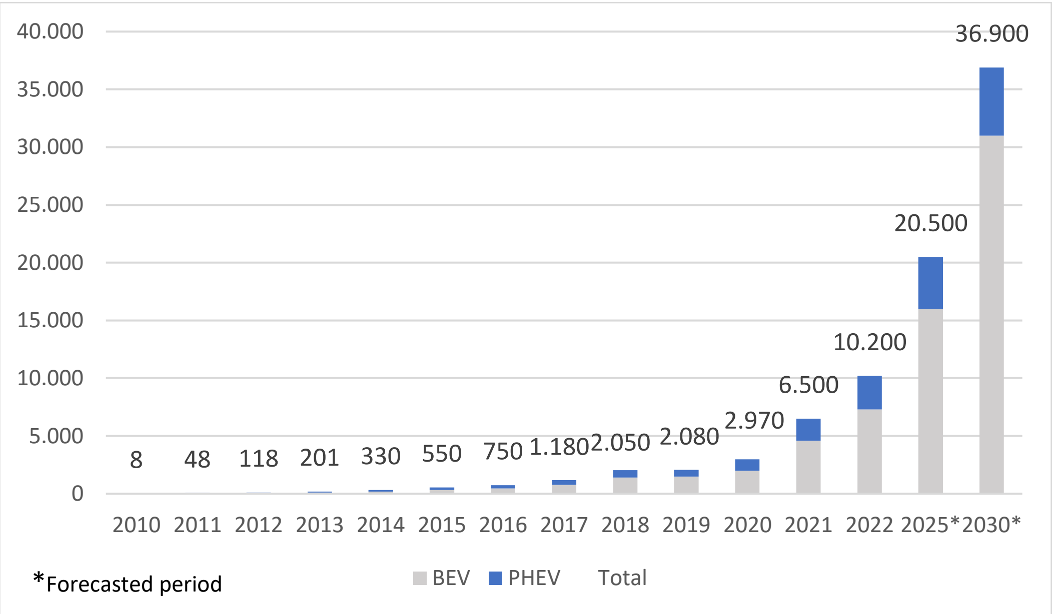
In some cases, difficulties were encountered in obtaining comprehensive data for several minerals included in the thesis. These challenges arose due to limited access to updated datasets, proprietary information held by private companies, and inconsistent reporting practices across regions and mining operations. Additionally, the variability in reporting standards between public and private entities, as well as fluctuations in production volumes due to environmental or market conditions, complicated data collection efforts. To address these gaps, the work relies on a combination of publicly available financial reports, market analyses, and industry publications as well as other academic work. This limitation underscores the need for more transparent and standardized reporting mechanisms in the mineral extraction sector.

2 OVERVIEW OF MINERALS USED IN ELECTRIC VEHICLE PRODUCTION

2.1 Analysis of the minerals and their roles in electric vehicles

In 2022, electric car sales hit a new high, overcoming challenges like supply chain disruptions, economic and geopolitical uncertainties, and elevated prices for commodities and energy. This surge in EV sales occurred against the backdrop of a global decline in overall car sales, which fell by 3% compared to 2021 (IEA, 2023). Based on past sales data and the future forecast provided by the International energy agency (IEA), a figure containing a graph displaying the trend can be presented.

Figure 1: Sales of EVs by type in thousands



Source: Own work based on IEA (2023)

As seen in figure 1, sales of electric cars, including both battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), surpassed 10 million in the year 2022, marking more than a 55% increase from 2021. This number, above 10 million EVs sold globally not only outstrips the total car sales in the European Union at 9.5 million vehicles but also accounts for nearly half of the total cars sold in China in 2022. From 2017 to 2022, EV sales skyrocketed from about 1 million to over 10 million, a growth rate significantly faster than the previous five-year period from 2012 to 2017, where sales grew from 100,000 to 1 million. This highlights the exponential growth in EV sales. Furthermore, the proportion of electric cars in total car sales increased from 9% in 2021 to 14% in 2022, a more than tenfold increase from their market share in 2017 (IEA, 2023). Building on the growth trajectory of EV sales, which reduces carbon emissions by 47% compared to gasoline vehicles (Guo et al., 2023), projections for the coming years suggest a continuation of this expansion. By 2025, EV sales are forecasted to more than double from the 2022 figures, reaching approximately 20.5 million units. This forecast reflects the accelerating adoption of EVs globally, driven by advances in technology, increasing consumer awareness of environmental issues, and supportive government policies. Looking further ahead to 2030, the upward trend in EV sales is expected to maintain its momentum, with projections indicating a leap to around 36.9 million units sold annually. This growth, almost quadrupling the 2022 sales figures, underscores the transformative shift in the automotive industry towards electrification (IEA, 2023).

With the upward trend, it is assumed that the production of new energy technologies such as the EVs are way more mineral-intensive compared to conventional vehicles, which is correct. An EV requires six times more minerals than a conventional car, highlighting the demand for mining activities to support the transition to electric mobility (Ferreira & Odell, 2023). To develop an understanding of how the sales and demand for EVs affect the atmosphere of the EV mineral market, first an insight into the minerals themselves is required. This work focuses on lithium, cobalt, nickel, graphite, copper, manganese, iron, aluminium, neodymium, and dysprosium. These are the crucial minerals and rare earth elements that are in use in present EVs (Enuh, 2022; Habib et al., 2021). Further below, some are discussed in more detail than others depending on their importance in the EV environment. They all play vital roles in the advancement of EV technology. As analyzed and explained further on, Aluminium and Iron are utilized in the vehicles body as well as structural components. Copper serves as a conductor in motor windings and electrical components. Cobalt, nickel, lithium, and manganese are applied to lithium-ion batteries, enhancing their energy density and performance. While high strength magnets are produced because of neodymium and dysprosium which lead to increased motor and power output efficiency.

2.1.1 Battery components

Lithium holds a paramount status as an indispensable metal integral to the progression of cutting-edge technologies like energy storage, electric mobility, and portable devices (Ahmed et al., 2017). Its influence, however, does not only affect EVs, but fills an even broader spectrum, encompassing industries such as glass, enamel, ceramics, lubricants, pharmaceuticals, and aluminum production. The distinctiveness of lithium compounds lies in their irreplaceability across diverse applications. This demand is as stated heightened by the production of EV, a phenomenon that has assumed a central role in propelling the call for increased lithium supply (Martin et al., 2016).

Battery packs within EVs house numerous lithium-ion batteries, often referred to as cells, which are typically comparable in size to AA alkaline batteries. These cells comprise two fundamental components: the anode, the negative terminal during battery use and the cathode, the positive terminal. During battery operation, as in the discharge phase, lithium ions migrate from the anode to the cathode via an electrolyte (typically a liquid, other alternatives further discussed in the chapter of emerging technologies) and a plastic separator that acts as a barrier to prevent contact between the anode and cathode, thereby averting cell short-circuits. Simultaneously, electrons traverse around the separator, moving from the anode to the cathode, thereby powering the device connected to the battery. To ensure efficient charging and discharging processes, battery packs combine multiple cells organized into modules. These modules are then combined, along with additional protective packaging and thermal management systems, to conclude in the final battery pack employed within electric vehicles (Ambrose and O'Dea, 2021).

Different variants of lithium-ion batteries are described by the specific metals constituting their cathodes. This selection of materials applies to an influence over critical battery attributes like durability, expense, and energy density, measuring the energy contained within a given battery volume. Furthermore, this choice spreads its impact across various battery components, involving as well thermal and power management systems. The cathode, a component accounting for roughly a quarter of the entire battery cost, merges lithium with elements like nickel, manganese, cobalt, or aluminum serves a dual purpose as the cathode's current collector and as a material employed in the packaging of cells and modules. Conversely, the anode predominantly comprises graphite coupled with a copper current collector (Ambrose and O'Dea, 2021).

During the early stages of lithium-ion battery evolution, cathodes leaned heavily on cobalt. Modern iterations have significantly reduced cobalt content per kilowatt-hour (kWh) of energy capacity. Cobalt's significance endures due to its contribution to energy density and chemical stability. The cost of cobalt coupled with the harmful ecological effects of its extraction have provoked endeavors to reduce its presence in batteries. In 2018, lithium-ion batteries contained an average of 28 kilograms of cobalt per 100 kWh across diverse battery end uses and chemistries, a quantity poised to witness a 60 percent decline by 2035. Emerging cathode components, low in cobalt content, emit enhanced battery performance as elevated energy densities. Notable occurrences include nickel-cobalt-aluminum oxide and select nickel-manganese cobalt oxide compositions. Simultaneously, substantial adoption of cobalt-free cathodes, revolving around lithium iron phosphate, spin among manufacturers of both light and heavy duty BEVs. Despite concerted efforts to pare down cobalt and other important materials, overall consumption is poised for a robust upturn. This trajectory is a result of the expanding production of EVs coupled with the parallel expansion of individual vehicle battery capacities (Ambrose and O'Dea, 2021).

2.1.2 Structural components

In addition to the core battery components, the production of electric vehicles relies heavily on a range of other minerals, each serving specific structural and functional roles that are pivotal for the performance, durability, and efficiency of the vehicle.

Aluminium, iron, and copper each command distinct and crucial roles, connected in function and design. Aluminium, prized for its lightweight nature and flexibility, enhances the vehicle's driving distance and energy efficiency, while also offering designers the freedom to form innovative and aerodynamic structures (EVreporter, 2023). Iron, primarily through its transformation into steel, lends strength and durability to EVs, creating a robust skeleton that ensures safety without sacrificing cost-effectiveness (American Iron and Steel Institute, 2021). Meanwhile, the electrical conductivity of copper and its resistance to corrosion is indispensable in the EV landscape, ensuring efficient energy flow from batteries to motors and throughout electronic systems. Copper thus plays a significant role in the production of an EVs infrastructure and is heavily utilized. EVs use more than double the copper compared to internal combustion engine automobiles. (Lynch, 2021). Together, these materials represent the blend of strength, efficiency, and innovation in electric vehicle construction, each contributing unique attributes while mutually shaping the performance, safety, and design of modern EVs.

2.1.3 Motor components and rare elements

In EV motors, the unique properties of certain minerals and metals become evident. At the forefront are rare earth elements such as neodymium and dysprosium. Neodymium forms the backbone of high-strength permanent magnets, known as neodymium-iron-boron magnets (Ballinger et al., 2019). These magnets are prized for their magnetic properties, which play a fundamental role in ensuring that the motors are not only efficient in energy conversion but also compact in design, a crucial attribute for space-conscious electric vehicles (Hanejko, 2022).

Dysprosium, while used in smaller amounts, has an equally critical role. When alloyed with neodymium in magnets, dysprosium increases the resistance of these magnets to demagnetization, especially at elevated temperatures. This is essential for electric vehicle motors, where operational temperatures can vary widely and can potentially impact performance (Maani et al., 2021). Iron, beyond its primary structural role in vehicles as stated above, serves as a key element in the magnetic core of electric motors. This magnetic core, typically crafted from iron or iron-based materials, collaborates effortlessly with the magnets to convert electrical impulses into the mechanical motion that drives the vehicle (Lammotor, 2023).

Lastly, the role of copper, with its already mentioned electrical conductivity, shines through in the windings of the motor. These windings, made predominantly of copper, serve as conduits, channeling electrical energy effectively, and ensuring the smooth and responsive performance of the motor (Dexmat, 2020).

2.2 Geographical analysis of mineral source

With an established view and selection of the main mineral components that reside within the present day EVs, a deeper insight into potential supply chain disruptions, geopolitical considerations and even the issue of the effect of mining on the environment, can be built upon. An overview of global mineral production, reserves and mining capacities enables a better understanding of the market dynamics.

Geographically, the sourcing of minerals vital for electric vehicles is spread across the continents with notable concentrations. While Australia emerges as a key player for lithium, iron, and nickel, the DRC is the queen of cobalt. China's dominance in graphite and rare earth elements, like neodymium and dysprosium, highlights its significant role in the EV mineral supply chain. Meanwhile, Chile's vast copper reserves position it as a global leader. This diverse geographical distribution points to a complex interplay of supply chains, geopolitics, and economic implications. Using the data supplied by the United States Geological survey from the U.S. Department of the interior, total mine production, reserve and global resource quantities of Lithium, Cobalt, Nickel, Graphite, Copper, Manganese, Iron, and Aluminum used in EV production can be analyzed. A bigger emphasis with sharper detail on resources and production numbers, is given on the three more critical minerals of lithium, cobalt, and nickel. The data is further represented and discussed in the tables below. The following two terms in the source represent key distinctions in mineral classification: reserves refer to the economically extractable portion of a mineral resource under current market conditions and technology, while resources encompass the total estimated quantity, including both discovered and undiscovered deposits, regardless of economic feasibility.

2.2.1 Lithium production, reserves, and resources

Lithium supply hinges on the differentiation between reserves and resources. Surprisingly, the theoretical static range of lithium supply extends to 435 years, suggesting a robust and sustainable supply (Backhaus, 2021). Resources encompass confirmed and estimated deposits, while reserves are defined as known deposits (Martin et al., 2016). In 2022, according to the United States Geological survey, estimated lithium reserves exceeded 26 million metric tons, while resources, which are significantly more extensive, amount to approximately 98 million metric tons. Comparing resource quantities to the numbers provided by Martin et al. through the United States Geological survey in 2016 at 34 million metric tons (Martin et al., 2016), a noticeable increase of 64 million metric tons of lithium is observed. This increase is the achievement of continuous efforts in exploration (U.S. Geological Survey, 2023).

Table 1: Lithium production and reserves in tons

Country	Mine production (tons)	Production share (%)	Reserves (tons)	Reserves share (%)
Australia	61,000	47%	6,200,000	24%
Chile	39,000	30%	9,300,000	36%
China	19,000	15%	2,000,000	8%
Argentina	6,200	5%	2,700,000	10%
Brazil	2,200	2%	250,000	1%
Zimbabwe	800	1%	310,000	1%
Portugal	600	0%	60,000	0%
Canada	500	0%	930,000	4%
Other*	n.a.	n.a.	3,300,000	13%
United States	n.a.	n.a.	1,000,000	4%
Total World	**129,300**	**100%**	**26,050,000**	**100%**

*Countries: Austria, Congo, Czechia, Finland, Germany, Ghana, Mali, Mexico, Namibia, Serbia, and Spain

Source: Own work based on U.S. Geological Survey (2023)

In 2022 the production is at 129,300 metric tons, excluding the production of the United States of America, where the data is withheld to avoid disclosing company proprietary data. Presently, lithium extraction is predominantly carried out in Australia, Chile, Argentina, and China as seen in Table 1 (U.S. Geological Survey, 2023).

Table 2: Lithium resources in tons

Country	Lithium Resources (tons)	Share (%)
Bolivia	21,000,000	21%
Argentina	20,000,000	20%
United States	12,000,000	12%
Chile	11,000,000	11%
Australia	7,900,000	8%
China	6,800,000	7%
Germany	3,200,000	3%
DRC	3,000,000	3%
Canada	2,900,000	3%
Mexico	1,700,000	2%
Czechia	1,300,000	1%
Serbia	1,200,000	1%
Russia	1,000,000	1%
Other*	5,000,000	5%
Total world	**98,000,000**	**100%**

*Other countries: Peru, Mali, Zimbabwe, Spain, Portugal, Namibia, Ghana, Finland, Austria

Source: Own work based on U.S. Geological Survey (2023)

Geographically, global lithium resources, as seen in Table 2, are distributed with approximately 60% found in South America, particularly in Chile, Bolivia, and Argentina. North America houses approximately 13.9 million metric tons of lithium, while China displays another 6.8 million metric tons. European lithium deposits, on the other hand, represent about 7% of worldwide resources, amounting to approximately 6.4 million metric tons. Two distinct types of lithium deposits are crucial in the supply chain: brine deposits and lithium ores. Brine deposits are lithium-rich saltwater reservoirs found in underground aquifers and salt flats, where lithium is extracted through evaporation or direct extraction, whereas lithium ores are hard rock deposits containing lithium-bearing minerals like spodumene, which require traditional mining and processing methods. The Salar de Atacama in Chile stands as one of the most important brine deposits, while the Salar de Uyuni in Bolivia is even larger. Challenges such as high altitude at 3,650 meters, relatively low average lithium content of 320 parts per million, and less favorable climatic conditions have hindered large-scale lithium production and present additional challenges for future production (Martin et al., 2016). Lithium-containing deposits are also found in igneous rocks, with pegmatites housing minerals like spodumene, lepidolite, petalite, and zinnwaldite. The Greenbushes spodumene mine in Australia is a prominent example (Kesler et al., 2012). While the global production landscape is being monopolized by merely four enterprises, who have a stronghold over almost 60% of the total output further described below in section 3.1. Nonetheless, the recent upswing in lithium's star status has signaled a transformative phase for its market. This transformation is not only seen in the amplification of current extraction facilities but also in the initiation and execution of grand-scale projects in new territories including Canada, Mexico, and Bolivia. Europe too, holds substantial promise in this domain. While the current scenario does not exhibit bottlenecks, majority of academic research foresees geographical concentration of production in a handful of countries as a continuing trend (Backhaus, 2021).

2.2.2 Cobalt production, reserves, and resources

It was anticipated that the global production of cobalt from mining and refining would reach new heights in 2022. Notably, this surge was expected primarily due to increased activities in the DRC and Indonesia, because of new mining and processing endeavors. Maintaining its position, DRC remained the predominant provider of cobalt globally, contributing to approximately 70% of the worldwide cobalt mining output. Apart from some output in the United States, Moroccan production, and small-scale artisanal mining in DRC, most of the cobalt extraction occurs as a secondary product of copper or nickel mining. Simultaneously, China stood as the main refiner and consumer of cobalt globally, predominantly using cobalt imported in semi-refined form from the DRC. In China, around 80% of the consumed cobalt was allocated for use in the rechargeable battery sector, emphasizing its part in powering a range of electronic devices and electric vehicles (U.S. Geological Survey, 2023).

Table 3: Cobalt production and reserves in tons

Country	**Mine production (tons)**	**Production share (%)**	**Reserves (tons)**	**Reserves share (%)**
Congo	130,000	70%	4,000,000	48%
Indonesia	10,000	5%	600,000	7%
Russia	8,900	5%	250,000	3%
Australia	5,900	3%	1,500,000	18%
Other	5,200	3%	610,000	7%
Canada	3,900	2%	220,000	3%
Cuba	3,800	2%	500,000	6%
Philippines	3,800	2%	260,000	3%
Madagascar	3,000	2%	100,000	1%
Papua New Guinea	3,000	2%	47,000	1%
Turkey	2,700	1%	36,000	0%
Morocco	2,300	1%	13,000	0%
China	2,200	1%	140,000	2%
United states	800	0%	69,000	1%
Total world	185,500	100%	8,345,000	100%

Source: Own work based on U.S. Geological Survey (2023)

Table 3 outlines cobalt's global footprint, spotlighting DRC's 130,000 tons production and 48% reserve share, indicative of its central role in the cobalt sector. Noticeable as well is Australia's 5,900 tons production and an 18% stake in the 25 million tons of world reserves, emphasizing its robust position. Other significant contributors like Indonesia, Canada, and China underline the strategic international spread of cobalt, crucial for the rechargeable battery industry and technological advancements, reflecting not just economic but geopolitical nuances shaping the future of global energy and manufacturing sectors. With a total world reserve of 8,345 million tons, the table encapsulates the interplay of natural resource allocation and industry demand.

Table 4: Cobalt resources in tons

Category	Cobalt Resources (tons)	Key Locations
Oceanic	120,000,000	Atlantic, Indian, and Pacific Oceans
Land	25,000,000	DRC, Zambia, Australia, island countries, Cuba, Canada, Russia
United States	1,000,000	Minnesota, Alaska, California

Source: Own work based on U.S. Geological Survey (2023)

The United States is estimated to have approximately 1 million tons of identified cobalt resources, predominantly located in Minnesota, with significant volumes also found in other states. Globally, identified terrestrial cobalt resources amount to about 25 million tons as observed in Table 4. A large portion of these resources are in sediment-hosted stratiform copper deposits in the DRC and Zambia, in nickel-bearing laterite deposits across Australia, its neighboring island nations, and Cuba, as well as in magmatic nickel-copper sulfide deposits in mafic and ultramafic rocks in Australia, Canada, Russia, and the United States. Additionally, over 120 million tons of cobalt resources have been discovered in the form of polymetallic nodules and crusts on the seabed of the Atlantic, Indian, and Pacific Oceans (U.S. Geological Survey, 2023).

2.2.3 Nickel production, reserves, and resources

Land-based worldwide resources with an average nickel content of 0.5% or higher are estimated to hold at least 300 million tons of nickel. Approximately 60% of this nickel is found in lateritic formations, while the remaining 40% is contained within sulfide deposits. Additionally, significant quantities of nickel are present in manganese crusts and nodules located on the seabed (U.S. Geological Survey, 2023).

Table 5: Nickel production and reserves in tons

Country	**Mine production (tons)**	**Production share (%)**	**Reserves (tons)**	**Reserves share (%)**
Indonesia	1,600,000	49%	21,000,000	21%
Philippines	330,000	10%	4,800,000	5%
Russia	220,000	7%	7,500,000	7%
New Caledonia	190,000	6%	7,100,000	7%
Australia	160,000	5%	21,000,000	21%
Canada	130,000	4%	2,200,000	2%
China	110,000	3%	2,100,000	2%
Brazil	83,000	3%	16,000,000	16%
United States	18,000	1%	370,000	0%
Other	440,000	13%	20,000,000	20%
Total World	3,281,000	100%	102,070,000	100%

Source: Own work based on U.S. Geological Survey (2023)

Table 5 displays data as of 2022 of mine production, reserves, and the percentage share of global reserves for various countries. Indonesia and Australia each hold a 21% share of global reserves, the largest among the listed nations, with mine productions of 1.6 million metric tons and 160,000 metric tons respectively. Among Nickel producers, Indonesia holds the crown as its production represented a rough 49% of total world production in 2022. The

Philippines, Russia, and New Caledonia each contribute 5%, 7%, and 7% to the global reserves, with the Philippines notably producing 330,000 metric tons in mines as the world’s second largest producer. Brazil accounts for a significant 16% of the reserves, with a production of 83,000 metric tons, while Canada and China both have a 2% share, with Canada producing 130,000 and China 110,000 metric tons. The United States, with a production of 18,000 metric tons, holds a minimal share of less than 1%. The rest of the world measured and observed under Other collectively make up 20% of the reserves with a production of 440,000. In total, the world production reaches a rounded 3.3 million metric tons with global reserves summing up to 102.07 million metric tons.

2.2.4 Overview of graphite, copper, manganese, iron, aluminum, and rare earths

Significant natural **graphite** mining production can be observed in Brazil contribution with 87,000 metric tons produced and 74 million metric tons in reserves, accounting for approximately 23% of global reserves. A more impressive volume is found in China, which follows with the largest production of 850,000 metric tons and reserves of 52 million metric tons, representing 16% of the global reserve share. Madagascar and Mozambique each hold 8% of the world's reserves, while Turkey has the largest share at 28% with reserves totaling 90 million tons. India, North Korea, and South Korea each have 1% or 2% shares, contributing modestly to global reserves. The total world mine production of graphite is estimated at 1.3 million metric tons, with total reserves at 323 million metric tons. The total world resources of graphite are estimated at 800 million metric tons of recoverable graphite.

Continuing with an overview of **copper**, Chile stands out with 5,200 metric tons produced and a significant 21% global reserve share. The United States and Peru also make notable contributions, each with a 5% and 9% share of global reserves, respectively with Peru also being the second biggest mine producer at 2,200 metric tons. Other substantial contributors include Australia with an 11% share and Russia with 7%, while countries like China and Indonesia each hold a 3% share. The estimated figure of total copper is 21,960 metric tons in global mine production and 885.6 thousand metric tons in reserves. Copper surveys conducted in 2015 identified resources at approximately 2.1 billion metric tons, as well as providing an estimate of undiscovered resources to be at 3.5 billion metric tons.

Estimates of **manganese** show that Australia and Brazil each have significant reserves of 270,000 metric tons, both accounting for 16% of the global reserve share. South Africa dominates with the highest reserves at 640,000 thousand metric tons establishing a 37% share of the total global reserves and has the highest mine production at 7,200 thousand metric tons. A strong position is as well observed in China with a 16% share and 280,000 thousand metric tons in reserves, and Ukraine with an 8% share. Gabon also stands out with 4,600 thousand metric tons produced and 61,000 thousand metric tons in reserves, making up 4% of the global share. The global totals reveal 20,090 thousand metric tons produced and 1.718 million metric tons in reserves. World Resources of manganese are enormous yet not efficiently distributed. The United States resources are of very low grade and have high extraction costs while South Africa, the queen of manganese, accounts for an estimated 70% of the world's manganese resources.

The highest production of **iron ore** as of 2022 occurred in Australia, at an estimated 880 million metric tons of usable ore with an iron content of 540 million metric tons, Australia as well maintained the highest share of reserves at roughly 28% of world total reserves. In terms of iron ore production, Australia is followed in order of quantity production by Brazil, China, and India. The total world resources of crude iron ore are estimated at 800 billion metric tons which contains above 230 billion metric tons of iron. (U.S. Geological Survey, 2023).

Aluminum mostly requires extractions from its primary ore, bauxite, which is responsible for over 99% of primary aluminum production as is not commonly found in its pure form. Bauxite is primarily obtained from surface open pit mines and has an alumina content ranging from 40% to 60%. This alumina is present mainly as aluminum oxo-hydroxides gibbsite, boehmite, and diaspore. Refining is often necessary as bauxite contains additional oxides and compounds. Around 85% of mined bauxite is refined to produce aluminum oxide. The leading bauxite producers include Australia, China, Brazil, Guinea, and India. In the refining process, the Bayer process is the most widely used method, which purifies bauxite to produce alumina (Al2O3) by reacting ground bauxite with sodium hydroxide under high temperature and pressure. Impurities are filtered out, and the remaining sodium aluminate solution is led to recovering alumina. The alumina then undergoes calcination at high temperatures to yield anhydrous aluminum oxide, which is transported to primary smelters for further processing. Most alumina from the Bayer process heads to primary aluminum smelters, employing the Hall-Heroult process, where alumina is dissolved in molten cryolite and reduced to aluminum via electrolysis. This process is energy-intensive, often powered by hydroelectric sources. China leads in primary aluminum production, which reflects its dominance in the industry. (Brough & Jouhara, 2020). In 2022, the total smelting production of aluminium measured at an estimated 69,000 metric tons globally, a rough 58% was smelted by China followed by India with a share of 6% (U.S. Geological Survey, 2023).

Leading to **rare earths** where Chinas rule is more than obvious. However large natural deposits have been discovered as well in the United states, Brazil, Canada, and Australia, still little mining production is currently occurring in these countries, some affected also by the time it requires to set up mines (Ciacci et al., 2019).

Table 6: Rare earth mine production in the year 2022 in metric tons

Country	Production in 2022 (tons)	Share (%)
China	210,000	70%
United states	43,000	14%
Australia	18,000	6%
Myanmar	12,000	4%
Thailand	7,100	2%
Vietnam	4,300	1%
India	2,900	1%
Russia	2,600	1%
Madagascar	1,000	0%
Rest of the world	100	0%

Source: Own work based on Statista (n.d.)

As seen in the Table 6 above containing rare earth mine production in 2022 from Statista (n.d.), China holds a share of roughly 70% of the total global production. The closest country in terms of successful production are the United states, at 14.3%. The rare earths mineral supply is significantly limited by geography as observed, with China dominating the globe, a situation that has historically contributed to price fluctuations, more covered in section 2. Beyond the issues of cost, there are also environmental concerns. Rare earth elements are mined from ores that may include radioactive elements like thorium, and the extraction process often involves large quantities of harmful substances such as ammonia, hydrochloric acid, and sulfates. It is estimated that processing one ton of rare earth elements can result in up to 2,000 metric tons of hazardous waste (Edmondson, 2021).

2.3 Impact of electric vehicle demand on other industries dependent on the minerals

The growth of the EV industry, presented in the transport sector as one of the best solutions (Bajolle et al., 2022), has not only transformed the automotive landscape but impacted different industries that are bound to the vital minerals of its production. The boom of the EV market could cause ripple effects that are felt across multiple industries. From smartphones to the construction of skyscrapers, jet engines to wind turbines, the heightened competition for crucial minerals is reshaping supply dynamics. While this demand points toward the global shift of sustainable mobility, it also emphasizes the urgent need for diversified sourcing, increased recycling, and alternative material innovations to ensure that one industries growth does not cause destructive winds in another.

As an example, the narrative of mineral resource investments is being redefined by climate change. Significant financial institutions are transitioning from thermal coal investments by engaging in the energy transition sphere. The infusion of funds into low-carbon energy technologies now encapsulates about 30% of the global energy investments. Remarkably, the count of electric cars worldwide has been on a more than 50% yearly ascension for a continuous decade, reaching a count of 5.1 million in 2018. This rate of growth is aligned to achieve the global aim of 100 million electric cars by 2030. To uphold this growth trajectory, there may be a necessity to double the global lithium production in the forthcoming decade. Besides the growth, it's noteworthy that the generation of the same power output through low-carbon energy technologies demands a higher metal input compared to fossil fuel-based methods. For example, the generation of photovoltaic power requires up to 40 times more copper than what fossil fuel combustion does, and wind power necessitates up to 14 times more iron (Lèbre, 2020).

The primary demand for **lithium**, before the rise of EVs, resided in batteries for laptops, smartphones, and other electronic gadgets. As recently as 2015, less than a third of lithium's demand came from the battery sector, with the majority being divided between ceramics and glasses (35%) and a mix of greases, metallurgical powders, polymers, and various other industrial applications (over 35%). Nonetheless, by 2030, it is probable that batteries will dominate lithium usage, comprising 95% of its demand. Lithium, frequently also termed as the white gold, is as before mentioned central for EV battery production. As the global shift towards sustainable transportation intensifies, lithium demand continues to dramatically surge. This growing demand threatens to overtake the supply, with potential implications for the global push to achieve net-zero emissions (Azevedo et al., 2022; World economic forum, 2022).

Cobalt on the other hand possesses the property of magnetization, thus making it a component in the creation of magnets, especially when it is combined with aluminum and nickel to form high-strength magnets, is also integrated into alloys that are essential for jet turbines and gas turbine generators, where the ability to withstand high temperatures is the top priority. In the realm of electroplating, cobalt is valued not only for its aesthetic appeal but also for its notable hardness and corrosion resistance. Historically, cobalt salt has been treasured for its capacity to yield a rich, blue hue, which has been sought after in the crafting of paints, porcelain, glass, pottery, and enamels. Moreover, the radioactive isotope cobalt-60 serves with a vital role in medical treatments, being utilized in the battle against cancer, and is employed in some countries for food irradiation to extend shelf life (RSC, n.d.). Overall, the shift of cobalt usage towards EVs, underscored by the metal's role in enhancing energy density, safety, and battery performance, applies to those industries using cobalt for other purposes, such as the beforementioned alloys for jet turbines, medical applications etc., may experience tighter supply issues which could likely result in higher prices. This could incentivize the development of alternative materials or the adoption of recycling and recovery processes in the long term.

Nickel, a shiny, silver-white metal, ranks as the fifth most abundant element on Earth (Garside, 2022). Diving deep on nickel leads to the recognition of its usage as a component of stainless steel and alloy steels with its properties of corrosion and resistance to high temperatures. It is also an input for nickel-based alloys, serving the sectors of aviation, chemical and energy with its oxidation and corrosion resistance while also carrying strength. Also important is nickel plating. A significant application providing durable corrosion resistant coatings for multiple products, which carries protective properties across multiple industries (ARM, n.d.). As the demand for EVs increases, this increase will of course be felt across all the above-mentioned sectors. Based on current estimates provided by Statista (2023), nickel demand has surged globally by 48% in the period from 2018 till 2023. Research by Statista (2023) also states that most of the growth in the period is due to an increase in the production of EVs.

Natural graphite is widely used in the thermal management sector for applications including heat dissipation in electronic devices and phase change heat storage, due to its superior thermal and electrical conductivity, along with its resistance to high temperatures and corrosion. It is also a key component in various energy storage electrode products, as mentioned above serving as an anode material in batteries, electrodes in fuel cells, cathodes in dual-ion batteries, and electrodes in supercapacitors. The attributes of natural graphite are used within the nuclear energy sector (Duan et al., 2023). The rising demand for graphite due to the growth of EV production is without a doubt reshaping graphite supply chains and having a ripple effect on the before mentioned industries. As EVs require significant amounts of graphite, this demand surge is intensifying the pressure on the graphite supply chains (Erickson, 2021).

Manganese demand from EVs somewhat affects steel manufacturing, as manganese is essential in steel alloy production. Battery applications make up only a small part of the manganese market. The primary consumer of manganese is thus as mentioned the steel industry, accounting for about 90% of the global utilization. At present, a mere 0.2% of the globally extracted manganese is allocated for use in lithium-ion batteries. Moving forward, this percentage is anticipated to see a modest rise, reaching approximately 1%. (Backhaus, 2021).

Aluminium, vital for modern societies, offers unique properties leading to its widespread use across several industries. Its lightness and conductivity make it ideal for electricity transmission over long distances. In transportation, aluminium's strength and lightweight contribute to fuel efficiency in cars, trains, and planes. Additionally, aluminium's flexibility allows for its transformation into thin sheets for packaging, underscoring its versatility in various applications essential to daily life (Gándara, 2013). This makes it ideal for transportation applications including automobiles, aircraft, trucks, railway cars, marine vessels, bicycles, and spacecraft. Its non-toxic nature, coupled with its non-adsorptive and splinter-proof characteristics, also makes it suitable for packaging purposes, such as cans and foils. In building and construction, aluminium is preferred for windows, doors, siding, and roofing, where its lightness and corrosion resistance outweigh the cost advantages of steel. For electricity-related uses including conductor alloys, motors, generators, transformers, and capacitors, aluminium is chosen for its combination of low cost, high conductivity, mechanical strength, and resistance to corrosion. Additionally, its use extends to a broad range of household items, from cooking utensils to furniture, and machinery and equipment, owing to its corrosion resistance, non-pyrophoricity, mechanical strength, and its overall aesthetic and durable properties (Davis, 1999). Given aluminum's important role across transportation, electricity, construction, packaging, and manufacturing sectors, it might be obvious that advancements in its application and demand, particularly the surge from the EV market, will continue to shape and significantly influence the trajectory of these critical industries in which it is used.

The increasing use of **neodymium** in various applications, particularly in permanent magnets found in hard disk drives, mobile phones, and audio-visual systems, is driving its market growth. These magnets are also crucial in medical devices, satellite communications, and transportation, including magnetic trains and luxury cars. The demand for neodymium is set to further escalate due to its role in green energy technologies like wind turbines, highlighting its position in future energy solutions and electronic advancements (Transparency Market Research, n.d.). According to Britannica (n.d.) dysprosium on the other hand enhances permanent magnets by substituting neodymium to improve high temperature performance. It is also used in nuclear reactor control rods due to high neutron absorption, and in laser, phosphor, and metal halide lamp technologies, showcasing its versatility in advanced material applications.

Iron is mostly used in general construction. In other terms, industry like such heavily relies on iron quantities and prices. Due to strength, formability, and low cost it is also a great material for it is of course also found in various other industries such as shipbuilding, railway construction or bridge building (Lu, 2015). Iron, however, has absorbed the impact of the surge of EV demand. It is highly unlikely that current EV production might however affect the iron market, there is also no present literature yet that concluded the real effects on Iron ore demand due to the rise of EV production.

Copper is used in industries due to its electrical and thermal conductivity, corrosion resistance like nickel, and ductility, which is the ability to be stretched. It's a key component in electrical wiring, plumbing, and in the manufacture of machinery. Copper alloys, like bronze and brass, are used for their strength and resistance to corrosion. Metal is also fundamental in producing coins, electronics, and architecture, highlighting its versatility in modern industry and technology (ASM, 2001). An EV may contain up to 80 kilograms of copper, substantially more than traditional vehicles. EVs significantly contributed to copper's global demand growth in the past year. However, innovations in EV and battery manufacturing are leading to reductions in both vehicle weight and costs, which could decrease the amount of copper required per vehicle, according to insights from Goldman Sachs and CRU Group mineral market analysis. As an example, Tesla, the carmaker, expects that through optimization by using a 48-volt system in the secondary battery, the battery responsible for power functions of lights and wipers, the need for copper might be cut by 25% (Nguyen, 2023). Further innovation in batteries will thus likely lead to the demise of coppers surging demand, at least concerning EV production.

By 2030, the demand for primary raw materials for vehicle battery production is projected to be between 250,000 and 450,000 tons of lithium, between 250,000 and 420,000 tons of cobalt, and between 1.3 and 2.4 million tons of nickel. The geographical distribution of these materials will significantly impact the ability to meet this demand (Backhaus, 2021). More than 20 energy transition metals, including iron, copper, aluminum, nickel, lithium, cobalt, and rare earth metals which are discussed in this work, are predicted to face market pressure as the transition towards cleaner energy solutions accelerates (Lèbre et al., 2020). The mineral market landscape has been shaped by a blend of historical trends, evolving demand-supply dynamics. Charting further into the analysis of past market prices to today's involved supply chains, it becomes evident that a collection of factors, from technological innovations to geopolitical events, have left their imprint on this market.

2.4 Analysis of mineral market prices, supply, and demand

The historical prices analysis considered the period, for most minerals, from the end of the year 2010 until 2023 end. This period marked significant developments in the observed technology and global markets, making it a crucial timeframe for understanding the dynamics influencing prices of the minerals covered in this thesis. The primary objective of this analysis is to trace the historical price trends of the minerals, offering insights into their market behavior over the last decade. Given the increasing importance of minerals in the electric vehicle and renewable energy sectors, this analysis is not only relevant but also critical for future market predictions and policy making.

To successfully compare the price trends of the various minerals with different price ranges covered in this thesis, an index measure was constructed to achieve a common starting point which would allow for the observation of relative changes over time. A method that is often used in financial analysis to compare the performance of different stocks or commodities. As the method is expressed in a relative index, this also allows for ignoring the differences in measurements, due to restriction in obtaining the data. The mineral price index (MPI) presents a specific relative measure of the price in each time point. The analysis covers the thesis materials where data is standardized, and the prices are quoted. Based on the constraint of quoted prices, the analysis temporarily sets aside graphite and the two rare earths, with the assurance that these areas receive separate attention at the end of this analysis.

Table 7: Mineral price index year-end since 2010

MPI Mineral Year	Lithium	Cobalt	Nickel	Iron ore	Aluminium	Copper	Manganese
2010	100.00	100.00	100.00	100.00	100.00	100.00	n.a.
2011	116.13	77.74	75.71	80.97	85.90	82.58	n.a.
2012	130.65	65.93	72.40	76.47	88.55	87.04	100.00
2013	116.13	75.12	57.78	80.58	73.82	78.83	97.42
2014	122.58	81.44	66.23	40.75	81.02	70.43	83.87
2015	335.48	62.17	36.13	24.26	63.53	50.68	49.03
2016	364.52	84.95	45.53	47.13	73.31	61.84	122.58
2017	483.87	195.08	47.70	42.57	88.28	74.66	91.61
2018	220.97	142.67	44.96	40.89	81.49	66.38	108.39
2019	127.42	83.96	57.38	53.98	75.16	66.40	81.29
2020	156.45	83.09	69.81	90.83	85.49	84.92	80.65
2021	**853.23**	**182.18**	83.05	65.54	114.38	104.35	86.45
2022	**1,530.65**	**133.83**	120.28	66.11	101.76	91.46	80.65
2023	279.03	74.68	68.23	81.62	93.01	91.86	75.48

Source: Own work

Table 7 provides a detailed view of the price changes, constructed from the MPI formula from the year 2010 through subsequent years, using an index where the year 2010 is set as the base with a value of 100 (Exception was made for manganese, due to no prior data availability in 2010 and 2011). Analyzing Table 7 from 2010 to 2023 reveals certain market dynamics, with each mineral projecting its own course through the period. **Lithium** stands out with its trend, initially marked by a baseline index of 100 in 2010, in real terms CNY31,000 per metric ton or $4,700 at the exchange rate of the date, it increased to a peak in 2022 with an index value of 1,530.65. This surge underscores Lithium's role in the renewable energy and electric vehicle sectors, though it later experienced a notable decline to 279.03 in 2023, reflecting the volatile nature of its market, ending at CNY86,500 or $12,200 per metric ton.

The volatility was, according to OilPrice.com (2023), caused by surprising slowdown in the demand for EVs in China, a critical market for lithium, played a significant role. Sales of new energy vehicles, including pure battery EVs and plug-in hybrids, saw a decrease of 6.3% in January 2023 compared to the explosive growth of 90% in 2022. This decline was partly due to the cessation of government subsidies for EV purchases, which had been instrumental in achieving price parity with internal combustion vehicles. The world’s largest manufacturer of lithium-ion batteries, China's CATL, also began offering discounts on batteries to some Chinese automakers, this move likely reflected anticipations of a continued downturn in lithium prices and affected market sentiment which reflects on the price in the Table 7. As stated by Krass (2023), an increase in lithium supply particularly from China, Australia, and Chile, is expected to further depress prices in the coming years. According to Krass, the supply of lithium carbonate is forecasted to grow at a rate outpacing demand, contributing to a downward pressure on prices. Krass also reveals that analysts have predicted a significant increase in global lithium supply, driven chiefly by production increases in Australia and China. Quantitatively, a single electric car's lithium-ion battery pack demands approximately 8 kg of lithium. Global lithium production in the recent past was recorded at 90.7 million kg (US Geological Survey, 2022). Notably, while global reserves are estimated at around 22 million tons, it is crucial to discern that not all reserves are technically recoverable or of the requisite quality suitable for EV battery production (World Economic Forum, 2022). Geographical concentration of lithium resources presents a looming challenge. Predominantly, the global lithium reserves are concentrated in a few regions. The "Lithium Triangle", comprised of Chile, Argentina, and Bolivia, holds nearly 60% of the planet's lithium resources (US Geological Survey, 2022).

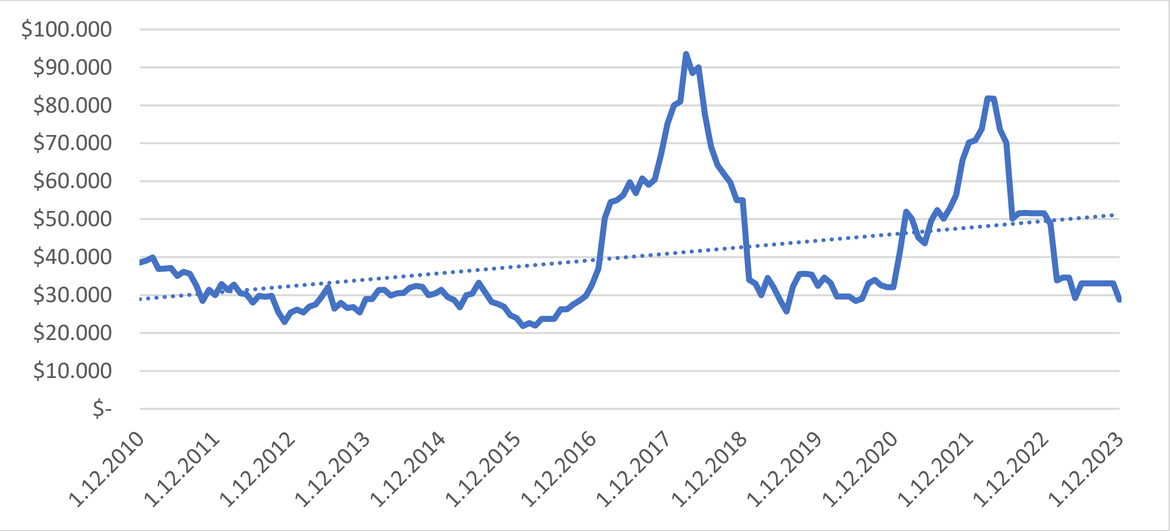
China, meanwhile, is dominant in the production chain, overseeing 60% of global lithium chemical production. Yet, extracting lithium, especially in these concentrated areas, has environmental implications, notably due to the high water demands of the extraction process. A significant portion of lithium production occurs in regions grappling with high water stress, further exacerbating regional water scarcity issues. Such environmental concerns have even led to public dissent, as observed in Serbia, where local protests culminated in the withdrawal of mining licenses (World Economic Forum, 2022). While the present scenario portrays potential lithium shortages, the evolution of the EV market and technological advancements might offer respite. Innovations in direct lithium extraction and recovery from waste streams or low-grade ores could redefine lithium supply paradigms (IEA, 2022). Furthermore, as the first generation of EVs reaches the end of its lifecycle, recycling spent batteries could offset approximately 10% of lithium demand by 2040. Parallelly, the emerging second-hand EV market may further alleviate some demand pressures (World Economic Forum, 2022).

While current trends suggest potential supply-demand imbalances, technological innovations, recycling strategies, and market dynamics might pivot the trajectory. The broader challenge, however, remains in balancing the quest for green transportation with the sustainable extraction and utilization of lithium, there is a need for change in both the extraction methods of materials and their utilization post-extraction in our appliances. The industry must adopt sustainable practices to reduce its growing negative impact as demand escalates (World Economic Forum, 2022; Evans, 2022). The adoption of EVs has cast a spotlight on lithium's critical role in this green transition. As an example, the period from 2000 to 2015 witnessed an impressive annual growth of approximately 20% in global lithium production specifically for battery use (Martin et al., 2016).

No doubt demand for lithium is rising quickly which can be noticed through the price increases in Table 7, as an example the in 2020 to 2021, not only the price surged, but the production in 2021 increasing by 32% from 2020, totaling over 0.54 million metric tons of Lithium Carbonate Equivalent (LCE). Multiple predictions indicate a demand for 3.3 million metric tons by 2030, with visibility on only 2.7 million metric tons of supply. At present, 98% of lithium mining is as established before in section 1.2.1. is concentrated in Australia, Latin America, and China. However, announced projects may bring new producers into the field, notably from regions like Europe, Russia, and the CIS, allowing supply growth at a 20% annual rate to potentially meet the demand by 2030 (Azevedo et al., 2022). But there is a need for change in both the extraction methods of materials and their utilization post-extraction in our appliances. Given the European Commission's report of a ten-fold increase in lithium usage in portable batteries from 2010 to 2020, the industry must adopt sustainable practices to reduce its growing negative impact as demand escalates.

Analyzing the numbers of the **cobalt** MPI in Table 7 reveals that cobalt experienced noticeable volatility, with its index value peaking at 195.08 in 2017, only to retract to 74.68 by 2023, translating to an overall decrease from the baseline year.

Figure 2: Cobalt price in USD per metric ton since 2010



Source: Own work based on Investing.com (n.d.)

As Figure 2 above demonstrates, the price of cobalt mostly remained below the initial price with two periods representing a significant hike, the average overall in this period remained somewhat stable, as can be observed by the linear trendline in the chart of Figure at the value of rounded $40,000 per metric ton. It is interesting that the price as of the latest cutoff period remains below the initial value, even though the demand for the critical mineral cobalt has dramatically surged, driven by decarbonization initiatives and the rise of digital technologies and electric vehicles. In just the past ten years, the global need for cobalt has seen a threefold increase, and projections indicate that it will double again by 2035 (Calvão et al., 2021), the price does not seem to reflect this doubling demand. These market activities were caused by a drop in cobalt prices in 2023 and can be attributed to a significant influx of new supply into the market. After reaching a four-year high in May of the previous year, cobalt prices plummeted to the lowest level since 2019. In 2023, the global supply of refined cobalt, essential for rechargeable batteries, increased primarily due to contributions from the DRC, the leading cobalt producer with analysts forecasting that they continue to exert downward pressure on prices (OilPrice.com, 2023). On the other hand, cobalt has faced competition from lithium as the Chinese EV market, among others, has shifted towards non-cobalt battery chemistry, further dampening cobalt's demand prospects. This shift reflects a broader industry trend towards reducing dependency on cobalt in battery technologies, primarily due to cost considerations and the pursuit of alternative chemistries that offer a better cost-to-performance ratio, such as lithium-iron-phosphate (Home, 2023).

Yet according to Calvão et al. (2021) the demand for the critical mineral has surged, driven by decarbonization initiatives and the rise of digital technologies and electric vehicles. In just the past ten years, the global need for cobalt has seen a threefold increase, and projections indicate that it will double again by 2035 (Calvão et al., 2021). Another study explored the implications of EV market growth on cobalt demand, considering various scenarios of battery technology evolution, including the adoption of low-cobalt and cobalt-free technologies. It emphasized that despite the potential reduction in cobalt demand through technological advancements and recycling, a significant increase in primary cobalt production is essential to avoid future shortages. The article highlights China's dominant role in cobalt consumption and production, as well as the global distribution of cobalt demand across different sectors. It argues that even with advancements in battery technology and increased recycling, there's still a potential risk of cobalt supply shortages due to the anticipated surge in demand from the EV sector (Zeng et al., 2022). Tisserant & Pauliuk (2016) assessed that future cobalt demand could be met with emphasis on the importance of strategic planning and mining production.

Nickel reached its pinnacle in 2022 at an index of 120.28 or $28,986 per metric ton. This uptick was largely credited to the increased usage of nickel in electric vehicle battery production coupled with a sustained, strong market for stainless steel (U.S. Geological Survey, 2023), but then receded to 68.23 in 2023, resulting in a decrease at the end of observed period. What is particularly of interest is the period between 2013 and 2019, where nickel averaged at an index value of 51. The low nickel prices between 2013 and 2019, compared to 2010 or 2022, were influenced by a combination of factors including global supply surpluses and shifts in demand, particularly from the stainless-steel sector which is a major consumer of nickel. A significant factor contributing to the surplus was the ramp-up in nickel pig iron (NPI) production in China, which kept the market well supplied and prices low due to the lower cost of production for NPI compared to traditional nickel mining and refining processes (OilPrice.com, 2024). Additionally, weaker sentiment in China, a key consumer of nickel, and overall pressure on the LME complex contributed to the downward price trends during this period. The global nickel market experienced a surplus of over 80,000 tons, indicating an oversupply that the industry struggled to absorb further depressing prices. This situation was worsened by concerns about demand weakness from the stainless sector, which did not stimulate additional buying or demand in the US market or globally, despite the low prices (Home, 2023). At the end of 2023, nickel prices experienced significant downward trends, marking it as the worst-performing base metal of the year. The price decline was largely attributed to a combination of lower demand and higher supply pressures. Despite starting the year on a high note, riding the momentum from a rally at the end of 2022, nickel faced a continuous decline throughout the year. By the end of 2023, the metal's price had dropped nearly 50% to close at $16,375 per metric ton, a stark contrast to its opening (Bastin, 2023). Several other factors contributed to this trend according to Belder (2024), rapid production increases, particularly in Indonesia which led to an oversupply in the market. Weak demand in China due to slow Covid-19 recovery and overall weak demand from the EV sector in 2023.

Iron ore, less crucial in the analysis as already discussed as being not a critical mineral due to its small share in EV production compared to the global usage in other industries, had a downward trend. The iron ore MPI was on a constant downward slide throughout the period. The index never peaked after 2010, indicating an oversupply situation on the markets. The PMI settled on 81.62, or $138 per metric ton in 2023. Expansions in iron ore production have contributed to lower prices, stemming from extended lead times and uncertainties in project development, not from producers holding back supply. During the period China leaned away from iron ore, towards scrap steel and reducing steel production due to environmental pressures. This transition created uncertainty for marginal producers and stalled projects, with investment focusing on operational efficiency (Hurst, 2015). As also stated by Hurst (2015), lower iron ore prices challenged the viability of fringe projects, leading to their suspension affecting demand. Also stating that it's improbable that iron ore prices will return to the highs of over $160 per ton seen in the period before 2010. A conclusion can be stated that EV production ahead will most likely not even scratch the demand curve of iron ore.

The **aluminum** MPI experienced moderate fluctuations, decreasing to a low of 63.53 in 2015, indicating a significant drop in aluminum prices to $1,500 per metric ton relative to the base year. The price index climbed significantly to 114.38 in 2021, showing a substantial increase in aluminum prices compared to the base year. By 2023, the index adjusted slightly to 93.01, $2,190 per metric ton, indicating a decrease from 2021 but remaining below the 2010 baseline where the price per metric ton stood at $2,360. The global market for aluminium is on the other hand projected to experience significant growth, driven by, as already discussed, its diverse applications across various industries. As of 2023, the market size was valued at $169 billion and is expected to reach $287 billion by 2032, with a CAGR of over 6.1% from 2024 to 2032. Aluminium is as discussed not a critical or animalistic sense “endangered” material, therefore the future supply and demand should be sufficient, as is the case above with iron ore, and should not impact the production of EVs as compared to the other more scarce materials. This growth is mostly propelled by the rising preference for its packaging in the food and pharmaceutical sectors (Global Market Insights, 2023).

Copper peaked in 2021 with an index of 104.35 or $9,550 per metric ton, and later settled at 91.86, $8,407 per metric ton in 2023. Between 2010 and 2023, copper prices were influenced by a mixture of economic, political, and environmental factors including global economic recovery pace, China's economic fluctuations, supply chain disruptions, and a strategic shift towards renewable energy and electric vehicles, heightening copper's demand as an essential component in green technologies. Recent copper price volatility reflects economic recovery pace concerns in China and the US, significantly impacting global copper prices (Manthey, 2023). The future demand of copper is according to Ampofo (2023), expected to surpass supply within four years, leading to a potential 20% price increase by 2027. A primary supply deficit, particularly evident in 2024, is projected, with secondary production increasingly filling the gap. Economic sentiment rather than supply-demand dynamics is likely to influence short-term price fluctuations. Post 2025, a supply deficit peak may incentivize recycling to meet demand. According to ING (2023) despite a bearish short-term outlook, the long-term prospects for copper remain bullish due to their crucial role in the energy transition. The balance of supply and demand will be a key price driver in 2024, with strategic needs for copper in green industries expected to support higher prices in the coming years.

Manganese, for which the base of the index begins in 2012 at CNY 38,750 per metric ton or $6,120 at the exchange rate at the point in time, has experienced interesting price fluctuations. The MPI peaked in 2016 at 122.58, indicating an extreme rally after a deep dive to 49.03 in 2015. In the last five years, however, a stable price index can be observed within the average range of an index value of 81 or CNY 32,000 or $4,500 per metric ton. The 2015 volatility in the manganese market was hit by a decline in global crude steel production, resulting in reduced demand for manganese, as mentioned, an essential component in steel manufacturing. The situation was as well compounded by a slowdown in Chinese steel production, attributed to stricter environmental regulations and a weakened construction sector. Additionally, an oversupply in the steel market prompted steelmakers to adjust output more closely to demand, further impacting the minerals price (Moran, 2015). Later in 2016 as stated above, the market experienced a surprising rally, with prices for manganese ore increasing dramatically. This rise came after producers had cut production due to low prices, which contributed to a tighter supply and increased prices. The rally was particularly notable in March when traders and consumers restocked, leading to contract renegotiations and price increases across the market (Davies, 2016). The current global manganese market expects a growth from 23.24 million metric tons in 2024 to 28.10 million metric tons by 2029, with a CAGR of 3.87%. This growth will be driven by increasing demand for manganese from both the steel alloy industry as well as the lithium-ion battery production required for EVs. Particularly, The Asia-Pacific region is anticipated to dominate this market growth, benefiting from rapid urbanization and infrastructure development (Mordor Intelligence, n.d.).

Graphite pricing on the other hand, as mentioned, lacks standard quoted rates, relying on direct buyer-seller negotiations without a spot or futures market. Pricing insights are often provided by subscription-based services like Benchmark Mineral Intelligence and Fastmarkets IM, which gather data from large-volume buyers, offering conservative figures that smaller buyers typically exceed. Graphite processing involves crushing, grinding, and flotation to separate and concentrate graphite flakes, which are then sorted by size and purity, affecting their market price. Prices vary by flake size and purity, with larger and purer flakes commanding premiums. In the 1990s, China's influx of graphite significantly lowered global prices, mirroring the rare earths market impact and stifling Western production. Prices stagnated until 2005, when China's growth and the commodity super cycle spurred a demand surge from the steel industry, peaking in 2012. Post-2012, economic slowdown and reduced steel demand led to a price decline. Graphite demand from the lithium-ion battery market, growing due to electronics and nascent EV sectors, now promises to boost prices, necessitating a production increase to meet the anticipated demand surge. (Northern Graphite Corporation, n.d.)

Table 8 : Graphite prices in USD per ton by flake size

Flake Size	Price ($)
+32 XXL	2,300
+50 mesh (XL)	1,750
+80 mesh (large)	1,400
+100 mesh (medium)	1,200
+150 mesh (small)	800
-150 mesh (fines)	500

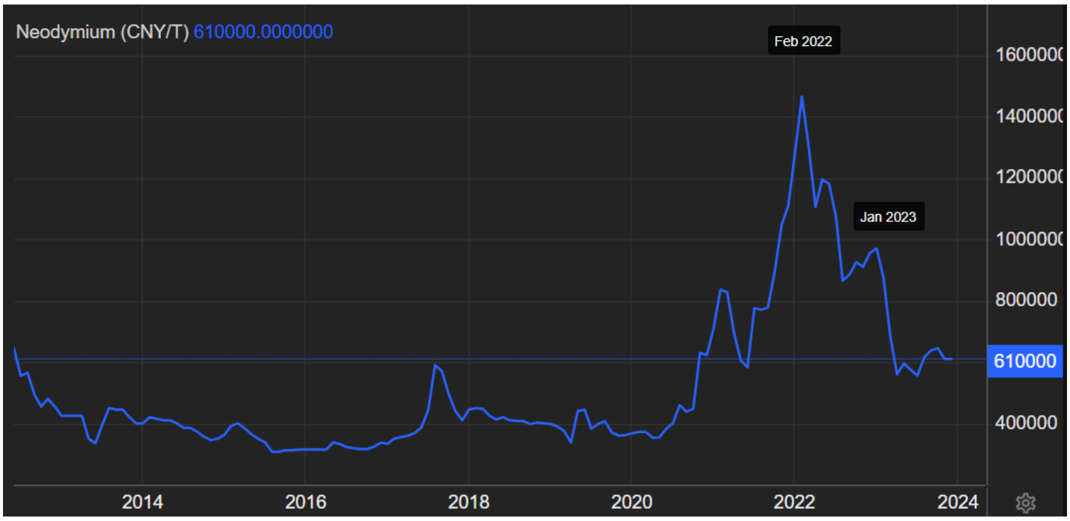
Source: Northern Graphite Corporation (n.d.)

Table 8 outlines the prices for different flake sizes of North American Feasibility Study Level Graphite, where larger flake sizes command higher prices. The highest-priced graphite is the +32 XXL size at $2,300 per ton, followed by +50 XL at $1,750 per ton. The price decreases with the flake size, with +80 large at $1,400 per ton, +100 medium at $1,200 per ton, +150 small at $800 per ton, and the smallest, -150 fines, at $500 per ton. The pricing reflects the value placed on the size and quality of graphite flakes in the market.

Graphite prices, which spiked in 2012, fell sharply afterwards due to China's economic downturn and stagnant Western economies. Since then, the prices have largely plateaued, with the industry anticipating demand from the electric vehicle (EV) and lithium-ion (Li-ion) battery sectors to absorb China's excess production. A new, costly African mine that operated below capacity before closing did little to alleviate China's production surplus. With Li-ion batteries nearing half of graphite's demand, the need for graphite, particularly large flakes, is growing, and the market outlook is optimistic, especially with significant investments in EV development and new LiB mega-factories poised to increase graphite demand substantially by 2025. Hence, doubling graphite production soon is crucial to meet the increasing demand (Northern Graphite Corporation, n.d.) According to Mordor Intelligence (n.d.), the graphite market size is estimated to grow at a CAGR of 5% during the forecast period from 2024 to 2029. They state that the growth is partly attributed to the increasing demand from the lithium-ion battery industry, which has been expanding due to the proliferation of handheld devices and the emerging EV and grid storage markets. Fortune Business Insights (2024) expects the $7.28 billion graphite market to grow to $11.58 billion by 2030, exhibiting a CAGR of 6.9% during the forecast period.

After establishing the case for all the minerals, a continuation of analysis follows for the two rare earths, **neodymium** and **dysprosium**. As of end of 2023 the price of Neodymium and Dysprosium, according to Strategic metals invest (2024), are up by 25.4% and 54.3% respectively compared to the average prices of Jan 2020, at $432.80 per kg for Dysprosium and $100.30 per kg for Neodymium.

Figure 3 : Neodymium prices in CNY per metric ton



Source: Trading Economics (n.d.)

While price since 2020 for neodymium is still higher compared to 2020, a sharp decrease in the peak since February 2022 (1 CNY = 0.15849 USD) can be noticed as seen in Figure 3. This sharp drop occurred due an increase in supply from China. The country's efforts to maintain market dominance and normalize supply chains have contributed to the price decrease. Additionally, the reduction in new wind power capacity and the overall global automotive sales remaining below pre-pandemic levels have temporarily impacted the demand for rare earths (Burton & Nguyen, 2023).

However, even though there appears to be a current downtrend in both price and demand, it is likely that on the long run the demand will force both the prices and the demand to reverse. Given a combination of quantities of neodymium that are required for applications in EV and the aggressive investments by major automotive companies in EVs, a surge in neodymium prices is likely over the next two decades. This is as neodymium's role might as well extend beyond its current applications due to the unique properties which will likely make it a crucial element in a range of new technologies, emphasizing its potential to shape future innovations (Strategic metal invest, n.d.).

Filippas et al (2021), with an analysis of rare earth production trends anticipate that in 2026, the demand for neodymium will outstrip its production. Dysprosium has already reached this point. In the article they emphasized the necessity of recycling from end-of-life products to meet demand needs. Recycling, while vital, will not be a complete fix; advancements in recycling efficiency and the creation of new permanent magnets that don't rely on rare earth elements will be crucial for future supply stability according to Filippas et al (2021).

3 THE SUPPLY CHAIN OF MINERALS AND THE ROLE OF CORPORATIONS

3.1 The workings of the supply chain of minerals for electric vehicles

The shift towards sustainable transportation, represented by EVs, has brought forth both opportunities and challenges in the global mineral market. The complex web of the EV mineral supply chain involves multiple stages, each of which has its own set of difficulties. The structure of the supply chain is further reviewed through four different stages, a framework used by the Rocky mountains institute (2023) which allows for a clear view of the supply chain workings.

Figure 4 : EV supply chain stages

Source: Carreon (2023)

The above Figure 4 provides a graphical representation of the stages of the EV supply chain. The journey of an EV battery begins with the extraction of raw materials. This phase, known as the upstream portion of the supply chain, involves identifying mineral deposits through geological exploration and assessing their economic viability. Depending on factors like the depth and concentration of minerals, mining techniques vary between open-pit and underground methods. The extraction process has however raised environmental and ethical concerns, including human rights abuses and the impact on local communities, particularly Indigenous populations. In response, there's a push for more sustainable mining practices and better governance to address these issues (RMI, 2023). One such tragic abuse because of large demand of the critical minerals is child labor. As stated by the International Labour Organization (2019), child labor in mining is affecting over a million children globally, and as such poses a critical challenge to child welfare, economic growth, and ethical business practices. Particularly prevalent in mineral sectors of third world countries. It also extends to cobalt mining in the DRC further covered in section 4.1 of the thesis.

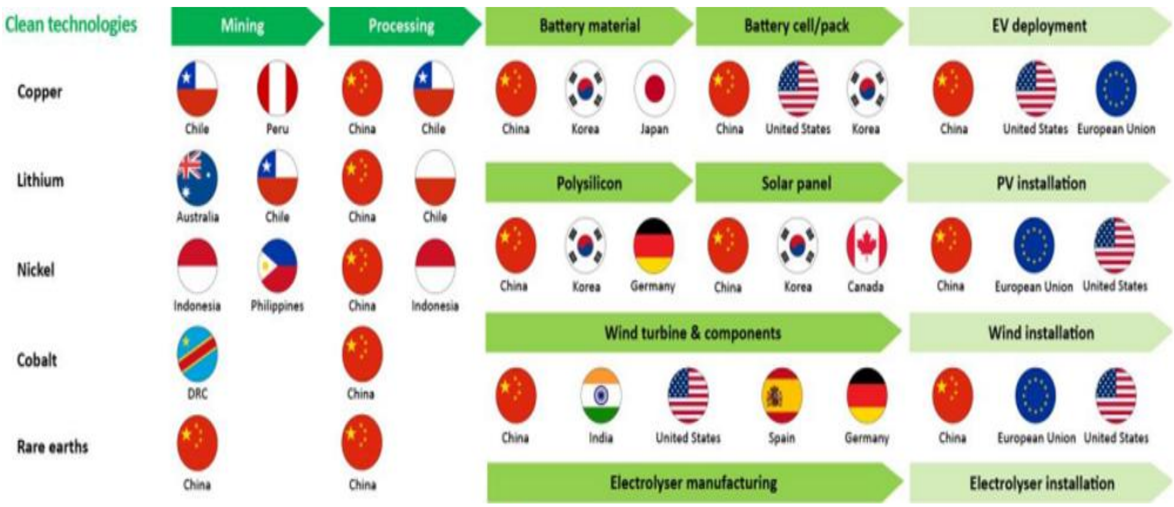
Once extracted by ethical or unethical methods, these raw minerals are refined and processed into usable forms for battery production. The midstream phase involves transforming the processed materials into battery components, such as cathodes and anodes, and then assembling these components into battery cells. This stage is critical for ensuring the quality and performance of EV batteries. The focus here is also on improving manufacturing processes to reduce costs and enhance efficiency, making EVs more accessible to a broader market (RMI, 2023).

The downstream stage of the EV battery supply chain covers the distribution of EVs to consumers, their usage, and the suite of aftermarket services. Once EV batteries are manufactured and assembled into battery packs, these packs are then integrated into electric vehicles. The vehicles are subsequently marketed and sold to consumers through a network of dealerships and direct sales channels. This phase is crucial for the adoption of EVs as it involves not only physical distribution but also the promotion and support services that encourage consumer uptake. After the sale, the focus shifts to the use phase, where the longevity and performance of the battery are paramount. Consumer experience during this stage can significantly influence broader perceptions of EV technology and its viability as a sustainable alternative to internal combustion engine vehicles. Manufacturers and service providers work to ensure reliability, offer maintenance services, and provide updates or upgrades to enhance vehicle performance and battery life. Additionally, the downstream stage considers the end-of-life options for the vehicle and its components, beyond recycling. This includes repurposing EV batteries for secondary uses, such as energy storage systems for residential or commercial applications. These secondary applications can extend the useful life of EV batteries beyond their automotive use, contributing to the sustainability of the battery lifecycle. The downstream phase is integral to the overall success of the EV ecosystem, requiring effective coordination among manufacturers, dealers, service providers, and recyclers to ensure a positive consumer experience and support the long-term viability of EV technology. Efforts in this stage aim to streamline distribution, enhance user satisfaction, and develop innovative solutions for battery repurposing, ultimately driving forward the transition to sustainable transportation (RMI, 2023).

3.2 Review of stakeholders and major corporations involved in the supply chain

The mineral supply chain for EVs features a diverse bag of stakeholders, each playing a role in ensuring the transition from raw minerals to the final EV product. Understanding the key players and their respective roles is important to getting a comprehensive view of the entire supply chain. The vast landscape of stakeholders in the EV mineral supply chain underscores the complexity of the industry. From miners in remote areas to tech innovators in urban centers, each player is integral to the functioning and sustainability of the entire chain. Recognizing their roles and interdependencies can offer insights into potential challenges and areas for optimization. Mining and extraction entities are at the starting point of the supply chain, responsible for the extraction of critical minerals like lithium, cobalt, and nickel from the earth. Their operations are often situated in remote areas, necessitating robust logistical and infrastructural support (Carreon, 2023). The supply chains for critical minerals are complex and developing more varied and robust chains requires substantial investments in time, knowledge, and resources. Over the past ten years, there has been notable diversification in the sourcing of these minerals, along with a modest increase in the diversification of global processing and manufacturing capacities (Cohen et al., 2023).

Figure 5: Clean technologies supply chain trends



Source: IEA (2021)

To further grasp an understanding of the importance of single nations in the material supply chain, Figure 5 provides such an overview of the supply chains for copper, lithium, nickel, cobalt, rare earths. Each stage is represented by the flags of the countries involved. For instance, Chile and Peru are involved in the mining of copper, while China is involved in almost every stage of processing for the listed materials. According to IEA (2021), these are the current established patterns of trade and geopolitical power.

3.2.1 Mining companies, processors, and refiners

Mining and extraction entities are at the starting point of the supply chain, responsible for the extraction of minerals like lithium, cobalt, and nickel from the earth. Their operations are often situated in remote areas, necessitating robust logistical and infrastructural support (Carreon, 2023).

As of 2023, the world of **lithium** producing companies is dominated by several key players with extensive mining operations and partnerships. Headquartered in North Carolina, **Albemarle Corporation** in the US, a specialty chemicals producer, claims the title of the most valuable lithium-producing entity globally. A company that generated an annual revenue of $9.6 billion, with a net income of $1.6 billion and a market value of $17 billion at the end of the year 2023. Their operational footprint spans across continents, with facilities in nations like Chile, Australia, and of course the United States. An important supplier for industries that utilize lithium, most importantly in the production of lithium-ion batteries that are central to the energy sector's evolution. The company is focused on advancing its production methods, through the adoption of direct lithium extraction technologies to boost efficiency. As of 2023, the capital expenditures of the corporation were $2.1 billion, reflecting significant investments in expansion of its energy storage and specialty capacity expansions resulting in the growth of its production process and allowing it to remain competitive in the market (Albemarle Corporation, 2024).

Another significant entity is **Ganfeng Lithium**, with its headquarters in China and an annual revenue of $4.6 billion. Their operations and interests stretch over several continents, including ventures in Australia, Argentina, and Ireland. Their portfolio includes major stakes in international projects, and they have forged crucial supply contracts with prominent automotive and battery manufacturing corporations (Ganfeng Lithium, 2024). China's **Tianqi Lithium** holds the title of being the leading producer of hard-rock lithium on a global scale, with a portfolio that holds assets in Australia, Chile, and China. Known for overseeing the Greenbushes mine operations in Australia, the company is also expanding into the development of lithium hydroxide production plants to meet the growing market demand. In 2023, Tianqi Lithium reported an annual revenue of approximately $6.3 billion. This was achieved despite facing industry cyclical challenges within the global economic environment (Tiangi Lithium, 2024).

Mineral Resources, with its roots in Australia, has a strong presence in the lithium mining sector through collaborative ventures with other notable market leaders. The company generated revenues of $3.12 billion in fiscal year 2023, which was mainly due to high lithium demand and its pricing, surging the EBITDA by 71% to a total of $1.2 billion. The company has strategically revamped its joint venture arrangements recently to optimize the management of lithium resources and their processing. A notable example is its MARBL joint venture with Albemarle Corporation (Mineral Resources, 2023). Another Australian company, **Pilbara Minerals**, is at the helm of the Pilgangoora lithium-tantalum project and is on an active trajectory to amplify its production capabilities. Their strategic moves have included acquisitions aimed at solidifying their position in the market. In fiscal 2024, the company reported strong financial results. Its revenue from operations benefited from high demand, and it had about $1.2 billion in cash reserves by March 2024, providing ample financial flexibility for future expansions. Pilbara's strategic efforts to scale production have included the P680 project, which increased Pilgangoora’s output by 30%, and the upcoming P1000 and P2000 projects, which are set to further boost production to over 1 million tonnes per year. These expansions are the core growth drive as Pilbara seeks to double its lithium output to meet global demand. The company has allocated $799.2 million for infrastructure development and plans for additional lithium processing facilities.

The last to be mentioned, **Allkem**, emerges from the merger between Orocobre and Galaxy Resources, with its base of operations in Buenos Aires, Argentina. The company administers an assorted range of projects, which includes the Olaroz lithium brine operation, and is pushing forward with numerous expansion initiatives. Allkem achieved an annual profit of $306 million, with revenue of $770 million (Kelly & Barrera, 2023; Dyer, 2023).

Much like the lithium sphere, the **cobalt** mining industry has major players. Such an entity is **Glencore**, which is at the forefront as the world's largest cobalt-producing mining company, with a substantial margin in production volume. A Swiss company with a market value of $73.8 billion as of end of year 2023, which in 2023 collected an annual revenue of $217.8 billion with a profit after taxes of $3.2 billion. The company expects growth in output, particularly from its operations in the DRC, including the Mutanda mine and Katanga. Glencore is not only a major player in cobalt but also engages in nickel sulfate battery material projects to support the EV market (Glencore, 2024). Comparing the GDP of the DRC to $66.38 billion (World Bank Group, 2023) in 2023 with Glencore’s revenue in 2023 it is observable that Glencore is at least three times larger than the DRC in revenue terms. Following Glencore is **Eurasian Resources Group**, a privately held diversified international miner. It is noted for its production volume and its Metalkol RTR recycling project in the DRC, which reprocesses historic mine tailings**. China Molybdenum**, partially owned by the Chinese government, is another significant producer, owning 80% of the Tenke Fungurume mine in the DRC, renowned for one of the world’s largest concentrations of cobalt. The company has also committed a substantial investment to nearly double the production of copper and cobalt from this mine. **Gecamines**, a state-controlled company in the DRC, has been named a third-party operator of the Tenke Fungurume mine following a court ruling, which adds to their substantial production capabilities. **Zhejiang Huayou Cobalt**, based in China, is a major producer with an estimated production of cobalt and has expanded its reach globally, including acquiring the Arcadia hard-rock lithium mine in Zimbabwe to support the EV sector's demand for battery minerals (Pistilli, 2022). Other notable companies in cobalt mining include Jinchuan Group International Resources, which has a strong presence in the Central African Copperbelt and is involved in mining operations focusing on copper and cobalt production. Sherritt International, a Canadian company, mines and refines nickel and cobalt from lateritic ores with its significant operation in Moa, Cuba, and Fort Saskatchewan, Alberta, Canada (Investing Channel, 2023).

Data collection and review about **nickel** related companies, resulted in the following conclusions in terms of largest mining companies. These companies are Nornickel, Vale, Metallurgical Corporation of China, Terrafame, IGO Limited, South32 Limited, and Eramet (Conte, 2021). Nornickel is for its largest production, with the majority coming from its Norilsk division in Russia. Nornickels generated approximately 35% of its $14.4 billion total revenue in 2023 with nickel activities (Nornickel 2024). Following Nornickel is Vale, which is based in Brazil. Vale's Long Harbour processing plant in Newfoundland and Labrador is known for producing nickel with a much lower carbon footprint compared to the industry average. As it is with Nornickel, nickel contributes a generous share in the total revenue of Vale, which raked in $4.3 billion dollars in 2023 (Vale, 2024). Metallurgical Corporation of China is another significant producer with a major contribution from the Ramu Nico project in Papua New Guinea. The company is also engaged in various mining projects across Pakistan and Afghanistan. While the total share of nickel in its business operations is not available, the company generates more than twice the combined revenue of both Nornickel and Vale across all its segments (MarketScreener, 2024). Terrafame, from Finland, uses environmentally sustainable bioleaching technology for its mining operations. Its Talvivaara mine is considered Europe's largest mine deposit and is vital to produce nickel sulfate, mainly for electric vehicles. Australian company IGO Limited produces all its nickel from the Nova nickel-copper-cobalt project in Western Australia and is also involved in the gold sector with its Tropicana Joint Venture. South32 Limited, operating out of Western Australia, has a diversified mining portfolio, including nickel production concentrated in the Cerro Matoso mine in Colombia. Eramet, a French company, extracts nickel, steel alloys, and manganese and has a long history of nickel production through its subsidiary in New Caledonia. These companies are central to the global nickel supply chain, especially considering the rising demand for nickel in electric vehicle batteries and clean energy infrastructure (Mir, 2023). While the latter companies are not of the same scale as the previous mentioned three, significant financial impact is present across all from its nickel operations ranging from 10-25% of its total revenues with Terrafame as the lowest revenue generating firm at $620 million (IGO, 2024; Eramet, 2024; Terrafame, 2024; South32, 2024).

3.2.2 Electric vehicle and battery manufacturers

The landscape of EV battery manufacturing is highly competitive with several companies vying for a larger share of the market. The below stated manufacturers play a crucial role in the global EV ecosystem by supplying the necessary battery technology to power electric vehicles. Their operations and market positions are indicative of the global efforts to transition towards more sustainable automotive solutions. **Contemporary Amperex Technology Co., Ltd.** (CATL) is a Chinese company renowned for manufacturing lithium-ion batteries for EVs, energy storage systems, and battery management systems. It has expanded its market share to become the world's top supplier of EV batteries, providing lithium-ion batteries to automotive manufacturers like BMW, Honda, Hyundai, Peugeot, Tesla, and Volvo (Blackridge research, 2023). In 2023, CATL posted record revenue of $55.71 billion, a 22% increase year-on-year, with a net profit of $6.21 billion, indicating a 43.6% growth. Out of its annual revenue of 71% came from EV batteries. This was a key driver for the company's overall growth, with its EV battery consumption reaching 36.8% of the global market, maintaining its top position in the industry for the seventh consecutive year. This success was supported by supply contracts with major automotive companies like BMW, Volkswagen, and Honda (Xinhua, 2024).

Another **BYD**, based in Shenzen, Guangdong, China, is not only a major EV company but also a leading producer of rechargeable batteries including lithium-ion batteries. It owns the entire supply chain layout, from mineral battery cells to battery packs. BYD's batteries are utilized in a variety of applications including consumer electronics, energy storage, and new energy vehicles. LG Energy Solution is a significant supplier of EV batteries, holding a notable share of the global EV battery market. It was the second biggest supplier of EV batteries, following CATL (Blackridge research, 2023). For 2023, BYD achieved total revenue of $83.3 billion, marking a 42% increase year-on-year. The company's revenue was driven by its automotive sector, with about 80.27% of the total revenue coming from its new energy vehicle sales and related automotive products, totaling approximately $66.9 billion. This surge reflects the growing dominance of BYD in the global electric vehicle market, where it sold over 3 million NEVs in 2023, surpassing Tesla in annual sales (TSC, 2024).

Panasonic is another key player in the EV battery manufacturing industry. In 2023, Panasonic generated significant revenue from its energy division, primarily driven by its EV battery business. Total revenue for the year was $57 billion. While the company does not break down the exact percentage of revenue attributed to its EV battery business in its public reports, it has been clear that this sector is a key growth area. Panasonic's EV battery business, especially with partnership like the one with Tesla, contributed substantially to its energy division revenues (Panasonic, 2024).

Like Panasonic, **Samsung SDI** is known for its contributions to the EV battery manufacturing sector. In 2023, Samsung SDI achieved total revenue of $17.1 billion, with a significant portion driven by its EV battery business, which saw a 40% increase in revenue compared to the previous year. The EV battery sector was a major contributor to the company's strong performance, supported by rising demand for high-end batteries used in premium EVs (Samsung SDI, 2024).

Tesla is not only a leading EV manufacturer but also engages in battery manufacturing to support its EV production (Blackridge research, 2023). In 2023, Tesla reported a total revenue of $94 billion, with its EV business at the front of this performance. Tesla's automotive segment, which includes vehicle sales, services, and regulatory credits, contributed the majority towards its revenue. The company delivered 1.81 million vehicles, representing a 38% year-on-year increase in deliveries. Tesla's energy generation and storage business, which includes its Powerwall and Megapack battery products, also played a key role. This segment achieved substantial growth, contributing to the company's overall revenue. Tesla continues to invest in scaling its battery production, particularly with its 4680-battery cell, which is set to significantly reduce production costs and increase battery efficiency for future EVs. The Gigafactories, particularly the Nevada and Texas sites, are central to its battery production strategy. In addition to producing batteries for its vehicles, Tesla is as well expanding its energy storage systems to meet growing demand from residential, commercial, and utility-scale customers (Tesla, 2024).

Other notable companies in the EV battery manufacturing sector include Exide Industries Ltd., GS Yuasa Corporation, Clarios, and Tianjin Lishen Battery Joint-Stock Co., Ltd. (Blackridge research, 2023).

3.2.3 Governments, regulatory bodies and non-governmental organizations

Many countries focus on adopting energy transition policies to reach or shape their carbon targets (Lebrouhi et al., 2021). Governments and other regulatory bodies play an important role in guiding the mining, processing, and sale of EVs. The duration required discovering a mineral deposit that is economically viable, obtain funding, land, mineral rights, and permits, among other prerequisites, can span multiple years (Congressional Research Service, 2022).

By impacting the mineral supply chain through regulatory frameworks, as an example such that directly impact the bureaucracy requirements of the previous line, and by addressing geopolitical and capital pressures that might hinder the security of mineral reserves. Their influence can be direct, via regulations, or indirect, by offering incentives to promote EV adoption. They also engage in international diplomacy to ensure a stable supply of these critical minerals, especially in a scenario where geopolitical uncertainties could disrupt mineral production and restrict access (Mitchell & Miller, 2021).

Governments worldwide have implemented various policies to boost EV adoption, including financial incentives, regulatory requirements, and public investments in infrastructure. As an example, China's policies are particularly crucial, given its significant share in the global EV market. While detailing all Chinese measures is extensive, a brief overview can provide insights for policy makers about these significant external influences. For instance, the study of varying EV penetration rates in China by 2030 shows how increased adoption can significantly strain global cobalt and lithium supplies, while moderately affecting copper and nickel demands. This emphasizes the need for careful resource management in response to evolving EV market dynamics (Jones, 2020).

Observing the policy stances in Europe reveal an increasing recognition of the need for governance in the field of critical minerals, involving both governmental and non-governmental collaborations. The European Union, during an event by the ERMA network, emphasized this need. Their stance is that sustainable mining within the EU is crucial, not just for economic and geopolitical reasons, but also due to moral obligations. They advocate an open discussion about responsible mining in Europe to ensure that the sourcing of raw materials meets high environmental and social standards, moving away from the practice of importing materials without considering their origins. This approach is aimed at fostering a European model that is transparent, responsible, and enjoys broad stakeholder support (Agusdinata et al., 2022).

However, the review of initiatives by Agusdinata et al. (2022), indicated a limited focus on international or universal governance in mining. They found that research from the past decade often described mining within a global neoliberal regulatory framework, emphasizing voluntary industry standards and reporting over direct government regulation. This includes voluntary contributions to global sustainability efforts like human rights and biodiversity protection. However, specific international cooperation for improving critical mineral mining's sustainability according to the findings, remains underdeveloped. The review highlighted the predominant contribution of researchers from the Global North across various knowledge domains, with a focus on supply and criticality issues relevant to these regions. In its final form, it suggested that utilizing a telecoupling framework can unify stakeholders from diverse geographies, including academics, NGOs, policymakers, and the private sector. This collaboration would aim to address global challenges around critical minerals, encompassing extraction, usage, and end-of-life impacts. Such an approach could enhance the governance of critical minerals and offer insights into managing other complex, globalized supply chains essential for sustainability transitions.

3.3 Emerging technologies and players in the mineral supply chain for electric vehicle production

The mineral supply chain supporting the EV industry is currently experiencing a transformative phase, driven primarily by rapid technological advancements. These innovations, spanning from exploration to the product, are not only reshaping established ideas but also positioning the sector to address increasing demand and growing challenges more effectively. Foremost among these advancements are techniques related to mineral exploration. As well Several emerging players are making advances in the EV mineral supply chain by incorporating groundbreaking technologies or establishing new improved facilities. These players and ongoing efforts highlight the evolving landscape of the EV mineral supply chain, driven by the imperative to meet the growing demand for EVs while mitigating environmental impacts. Many are focusing on emerging technologies to address the metals supply crunch as EV sales surge (Erickson, 2021).

One such advancement is the use of seismic imaging, a technique adapted from the oil and gas sector, which has emerged as a powerful tool, granting geologists and explorers the capability to visualize subsurface formations in greater detail (Malehmir et al., 2012). This technique, coupled with satellite remote sensing, which is in a scientific approach that acquires then processes and interprets data and images that record the interaction between matter and electromagnetic energy (Sabins, 1999), allow for the detection of specific signatures associated with rock formations, thereby identifying mineral-rich zones with heightened precision. The combination of these methods leads to an understanding of mineral deposits, thereby enhancing the extraction process.

However, the innovations are not limited to just the exploratory phase. Automation in mining is heralding a new era of efficiency and safety. Computer controlled drills, by ensuring exactness in drilling, substantially reduce waste, ensuring that each extraction process yields maximum output (Rogers, 2019). Moreover, the introduction of driverless trucks in some of the world's leading mining operations such an example found in the Pilbara mines deployed by Rio Tinto (Rio Tinto, n.d.), stands as a testament to the relentless pursuit of efficiency, given their capability to operate nonstop without human intervention. The processing part of the chain has not remained untouched either. In an age where sustainability is more than just a buzzword, the emergence of greener processing methods is particularly noteworthy.

Hydrometallurgical processing, for instance, deploys water-based solutions to extract metals. Not only does this method potentially mitigate environmental harm when compared to traditional techniques, but it also showcases the industry's commitment to eco-friendly practices (Vieceli et al., 2021). Parallelly, bioleaching, a method wherein microorganisms are harnessed to extract metals from ores (Bosecker, 1997) further exemplifies this green shift, holding promise for more ecologically appropriate extraction methods. Battery technology, the cornerstone of the EV industry, is also experiencing tectonic shifts. Solid-state batteries, replacing traditional liquid electrolytes with solid counterparts, are being heralded as game-changers. Their potential benefits might range from enhanced energy density to increased safety (Janek & Zeier, 2023).

Alongside this, battery recycling techniques are evolving. Recycling batteries salvages vital metals like cobalt, lithium, nickel, and manganese, crucial for lithium-ion battery components. This process not only lessens the environmental impact of battery production and curbs the need for further mining but also cuts costs by using recycled materials and reduces environmental and health risks from improper disposal. Developing effective recycling infrastructures is key to a sustainable battery lifecycle, promoting a circular economy where materials are reused rather than discarded. Despite its benefits, recycling faces challenges that impede achieving full circularity in battery use. However, to harness battery recycling's full potential, it is essential to tackle a spectrum of challenges.

Economically, recycling must become competitive against primary mining, hindered by low recovery values. Environmentally, conventional methods like pyrometallurgy and hydrometallurgy exert substantial ecological impacts and byproduct management issues. Safety hazards during recycling operations necessitate strict regulations. Logistical difficulties, such as disparate waste streams and inadequate sorting, complicate collection. Ambiguous laws, lack of infrastructure, and nascent technologies for new battery types also obstruct progress. A holistic approach involving all stakeholders is crucial for advancing towards a circular battery economy. (Toro et al., 2023).

There has also been a focus on power hidden within the ocean. An alternative source of nickel and other battery metals lies in it, mostly within the Clarion-Clipperton Zone (CCZ) in the Pacific Ocean, home to trillions of avocado sized nodes rich in nickel, cobalt, manganese, and copper.

Figure 6 : The Clarion-Clipperton Zone

Source: Economist (2023)

The CCZ's nodes as depicted on Figure 6 above, contain more than triple the estimates of the world's land-based nickel reserves established in point 1. With the regulatory environment possibly opening for deep-sea mining, companies began showing interest. The Metals Company plans to mine these nodules using robots to collect them from the seabed, which could be more environmentally benign than land mining in some views. Deep-sea mining does however pose its own environmental challenges, including the destruction of benthic organisms and the potential for residue plumes to harm marine life. Although the deep-sea ecosystem has lower biomass compared to rainforests, it harbors significant genetic diversity, raising concerns about biodiversity loss. Despite these challenges, deep-sea mining could offer several environmental advantages over traditional land mining, including higher metal concentrations in nodes, reducing energy consumption and greenhouse gas emissions during processing. The global rush for nickel to meet battery production demands might be further alleviated by deep-sea mining, and with that as well reducing the pressure on terrestrial ecosystems like Indonesia’s rainforests. As the demand for nickel and other battery metals grows, the choice between terrestrial and deep-sea mining presents a debatable trade-off of environmental impacts, requiring careful consideration and management to balance the needs of renewable energy expansion with the protection of ecosystems (Economist, 2023).

When it comes to countries that are engaging strategically, Canada and Indonesia must be considered, which are two emerging players in the EV mineral supply chain, each with their unique contributions and challenges. Canada is making steps to become a leader in the EV and battery technology supply chain, backed by its Critical Minerals Strategy and $3.8 billion in industry supports. This includes investments in mining research, infrastructure, and new roads to mineral-rich areas. With the sixth-largest proven reserves of lithium globally, along with significant amounts of nickel and cobalt, Canada is well-positioned in the EV market. Companies like E-One Moli, Volkswagen, Stellantis, and Northvolt have made significant battery plant investments in Canada, driven by its resources and clean energy access. However, Canada faces challenges such as the need to improve permitting efficiency for mining projects and the high cost of extracting lithium due to its remote and hard rock locations (Bibra, 2023).

Indonesia as opposed to Canada, is leveraging its status as the world's largest nickel miner to become a key player in the EV supply chain, focusing on transforming its nickel industry to meet the rising demand in EV batteries. The country banned exports of raw commodities to encourage downstream investment and development. Despite these efforts, Indonesia's nickel sector is marked by environmental challenges. Its nickel processing industry, heavily reliant on coal, is both carbon-intensive and environmentally damaging, posing risks of deforestation, pollution, and disruption to indigenous communities. These issues present a problem for EV manufacturers looking to manage ESG issues in their supply chains (Castillo et al., 2022).

As opposed to National players, private players in the field of data processing have risen as well. Such is the case of data powerhouse Benchmark Mineral Intelligence. The UK-based company has recently seen a 20% stake acquisition by the private equity fund Spectrum Equity. Benchmark is recognized for its expert pricing and data on lithium, nickel, cobalt, and other metals required in the energy transition from fossil fuels. With plans to expand globally, including establishing a further presence as well in Indonesia and Australia, Benchmark aims to leverage the investment to enhance its sales and technology infrastructure. This expansion is indicative of the growing demand for precise and up-to-date data among automakers, battery makers, and policymakers steering the electrification space (Scheyder, 2023).

All the stated advancements, ranging from the tangible to the intangible, as well as the emergence of new private and national players is reshaping the landscape of EV mineral supply chain, ensuring that the industry itself is poised to meet the challenges of the future with agility and efficiency.

4 IMPACTS OF THE MINERAL MARKET ON ECONOMIES OF SELECTED COUNTRIES AND THE ENVIRONMENT

The intertwining of the mineral market with economies, especially of resource-rich countries, is marked by both opportunity and harsh conditions. While there are economic advantages, they are often contrasted with political complexities, labor concerns, and environmental challenges. Local communities find themselves at this crossroads, negotiating between the promises of development and the realities of its consequences. The focus further on, lies on five different economies, which are most impacted by the demand itself. These countries are the Democratic republic of Congo, China and the lithium triangle consisting of Bolivia, Chile, and Argentina. All are important in the global supply chain for EV production minerals in both resources and mining production as stated above and will most likely as well face challenges in that relation within the near future. On the other hand, a surge in geopolitical power is also likely to occur such is the example of China, which has an opportunity to increase its rising dominance within the global economy due to its supply position.

While an increase in geopolitical power might occur, mining operations for critical minerals can also cause environmental degradation including deforestation, water and soil contamination, and air pollution. This is of course a global issue occurring in various regions where these minerals are extracted. Mining companies have indeed increased their accountability efforts by adhering to both national and international regulations and codes of conduct. However, these mechanisms tend to rely heavily on formal data and expert-provided information, often overlooking the valuable knowledge and practices of local and indigenous communities (Banvick & Gupta, 2014). In such scenarios, local communities often find themselves with limited opportunities to express their concerns or contribute their knowledge. The importance of local knowledge is especially significant in understanding the social-cultural and intangible impacts that mineral extraction activities have on these communities (Agusdinata et al., 2022). Mining operations can lead to water pollution, affecting both surface and groundwater quality. The process may release harmful chemicals and heavy metals into water bodies, impacting aquatic life and human health (Sandalow, 2023). Particularly, lithium mining requires a significant amount of water. For instance, about 400,000 gallons of water are needed to extract one ton of lithium. This high-water demand can be detrimental in arid regions like the Atacama Desert in Chile, exacerbating local water scarcity issues (Osborne, 2022).

Mining operations contribute to greenhouse gas emissions, primarily through the burning of fossil fuels to operate mining equipment. This aspect contradicts the primary goal of EVs, which is to reduce greenhouse gas emissions (Sandalow, 2023). The establishment of mines can lead to significant land degradation, including soil erosion and deforestation. Mining operations often require clearing large areas of land, disrupting local ecosystems and biodiversity (OSVehicle, 2022). Furthermore, mining activities might cause people to move off their land, stripping them off their homes, livelihoods, and culture due to the occupation of land for mining purposes (Sandalow, 2023).

The process of mining lithium, cobalt, and other materials needed for batteries releases harmful chemicals and pollutants into the air. This can pose health problems for both humans and animals (OSVehicle, 2022). The discussion on environmental impact extends to the end-of-life phase of EV batteries. Effective recycling and waste management strategies are crucial to mitigate the environmental impacts associated with the disposal of used batteries and the extraction of new minerals (Sandalow, 2023).

4.1 Democratic Republic of Congo

Different countries have varying regulatory frameworks governing the extraction, processing, and use of these minerals. These regulations can affect the operations of EV and battery manufacturers worldwide. The mining conditions in some mineral-rich countries are often harsh, with workers facing dangerous and degrading conditions. The extraction of minerals, particularly cobalt in the Democratic Republic of Congo, has been linked to child and forced labour under hazardous conditions (Ohnsman, 2023). This is a global concern requiring attention from international bodies and industry stakeholders. The current cobalt mining practices in the leading producer country, are heavily criticized for exploiting vulnerable communities. This situation ties together issues of slavery, environmental harm, gender inequality, and climate change, all rooted in the exploitation of both natural and human resources (Sovacool, 2021).

Figure 7 : DRC Cobalt mine

Source: Independent (2023)

As seen in Figure 7 these mines in DRC are often characterized by their artisanal mining operations. Such mines can include vast open pits or more hazardous, informal digging sites known as "creuseurs". Miners, including adults and sometimes children, work under challenging conditions, using basic tools to extract cobalt ore. The environment around these mines can be stark, with minimal safety measures in place, reflecting the significant human rights and labor issues associated with cobalt mining in the region (Amensty International, 2016).

In the DRC, significant cobalt reserves are concentrated within the provinces of Tanganyika, Haut-Lomami, Lualaba, and Haut-Katanga, found mainly in the dark grey mineral called heterogenite. Around 20% of this is mined by hand by an estimated workforce of 150,000 artisanal miners, known as creuseurs, who endure extremely perilous work conditions. The unregulated nature of small-scale mining leads to severe environmental damage, including the contamination of waterways and soil with toxic metals, destroying habitats for animals and polluting farmland. These miners, including children as young as seven, face harsh realities such as inadequate protective gear and exposure to toxic substances, with the constant threat of mine collapses. Despite the illegal status of most artisanal mining, cobalt sourced from these operations still enters the global market due to slack trading standards. Artisanal cobalt, once mixed with legally mined cobalt by local dealers, makes its way to international refineries and into the global supply, highlighting the regulatory gaps in the trade. This practice starkly contrasts the healthcare disparities between the exporting nation and the importing countries, with virtually no cobalt, even that used in medical implants like knee replacements, returning to aid the Congolese population's health (Williams et al., 2021).

In GDP terms, the mining sector in the DRC has been a major driver of economic growth. In 2023, the mining sector's growth rate was 15.4%, contributing significantly to the overall economic growth of 7.5% that year. The precise contribution of artisanal mining to GDP is difficult to determine, as most of it is informal and often not fully captured in official statistics. The informality of the sector results in a substantial loss of tax revenues and limits the government's ability to invest in broader social and economic development (AFDB, 2024).

One of the proposed solutions tackles the absence of a robust legislative framework, there is a call for more companies to proactively conduct and disclose cobalt-focused due diligence reports voluntarily. By increasing awareness among key stakeholders, the push for adherence to international standards and benchmarks can motivate industry peers to adopt similar practices, setting a precedent for broader industry participation (Williams et al., 2021).

Some concrete recommendations can be found within the article by Baumann-Pauly (2023), which emphasizes the role of cobalt in the global tech and green sectors, sourced from the DRC, mostly through artisanal small-scale mining (ASM). ASM is fraught with human rights violations, including child labour, and unsafe working conditions. The Mutoshi Pilot Project offered a beacon of hope, showcasing how formalization can enhance safety, reduce child labor, and empower women within the sector. However, the COVID-19 pandemic has undone much progress, worsening abuse of the project. Baumann-Pauly's work calls for a joint action framework involving global buyers, local governments, and international bodies to enforce ethical sourcing, improve working conditions, and ensure the empowerment of local communities. Baumann-Pauly emphasizes the positive legacy left by the formalization of the ASM mine site at Mutoshi despite its short duration of about two years. Key outcomes include the general acceptance of women in mining, leading to a reduction in child labor and increased school attendance. The local cooperatives continue to play a crucial role in enforcing basic safety rules and tracking statistics. However, without further support and access to resources like excavation machines, sustaining progress is challenging. The article suggests that ASM formalization can contribute to a global energy transition that is not only green but just as well. Campbell (2020) as well argues that it is not viable to simply cease ASM as it serves as a critical source of income for millions of Congolese living in severe poverty. Further implying that eliminating ASM from the cobalt supply chain is not practical because of its entangled structure, nor is it advisable from a standpoint of development. Campbell suggests that rather, companies that are dedicated to establishing ethical cobalt sourcing must assume accountability for rectifying the human rights abuses prevalent within the DRC’s ASM sector.

It is important for the DRC that local cooperation in breaking cultural barriers comes in affect to reduce the child labour, through above discussed solutions, such as female presence in DRC mining. As well standards must be developed that will be respected both by the corporations as well as the government of DRC. Further developments also require a reduction of the safety risk.

4.2 China

When it comes to the political aspect of the minerals involved in EV production, the key focus lies on China. China's dominant role in global mineral processing will most likely evolve, impacting its strategic position concerning critical minerals necessary for the global energy transition.

China is a major player in both the mining and processing of essential minerals. It dominates the global market, refining 85-90% of rare earth elements from mine to metal. In the realm of electric vehicle battery materials, China processes 68% of the world's cobalt, 65% of its nickel, and 60% of the lithium needed. Additionally, 75% of all batteries, as well as many EVs, are manufactured within China (Cohen et al., 2023). China's role in lithium geopolitics, as well as other critical minerals, thus shapes international relationships which could lead to new geopolitical alignments or tensions. As such, the geopolitics or dynamics of lithium and other minerals could create new interdependencies and political discords or potential conflicts, while on the other hand enhancing state interdependence in renewable technology energy production, showcasing the complex geopolitical dynamics at play (Wang et al., 2023). But the advantage of being a powerhouse of supply also resulted in an enormous boost of the domestic EV industry.

The Chinese government has strategically advanced this industry through multiple financial subsidies, tax breaks, and policy support ever since 2009, investing over RMB 200 billion to bolster the sector. This approach has contributed to China accounting for over half of global EV sales in 2022. The country's robust manufacturing ecosystem combined with a vast public transportation system has created a strong domestic demand for the EVs. This led to local governments in China also tailor policies which in end effect, support the growth of EV companies, such a case is the partnership between BYD and the city of Shenzhen. China has also made significant advances in battery technology, leading to the widespread adoption of lithium iron phosphate batteries, which are recognized for their safety and low cost. On the supply chain front, China dominates the production of lithium-ion batteries, with three thirds of global production, and has a significant share of the cathode capacity. The country's control over critical materials for battery manufacturing as discussed above has been a strategic advantage, ensuring a stable supply chain for its EV industry. Moreover, the EV supply chain in China is evolving, with Tier-2 and Tier-3 suppliers now able to directly supply new car manufacturers, bypassing traditional Tier-1 companies. This has allowed China for faster product iteration and adaptation to market changes.

The influence of internet and electronics giants in the EV and intelligent driving sectors is establishing a new landscape for the automotive industry in China. Challenges, however, persist. The fast expansion of capacity has sometimes outpaced demand, leading to oversupply and competition. The surge in prices for battery-grade lithium carbonate is also increasing manufacturing costs, and regulatory developments like the CHIPS and Science Act are impacting the supply chain, particularly in the semiconductor chip sector. A great environment has also been set up for foreign investments. Foreign companies looking to participate in China's EV industry can establish wholly foreign-owned enterprises or form joint ventures with Chinese partners to leverage local manufacturing capabilities and market access (Yang, 2023; Wu, 2023). As a measure of the effectiveness of Chinas strategy the Chinese EV makers are outpacing their American rivals due to superior performance and affordability, The Chinese EV market has seen a surge in sales, with a 36% increase to 7.7 million vehicles in 2023, which represents over a third of all new vehicles sold in China that year. In contrast, the U.S. market is smaller, with a 58% increase to 1.5 million EVs in 2023, accounting for 9.6% of total vehicle sales. BYD, as an example, has eclipsed Tesla as the world's largest EV producer. This highlights the success of Chinese manufacturers (Dempsey & White, 2024).

China's EV battery and related mineral industries contribute significantly to various regions, such as Guizhou, where the industry made up about 7.7% of the province’s GDP in 2022, valued at around $9.8 billion. By 2027, this sector aims to boost its output value to $70.3 billion, highlighting its expanding influence within the broader economy. In 2023, green energy technologies, which include EVs and critical minerals for batteries, accounted for around 9% of China’s total GDP and contributed 40% to GDP growth (Wang, 2024; Song-Pehamberger, 2024).

To combat Chinas dominance, rival countries are engaging in economically intensive solutions. An example to counter Chinas activities is the Inflation reduction act. The Inflation Reduction Act of 2022 in the United States and the European Union's Critical Raw Materials Act represent significant efforts by these entities to achieve greater self-reliance and sustainability in the renewable energy and EV sectors. Both acts are designed to reduce dependency on foreign suppliers. The U.S. Inflation Reduction Act aims to promote climate goals through investment in renewables and EVs, which includes building domestic supply chains and reducing reliance on overseas suppliers. As for the EU, a legislation seeks to improve the financing and permitting processes for mining and refining within the bloc, and to establish secure trade alliances to decrease Europe's reliance on Chinese raw material suppliers. China, however, holds a significant lead due to its already established relationships with resource-rich nations. Such an example, Chinese companies have substantial control over cobalt mining operations in the Democratic Republic of Congo. As the U.S. and EU nations look to build their lithium supply networks with allies such as Canada and Australia, China is developing its ties with African countries that are projected to be key producers of lithium in the near term. These efforts by the U.S. and the EU reflect a strategic effort towards securing raw material supply chains for technological frontier, but they also highlight the competitive nature of global trade and geopolitics, particularly in the face of China's already strong position in the market (Burton, 2023).

4.3 The lithium triangle

The lithium triangle consists of the top lithium resource holders of Bolivia, Chile, and Argentina. Nevertheless, these lithium powerhouses have struggled to enhance the value within their natural resource sectors because of their geographical remoteness from the primary demand hubs, which are predominantly situated in Asian processing facilities (Cervantes & Garduño-Rivera, 2022). Barandiaran (2019) explores three predominant viewpoints in which that case might come to cease, lithium as a banal commodity, as a strategic resource, and as a focused sociotechnical imaginary. In the case of the latter of the three, the triangle is reconsidering free-market approaches in favor of a model where lithium offers a chance for development that breaks from past cycles of inequality. This perspective, described as a lithium-focused sociotechnical imaginary, envisions a future where the state actively participates in the economy by investing in science, technology, and new industries to move beyond exporting raw lithium to producing value-added products. This shift aims to generate more wealth and position the triangle countries as a modern nation. However, whether these optimistic visions will materialize, and their environmental and social impacts, remains uncertain. This concept was strongly embraced by Bolivia under President Morales, who has pushed for a national industrialization strategy to manage lithium resources, and similarly by officials in Jujuy, Argentina. This approach involved creating state-owned enterprises to extract lithium and fostering innovation and human capital development. Chile also began to adopt this perspective after public pressure and scandals challenged the privatization efforts, with the government now promoting lithium as part of a broader strategy to transition towards a knowledge-based economy and solar energy production (Barandiarán, 2019).

Barandiaran (2019) critiques the simplistic binary between raw materials and industrial goods and the export-oriented nature of these visions, highlighting the need for a more ambitious development agenda around lithium to address the growing disillusionment with traditional mining practice

Figure 8 : The lithium triangle

Source: Barandiarán (2019)

With lithium as a banal commodity, the perspective, observed in Chile and the Argentine province of Salta as seen in Figure 8, regards lithium as a market commodity, not particularly valuable compared to other exports like copper or soy. It suggests deregulation to attract foreign investment, drawing parallels with uranium mining in France, where it was treated as a non-strategic, banal commodity. This view, however, was perceived as weak in Bolivia, where past efforts to engage foreign companies without ensuring equitable benefits led to public backlash and a reassertion of state control over mining (Barandiarán, 2019). Bolivia, as holding the world's largest lithium resources as established, is racing to capitalize on the metal for EV batteries, facing immense economic, political, and technical challenges. A $1 billion deal with Chinese firms that arise in 2023 could help enhance its development, yet experts believe over $5 billion is needed for Bolivia to significantly impact the global lithium market. Despite potential GDP growth, legal and social hurdles complicate foreign investment and mining operations. Technological challenges, particularly around direct lithium extraction, add to the complexity, as Bolivia aims to compete in the lucrative market (Castano, 2023).

In this case of latest financing, the fear of Barandiarán (2019) strikes in action, exposing the ineffectiveness to secure large enough investments. And tackling the final viewpoint which sees lithium as akin to oil or uranium, potentially lucrative but also a source of geopolitical power and environmental concerns. It's a prevalent perspective in the United States and was initially shared by some Argentine officials under the Kirchner government, who suggested forming a cartel to maximize rents from lithium. However, this idea was not widely accepted in Chile or Bolivia and lost traction in Argentina with the change in government (Barandiarán, 2019). As of latest due to lithium demand, there speculation of potential formation of a lithium cartel by the Lithium Triangle countries which could significantly influence global lithium markets, akin to OPEC's impact on oil. This development holds implications for international relations, trade, and the push towards electrification, with strategic management of resources central to addressing the soaring demand for lithium in technology and renewable energy sectors (Ross, 2023). This points toward a future which resembles the viewpoint of lithium as a strategic resource. Lithium production can be felt in the economies of the countries. As an example in Chile, lithium has become a significant economic contributor, with exports reaching $8.14 billion in 2022, marking a substantial increase from the previous year. Lithium represented 8.2% of Chile's total exports in 2022, outpacing traditional industries like fruit cultivation and salmon farming, and nearly doubling exports from industries like pulp and paper. Argentina, on the other hand, is on a trajectory to significantly enhance its lithium sector's contribution to the national economy. With lithium exports totaling approximately $695 million in 2022, the lithium complex ranked as the 18th largest exporter at the national level. Projections suggest that, starting in 2025, Argentina's lithium production could catapult it to the fifth-largest exporter in the country, potentially exporting more than $7 billion annually based on ongoing project projections (Álvarez, 2023).

However, the extraction of lithium and its economic benefits for the triangle countries presents sustainability challenges. Mining operations, necessitating millions of liters of water per ton of lithium, strain water resources, exacerbate water stress, and risk ecological damage in regions like Bolivia's San Cristóbal and Chile's Salar de Atacama. Indigenous communities, dependent on these water sources, face livelihood threats. Initiatives like Livent's to mitigate environmental impact highlight the complex balance between advancing green technologies and preserving natural resources and local ways of life (World Economic Forum, 2023). Increasing lithium demand will most likely result in higher economic benefits in the long run for the triangle countries, but a sustainable approach will be required to not devastate the environment due to operations required for extractions. In the long run Berg & Sady-Kenndy (2021) claim that the Lithium triangle will without doubt become the nexus for lithium.

5 THE FUTURE OF THE MINERALS MARKET FOR ELECTRIC VEHICLE PRODUCTION

5.1 Challenges and opportunities in the mineral market for electric vehicle production

The mineral market critical to EV production is facing significant challenges that may impact the pace and cost of the EV transition. A major concern is the rapidly increasing demand for the minerals which is not matched by current supply and investment plans. There is a looming mismatch between climate ambitions and the availability of critical minerals needed to realize those ambitions. EVs require six times the mineral resources of conventional petrol cars, and the total mineral demand for EV and battery storage is projected to grow more than 30 times by 2050 under a sustainable development scenario (van Halm, 2022). EY estimates that investments of approximately $1.7 trillion are needed over the next 15 years in the mining and metals industry to ensure an adequate supply of copper, cobalt, nickel, and other critical metals (E&Y, 2022). The dominance of certain countries as well in the production of these minerals, such as Australia's control over 48% of global lithium production and China, poses risks of price volatility and supply disruptions (van Halm, 2022). Another layer of the complex cake comes from geopolitical concerns and supply chain vulnerabilities. The US, for instance, heavily relies upon imports from China for many of the minerals classified as essential. This reliance creates vulnerabilities to economic or political complications. Efforts are underway to develop large and diverse critical mineral supply chains that respect high environmental standards and human rights while reducing dependency on a few countries (Majkut et al., 2023). Addressing these challenges requires coordinated efforts among governments, private sector, and international partnerships or in other words all the stakeholders involved in the EV production chain. Investments in domestic resource exploration, development of new mining projects, and diversification of supply chains will be and already are crucial to minimize risks associated with critical mineral supply for EV production.

The future of EV production is marked by several significant opportunities, backed by substantial investments, and anticipated growth across key markets. Automakers worldwide are projected to invest over $515 billion by 2030 to develop and manufacture new electric vehicles and their batteries. This investment aims to meet the growing demand for EVs, with more than 100 models expected to be available to U.S. customers by 2025. This growth is not only confined to light-duty vehicles but extends to medium and heavy-duty vehicles like trucks and buses, which are projected to reach cost parity with diesel models within the decade. The push for EVs is driven by regulatory support, consumer interest, and technological advancements (Lewis, 2022).

In the US, the EV market continues to grow, with sales constantly increasing. This growth is supported by the Biden administration's target for 50% of new car sales to be electric by 2030, which is likely to further accelerate EV adoption. Additionally, the U.S. benefits from its trading partners' abundant critical minerals, such as copper and lithium, essential for EV production. However, challenges remain in securing supplies of minerals like graphite and cobalt, where production is concentrated in countries like China and the DRC (Foran, 2023).

Globally, China is expected to maintain its position as the largest EV market, with an anticipated EV share of over 70% of new car sales by 2030 under an accelerated scenario. In Europe, achieving around 75% EV sales by 2030 will have widespread implications for the automotive supply chain, requiring significant investments in battery production, charging infrastructure, and the decarbonization of vehicle lifecycles. The transformation towards e-mobility will disrupt the automotive industry, shifting market sizes for components and necessitating a transition in production from ICE components to EV parts (Mckinsey, 2021).

These developments indicate a significant opportunity for growth and innovation in the EV sector, pushed by investments, policy support, and ever-evolving consumer preferences. There is also great potential in the coming future for countries, such as the triangle in South America, where great economic advances due to the mineral abundance of the economy could be expected. This, however, now of course rests on achieving correct policy and corporate deal making discipline. It is unavoidable that EV production with its mineral supply, which of course affects, as discussed, all the green sectors, will affect the world in the coming years. As Fama & French (1988) revealed that metal price fluctuations during the sampled period were significantly influenced by the business cycle, particularly noting sharp increases and decreases around the peaks of 1973-1974 and 1979-1980, which suggested an immediate supply inadequacy in response to demand surges, a trend that, given the historical performance of commodities, the mineral market for EVs is also likely to emulate in its distinct business cycle.

Adding to the discussion on the challenges in the EV mineral market, tariff restrictions in both the Eastern and Western regions are influencing the cost and stability of EV supply chains. Since 2019, the U.S. has imposed tariffs on key EV components imported from China, including lithium-ion batteries and other critical mineral-based products, while China has retaliated with tariffs on U.S. vehicle imports. These tariffs contributed to increased costs and created an additional layer of geopolitical complexity in the global EV market. Similar tariff environment complicates efforts by automakers and governments to secure a steady and affordable supply of minerals. Addressing these trade barriers requires international coordination and strategic partnerships to mitigate risks and foster a stable global supply chain for EV manufacturing (Batabyal, 2019).

As of late, in 2024, the EU implemented new tariffs on EVs imported from China, with rates ranging from 7.8% to as high as 35.3% depending on the manufacturer. This decision followed a year-long investigation by the European Commission into allegations of unfair Chinese subsidies that support domestic EV production. These tariffs aim to protect European carmakers from what the EU views as market-distorting state subsidies by Chinese firms. The tariffs are expected to last for at least five years unless China addresses the EU's concerns during ongoing negotiations. However, the decision has not been universally supported within the EU. Beijing has responded by labeling the tariffs as protectionists and has indicated potential retaliatory measures, including investigating European imports such as brandy and dairy products. The situation underscores the geopolitical tensions between the EU and China, with the EV market becoming a critical battleground. The tariffs could raise the cost of Chinese EVs in Europe, making it more challenging for Chinese brands to maintain their growing market share, and potentially influencing the global dynamics of the EV supply chain (Shetty, 2024).

Western collaboration remains strong at present. There have been ongoing dialogues between the US and EU to align their policies and reduce the impact of tariffs or conflicting regulations on each other's industries. This alignment is crucial as both regions aim to strengthen their EV sectors and reduce their reliance on China for critical minerals. Pointing towards further collaboration opportunities in the EV mineral supply.

Overall, the tariffs and trade restrictions have highlighted the vulnerability of global supply chains that depend heavily on a single producer for critical materials, pushing many countries to diversify their sources and reduce reliance on China. For example, in 2023, China imposed export restrictions on several key rare metals in response to U.S. trade tariffs on Chinese-made products. This caused a surge in prices and added pressure on Western industries that depend on these materials for products like semiconductors and renewable energy technologies (Business Insider, 2024).

The reliance on China for rare earth elements is a longstanding issue. In 2018, China accounted for approximately 71% of global rare earth elements production, which led to an outsized influence on supply and pricing. The U.S., Europe, and other regions have attempted to reduce this dependency, but alternatives have been slow to materialize. Historical export quotas and price manipulations by China have also pushed many global producers out of the market due to unsustainable price competition (Morrison, 2019).

5.2 Recommendations for policy makers and other stakeholders

There is a pressing need for governance frameworks and measures to sustainably manage mineral resources. This is due to socio-environmental and governance risks that could potentially limit mineral supply in the near future (Liu et al., 2022). It should also be taken into consideration, that the fact that there is no advantage to electrification of our transport habits unless the vehicles themselves as the fuel are produced sustainably (Guzmán et al., 2022).

In terms of alternative technologies or innovations to reshape the current supply chain, the recycling of batteries covered in 3.3. appears to be a valid approach to the reduction of mining activities, negatively affecting both the local communities of third world countries as well as the environment. Toro et al. (2023) propose the construction of a circular economy for batteries necessitates concerted efforts in enhancing recycling economics through scaling and automation, improving technology for efficiency gains, and designing batteries with recycling in mind. Designing batteries with recyclable property especially might lead to better practices. This improvement could be compared to the historical case of cathode ray tube (CRT), which contained leaded glass and as such presented a health hazard and challenges in safe recycling (Meng et al., 2016), to liquid crystal display (LCD) introduced complexities in disassembly due to mixed materials. This transition required recycling facilities to innovate new processing technologies, prompted updates in e-waste regulations, and increased emphasis on electronics' reuse and repair (Bhakar et al., 2015). The case illustrates the need for adaptable recycling strategies in response to evolving product designs, offering insights for improving battery recycling processes. Toro et al. (2023) also emphasizes the strengthening of collection systems, formulation of supportive policies, and fostering of research of high importance for effective recycling of batteries. According to the article stakeholders, including recyclers, manufacturers, governments, corporations, and academia, must collaborate, with each group playing a specific role from integrating recycling considerations in battery design to implementing educational and regulatory frameworks that support recycling initiatives. This collective approach is indeed key to advancing sustainable battery recycling practices.

In response to the urgent need for enhanced energy security, the reduction of pollution, and the fight against global climate change, countries around the world, both developed and developing, have implemented policies aimed at transitioning their transportation sectors to electric power (Wu et al., 2021). Policymakers must establish frameworks promoting ethical sourcing and environmental protection in mineral extraction. Invest in domestic mining and processing to reduce dependency on imports and enhance supply chain security. Incentivize research on recycling and alternative materials to diversify supply. Corporations will have to prioritize sustainability and ethical practices in the supply chain. Engage in partnerships for secure, responsible mineral sourcing. Innovate in material efficiency and recycling to reduce demand for virgin minerals. For other stakeholders, a recommendation of the support of transparency and traceability initiatives in mineral sourcing can be made. Advocation for policies that ensure sustainable and ethical practices across the EV production chain are required. As well as encouraged investment in technology to improve mineral recycling and recovery.

Sovacool et al. (2020) recommended diversifying mining enterprises for local ownership and livelihood dividends, exploration of new mineral streams, incorporating the minerals into climate and energy planning and acknowledging the limits of traceability. Diversifying mining to include both large-scale operations and ASM can enhance local economies and livelihoods. ASM, engaging over 40 million people globally, is more integrated into local and national economies than foreign-owned mines, often retaining more value domestically (World Bank, 2020). However, formalizing ASM faces challenges like permit scarcity, high costs, and bureaucratic hurdles. Encouraging ASM through bottom-up formalization and better integration into formal markets, as seen with initiatives like the London Metals Exchange's "nondiscrimination" policy, can support sustainable development and meet the mineral demands of a low-carbon future. Exploring new sources of minerals is vital for supporting clean energy infrastructure. Beyond emphasizing resource efficiency and recycling, there's a growing need to diversify supply chains through new streams like seawater desalination, geothermal brines, and technological substitution. While terrestrial mining will continue to be significant, oceanic mineral sources, as already established under the technological advancement review part of the thesis, offer long-term potential, necessitating environmentally cautious exploration. Innovations in recycling and advancements in materials science are key to extending mineral lifespans and ensuring sustainability in supply chains (Sovacool, 2020).

The aspect of incorporation of metals essential for low-carbon technologies into climate planning is crucial as well. This integration could occur through mechanisms like nationally determined contributions under the Paris Accord, the European Commission's National Energy and Climate Plans, or national energy policies. By aligning nationally determined contributions with a list of critical minerals for energy security, climate planners can address mineral sourcing challenges while promoting resource efficiency. This approach not only enhances mineral supply chain mapping and understanding of supply-demand dynamics but also fosters collaboration between the mineral sector and climate policy communities, aiming for a unified strategy that meets environmental, political, and economic goals (Sonter et al., 2018).

Lately the efforts to enhance transparency in mineral mining through traceability and ethical minerals schemes have gained international support. The practical enforceability of these schemes is, however, challenging, and they risk being more about public relations than real improvements for miners. Success in traceability hinges on accurate data and market trust in the schemes' authenticity. Lessons from initiatives like the Kimberley Process for diamonds suggest that while traceability can offer technical solutions, addressing the underlying political issues is crucial for meaningful change. Ethical challenges of mineral and metal supplies for decarbonization involve aligning trade policies with mineral supply in economically and ecologically efficient ways. It also requires strong reporting and consideration of the ecological impact of sourcing. Embracing principles of the circular economy, market transparency, and full lifecycle reporting could bring social and environmental benefits. Tools like the Responsible Mining Index can guide more responsible sourcing, aiming for a positive development footprint and manageable environmental impacts, thus supporting both decarbonization and sustainable development goals (Sovacool et al., 2020).

As reviewed by Bamama et al. (2021), technological innovations that tackle issues like climate change need to evaluate both their environmental footprint and societal effects to fully comprehend their overall impact. They further argue that achieving this comprehensive understanding requires collaborative work across various disciplines to improve Social Life Cycle Assessment (S-LCA). Such collaborations should, according to their article, engage social scientists skilled in discerning and describing social impacts, natural scientists capable of assessing environmental quality, and engineers dedicated to creating technology. With data from thorough Environmental Life Cycle Assessment (ELCA) and soon, enhanced S-LCA, decision-makers, corporate executives, and consumers are likely to be better positioned to accurately assess the societal and environmental repercussions of the technologies they endorse.

To communicate a strategic recommendation for stakeholders involved in battery production for EVs, focus on the procurement of raw materials to manage costs effectively and ensure a steady ramp-up of production capabilities is required. The raw materials are sourced primarily from either the extraction and refinement of new metals or the recycling of end-of-life batteries and production waste. Given that newly extracted materials are forecasted to dominate the supply until at least 2030, battery manufacturers' dependency on fluctuating commodity prices is high. In response to this, it is recommended that in the short term, manufacturers should secure stable material costs and availability by entering multi-year contracts with mining firms. In the long term, to soften potential supply constraints due to geopolitical and labor factors, stakeholders should develop comprehensive recycling programs that not only handle materials from their own batteries but also from external sources. This could be integrated into the initial sale of batteries through recycling agreements to widen the supply base. Larger entities should consider direct investments in raw material extraction and refining processes, capitalizing on the growing economic potential within the material market. Furthermore, aligning battery production with EV manufacturing is becoming increasingly significant. Despite the global push towards investment in the battery value chain, most of the equipment suppliers, particularly in the coating and cell assembly segments, are in Asia. This forces companies, particularly those in North America and Europe, to establish robust international sourcing relationships to overcome this geographical disparity. Considering that most raw material refining activities are currently concentrated in Asia, with localization prospects appearing limited, companies should also weigh the feasibility of refining location decisions against the backdrop of energy costs, since refining is energy intensive. As such, sitting refineries closer to raw material sources might be more economically sensible than near the end markets (Breiter et al., 2022).

6 CONCLUSION

The thesis examined EV production minerals, examining the layers of their applications, from batteries to structural components, and emphasized the significance of rare elements in motors. The analysis delved into the geographical distribution of minerals, revealing the global dynamics of production, reserves, and resources. Historical prices through the past years revealed price volatility across all involved minerals while future demand forecasts of the covered minerals required in EVs revealed an overall increase across all minerals as of this point. Further exploration provided insight into the effect of the demand for EVs on other industries reliant on the same minerals, casting light on the interesting interdependencies that characterize our modern industrial ecosystem. The dive into the supply chain workings created a clearer shape of the complex role of corporations and stakeholders, from mining companies to EV manufacturers, and highlighted the critical oversight of governments and NGOs which battle for ensuring ethical and sustainable practices. An observation of what lies ahead identified emerging technologies and players poised to redefine the mineral supply landscape for EVs. The evolution of battery technology, particularly the development of solid-state batteries and advancements in battery recycling, showcase the industry's commitment to sustainability. These technologies not only promise enhanced performance and safety for EVs but also pave the way for a circular economy in which critical minerals are reclaimed and reused, reducing the environmental footprint of battery production, and minimizing the need for new mining. A further analysis of the mineral market's impact on economies, particularly in the DRC, China, and the lithium triangle countries, unveiled the socio-economic and environmental challenges these nations face. Yet, it also highlighted opportunities for growth, sustainability, and innovation. The future of mining in DRC will require a drastic change in its operations and overall control to secure a bright environment that respects human rights and ethics. China will likely reign supreme in the near term all due to its mineral dominancy unless a sound strategy is developed by competing countries. The lithium triangle countries have a unique opportunity to reshape their economies which could advance them to the levels of present oil dominant Arabic countries.

Looking forward, an outline on the challenges that loom over the mineral market for EV production, such as supply constraints, geopolitical tensions, and environmental degradation was presented. Considering these challenges, a meta-analysis and proposition of targeted recommendations for policymakers, corporations, and other stakeholders to foster a more sustainable, equitable, and efficient mineral supply chain was delivered. In conclusion, the transition to full electric mobility is not merely a technological shift but a socio-economic transformation as demonstrated, that relies on the sustainable and ethical procurement of essential minerals. As we are already all embarked on the ship of this green revolution, it is needed for all stakeholders to collaborate in successfully navigating this ship, leveraging opportunities, and shaping a future where the environmental promise of electric vehicles can be fully realized without compromising the health of our Earth or the dignity of its inhabitants.

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APPENDICES

Appendix 1: Povzetek (Summary in Slovene language)

Zaključno delo je preučevalo minerale - litij, kobalt, nikelj, grafit, baker, mangan, aluminij, železo ter redki zemlji neodimij in disprozij - ki se uporabljajo pri proizvodnji električnih vozil, ter analiziralo korist njihove uporabe, od baterij do strukturnih komponent. Med drugim je poglobitev v geografsko razporeditev mineralov razkrila globalno dinamiko proizvodnje, zalog in virov. Zgodovinske cene v zadnjih letih so pokazale volatilnost cen vseh vključenih mineralov, medtem ko so napovedi povpraševanja po mineralih, potrebnih za proizvodnjo električnih vozil, pokazale splošno rast povpraševanja po vseh mineralih. Nadaljnje raziskovanje je ponudilo vpogled v vpliv povpraševanja električnih vozil na druge industrije, ki so prav tako odvisne od istih mineralov, ter izpostavilo zanimive medsebojne povezave, ki zaznamujejo sodobni industrijski ekosistem. Poglobitev v delovanje dobavne verige je razkrila kompleksno vlogo korporacij in deležnikov, od rudarskih podjetij do proizvajalcev vozil, ter poudarila kritično vlogo vlad in nevladnih organizacij, ki si prizadevajo za zagotavljanje etičnih in trajnostnih praks. Pogled v prihodnost je izpostavil nove tehnologije in akterje, ki obetajo preoblikovanje oskrbe z minerali v sektorju električnih vozil. Razvoj tehnologije baterij, zlasti razvoj trdnih baterij in napredek pri recikliranju baterij, kaže zavezanost industrije trajnosti. Te tehnologije ne obljubljajo le izboljšane zmogljivosti in varnosti za EV, temveč tudi odpirajo pot krožnemu gospodarstvu, v katerem se ključni minerali ponovno pridobijo in uporabijo, s čimer se zmanjša okoljski vpliv proizvodnje baterij in potreba po novih rudarskih aktivnostih. Nadaljnja analiza vpliva trga mineralov na gospodarstva, zlasti v Demokratični republiki Kongo, na Kitajskem in v državah litijevega trikotnika, je razkrila socio-ekonomske in okoljske izzive, s katerimi se te države soočajo. Kljub temu pa je razvidna tudi priložnost za rast, trajnost in inovacije. Prihodnost rudarjenja v Demokratični republiki Kongo bo zahtevala drastične spremembe v operacijah in celovitem nadzoru, da se zagotovi svetla prihodnost, ki bo spoštovala človekove pravice in etiko. Kitajska bo verjetno ostala dominantna v bližnji prihodnosti zaradi svoje mineralne prevlade, razen če konkurenčne države razvijejo učinkovito strategijo. Države litijevega trikotnika imajo edinstveno priložnost, da preoblikujejo svoja gospodarstva in se približajo ravni naftno dominantnih arabskih držav. Z napovedjo prihodnjih izzivov na trgu mineralov za proizvodnjo električnih vozil, kot so omejitve dobave, geopolitične napetosti in okoljska degradacija, je bila predstavljena tudi meta-analiza in predlogi usmerjenih priporočil za oblikovalce politik, korporacije in druge deležnike, da se spodbudi trajnostna, pravična in učinkovita oskrbovalna veriga mineralov. Zaključek naloge poudarja, da prehod na popolnoma električno mobilnost ni zgolj tehnološka sprememba, temveč tudi družbena transformacija, ki temelji na trajnostni in etični pridobitvi ključnih mineralov. Ker smo že vkrcani na ladjo te zelene revolucije, je nujno, da vsi deležniki sodelujejo pri uspešnem krmarjenju te ladje, izkoriščajo priložnosti in oblikujejo prihodnost, kjer se bo okoljska obljuba električnih vozil lahko v celoti uresničila brez ogrožanja našega planeta ali dostojanstva njegovih prebivalcev.